Memoir 56

J.B. AUDEN

A Centenary Tribute

B.P. Radhakrishna

GEOLOGICAL SOCIETY OF INDIA
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Preface

This book is brought out to honour the memory of J.B. Auden, formerly of the Geological Survey of India (1927-1953), a truly great scientist specialized in studies of the Himalaya, a pioneer in the field of Engineering Geology and Groundwater and a versatile genius with varied interests. His two essays on the Geology of the Krol Belt and the Geology of the Vindhyan Sedimentation are excellent treatises which every student of geology of India should read.

The lengthy introduction giving the outline of his career is intended to revive the memories of this large-hearted geologist, of his interest in India and its culture. Younger geologists will derive inspiration from his works and become better geologists in following his footprints.

I am grateful to Anita Money, eldest daughter of J.B. Auden for furnishing information on the family background of her parents.

Prof. R. Vaidyanadhan, formerly of the Andhra University, Sri B. Ramachandran of the Geological Survey of India and a close associate of J.B. Auden, Sri S.V. Srikantia, also of the Geological Survey of India and Dr. H.K. Gupta, Secretary, Department of Ocean Development, Government of India, have rendered help in editing and furnishing editorial comments, highlighting the importance of each contribution. The Director General of the Geological Survey of India has permitted reprinting some of the articles of Auden, which were originally published in the Records and Memoirs of the Geological Survey of India. I am grateful to all of them for their help and assistance.

B.P. RADHAKRISHNA

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John Bicknell Auden
(1903-1991)

"55 years ago, on a beautiful pre-monsoon spring Arnold Heim and the writer met John Auden in his mapping area, the hills of the Mussoorie region in the Kumaon Himalayas. Following special arrangements with the Geological Survey of India,.. we had the great privilege to be introduced into the Himalayan geology by one of its greatest experts, John Auden."

This is how Augusto Gansser, the well known Swiss geologist and the author of the classic work on Himalaya, sized up John Auden. Gansser recalled with great pleasure the one week spent with Auden walking through the hills, covered with large and flowering rhododendron trees and with a background

of over 200 km of the glacier covered Himalaya, dominated by the Badrinath and Nanda-Devi peaks glistening in the beautiful sunshine.

Auden was the last Englishman to be recruited to the permanent cadre of the Geological Survey of India in November 1926 as Assistant Superintendent and the last to leave that organization in 1953. Offered the Directorship of the Survey, he declined partly on health grounds and partly because he felt that an

Indian should succeed M.S. Krishnan, the first Indian Director, but also because he felt that 'the Geological Survey would be expanding and would be getting almost out of control resulting in too many headaches with recruitment and State representation.' He served for 27 years in the Survey of which 10 years were spent in Himalaya and the rest in organizing work in the new division of Engineering Geology and Groundwater.

Early life (1903-1926)

Auden was born on 14th December, 1903, at York, as the eldest son of Dr. George Augustus Auden, a distinguished psychologist as-well-as archaeologist, and a medical practitioner who maintained wide scientific interests. Auden's mother was a graduate in French from the University of London and served as a nurse in St. Bartholomeau Hospital. John spent a happy childhood with his brothers Bernard and Wystan, in an atmosphere at home which was more scientific than literary. The family moved to Birmingham in 1908 where his father served as a school medical officer and Professor of Public Health. Even as a child John evinced keen interest in the three dams of Birmingham water works, and recalled sixty years later how holidays spent in the hills with his brother Wystan satisfied his intellectual curiosity about natural phenomena. Wystan Auden, younger brother of John became a famous poet and man of letters with leftist leanings whose verse dramas were written in collaboration with Christopher Isherwood. In 1939 Wystan settled in US, becoming a US citizen.

John went to Cambridge to study geology, graduated in 1926 and joined the Geological Survey of India almost immediately thereafter.

Geological Survey of India (1926 - 1953)

Joining the Survey Auden was immediately assigned work in the Raniganj coal field (1927-28) and later (1929-31) worked in Uttar Pradesh and Rajasthan. The ten-year period between 1928-39 was, however, spent in studies in Himalaya mostly in Punjab and Uttar Pradesh, Nepal and Sikkim during which, apart from official surveys, he participated in six expeditions to the high ranges between Karakoram and Sikkim. During this period he was mostly out in the field, spending the summer months in the study of Himalaya and the winter months surveying the Vindhyans of the Son Valley.

Himalayan Geology

In October 1935, he was in the Gangotri, an unknown area of Garhwal with D.G. MacDonald and three sherpas. Here, in 1939 he crossed a pass at the head of the Rudugaira valley in the north, to the Bhilanganga valley in the south, which is now known as 'Auden's Col'. He also explored the Jadh Ganga, Mana Gad and the Lamkhaga valleys.

One of his earliest papers published in the Records of the Geological Survey of India was on the Age of certain Himalayan Granites, basing his study on a small pebble of granite in a 'volcanic breccia' of Garhwal. Petrographically the pebble was considered to be an albite-oligoclase granite similar to the white granite along the Arwa valley. He argued that the granites of Central Himalaya, considered to be of Tertiary age really belonged to an older period (pre-Triassic), were of diverse type and probably of more than one age.

Eight years of work in the outer Himalaya between Jamuna river and Lansdowne in Garhwal area demonstrated for the first time existence of great overthrusts.

Based on traverses in the Himalaya, undertaken to study the effects of the Bihar earthquake of 1934, Auden was the first to give a comprehensive account of the geology of Nepal in 1935 and presented a generalized section across central Nepal. Referring to the work of Auden in this period Gansser stated:

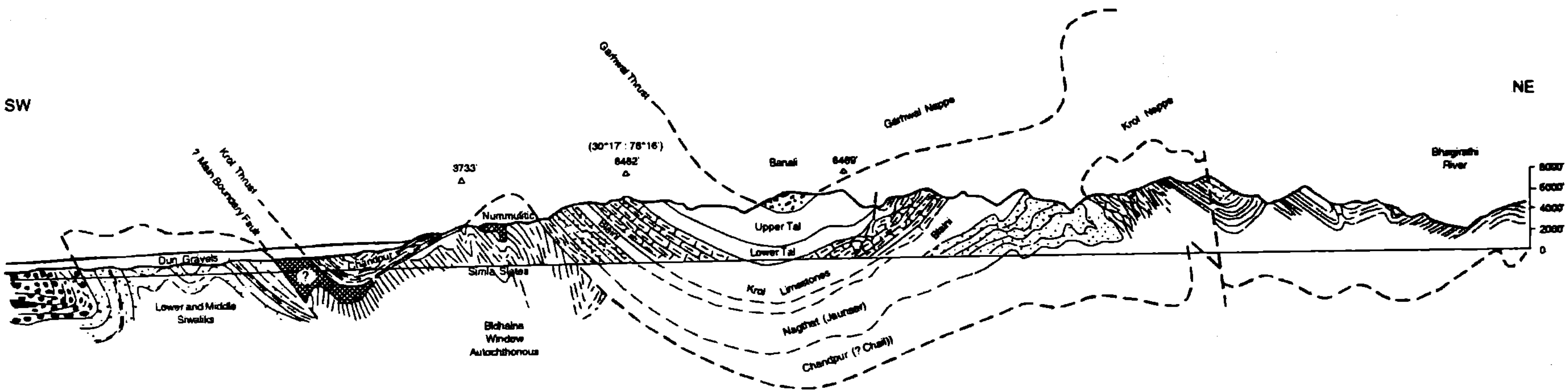
> 'With his great Himalayan experience Auden recognized the general structural outline. He stressed the widespread gneiss thrusts, reminiscent of the Darjeeling gneiss, overlying vast extensions of Dalings. He also recognized the EW striking thrusts in the Katmandu region and drew attention to the remarkable cross features in the Arun and Tamur valleys and compares them with the cross structures of Sikkim' (Gansser, 1964, p252).

Auden worked for many seasons between Solon and Lansdowne and recalling the fine time spent in the Himalaya, he wrote:

> 'Happy periods not withstanding the sweat and fatigue, during six years of which 1.6 million feet (488 km) was ascended. Work in the main ranges of Baltistan, Garhwal to Sikkim had to be done during the period of leave and the purchase of high altitude equipment and transport at one's own expense because there was reluctance by the authorities to realise that traverses in the high ranges could produce any result of value.'

In 1937 Auden joined the Shakagam expedition for four months under the leadership of Eric Shipton – exploring the glaciers and watersheds of the high Karakoram and Aghil ranges with the 8611m Mount Godwin Austin (K_2), the second highest mountain peak in the world and the only fixed point the expedition could use for locating itself.

Gansser considered Auden's greatest contribution to the geology of the Himalaya was the result of his regional reconnaissance expeditions from early



Diagrammatic representation of the nappe structure of Garhwal Himalaya (J.B. Auden, 1937).

1933 to 1935, covering large areas from Karakoram to Sikkim and published in the Records of the Geological Survey of India between 1935 and 1937. In 1939 Auden went on an expedition to the Nelong-Gangotri region in one of his self-sponsored traverses and he was also the first to survey the Saraswati valley (Badrinath at an elevation of 5900 m). Many of the problems in Himalayan geology which confront present-day workers bothered Auden in those early days. He had realized the danger in early generalization from incomplete observations. However, he felt it desirable to place his observations on record so as to build a scaffolding for later formulation of a geological structure which would eventually emerge from detailed work.

Auden was convinced that crystalline rocks of the Peninsula were involved in the Himalaya and the Aravalli strikes found locally in the rock structures in the Garhwal Himalaya suggested a northward extension of Peninsular rocks within the Himalaya. In order to stress this point he coined the word 'Peninsular Himalaya'. The structure of this early pre-Vindhyan orogeny is believed to have been incorporated in the Himalayan folding phase, and the structural grain of the Aravallis had influenced the tectonics of the Himalaya in many ways.

Bihar Nepal Earthquake of 1934

A devastating earthquake of great intensity struck north Bihar and Nepal on 15th January 1934. Within three minutes Monghyr and Bhatgaon were in ruins, as also large parts of Motihari, Muzaffarpur, Dharbanga, Katmandu and Patan. Thousands of people lost their lives and extensive damage to property was caused. J.A. Dunn, D.N. Wadia, J.B. Auden and A.M.N. Ghosh were deputed to investigate the central devasted area of Bihar and Nepal, while studies of the Nepal region were undertaken by Auden alone.

The report written by him gives an excellent account of the effect of the earthquake, ground movements, collapse of buildings, damage to railway, fissures, emission of sand and water, ground affected by slumps, changes in water level, permanent changes in drainage, landslides and lakes, increased flow of water in mines and such other features.

Dunn and Auden, in a separate chapter, analysed the 1833 and other shocks in Bihar and Nepal. Wadia and Auden presented a summary of the geology and structure of northern India in which an important point made out was that the Indian portion of Gondwanaland extended northwards beyond the Indo-Gangetic alluvium and included what is now the Himalaya. They also made special reference to the great thickness of boulder conglomerates, as much as 5000 feet, in NW Punjab.

The account provided by Wadia and Auden is an excellent summary of the history of Northern India during the Tertiary and Quatern ·v. According to them the Bihar earthquake originated not in Himalaya but belo\\ ·n the Gangetic alluvium which was a downwarp, a depression filled with light alluvial sediments. They also pointed out that the downwarped Gangetic basin had not yet begun to rise and become isostatically adjusted.

Krol Belt of Simla-Chakrata region

Auden's study of the highly complicated geology of the Krol belt is one of his best contributions to Himalayan geology and one that is frequently quoted by all subsequent workers. The controversy about the Krol was centred round the Blaini Boulder Bed which was correlated with the Talchir of upper Carboniferous age. Recent work, however, has revealed it to belong to terminal Proterozoic, based on the presence of Lower Cambrian fossils in the Tal. The geological map of the Krol belt by Auden (1934) has formed the basis for all subsequent work in Lesser Himalaya and his recognition of Jaunsar and its classification into Mandhali, Chandpur and Nagthat has stood the test of time.

Auden (1937) too postulated nappes, the Krol and the Garhwal nappe superposed one over the other and thrust forward to the obliteration of the autochthon at places. This interpretation has been confirmed by Heim and Gansser who have recognized a number of nappes and several compound thrust sheets of different sizes and depth from north to south. In presenting the newer interpretation Auden stated:

> 'In no sense can the present opinions be considered final. They are put forward for the purpose of crystallizing out the information and deductions before the collected data becomes too unwieldy. In regions of such complexity, modification is bound to result from continued work and fuller knowledge, but the later work is only a growth from that which has preceded and dependent on it (Auden, 1934, p.364).'

This humility of approach even while making outstanding contributions towards our knowledge characterizes the work of Auden in the Himalaya.

In the Simla region of the Punjab area, Auden considered the arkoses from the Jaunsar and Tal formations as derived from older granitic rocks. He also mentioned the presence of older granites with abnormal Aravalli trends.

Gansser refers to Auden's early geologic work in the Kumaun region, specially the Krol belt, as *brilliant* (Auden in his copy of Gansser's book has a pencilled remark – '*Nice bouquet*'). He is credited with recognising the magnitude of the crystalline thrust sheets in the Kumaun Himalaya, later confirmed by Heim and Gansser. Auden also worked out the stratigraphy of the Simla-Krol belt, describing the Jaunsars and classifying the sequence from bottom to top as the Mandhalis, the Chandpurs and the Nagthats. Auden's account of the Krol belt is labelled *'masterful account'* by Gansser.

Even after leaving India and involving himself with newer assignments, Auden never lost interest in Himalaya. He kept in close touch with all that was happening and never missed an opportunity to question newer interpretation of features described by him, thirty to forty years earlier.

The criticism of A. Ranga Rao of the ONGC, questioning his earlier observations of the Krol nappe hypothesis and his lengthy reply (*JGSI*, v.11, no.3, 1970, pp.288-302) can be cited as an example of his continued interest in Himalayan geology and the accuracy of his earlier observations. Commenting on Ranga Rao's work he wrote:

> 'It is 31-42 years since I mapped in the region between Solan and Lansdowne and 36 years since my publication appeared which suggested that the rocks of the Krol belt occur as a nappe. Both time and subsequent occupation with other aspects of geology in several countries have tended to dim my memory of many of the critical localities and geological problems.'

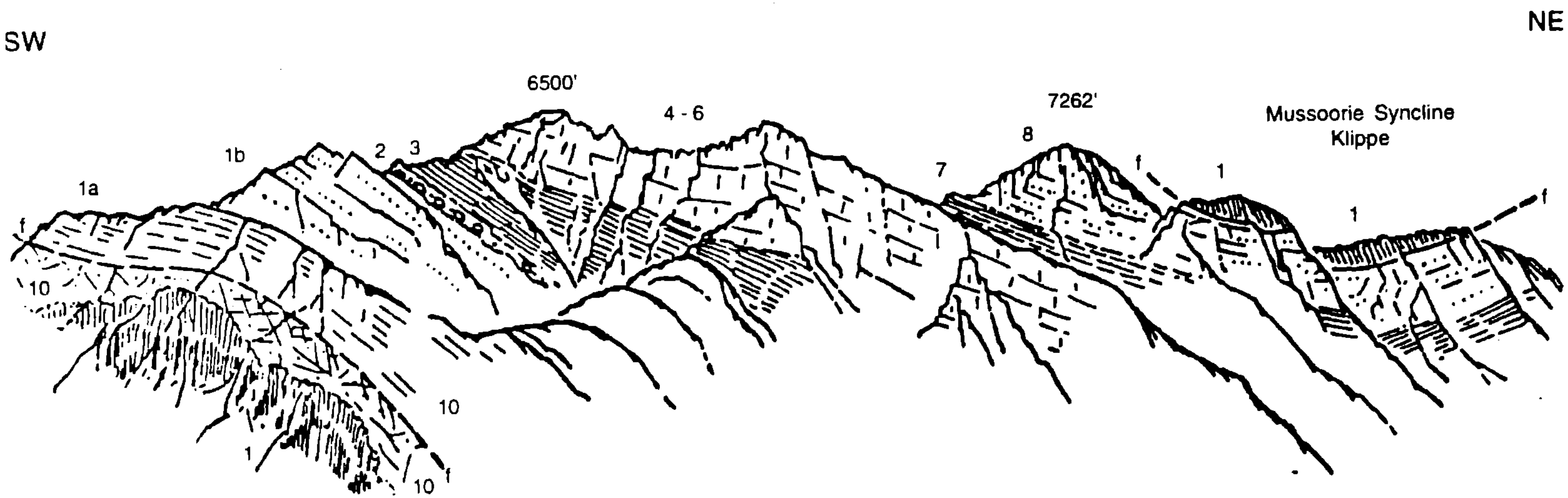
Notwithstanding these deficiencies he replied to the criticism of Ranga Rao at length and concluded that the different nature of the formations which occur below and above the Nummulites throughout the Himalayan foothills is not stratigraphical but is due to a succession of thrust plates having broken up the original diversified floor upon which the Nummulites were deposited.

'One of the greatest Himalayan geologists'

The early insights to Himalayan geology based purely on Himalayan field interpretations made Gansser rank Auden as one of the greatest Himalayan geologists. Auden's devotion to duty is unmatched in the entire history of the Survey. He had surrendered European furlough leave on several occasions in order to be able to traverse high Himalaya of Baltistan, Garhwal and Sikkim with his own high-altitude equipment and at his own cost in travel expenses, field guides and manual transport! Auden's important contribution to Himalayan geology was based on extensive mapping during the period 1934 to 1937.

Gansser, recapitulating his first encounter with Auden when he was assigned to introducing him to Himalayan geology recorded:

> '.... During these days John Auden acquainted us with the facts of the highly complicated geology of the Krol belt, the subject of one of Auden's best publications: 'The geology of the Krol belt, 1934'. He clearly recognized the various lithologies and structures, but he was very cautious in assigning ages based on the scarce and unconvincing fossil evidence. No rock sequences in the whole Himalaya have subsequently changed their stratigraphy as much as the deposits of the Krol belt.



The Krol Formation in the Mussoorie hills. Field sketch by A. Gansser, geology by Auden. **1** - Simla slates, **1a** - Chandpur slates, **1b** - Nagthat quartzites, **2** - Blaini tillites, **3** - Infra Krol, **4** - Lower Krol, **5** - Red shales, **6** - Upper Krol limestones, **7** - Lower Tal, **8** - Upper Tal quartzites, **9** - Upper Tal limestones, **10** - Nummulitic (Eocene) transgressing authochthonous Simla slates. Sketch drawn in 1936.

'John Auden had a very convincing way explaining the field facts which I immediately tried to sketch into my field book (Fig.2). In the evenings, in the various very well organized field camps followed an animated discussion, not only about local problems, but we were able to listen to Auden's reminiscences from his many traverses done just a few years before, from the Karakoram in the west to Sikkim in the east. On the last day, we followed the long ridge leading to Mussoorie. Auden striding ahead with his long legs and his curly blond beard, still walking through rhododendrons and the far High Himalayas with rising cumulus clouds. In the Savoy Hotel of Mussoorie we soon became civilized and ended the day with a game of ping-pong. Mussoorie was still a small place, superb with blooming gardens. It became famous already in 1832, when George Everest chose it as his headquarters for one of the greatest achievements of those days, the measurement of the great meridional arc over a distance of 2400 km from Cape Comorin to near Mussoorie.'

'The farewell in Dehra Dun came much too soon and it was only 35 years later that we met again, when I had to deliver the William Smith lecture in London'.

'With the war, John Auden was transferred to assignments in economic geology and had to leave Himalayan research. In a letter, in connection with the publication of his Wadia Memorial lecture, written in September 1982 – he was then 79 years old – he told me: *'It seems another era when you, Arnold Heim and I were together in the Dehra Dun foothills. My great regret was being transferred as soon as the 1939-45 war broke out to work on economic, engineering and groundwater geology. Not that work was not of absorbing interest, but the transfer meant that it was impossible to continue with the Himalayan work, except for periodic visits to the mountains in connection with dam sites and diversion tunnels. While working on an alternative alignment for a diversion of the Sun Kosi through the Mahabharat Lekh in 1965 and 1966 a Pilatus Porter plane would drop me down on a 200 m alluvial terrace and pick me up 2-3 weeks later. The same plane unfortunately crashed near Bodhinath Temple, Kathmandu, killing Hillary's wife and daughter.'*

* * * *

'In Sikkim and eastern Nepal, John Auden observed already that the section between the Dalings and the Darjeeling gneisses *'may be regarded as illustrating a true progressive increase in metamorphism upwards'* (Records, 1935, p.163), a fact still vividly discussed today and which as early as 1878 led Louis de Loczy, while visiting the Darjeeling area, to suggest large recumbent folds (nappes). In northern Sikkim Auden emphasized the presence of discordant white tourmaline granites (leucogranites) within the gneisses of the High Himalayas, clearly cutting folds but also intruding some gneisses in lit-par-lit fashion, a fact stressed by Heron – then Director of the Geological Survey of India – already, in 1922, in the Everest region. *'All that can be stated at present is that the white, fine-grained tourmaline-granite of northern Sikkim appears to be youngest of the intrusives present, and, by analogy with the Chumbi granite, is probably Tertiary, while the intrusives it cuts may be either Tertiary or older'* (Records, 1935, p.166). Auden was further convinced that crystalline rocks, reminiscent of the northern Indian shield – where Auden worked for 10 years prior to his Himalayan assignment – were involved in the Himalayas. *'The Aravalli strikes found locally in rock structures in the Garhwal Himalaya also suggest a* *northward extension of Peninsular rocks into the Himalaya. These rocks have been subsequently involved in the Tertiary movements, without, it is believed, the original structures having been rotated by the later movements so as to lose their former orientation.*' (Records, 1935, p.157). This most important statement was later found valid in many parts of the 2500 km long Himalayan chain, variously stressed by K.S. Valdiya and the writer'.

'Himalayan geology received a decisive impulse by John Auden's recognition of large crystalline thrust sheets as the Garhwal nappe, in 1935, fully confirmed in the field a year later by Heim and Gansser. It was Auden's merit to reach these conclusions purely by Himalayan field interpretations and not influenced by the famous Alpine export product'.

'Later theories, such as the indiscriminate application of plate tectonics to the Himalaya 35 years later, left John Auden rather skeptical. He just could not fit the thousands of kilometers of travelling in India into his geological frame. In his last major paper, in honour of his friend D.N. Wadia, with the inspiring title 'India's former crustal neighbhours' (1981), we read: '*It would seem to the author that India has had a relatively close association with Eurasia throughout the Phanerozoic, notwithstanding the allowance which must be made for the crustal shortening during the formation of the Himalaya.*'

'And now that one of the greatest Himalayan geologists has passed away, we may recall him, striding with his long legs through blooming rhododendrons with a background of hundreds of kilometers of glaciated High Himalayan peaks to whose understanding he had contributed so much (Gansser, *JGSI*, v.37, pp.613-617).'

If Auden had been allowed to continue working in the Himalaya he would have probably produced a more satisfactory synthesis of the geology of Himalaya. This was left to Augusto Gansser who, in 1964, brought out the magnificent book on Himalayan Geology which remains a classic to this day.

Auden had developed a close personal relationship with Wadia and maintained a steady correspondence with him, exchanging notes on different aspects of Himalayan geology. When he heard of the establishment of Wadia Institute of Himalayan Geology he wrote: "It is good that the pioneer work of D.N. Wadia should now be perpetuated by the Institute after his name and should be the source of encouragement to a new generation of geologists working with modern concepts and techniques."

Auden kept up his interest in Himalayan geology by reviewing the publications brought out by the Wadia Institute, recalling in the course of the review facts gathered by him during his surveys carried out forty years earlier. These reviews have been of great value to the younger geologists working in the Himalaya.

Left to himself Auden would have probably continued tectonic studies of the Himalaya and come out with a synoptic summary. But the shift in his studies necessitated by the 1939-1945 war, the ushering in of Independence, and the organising of studies in Engineering Geology and Groundwater did not give him a chance of producing a more detailed and comprehensive account of the geology of Himalaya. Although no longer officially connected with surveys in Himalaya, he kept in close touch with what was happening. Opportunities came his way of evaluating hydroelectric and irrigation projects in the Himalaya in later years and his close association with the large number of workers engaged in the systematic surveys of the Himalaya kept him fully informed on the subject. His interest is revealed in the several reviews he wrote on contributions to Himalayan geology from time to time and his correspondence with the geologists engaged in Himalayan studies.

In one of his letters to Wadia (16 September, 1954) he wrote "How I wish it were possible to round off those years of work in the Himalaya from 1928 to 1939 with 2 to 3 seasons for integration and tidying up of loose ends. All my maps lie at Calcutta and I need permission to take them out, but even that permission would not take the place of field work and that alas seems to be very remote."

He developed great regard for Gansser for his book on the 'Geology of Himalaya' and felt that this treatise 'will long remain the most comprehensive and authoritative summary of the stratigraphy and structure of this wonderful range.' The beauty of this great work consists in its numerous text figures, superb photographs of the mountain peaks of this noble range, a series of profiles – all of them setting out facts more clearly than lengthy descriptions.

Auden was a very good correspondent and his colleague Ramachandran recalls his habit of very prompt reply to all geological correspondence coming to him from his young colleagues. In his reply he would take great pains to give a fuller account on the subject, besides references and cross references, recalling information from his own maps, diaries and notes, gathered thirty years back. This revealed his amazing knowledge of the science of geology in all its aspects, his wide reading and prodigious memory. "In his early years he was a member of the Lake Rowing Club besides being a founder member of the Himalayan Club. He was a keen photographer too and several picturesque views of the Himalayan peaks adorned his London home" (Ramachandran, 1993, p.5). His daughter Rita describes him as a dedicated scientist, a writer of distinction and lover of fine arts including painting, music and literature.

Vindhyan Sedimentation in the Son Valley

Detailed mapping of the Son Valley was one of the earliest works assigned to Auden as Assistant Superintendent of the Geological Survey of India.

The outcome of his detailed work on the Vindhyans resulted in the recognition of Semri Series replacing the term Lower Vindhyans and the grouping of Kaimur, Rewa and Bhander as fluvio-marine sediments showing sufficient similarity to be included in one major Vindhyan System. The Lower Vindhyans were folded while the Upper Vindhyans were generally undisturbed.

Auden recognized a distinct change in facies between Semri and Kaimur, from a calcareous to arenaceous facies reflecting a change in the environment of deposition, from a marine to a fluviatile regime.

Social Life in Calcutta

The European officers of the Geological Survey of India of those early days were an exclusive lot and avoided all social contacts with Indians. The advice given to the British community in India was: 'never under any circumstances give way to a native or let him regard himself as your superior. We rule India in one way – by safeguarding our position.' The Indian officers too came to accept western culture as superior to their own and started aping European customs and manners. The Englishman of those days had no sympathy for Indian aspirations towards Independence.

Auden proved a notable exception to this general rule and mingled with his Indian colleagues and took part in the cultural activities of Bengal. He first met Sudhindra Dutta, a most original figure of Bengali culture who was thoroughly modern and profoundly Indian in 1930. Dutta who had a deeply liberating effect on the new generation of poets in Bengal, was an official of the Damodar Valley Corporation, Assistant Editor of *Statesman* of Calcutta and Director of the Indian Institute of Public Opinion. He had a charming and gifted wife who was extremely active and sociable and noted for her catholicity, grace and warmth. None left Calcutta without a vividly moving impression of the beauty of Dutta's bearing, of his generous heart and his refined and discriminating tastes in every sphere of life. Auden very early in his life at Calcutta was attracted to this charming circle.

Marriage with Sheila (1940)

Auden first met Mrinalini Bonnerjee, daughter of R.C. Bonnerjee, a well known barrister and grand daughter of W.C. Bonnerjee, the founder President of the Indian National Congress. Mrinalini introduced her talented sister Sheila to Auden in 1939. Auden had learned to fly by then and had obtained a pilot's license. Sheila accompanied him on many of his flights and the two married in 1940 after which Sheila started travelling with him on his geological expeditions.

Two daughters (Anita in 1941 and Rita at Simla in 1942) were born to them and Auden had to run two establishments, one at Calcutta and the other at London to get his daughters properly educated. Anita studied at Oxford and Rita took to science, preparing herself to become a doctor. Auden had to pass through a difficult period as revealed in his letters to his daughters.

One of the reasons for leaving the Geological Survey of India was the poor salary which was not adequate to run two establishments, and meet the heavy expenses of educating his two daughters at prestigious colleges in UK.

Rita and Anita, daughters of Auden.

Sheila brought nothing except her love and recalling the hard days of their early life has written:

> 'For my sake you had to give up being a member of the Saturday Club at Tallygunge and many other privileges you could have enjoyed had you not had an Indian wife. I think in many ways it has been a disadvantage to your career and you have sacrificed a lot for your unusual marriage.'

Ramachandran records – 'In the late forties he contributed to the social life of Calcutta ably aided by his talented wife Sheila and in the company of his brother-in-law, Lindsay Emmerson of Statesman and Mrinalini Emmerson. There were long evening sessions at Emmerson's residence, where the poet Sudhindra Dutta, Bishnu Dey, S.N. Mazumdar of DVC, Air Marshal Subroto Mukherjee, General J.N. Chaudhary, P.C. Mukherjee and others used to join. The painters Jamini Roy and Atul Bose were his close personal friends.'

What is endangered in the world today, an Englishman wrote, is not the tiger or the lion but the family. India is to be admired for conserving and valuing the integrity of family life. The Audens were truly Indian in this respect. Indianness of India will be preserved only if it maintains a modest life for all rather than the luxury living for a few. Indian philosophy was great because it was most ancient but because it emphasised eternal and universal values. The Audens were a hospitable couple, played host to all people visiting their home and were a happy family.

In order to look after the education and upbringing of their two daughters Sheila spent a good part of her time in London. She found life lonely and the days which ought to be spent together were squandered. Her letters addressed to Auden during this period paint a picture of her loneliness.

> 'You have given the world the impression that I am a selfish spoilt wife - tied to her children, neglectful of her husband, who brave and lonely works hard in isolation to keep her in luxury. ....loneliness hurts .... No one knows the utter void in my life.'
>
> * * * *
>
> 'It is strange and lonely without you, but this time I shall try to get down to worthwhile activities. I do hope things won't be too awful and that there will be many rewarding moments for all the 'blood sweat and toil' – all my love and God bless you (Sheila 19-3-1969).'

The following excerpts from the correspondence of Sheila gives a picture of their life together in those early days of marriage.

> 'I want to be happy. But I can't be happy, till I have made you happy too.'
> 'You must be happy for my sake.'
>
> 'You have had plenty of glamour in your life and ENORMOUS achievement. Don't let lack of recognition turn everything to dust and ashes.'
>
> 'I don't know how much you felt bereft of love as a child but surely in later life you have been given some true love, most certainly the love of your children. And if my love lacked glamour – at least it was something to learn. Now it is time we used time and not let it use us. We shall insist on being happy and wear our painted smiles till they become real ones.'
>
> 'Come home quickly and be friends again. It is silly to quarrel when we need each other so much, or at least when I need you so much'.
>
> 'I must reconcile myself to the fact that you will always need excitement and that excitement you can never find in me. I shall just have to make myself more self sufficient and be truly grateful for the kindly protection you have given me for so many years despite my bad temper and cruel tongue.'

His first daughter Anita Money, M.A. (Oxon), ran an antique shop in London and later taught English and callisthenics.

Second daughter Rita, M.S., FRCS, became a doctor and worked in a

London hospital, sometimes performing six to eight operations a day and was on a deputation to Vietnam and Northern Ireland.

Sheila Auden was a good painter and when her right hand became insensitive due to arthritis she used her left hand. She passed away in London on 4th June, 2001, in her 88th year.

Auden as a teacher; Comments on geology as taught in India

As far back as 1892, the Geological Survey of India had assumed the responsibility of imparting education in geology to the Indian youth. One of the officers of the Survey was permitted to work as a part time Professor of Geology at the Presidency College, Calcutta. Auden, appointed as petrologist of the Survey in 1940, took to teaching geology. This teaching experience enabled him to make a correct assessment of the deficiencies in geological education in the country and he presented a paper entitled 'Some Deficiencies in Geological Training'. His observations were later printed in the Transactions of the Mining, Geological and Metallurgical Institute of India and excerpts from this paper give us an idea of his perceptions about teaching geology in India.

> 'The laboratory has thus in some places tended almost to usurp the whole scope of geology, under the false assumption that the supposedly precise chemical analyses of a few random, isolated specimens will provide, after suitable indoctrination, the total picture of the environment of the material, and the structural background of the region. Certainly it can be said that this procedure is one form of mental discipline, but under unwise control it tends to develop into learned nonsense. And it is highly questionable if such a discipline is at all an adequate training for the normal student who will not spend a lifetime of specialization in petrology.'
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> 'The science of petrology has been greatly advanced by the Niggli and other interpretative schools. But as developed in India, uprooted from the environments and educative systems in which they took growth, they have only a limited value in the teaching of geology. Admittedly an interpretation of analyses is essential, and this necessitates diagrammatic representation. Chemical, microscopical and petrofabric studies of rocks are all vital to the science. But in my opinion there is a danger that these formal systems of classification, as expounded in India, may become so enmeshed in their own symbolism that the significance of the field relationships is lost, and the purpose of the study becomes obscured and even forgotten. Papers on petrographic subjects in America, Britain and Scandinavia would appear in general to avoid the conception that the ultimate purpose of petrographic research is to place the rocks in a certain idealized triangular field with an obscure nomenclature. I should stress that I am not in any way criticizing modern petrographic research, but only the perversion of such research. If the student is not taught to have at least one eye directed more firmly on the ground and scenery, he will fail to understand that in hard practice, especially in the investigations of economic geology, precise field relationships are of paramount

the integrity of family life. The Audens were truly Indian in this respect. The Indianness of India will be preserved only if it maintains a modest life style for all rather than the luxury living for a few. Indian philosophy was great not because it was most ancient but because it emphasised eternal and universal values. The Audens were a hospitable couple, played host to all geologists visiting their home and were a happy family.

In order to look after the education and upbringing of their two daughters Sheila spent a good part of her time in London. She found life lonely and that the days which ought to be spent together were squandered. Her letters addressed to Auden during this period paint a picture of her loneliness.

> 'You have given the world the impression that I am a selfish spoilt wife – tied to her children, neglectful of her husband, who brave and lonely works hard in isolation to keep her in luxury. ....loneliness hurts .... No one knows the utter void in my life.'

* * * *

> 'It is strange and lonely without you, but this time I shall try to get down to worthwhile activities. I do hope things won't be too awful and that there will be many rewarding moments for all the 'blood sweat and toil' – all my love and God bless you (Sheila 19-3-1969).'

The following excerpts from the correspondence of Sheila gives a picture of their life together in those early days of marriage.

> 'I want to be happy. But I can't be happy, till I have made you happy too.'
> 'You must be happy for my sake.'

> 'You have had plenty of glamour in your life and ENORMOUS achievement. Don't let lack of recognition turn everything to dust and ashes.'

> 'I don't know how much you felt bereft of love as a child but surely in later life you have been given some true love, most certainly the love of your children. And if my love lacked glamour – at least it was something to learn. Now it is time we used time and not let it use us. We shall insist on being happy and wear our painted smiles till they become real ones.'

> 'Come home quickly and be friends again. It is silly to quarrel when we need each other so much, or at least when I need you so much'.

> 'I must reconcile myself to the fact that you will always need excitement and that excitement you can never find in me. I shall just have to make myself more self sufficient and be truly grateful for the kindly protection you have given me for so many years despite my bad temper and cruel tongue.'

His first daughter Anita Money, M.A. (Oxon), ran an antique shop in London and later taught English and callisthenics.

Second daughtei Rita, M.S., FRCS, became a doctor and worked in a

London hospital, sometimes performing six to eight operations a day and was on a deputation to Vietnam and Northern Ireland.

Sheila Auden was a good painter and when her right hand became insensitive due to arthritis she used her left hand. She passed away in London on 4th June, 2001, in her 88th year.

Auden as a teacher; Comments on geology as taught in India

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importance, and the laboratory is there as a tool, certainly a most important tool, to add precision to studies which should already in the field themselves be quantitative.'

* * *

'The teaching staff in the universities is of course badly paid, and often grossly overworked with lectures and demonstrating. Moreover, university grants are small. But most of the Indian universities are well placed in regard to working areas, and the local geology could be the subject of a sustained perennial examination by staff and students. There are not many professors in this country who really undertake any sustained field work with a view to the detailed study of even portion of a single 1/4" topographical sheet (say 4,500 sq. miles) in the manner done in Britain and on the Continent. Instead, there is a tendency to undertake a multitude of small investigations, involving minor field collections, rather than any prolonged endeavour to unravel the structure of the area.'

'For the normal geological student who is going to enter the Geological Survey of India, or the geological staff of a company, it is vital that there is change of emphasis on the part of the university teaching. First things should come first, elementary before difficult, crustal structure and the megascopic before petrofabrics and the microscopic, and it should be realized that the aim of all the specialized sub-studies, was as far as a university is concerned, is to provide a synoptic view of the region.'

Saurindranath Sen, former Professor of Geology, Calcutta University, recalls in his reminiscences how Auden, as a visiting lecturer from the GSI, captured his imagination with the sweep of his vision. 'His inspiring lectures motivated me to continue with my studies of geology and to embark on an intellectual journey through a process of self-education.' Auden felt that Departments of Geology should have a reasonably large travel grant so that research should be done by the staff and students in distant areas. Too many professors become immobilized through lack of funds for travel.

Educationists of present-day India would do well to take note of these comments and effect such changes as are necessary to make the student of geology a worthy leader in his profession, with field work as an essential part of his education.

Dykes in Western India

Auden undertook several air journeys from Calcutta to Mumbai in 1947 and, watching the unfolding scene below, became interested in the distribution of dykes cutting the Deccan trap in the Konkan region between the *Sahyadri* (Western Ghats) and Kalyan. The prevailing view was that the dykes in Kathiawar, Gujarat and Konkan functioned as feeders to the lavas. Auden came to a different view – that the dykes probably belonged to a post-lava hypabyssal phase. He showed that the dykes were not distributed in any haphazard manner, but occurred in clusters/swarms and in arcuate forms and were related partly to the plutonic masses of Kathiawar and partly to the folded zones in the trap of Gujarat and Konkan. He was the first to point to the existence of a folded zone in the trap near Panvel and Kalyan and to the relationship between the Panvel flexure and the dykes of Konkan and was of the view that the dykes were intruded after the full thickness of the traps had been erupted and folded (Auden, 1947, p.135). In making these suggestions Auden was apologetic about expressing an opinion on a field which was alien to his main interest. The Western dykes region of Kathiawar, Gujarat and Konkan, according to him, was a classic region with its own unique peculiarities, worthy of comparison with Greenland and the Western Isles (Auden, 1947, p.155).

The Satpura Hypothesis and the Garo-Rajmahal Gap

In 1944, S.L. Hora postulated the former existence of a mountain range extending from the Shillong plateau across the Rajmahal Gap, westwards to the Vindhyan-Satpura region, along which migration of fauna had taken place. The Garo-Rajmahal gap was considered to be of recent origin and had blocked the further migration of the eastern Malayan fauna.

Auden was greatly attracted towards tracing the geological history of the region extending from the present Satpura range eastward to the Mahadeo hills, Chhotanagpur, Rajmahal and the Shillong plateau, in the light of the earth movements which affected the Peninsula during the Tertiary and post-Tertiary times. Eruption of lavas in the Rajmahal hills took place in lower to middle Jurassic, but the 1500-3000 feet of Deccan traps in Sind, Cutch, Gujarat and Saurashtra erupted between upper Cretaceous and lower Eocene and exposed the traps to lateritisation before the deposition of the Laki beds. Over the rest of the Peninsula, eruption of the Deccan Traps took place in the Tertiary era. He also pointed to the existence of a profound unconformity between the folded Vindhyan, Gondwana and Deccan Traps as the latter showed no signs of folding because they erupted at a later date.

Auden did not envisage the existence of a major Satpura range extending across India during the Tertiary period which had worn down to the present elevations. The evidence available was more in favour of down-faulting along the Narmada and Tapti rifts at the close of eruption of the traps and to the unequal elevation of the region since the Miocene.

As regards the Garo-Rajmahal gap, he envisaged the existence of a probable connection between the Shillong plateau and the Peninsula during the Miocene. The creation of the gap itself took place during the Pleistocene along a NW-SE fracture extending from the Darjeeling Himalaya to Comilla and Chittagong. He felt it necessary to suppose that while the central part of the Peninsula was arched up during the Pleistocene, the bordering areas of Cutch, Saurashtra and northern Bengal were subjected to depression (Auden, 1949, p.334).

Auden considered it probable that climatic factors associated with the lower elevation of the Himalaya mountains permitted migration of fauna rather than the existence of any pronounced elevation along the present Satpura trend.

These arguments throw light on his fertile mind, constantly brooding over many of the geological problems encountered during the course of his work. The solutions offered indicate his brilliant analytical mind which enabled him to sift through the evidences and evolve interpretations acceptable to those actively engaged in research.

Engineering Geology and Groundwater Studies (1945-1951)

The outbreak of war with Germany and Japan, followed by the ushering in of India's independence from British rule, saw major changes in the work of the Survey. A new division, the Engineering Geology and Groundwater Division, was started in 1945 with Auden as its head. As a consequence, Auden had to give up his passion for Himalayan geology and transfer his attention to the study of major irrigation and power projects. Before initiation into the work of the new division, Auden was sent to the United States for a period of six months to get acquainted with the work of the Tennessee Valley Authority (TVA) under the Bureau of Reclamation.

On his return from US, he took charge of the new Division and plunged immediately into the work of investigating a number of multipurpose projects – DVC, Hirakud, Bhakra, Beas, Rihand, Narmada, Tapi, Koyna, Vaitarana and Mattupatty and a large number of water supply schemes for the civil and military establishments, townships and municipalities. He carried out studies on the groundwater resources of the arid region of Rajasthan, Kutch and Quetta which were the earliest systematic geohydrological studies in the country and paved the way for organized work under an independent Groundwater Division created in 1957. Very soon Auden became an authority on Engineering Geology.

Till then, engineers had completed structures like dams, tunnels, canals, power houses, bridges, rail roads, etc. without taking the assistance of geologists. Only when their structures failed, did belief in geologists and their analysis of foundation conditions began to dawn upon them.

'Dams must stand. Not all of them do and there are all degrees of uncertainties about them. Reservoirs must hold water, not all of them do and there are many ways by which water may be lost. The work may be done safely as a construction job. Not all of them are, and there are many sources of danger. The whole structure must be permanent and the work has a right to be done in the original estimate. Not all of them are and there are many reasons for their failure and excess cost, most of these are geologic or geologic dependent.' This is the statement made by C.P. Berkay and published in Tech paper 265 of AIME emphasizing the responsibilities of the geologist in engineering projects.

Auden devoted his entire energy to organizing work in this new division. Eight officers were selected and deputed to Melbourne University, Australia, for training under the supervision of Professor Sherbon Hill, noted structural geologist.

All the dam projects of Damodar Valley, Hirakud, Rihand, Bhakra, Beas, Narmada, Tapi, Koyna, Vaitarana, Mattupatty had the benefit of his advice and even after he left service in GSI he kept up correspondence with his former colleagues and wanted to know whether the conditions he had envisaged were actually encountered at the time of excavation. He very much wished that the final account of each dam had been published in the same way as the Bureau of Reclamation had brought out books on major dams in the Tennessee Valley. It is unfortunate that the engineers, as well as the geologists who reported on the geology of the dam sites, were not encouraged to take interest in publishing their results and the chance of preserving excellent case histories for the benefit of future workers was irretrievably lost.

Auden took his last leave of 28 months prior to premature retirement in 1953. In a letter addressed to W.D. West (14th January, 1983) he has given his reason for leaving the Survey:

> 'The GSI offered me in 1953, the Directorship but declined partly on health grounds, partly because I thought an Indian should succeed Krishnan, the first Indian Director and also because I felt that GSI expansion would soon be getting out of control resulting in too many headaches in the recruitment and state representation.'

His last visit to India was in 1981 when he came to deliver the Wadia Memorial lecture at the National Academy. He recalled his period with the Survey as one of transition.

> 'I was the last European to be appointed to the permanent cadre and the last to leave. We saw the beginning of jeep mobility at the end of the 1939-45 war, the introduction of aerial photographs in the early 1950's, but satellite pictures had not then been thought of. Independence in 1947 saw no violent upheaval in the tradition of the Survey, which in any case had for decades an international recruitment, but there was a growing recognition and support by the National Government of the importance of geology in the welfare of the land (Auden, 1976, p.44).'

His studies on the groundwater resources in the arid western Rajasthan, Kutch and Quetta were considered as landmarks in Indian Engineering Geology. (*Times*, Obituary note, 24 January, 1991).

In 1974 Auden delivered a lecture at Cambridge on "the Geological Aspects of Reservoirs and Reservoir Catchments". In introducing the subject he said:

> '... when I went out to India in 1926 I was totally ignorant of engineering matters. In the Geological Survey we had to learn the hard way, from ignorance to what I hope has been less ignorance; from a relatively academic study of the structure of the Himalayas to concern about the construction of dams and reservoirs in the Himalayan valley.'

He recalled also his association with the Indian engineer A.N. Khosla who later became the first Chairman of the Central Water and Power Commission and finally the Governor of the State of Orissa.

> 'We tramped many hundreds of miles through the Himalayan foothills and over many parts of the Peninsula, the Bhakra, 740 feet in height, being his greatest achievement.'

It is said that a doctor's mistake lies buried but engineer's mistakes live after them. The design of dams may be perfect but if it has not taken note of the environment or sub-surface geology the structure may end in disaster. Since the time of Auden a great deal of importance is given to the study of the geology of dam sites. Without a geological report no engineer will venture on the construction of dams. Not all geologists, however, are competent to furnish expert advice. They require to be suitably trained before allowing them to render advice. Engineering geology has become a highly specialized subject with dam site investigation becoming one of the most comprehensive branches of Applied Geology.

The Bhakra-Nangal dam across the river Sutlej was one of the major assignments with which the Geological Survey of India was connected. The site was examined by many geologists and engineers in order to verify the suitability and soundness of the construction of a high dam to store the surplus water of the Sutlej river. Originally a dam 400 ft (122 m) high was proposed without any provision for generation of power. In 1948, after independence, the final proposal of raising the height to 740 ft (226 m) was accepted in view of the greatly increased irrigation and power benefits.

The geological formation at the dam site was of Miocene age and consisted of alternations of shale and sandstone dipping downstream. These friable shales were obviously unsatisfactory for construction of an arch dam and, moreover, the dam site was only 90 km south of the epicentre of the Kangra earthquake of 1905.

Kosi was another river in the Himalayan region which presented a different type of problem having shifted its course by as much as 60 miles (96 km) at latitude 26°N. Floods of this river were severe and damage done every year to cultivation, roads and railways was great. Flood control studies, initiated by the Geological Survey in 1946 indicated that the only feasible means of flood control was the construction of a high dam within the Himalayan foothills before the river debouched into the plains. Here also the problem to be faced was geology and seismicity, as the dam site was 110 km away from the epicenter of the 1934 Bihar-Nepal earthquake. Another problem was the enormous quantity of silt carried by the river, amounting to 2000 m^3/km^2/annum which would considerably reduce the effective storage capacity of the dam.

Auden also became aware of the effect of the rising water table coming close to the surface causing toxic efflorescence of sodium carbonate, bicarbonate and sulphate rendering thousands of acres of fertile land unfit for cultivation. It became clear that drainage was just as much necessary as irrigation.

Many cases of reservoir induced earthquakes have been reported since the time of Auden. The earthquake at Koyna stimulated fresh interest in the triggering of earthquakes and a network of seismological stations was installed to monitor induced seismicity as a result of water loading in the reservoir. Tectonic explanation for the cause of the earthquake has been given, postulating the existence of rift valleys (Koyna and Kuradvadi) based on geophysical studies (Krishna Brahmam and Negi, 1973). The cause of seismicity at Koyna continues to be controversial.

Geologists have now to contend with environmentalists charging them with interfering with nature. 'Fill a lake, start an earthquake' is the title of a paper by a French Professor Rotha which appeared in *New Scientist* and provided 'ammunition to people who feel it as their duty to be the nostalgic guardians of our scenic heritage.'

> 'A great change has come over in our view of the utility of big dams. They were not viewed as commercial propositions but as an expensive form of national insurance to benefit the poor. The untold misery of the large number of people that would get displaced was shielded from public gaze. The glamour of building such structures has made us overlook the inexorable fact that their cost could be and often is out of all proportion to the number of persons likely to be benefited thereby'.

Groundwater in Rajasthan

One of the first reports authored by Auden on taking charge of the new branch of Engineering Geology and Groundwater was on the Groundwater Resources of Western Rajasthan. Success of the State tube well project in northwestern parts of Uttar Pradesh had led people to assume that projects of similar magnitude could be undertaken in west Rajasthan.

The greater part of the region was occupied by wind blown sand and the impression given was one of flowing rivers and fertile valleys before some changes in climate reduced the power of rivers to sweep back the ever increasing encroachment of the sand from the south. This change in climate probably took place in the last 5000 years as the Indus Valley Civilization could only have flourished in a climate which was less rigorous than now.

Auden must have been aware of the Saraswati problem and the views expressed by earlier workers about the existence of vast alluvial plains formed by the lost river, but he does not make any specific reference to it. He only refers to the large extent of blown sand which permits much of the rainfall to penetrate and not contribute to possible runoff. High temperature and strong evaporation had resulted in concentration of dissolved salts. Millions of tonnes of gypsum occurred a few feet below the sands of Jodhpur and Bikaner. Common salt and sodium sulphate were usual constituents of the groundwater rendering it brackish and sometimes so saline as to make it unusable. Salt lakes also occured as at Pachpadra, Sambhar and Didwana. He makes mention of the other view which attributes salinity of the region to the large quantities of salt (estimated at as much as 130,000 tonnes each year) transported by wind each hot weather from the Rann of Cutch.

Over very large areas of western Rajasthan the water table lies at a depth of more than 60 m. Most of the rainfall (85 to 100%) is not carried away as run-off but seeps underground, recharging the groundwater reservoir. The existence of extensive pans of gypsum and Kankar point to the return of the percolated water to the atmosphere through evapotranspiration.

Location of buried channels of the lost river Saraswati and its tributaries offers the only means of tapping good sources of groundwater for drinking and irrigation purposes. Auden has not commented on this possibility but he has advocated storage of surface run-off in reservoirs constructed at favourable locations. The success of the operation initiated by Rajinder Singh of the *Tarun Bharat Sangh* in recent years points to a method for securing fresh water for drinking and irrigation purposes.

The groundwater section of the Geological Survey of India started by Auden made rapid strides and had fifty geologists operating in different parts of the country. The section had also the benefit of advice from George Taylor and Paul Jones of USGS. The seed that Auden helped to germinate has now grown into a vast tree bringing great benefit to India ushering in a green revolution making India self-sufficient in her requirements of food grains.

Salt Problem in Rajasthan

During war time (1944-45) Auden was for a short time placed in charge of mica production in Rajasthan and he became interested in the study of the salt problem in the lakes of Rajasthan. There were two views on the origin of the salt. Holland and Christie held the view that the salinity of water in the lakes as well as groundwater was the result of wind-blown replenishment of salt from the Rann of Kutch. While the other view was that the salt lakes were remnants of the ancient Tethys sea. Auden found no evidence for the existence of Mesozoic and Eocene seas, as calcium and magnesium salts were absent in the Rajasthan salt lakes. Placing the problem in a world context, he pointed out that wind transported salt was an important factor in effecting an annual increment of salt. He argued that the aridity of the region, with low rainfall, high evapotranspiration and sluggish drainage interrupted by accumulation of wind blown sand, were mainly responsible for the accumulation of salts in the lakes.

Deep Main Faults in South India

A paper by John C. Grady was published in the Journal of the Geological Society of India (v.12, no.1, March 1971) with a map of South India showing the relationship between fault zones, intrusives and mineral deposits. This caught the attention of Auden and he immediately initiated a discussion. Auden had personal acquaintance with the subject as in 1947 he had investigated the Mattupatty dam site in the Anaimalai Hills, tunnels in Maharashtra and the Mahaveli Ganga Project in Sri Lanka (1965).

Examining the foundation conditions of the Mattupatty dam site in the Cardamom hills of Kerala, Auden was impressed by the control exercised by a system of long and deep fractures on the drainage pattern. Geological studies in the Vaitarana-Tansa tunnel project, Maharashtra, revealed the presence of numerous shatter zones in Deccan basalts which were responsible for the disposition of the overlying drainage pattern. The result of these studies formed the subject matter of the Presidential address he delivered as President of the Geological Section of the Indian Science Congress held at Bangalore in 1951. It also formed the main theme of a paper on 'Erosional Patterns and Fracture Zones in Peninsular India published in the *Geological Magazine* in April, 1954. He suggested the river system of western India was controlled by radial fracturing related to the three unique plutonic centers of Rampur, Junagadh and Chamardi-Chogat in Kathiawar.

He was skeptical of the recognition of fractures in south India on the basis of air photographs and topographic maps which was subject to personal opinion and selection. The fault pattern indicated by Gubin (1969, Figs.17,21) on the basis of geomorphology and seismicity was quite at variance with that of Eremenko and Gagalganz.

Gubin had postulated a series of peripheral faults in south India which were considered by him to have caused the relative elevation of the Nilgiri, Palni, and Anaimalai hills and the depression of the Palghat Gap. According to Auden, the scarps surrounding the elevated massifs were erosion features quite unrelated to faulting. The earth's outer crust was heterogeneous and the postulation of remarkably long rectilinear and parallel pattern of faults 380 km in length, cutting nonchalantly across the complex structures of the Archaean was suspect. He pointed out that major deep structural faults of the earth were not straight but curved.

He felt it was too early to suggest the significance of the fracture pattern in south India in terms of crustal thickness. These fractures were not comparable to those of the African rift system but may have some relationship with the thickness of the upper part of the lithosphere. The system of fractures which cut the Deccan volcanics and dyke swarms were of a different type to those crossing the Archaean of the South Indian plateau massifs.

All geologists may not agree with the viewpoint of Auden that the scarps surrounding the elevated massifs of the Nilgiri hills are simple erosional scarps quite unrelated to faulting. Many, especially geomorphologists believe that the elevated fault block mountains are of the nature of fault scarps. The occurrence of ultrabasics and carbonatites is quoted as evidence that the faults extend down to the mantle.

Koyna Earthquake and Seismicity of Maharashtra State

An earthquake of destructive magnitude struck Koyna in the early hours of 11 December 1967. It quickly razed almost all houses in the Koyna township to the ground and villages in the neighbourhood were also affected. The earthquake had a magnitude of 6.5 on the Richter scale.

As a sequel to the study of the Koyna earthquake, four consultants were engaged by UNESCO to investigate the seismicity of Maharashtra State. A concrete gravity dam, 85 m in elevation above the river bed and 105 m above the deepest foundation had been constructed at Koyna storing 2,780,000,000 m^3 of water. This water was diverted west through a tunnel to generate 540 Mw of electric power. Although much damage was caused in the area, the dam itself was not affected. Focal depth was estimated between 10 and 30 km below surface. The thickness of the volcanic pile was less than 2 km at Koyna and tectonic movements responsible for the shock are believed to have developed in the basement some 8 km or more below the base of the volcanics.

The work of the ONGC had indicated the existence of a narrow graben 60 km wide – the Cambay graben with nearly 5000 m of Tertiary sediments above the traps. The basin had sunk *pari passu* with sedimentation accompanied by syn-sedimentation faulting along the margins throughout the Tertiary and Quaternary.

Auden emphasised the need for further study about the behaviour of shields at the margin of continents, especially, the existence of monoclinal folding towards the oceans. Disposition of the drainage basins of peninsular rivers indicate that the edge of the ghats must originally have been further west before lateral erosion had driven the main scarp back towards the east, 40-70 km from the coast. Konkan was not a coastal plain. Over extensive areas there are isolated hills and ridges of considerable height separated by erosion from the main scarp. The coastal zone in the Bombay-Malabar area is not a coastal plain abutting against a straight scarp. The scarp is formed by the eastward erosion of the plateau, erosion being greater in the softer schists than in the interbedded khondalites and charnockites.

The credit for drawing attention to lateral erosion which had taken place along the whole coastal region from north of Bombay to Malabar, over a distance of 1400 km, driving the edge of the plateau back 40-70 km should go to Auden. Geological studies have not indicated existence of the horst-like fault in the zone which has been eroded. The unequivocal existence of surface faults has not yet been established relating it to the seismicity of the region. The *Sahyadri* (Western Ghats) scarp is an erosional feature and unconnected with faulting. Clearly more intensive work is necessary.

Reservoir Induced Seismicity

As regards the possibility of reservoir induced seismicity Auden considered it as unlikely. "When the small extra water load at Koyna (density 1) is considered in relation to the much greater thickness of volcanics that has been removed in geologically recent times by erosion from the plateau (at least 300 m, density 2.8-2.9) it is unlikely the unloading by erosion would be more effective in causing crustal movement than the loading due to the reservoir" (Auden, 1969, p.26).

There were no doubt other instances of reservoir seismicity as in the case of Lake Mead of USA and the Kamba Lake within the African rift zone. He suggested therefore, before making sensational deductions about the production of earth tremors by reservoir filling, more information should be collected about the relationship between large resevoirs and the local terrain, in regard both to geological structure and intensive seismicity.

The Geological Society of India has recently published a Memoir on the *Sahyadri* – The Great Escarpment of the Indian Subcontinent (Gunnell and Radhakrishna, 2002) where the evolutionary history of the west coast as well the great scarp has been considered in greater detail. Auden's conclusions are more in keeping with the conclusion drawn out of this recent study.

Diversion Tunnels in Eastern Nepal

While serving as a member of the Food and Agriculture Organisation, Rome, Auden made brief reconnaissance investigations in 1965, 1966 and 1968 of alternative alignments for a diversion tunnel between the Sun Kosi and terrain south of the Mahabharat Lekh. The project involved the diversion of water from the Sun Kosi for irrigation in the Terai plains and the generation of hydroelectric power.

He discussed the complex geological and tectonic set-up of the area and recommended that an alignment which avoided the Main Boundary Fault and passing through lower Siwaliks be selected. At the same time he suggested considering an alternative project of developing the groundwater resources of the Terai region by sinking 500 tube wells yielding 100 litres/sec (Auden, 1971). What was finally agreed to is not known but it is important to note the creative thinking and value judgement exercised by Auden in making his recommendations.

The Bearing of Geology on Multipurpose Projects

The Geological Survey of India held its centenary celebrations in 1951. Auden, who was elected President of the Geology and Geographic sections of the 38th session of the Indian Science Congress holding its session in Bangalore in June 1951, thought it appropirate to discuss certain aspects of the work of the engineering and groundwater division of the Survey which he had helped to organise in 1945.

The Indian continent presented certain special features:

> 'The mountain zone which forms the northern margin of India and Pakistan is geologically of very recent origin, notwithstanding that old rocks have been involved in the young movements. Large-scale overthrusts of middle Pleistocene and possibly even younger age have occurred while the Karewa formation of late Pleistocene age has been strongly tilted in Kashmir valley with dips as high as 40°. Destructive earthquakes are of frequent occurrence. Major glaciers occur which are actively abrading while recent river erosion and incision is marked. About 90 per cent of the rainfall is concentrated into one third of the year. In some areas rainfall is less than 5 inches per annum. In many others it exceeds 200 inches. The pressure of population has driven people to widespread felling

> of the forests, and to unsound systems of cultivation and grazing which have engendered disastrous soil erosion.'

This gives a good background for the likely problems that arise in investigations of dam sites in India requiring expert geological analysis not merely on a local scale but on broader issues of regional tectonics, earthquakes, soil erosion, siltation, water conservation and such other important aspects which constitute engineering geology.

Susceptibility of a region for earthquake shocks is one such aspect. Knowledge about the basic conditions responsible for earthquakes was not clear. Shocks have originated in such varied locations over the Makran coast, Kutch, Quetta, Kashmir, Kangra, North Bihar, Shillong Plateau and Assam Himalaya. There are fundamental differences in the geological nature of these regions and it would appear that no part of India is free from the possibility of being an epicentral region of major shocks. Each area had to be freshly assessed from the point of view of earthquake hazard *vis-a-vis* design. Historical records of earthquakes go back only to about 230 years and instrumental records are not available.

In his address, Auden concentrated on certain newer aspects of investigation which arose during the course of his studies of engineering projects in regions affected by earthquakes like Kutch (1819), Makran (1945), Baluchistan (1935), Bihar-Nepal (1934). He pointed out that Kutch should be considered as a part of the orogenic zone of Sind and Baluchistan rather than as belonging to the unfolded peninsular foreland.

The Baluchistan shock of 1935 and the Bihar-Nepal shock of 1934 had shallow foci, less than 10 to 15 km. The seismic instability of the area was related to relatively superficial crustal strains. Deep focus earthquakes however, are felt over a very extensive area but generally produce severe damage over only a relatively small tract, whereas a major earthquake of shallow focus tends to produce devastation over greater areas.

Commenting on landslides due to earthquakes, Auden concluded that slides definitely attributable to earthquakes are limited to a distance of 200 miles (320 km) from the epicentral tract. A large number of landslides are related to the effect of an abnormally wet monsoon on hill slopes perennially in an unstable condition.

Quite a number of dam sites in the Himalayan region are in close proximity to major thrust planes of Burdigalian age (20 Ma) in the Himalaya. Auden pointed out that these thrust planes had been strongly folded by later Tertiary and Pleistocene movements and subsequently eroded by rivers. They were old, dead structures along which there was no likelihood of further movements. The thrust units have indeed become incorporated into the general body of the Himalaya and the surface traces of the thrust planes may be regarded figuratively as "old scars of healed wounds rather than indications of anything pathological below." He felt that the Himalayan valleys, notwithstanding their proximity in certain parts of the range to seismic centres, are permissible locations for the construction of dams.

Analysing the compulsions favouring construction of relatively high dams of the order of 750 feet (228 km) as against smaller dams of 500 feet (152 km) and less Auden said:

> 'The Himalayan valleys are deeply incised with steeper declivities below kinks in the cross-sectional profile which are often 500 feet above river level. Reservoir volumes below 500 ft are relatively small. Further, most of the Himalayan rivers are excessively silty, so that a very large dead-storage capacity has to be included in the projects..... It is not until dams approach a height of 600-700 feet in these regions that there is satisfactory large ratio between the live and dead storage capacities. These factors both indicate the desirability of starting with as high dams as is feasible, but it should be noted that subsidiary dams are in any case indicated on the tributaries to retain some of the abnormally large quantities of silt and increase the life of the main reservoir.
>
> Destruction and misery caused by floods and frequent shifting of course and extensive silting have no doubt called for construction of high dams but the risk of earthquakes and their possible effect on high dams caused the engineers to desist from recommending construction.'

Auden critically evaluated these aspects and felt construction of high dams is warranted and a certain amount of risk has to be taken. Where engineers are satisfied that design allows for a reasonable factor of safety, projects should not be postponed on the grounds of incomplete information on crustal and sub-crustal structure. If good foundations are available, Auden felt that dams should be constructed. The most important factor to be considered is the degree of siltation. Siltation rates in the Himalaya are high, as much as 5 acre feet per square mile of catchment. The short life of the reservoir is a problem as in the case of projects like the Karnali, Gandak, Kosi, Manas and Dihang rivers.

Every dam site investigated had presented its own foundation defects which required engineering treatment. Engineers connected with the construction of these projects failed to give an account of the problems encountered at each of the sites and the way these defects were overcome. Such reports would have formed important case histories for guidance in future. Crores of rupees are spent on projects but no provision is made for the publication of reports furnished by the geologists and the remedial measures implemented by the engineers in overcoming the problem encountered. The reports produced by Auden and his assistants in the course of their work are either lost for ever or are eating dust in godowns of the Public Works

Departments. Much information of inestimable value has been irretrievably lost.

In concluding his address Auden emphasized the immense debt we owe to the small band of devoted workers who sustained the survey during the first hundred years of its existence. It is they who have laid the foundation for all recent work. Auden was the last among the giants who contributed substantially to our knowledge of the geology of the Himalaya and of the Peninsular shield and his pioneering contributions to the theoretical and applied aspects of our science should be gratefully remembered.

Peninsular Structures and Dam Sites

Auden during the brief period heading the newly created section in Engineering Geology and Groundwater had the chance of making a study of the geology of a variety of dam sites in the Peninsula. His studies indicated that the Peninsula had been affected by faults and Gondwana faulting had involved displacements of thousands of feet. Steep folding had affected the Vindhyans and folding and overthrusting in the Cuddapah. These movements had terminated before the eruption of Deccan traps. There was clear evidence of post-trap folding in the Peninsula, in particular along the Panvel monocline and the Gujarat folds (Oldham, 1893, p.271). Major faulting had dislocated the traps by several thousands of feet north of Pachmarhi and south of Gawilgarh (Crookshank, 1936, p.235).

Auden pointed to the existence of numerous regional shear zones which had influenced the drainage pattern. Since the straight river pattern was observed between altitudes of 800 and 7000 feet above sea level, the structural features were not only of great lateral extent but were developed through a vertical height range of 6200 feet.

Fracture Zones in Peninsular India

Auden became particularly interested in the study of lineaments in the Archaean basement of South India and in Deccan basalts. The fractures were seldom accompanied by fault displacements indicating them to be planes of shearing. Shears in Deccan basalts were seen cutting across the post-lava dykes and were considered to coincide with late magmatic mineralisation and the break up of the Gondwana continent in mid-Tertiary times (Auden, 1954).

His interest in lineaments was generated while flying over the Western Ghats and Konkan in 1947 and subsequent visits to Gujarat, Saurashtra and Kutch in connection with dam site investigations. He was also interested in the study of river patterns which appeared to be controlled by a system of long and deep fractures, similar control being suggested on a study of topographic maps of other river valley projects. Fractures at Mattupattai dam site in Kerala were not only of great length but occurred vertically over an exposed height of 6200 feet (1890 m) and continued further at depth. His conjecture was that these shears in Deccan Trap were related to the break-up of the Gondwana continent towards the close of the Deccan igneous cycle coinciding with the Himalayan Orogeny. Incidentally he recognized three unique plutonic centers at Rampur, Junaghad and Chamardi-Chogat which gave rise to radial drainage in this region.

Auden Medal

His colleagues in the Geological Survey of India, particularly in the Engineering Geology section, venerated Auden as can be seen from a letter written by V.S. Krishnaswamy, his close assistant, who later became the Director General of the Geological Survey of India. In this letter addressed to Auden dated 18 December, 1957, he said:

> 'I have not so far given expression to my feelings of regard for you as an able scientist, a benevolent boss and a very human personality. I have mentally paid homage to these excellent attributes on a number of occasions and wished to God that I may imbibe at least a fraction of these very desirable qualities for my betterment in life, both as a man and a scientist.'

Auden's colleagues wanted to bring out a volume in his honour giving a detailed account of his scientific career and some highlights of his professional life, together with an anthology of papers, but this was never pursued seriously. He, however, continued to remain in the minds of his colleagues as a true gentleman and a scholar who profoundly influenced people who interacted closely with him. His colleagues wanted to institute a medal in his name but Auden apparently did not relish the idea and wrote back to Krishnaswamy, who first mooted the idea: 'I much appreciate the suggestions you have made but somehow do not relish the idea of perpetuating myself, in my own life time, by providing a name to a medal for work which, even if of any merit, was largely done in collaboration.' Nothing came out of this suggestion and the matter appears to have been dropped.

Auden reviewed for the Royal Geographical Society books relating to the Himalaya. These reviews are some of the best of his writings, so much so, reading one of his reviews the editor of the Journal of Structural Geology wrote: "it is the type of book review which I hope we will become identified with; that is a review containing much more than a mere recital of the book's contents and a hasty opinion about its merits."

Premature Retirement from the Geological Survey of India, 1953

The end of Auden's service in the Geological Survey of India also marked the end of the first hundred years of the Survey. With the aid of just a handful of officers, the Survey had contributed substantially to our knowledge of the geology and mineral resources of India. A clear perception of the structural disposition of the great Himalaya had been obtained. The extent of the sedimentary basins of Vindhyan and Cuddapah had been mapped. A new Gondwana system with its extensive deposits of coal had been unraveled. Carboniferous glacial epoch had been recognized and its extension to Australia, South Africa and South America had sown the seeds for recognition of a great southern continent – the Gondwanaland. The study of earthquakes led to the postulation of three types of earthquake waves which paved way for an understanding of the internal structure of the earth. The study of the Siwalik hills brought to light wonderful collections of remains of mammals and helped in reconstructing the evolutionary history of mammals and of man himself.

These were no mean achievements. Auden played an important role in these developments. He enhanced the reputation of British officers who had laid the foundation for the Indian Geological Survey.

Auden had developed a real love for India and his colleagues at the Survey. In a letter addressed to A.M.N. Ghosh, he wrote: "No chance, alas as far as I can see of my coming to India, much as I would love to do so. It is now 7 years since I left and I miss India very much. It is naturally nice to be in England with my family, while one girl is at Oxford, and the other is about to enter University to study medicine. But later perhaps my wife and I might settle in a small cottage, say near Manali."

Events however, took a different turn altogether and Auden was not destined to return to India and spend his time in the peaceful surroundings of the Himalaya. Auden was the last British officer to leave in 1953.

Sudan Geological Survey (1953-55)

Soon after leaving India Auden accepted the post of Director of the Sudan Geological Survey but was never comfortable in his new position. Conditions in Sudan were so much different from the one he was accustomed to in India. The minister under whom he had to work interfered too much with the work of the department, ordering him to appoint people without qualification. Auden became so affected that after a service of few months (December, 1954 to June, 1955) he resigned and returned to London.

Advisor, Burmah Oil Company (1955-1959)

Auden accepted the post of an advisor in the Burmah Oil Company which he served for next five years evaluating the geological and geophysical reports coming from India, Pakistan and Burma in the light of known geological framework.

Meanwhile an Oil and Natural Gas Commission had been formed in India with which Auden was not particularly enamoured. In a letter addressed to Odell in 1958 he wrote:

> "... its personnel were all colleagues of mine, most of them I like. But I was from the start opposed to government controlled exploration of oil and gas, and from 1949 when acting as Director I wrote several long minutes explaining why government should keep off such a costly entertainment without any experience. Of course, these views were not accepted.
>
> "Any how ONGC exists and is numerically large, but without a single high caliber oil geologist or any development and exploration personnel; it has taken expert advice from both sides of the Iron Curtain and east and west of the Atlantic. It evidently has a mass of undigested advisory reports and by now immense quantities of uncorrelated geophysical data. And there is probably no one in the Commission who can digest those adequately and formulate a sound policy. But the worst omission is in the engineering and maintenance side..."

Auden does not appear to be fair in his assessment of the calibre of the officers of ONGC. At that point of time no private company would have come forward to explore for oil in a virgin field in India. In the earlier stages officers recruited may have lacked experience but soon made good the deficiency and laboured hard towards the goal of making India self-sufficient in her requirement of oil.

Before joining the Burmah Oil Co. Auden undertook geological investigations of dam sites and hydroelectric projects on behalf of the Food and Agriculture Organisation of the United Nations.

Candidature for the Fellowship of the Royal Society

In 1958, Sir Edward Bailey and Sir Lewis Fermor took the initiative in collecting the necessary signatures in support of Auden's candidature for the Fellowship of the Royal Society. Auden felt the chance of getting elected to the Royal Society exceedingly small. Not because of lack of reasonably good work done but because of his foreign service and the fact that 95% of the Fellowship had gone to academic chairs. Since he had taken up economic work which could not be published and there was little chance of any further publications in England except for residues of Indian experience, chance of getting elected remained remote.

Auden was eminently qualified to become a Fellow of this premier institution and his election would have brought great satisfaction to himself and to many of his admirers but this was not to be.

Foundation Fellow, Geological Society of India (1958)

The Geological Society of India was started in 1958 with its headquarters in Bangalore, the initiative for starting the Society being taken by a small group of enthusiasts in Bangalore with Prof. L. Rama Rao as their leader. Rama Rao drafted the Memorandum and Articles of the proposed Society and sent it to about fifty eminent geologists from all over India. Auden was one among this early group who supported the move and became a Foundation Fellow. The Society was formally founded in Bangalore on 28th May, 1958 with D.N. Wadia as the first President.

The Society was formally inaugurated at New Delhi on January 23, 1959 by K.D. Malaviya, the then Minister of Mines and Oil in the Government of India. The statement made by him at the inaugural meeting is worth recapitulating:

> 'I need hardly tell you how indispensable geologists have become for the various developments that are taking place in the world to make mankind happy and prosperous. No engineering work or industrial project worth the name can be conceived today without the basic help of a geologist and the more we advance in this modern age the more we realize how fundamental knowledge in the science of geology can help us to solve many problems of humanity.'

Auden took an active interest in the Society, reviewing books in the Journal of the Society and also initiating discussion on some of the controversial points of Himalayan geology.

UN Food and Agriculture Organisation (1960-68)

In 1960 Auden was invited to join the Land and Water Resources Division of the FAO of United Nations based in Rome. He worked first in Afghanistan and spent brief spells in Ceylon, Nepal, Brazzaville (Congo), Turkey, Crete, Argentina, Uruguay, Panama and South Korea.

During 1960-62 and on subsequent short visits to Afghanistan, Auden was responsible for geological work connected with a UN special fund project concerned with the survey of water resources of the upper Kabul basin, the Farah Rud and the Hari Rud. The report of the project was published by the FAO in 5 volumes. Volume three was concerned with the geology and topographical surveys and was contributed by Auden. There were 18 maps of geological information, some detailed ones of dam sites on a scale of 1:2000 reduced for publication to 1:4000, other photogeological interpretation on the scale of 1:50,000 and others with faults and seismic data on a smaller scale. Afghanistan was regarded as the meeting place between east and west and a cross road of Central Asia with its own cultural heritage.

Afghanistan has remained a troubled land throughout history. The landscape is harsh with wide stretches of desert and near desert with soaring mountain chains – the Hindu Kush and the Pamir. Its people always suffered from drought, poverty and internal strife. Asoka had extended his empire to Afghanistan. Buddhism had spread to this remote corner and endured for hundreds of years with giant sized statues of the Buddha indicative of the spread of Buddhist culture. Later, the entire region was engulfed by Islam.

Having lived and worked intermittently in Afghanistan, Auden found nothing but kindness and hospitality in the cities and villages and amongst the nomads. He felt that the Afghans themselves were good people and had suffered from their contact with the west. This assessment is radically different from that of the Taliban regime which had imposed its unholy writ on the freedom loving Afghan people, especially its women who were terrorized into abject submission. The Afghans had to endure the procession through their country,

in increasing number since 1960, of European misfits who, lacking constructive purpose and out of boredom followed the drug trail as far as Kabul and Katmandu, often with inadequate funds, expecting assistance from Hakims enroute and eventually from their long-suffering embassies. Proudly sloughing off what are regarded as the outmoded restrictive disciplines of their own home countries, and ignorant of the habits of others, many of these travellers caused offence in Islamic areas where custom over centuries expects both men and women to be suitably clothed and some measure of modesty. On March 25th and 26th a series of powerful earthquakes shook the north of the country killing at least 2000 people, injuring another 4000 and leaving 30,000 homeless. The town of Nahra, 160 km north of Kabul was razed to the ground. Afghans had their hands full dealing with the ravages of men, before being visited by this natural disaster.

Auden reported on the geology of a number of dam sites while he was in the Land and Water Development Division of FAO, in countries as far apart as Korea, Panama, Iran and Turkey. His last FAO report was written in August, 1968, on a Geological Reconnaissance of Damsite and Reservoir Basins in Naktong River, Republic of Korea.

These reports were quite exhaustive, dealing with factors like (a) functional effectiveness, (b) geological conditions, and (c) economic viability. They contained section on (1) topography, (2) geology, (3) groundwater conditions, (4) run-off and silting followed by description of individual dam sites, foundation conditions, seismicity and availability of raw materials. These were followed by suggestions regarding further exploration needed, including geophysical investigations and drilling.

Koyna Earthquake (1967)

An earthquake of magnitude 6.5 and intensity VIII shook Koyna and neighbourhood in Maharashtra on 10-11 December, 1967, the epicentre being only 3.5 km from the Koyna dam. The dam is 85 m in elevation from the river bed and 103 m from the deepest foundation and at full capacity could store 2,780,000,000 m^3 of water. This dam survived the shock, although in close proximity to the epicentre of the earthquake. Auden, along with two Japanese and one Russian, were invited by UNESCO to visit India to study the earthquake. A report in two volumes was submitted to the Government of India. Auden and Igor Gubin were again invited to India in 1969 to make a special study of the seismicity of Maharashtra State and suggest precautionary measures to be taken especially in designing high gravity dams. Auden's role was to make a study of the geological aspects of the problem of seismicity of the region.

General information till then was that the Indian Peninsula was seismically stable although the catalogue of Indian earthquakes published by Oldham in 1882 did indicate that several shocks had occurred in the Peninsula in earlier years. The more important conclusions arrived at by Auden about the seismic susceptibility of the region were:

> *Cambay Graben:* Near Broach, Deccan Volcanics are overlain by 5000 m of Tertiary and Quaternary sediments deposited in a graben only 60 km wide. Increase in sediment volume could have been accommodated by sinking *pari*

passu with sedimentation by syn-sedimentation faulting along basin margins throughout the Tertiary and Quaternary.

Panvel Flexure: The whole region of Panvel flexure had affected the western margin of the Deccan trap with dips locally as high as 15° and required much further study.

Basement Depth: Basement is at a depth of 4500 m, 140 km west of Cochin, or 7200 m lower than the summit of Cardamom plateau. To what extent the shield was downfolded and to what extent it was faulted had yet to be determined. Geophysical exploration had proved the existence of thick sedimentary succession in offshore basins, including probably the whole of Tertiary and it is evident that sedimentation began not later than the Eocene and that the coastline had developed at that time or even earlier.

Nilgiri-Cardamom Hills: Topography does not suggest the existence of a fault scarp bordering the western edge of the Western Ghats. The scarp was an erosion feature leaving a skeleton of harder elements that project from the plateau to the Arabian sea.

On the postulation of a complicated rectilinear system of faults by Eremenko and Gagelganz over the southern part of the Indian Peninsula and in the Arabian Sea as far as Laccadive islands, Auden remained highly skeptical. He said these faults were not supported by field work and appeared to be an "exercise in pedagogic imagination and that drawing of faults around every topographical expression requires confirmation by rigorous mapping and inspection of aerial photographs."

As regards fractures, he felt that they were manifestations of the upper levels of the shield and volcanic terrain. No fault displacements are known to be associated with the fractures and they must be regarded as the now passive consequences of stresses which had affected the Indian Peninsula and were not of any seismo-tectonic importance.

The system of faults bordering the Cambay graben was of great importance as nearly 5000 m thickness of sediments within a rift zone of only 60 km was very striking.

Plio-Pleistocene Uplift of the Indian Plateau

Auden recognized the uplift of the plateau to the extent of 2500 m. The elevation took place during the Miocene followed by extensive erosion in the Pliocene and by further uplift and warping in the Plio-Pleistocene. These uplifts were not accompanied by seismicity. About the *Sahyadri* scarp itself Auden has this to say:

"The impressive lateral erosion which has taken place along the whole coastal region from north of Bombay to Malabar over a distance of 1400 km, driving the

> edge of the plateau back 40-120 km was not connected with any horst-like fault in the zone which has been eroded..... If a fault exists, it is west of the present shore line.'
>
> '... the scarp is an erosional feature and unconnected with a scarp fault. The uplift would appear to be related more to the flexure of the shield at the continental margin, as this was evidently accompanied as crustal faults at depth, such as that which must have caused the Koyna earthquake (Auden, 1969, p.23).'

In making these observations, Auden was very much ahead of his times and had a clearer conception of the origin of the *Sahyadri* (Western Ghats) and its retreat eastwards.

Auden was cautious in interpreting gravity data. He felt "A fault deduced solely from gravity data without further evidence from surface geology and seismic profiling must be regarded as very tentative."

He advocated the creation of a Seismological Research Institute to coordinate the various lines of investigations and to collaborate with UNESCO, Japanese and USSR Institutes experienced in seismological research. This recommendation yet remains to be given effect to by the Government of India.

International Karakoram Project (1979)

In 1979, the Royal Geographical Society initiated an International Karakoram Project to celebrate 150 years of exploration and selected Auden as Chairman. Karakoram is the most extensive, highest and dangerous mountain in the Himalaya. Earlier, Auden had extended his studies to this range and had given a descriptive account of the region in his Traverses in the Himalaya (1935). It provided a link to the Pamirs and to the Central Asian region. Hunza valley in this range, considered probably as the fastest eroding valley in the world, the rivers coursing through the valley carrying the greatest sedimentary load. The great mountain system of Central Asia extended 480 km from east Afghanistan to Ladakh in Jammu and Kashmir.

Karakoram mountains formed an important link between the Himalaya in the south and the Central Asia mountain nucleus and the Pamirs in the north and formed the greatest extent of high mountains in the world. Geologically it still remains puzzling. K_2 (Mt. Godwin Austen) is considered the second highest peak in the world and the highest peak of the Karakoram and is made up of biotite-muscovite augen gneiss with large plagioclases. The connection of the N-S trending Nanga Parbat with the almost E-W striking Karakoram is puzzling and fórms one of the most fascinating studies in the Himalaya (Gansser, 1964, p.33).

Karakoram Project was an interdisciplinary expedition on a large scale involving scientists from China, Pakistan and the UK. The uniqueness of the project was due to the collision of the Indian Plate with the Asian Plate causing the most chaotic state of high mountains, deep river gorges, intensive earthquake activity and for most of the year impenetrable passes to remote areas. The project leader was K.J. Miller and the team included some fifty scientists (six Chinese, fourteen Pakistan, thirty Britishers) working between June and September, 1980.

For nearly three years Auden remained as Chairman but gave up his position as he was becoming more and more deaf (he was almost 77) and could not hear much of the discussion at the meetings. He also felt that as his work in Karakoram was carried out in 1933 and 1937 it was desirable to have a person actively connected with present-day exploration.

Indian National Science Academy

A National Institute of Science had been established in 1938 with the objective of promoting science in India including its practical application to problems of national welfare. Lewis L. Fermor who headed the Geological Survey of India and was also the President of the Indian Science Congress took a leading part in the organization of the Institute. A draft constitution was prepared and 125 Foundation Fellows were selected. The inaugural meeting was held at Calcutta with Fermor as President and the Institute started functioning with its headquarters at the Asiatic Society of Bengal, 1 Park Street, Calcutta, quite close to the offices of the Geological Survey of India. Auden took an active part right from the beginning and was elected as a Fellow in 1938. Foundation stone for the Institute was laid by Pandit Nehru, the first Prime Minister of India, on 19 April, 1948. The Institute moved to its present premises in New Delhi in 1951 and the name of the Institute was changed to the Indian National Science Academy (INSA) in February, 1970.

D.N. Wadia was a great name in Indian geology. The mother of all Geological Societies, the Geological Society of London, recognising the merit of Wadia honoured him with the presentation of the prestigious Lyell Medal in 1943. Commending the work of Wadia it said "He found stimulation in the magnitude of his problems and rose to meet them with courage and success." Twenty years older than Auden, there was not an opportunity for closer collaboration between them as they had worked in different parts of the Himalaya. They did, however, collaborate in the writing of two chapters of the Memoir on the 1934 Bihar-Nepal earthquake. Wadia left the Geological Survey with the 'permanent legacy of extensive work in the Western Himalaya.' He had also authored the text book on the Geology of India which remained the principal source of general information for many generations of students including Auden.

India's Crustal Neighbours – D.N. Wadia Medal Lecture - 1980

In 1977, long after India gained independence, the Indian National Science Academy decided to institute twelve subjectwise medals and awards, the award for Earth Sciences, Geology, Geophysics, Geography being named after the doyen of Indian geology, Darashaw Nosherwanji Wadia. Auden was the first recipient of the medal for the year 1980, specially coming to India to deliver the address and receive the medal. The subject he chose for his address was 'India's Crustal Neighbours'. As is so characteristic of him, in his introductory remark, he liked to think of the medal as an award for joint work with his colleagues in the Survey and Irrigation Departments.

In his address Auden advocated the existence of an extensive province of arid sedimentary formations suggesting the close association of India with neighbouring areas to the north and west as long ago as 600 m.y. Critical of the plate tectonic concept which conceived of the Indian Peninsula remaining 6500 km south of its present position and its migration northwards as a solitary crustal unit across the Tethys 70 m.y. ago, he subscribed to the view that India was separated from Eurasia during the Permian by a shallow epicontinental sea of no great width. Evaporite rocks and strongly current bedded sandstones indicated that they were linked to Asia although separated by epicontinental sea. Palaeomagnetic evidence did not much impress him. He subscribed more to the view that considerable areas of continental crust had sunk in the Indian ocean to account for the rise in continental crust in Tibet and the Himalaya.

He also suggested the division of Himalayan rocks into those belonging to Peninsular Himalaya and others to the Tethys Himalaya and conceded the Indus fault zone was a mega tectonic feature but found no evidence of subduction and the zone was also aseismic.

Plate Tectonics

Original paper on this new concept of Plate Tectonics which has revolutionised geological thinking appeared in the Journal of Geophysics Research (v.24, pp.427-528, 1971). A 75 million years magnetic record in the floor of the Indian Ocean had revealed how India had rifted northward for 5000 km before it collided with Asia, the encounter giving rise to the Himalaya. Reprint of this in Scientific American in May, 1973, is in the collection of papers of Auden (D.P. Mckenzie and J.G. Sclater). Auden has characterized it as '*a fine piece of scientific phantasia*'.

Himalaya was made up of sedimentary rocks laid down over many millions of years in shallow seas and was uplifted and heavily deformed by mighty tectonic forces. Geology text books of a decade ago could not provide a satisfactory answer as to how sediments became sandwiched between India and the great Asian landmass to the north.

The principle evidence supporting the Plate Tectonic Theory had come from oceanography rather than from classical geology. Harry Hess of Princeton University, in 1960, suggested that sea floor was continuously being generated along linear fissures running for thousands of kilometers through the major ocean basins. Molten rock from the mantle welled up through fissures creating new oceanic crust. As new crust was forming, plate boundaries elsewhere in the ocean floor plunged into a trench and then sank to great depths into the mantle.

It is clear from the numerous comments made in pencil on some of the excellent sketches illustrating the paper by McKenzie and Sclater that Auden although impressed by the theory, remained in doubt as to its acceptance. His own colleague in the Survey at that time, W.D. West, had characterized the theory as '*heady stuff*'. Closely connected with the theory was the parting of India and Madagascar based on matching of Precambrian lineaments. Auden remained skeptical of the new theory which postulated extensive horizontal movement of landmasses.

While he was prepared to concede the relevance of geophysical data in the understanding of geological processes, he wanted weightage to be given to stratigraphical and palaeontological data which were of critical importance. He drew particular attention to the existence of vertical movements which needed to be considered in attempts at a better understanding of present-day configuration of continental shelves. Considerable area of continental crust appeared to have sunk in the Indian Ocean in contrast to the phenomenal rise of continental crust in Tibet and Himalaya since the Pliocene. He felt there were strong grounds for considering that India was near to Eurasia even as far back as the Eo-Cambrian and Cambrian and had strong links with the Asian continent throughout much of the Mesozoic.

Auden considered Himalaya and Tibet, as classic cases of vertical uplift. In Tertiary, the Tibet plateau was not higher than 1000 m in elevation. Three successive periods of uplift at the end of the Pliocene had raised the Tibetan plateau to its present position during the last 100,000 years at the rate of 10 mm per year. Himalaya was also uplifted during the same period as revealed by river terraces which are clearly part of the present river system found at heights of 500 m above present valley bottom.

He also pointed to the existence of deep sedimentary basins with the basement crust sunk thousands of metres. The basement of Rajmahal volcanics of lower Cretaceous age was 8 to 9 km below sea level near Dacca, 300 km to the east of the outcrops. The continental shelf west of Bombay showed 6 km of

Cenozoic sediments overlying the Deccan Volcanics and Precambrian basement. Deccan lavas, were for the most part terrestrial in origin and not the product of deep oceanic eruptions. Vertical tectonics according to Aduen, played a greater role in the uplift of Himalaya than horizontal migration on a large scale. He held the view that India was close to Eurasia throughout the Phanerozoic and the idea of the existence of an immense ocean between India and Eurasia was untenable. The existence of vast Tethys ocean according to him was a myth.

'Geology of India'

The Geological Society of India was keen on bringing out a concise modern up-to-date account of the Geology of India to mark the occasion of the Silver Jubilee of the Society in 1983. A brief synopsis giving the objective, motivation and organisation of the project was prepared and circulated among the leading geologists of India. A copy of the letter was also sent to Auden on 20 March, 1980. The following objective was envisaged:

'The aim is to incorporate the results of investigations during the last 25 years, by synthesising and, where required, reinterpreting the available information taking note of some of the major advances in earth science which have received wide acceptance. Economy in size and style will be aimed at. It is not intended to be a work of reference like a Manual. Certain topics which are widely known may not be mentioned. The aim is to present a balanced, unbiased, comprehensive but critical up-to-date review of existing knowledge of the geology of the country.

Subject matter under each section was proposed to be covered by individual contributions by specialists in the field. The contributions would be edited by coordinators for each section whose responsibility will be to ensure a consistent and balanced account of the material contributed by the different authors.

To this letter Auden sent the following reply:

'You raise the question of an up-to-date account of the GEOLOGY OF INDIA. You probably know that W.D. West and Sharma have been engaged to revise Wadia's textbook, which I think they are now doing. I was also asked but refused: (1) because I am 76; (2) becasuse although I regard India as more than half my home, I live abroad; (3) because I find it impossible to keep up-to-date with all the research work now being undertaken in India, and by visiting foreigners.'

'Seven years ago I was approached by the then D.G., GSI, about producing a 4th edition of the official Geology of India. I enclose a copy of my reply, dated 5th June 1973, to Roy Chowdhury since it sets out my views then, and now, about any 4th edition of the official Geology of India. That letter, being 7 years old, and not being confidential in any manner, is sent to you even though I have not indicated to Calcutta that a copy has been sent. And in any case, I think that with all the changes in the D.G. of the Survey the whole issue of a new 4th edition has lapsed, and would probably not have the financial approval of the relevant Ministry of the Government of India.'

'Do you think that you have left sufficient time for authoritative articles on the 11 sections indicated in your project Memo? In addition to those sections I am strongly in favour of chapters on applied geology, such as indicated in paragraph 7 of my letter of 5 June 1973 to Roy Chowdhury.'

The letter of Auden to Roy Chowdhury, the then Director General, Geological Survey of India, sets out the view of Auden on this matter of bringing out a new edition of the Geology of India.

My dear Roy Chowdhury,

....During your visit here you asked for my opinion on bringing out a 4th edition of the Geology of India, and you even asked if I would be prepared to write one.

I think that it is now almost impossible for any single individual to write a major treatise on Indian geology on the same authoritative scale as the previous 3 editions. Pascoe spent something like 19 years on the 3rd editon which, although in as much as three volumes, is devoted almost entirely to the work of the GSI when it was a small department, prior to the 1939-45 war and prior to Independence. It is now 100 times large!

In the pre-war years the GSI was indeed almost the sole authority on Indian geology aside from the work of the Mysore Survey. As I emphasised in my review of the Wadia Institute publication HIMALAYAN GEOLOGY (Jour. Geol. Soc. India, v.13, p.308, 1972) important work is now being done by the ONGC and by several flourishing University Departments, and indeed the Journal of the Geologial Society of India is one of the many indications of activity which is independent of the GSI.

In my opinion, it would seem that any new edition of the Geology of India would have to be the combined work of many specialists under either a single editor or a editorial board. Moreover, some of the specialists would almost certainly be university teachers, members of the Mysore Survey, and members of the ONGC. To obtain collaboration between so many sources would no doubt be difficult, and there might be a dispute as to which source would have the ultimate authority for publication. I would have no doubt that the GSI should be that authority, being the senior Survey and already having published the three previous editions.

I would suggest that if it is decided to prepare a 4th edition, there should only be one volume, of the order of 700 pages. Oldham's 2nd edition in one volume followed the first which was (if I remember correctly) was in three volumes....

Nothing tangible came out of these preliminary exercises. Bringing out a new concised version of the Geology of India is being attempted by R. Vaidyanadhan, former Professor, Andhra University and M. Ramakrishnan of the Geological Survey of India.

Years of Retirement, His London Home

I had the good fortune of visiting UK in 1974 to attend a conference on the Early History of the Earth convened by Brian Windley at Leicester. While passing through London, I took the opportunity of calling on Auden at his house in Thurloe Square, S. Kensington. I had not met him before and our acquaintance was only through correspondence. When I called on him I was overwhelmed with the warmth of his reception. Mrs. Sheila Auden was not in good health but in spite of this she had specially prepared tasty Indian food. I spent the whole day with them talking about India. It was drizzling outside. In spite of the inclement weather Auden took me to the office of the Geological Survey at Burlington House which was nearby and spent some time in the Library. He wanted me to meet K.S. Dunham, the Director of the Survey, but he was busy at a meeting. I had a wonderful day. This was the only occasion on which I met this great scientist and the recollection of that happy day still lingers in my mind.

We kept in touch with each other through correspondence. In 1986, I made a request to him for his photograph to illustrate the special volume on the Proterozoic of India. He wrote in reply that the only photograph he had was for 'passport purposes and was really rather horrible' to use his own words. The photograph was never received. What was charming in his letter was the reference made in the last para to the Geological Society of India which read:

> 'I should like to thank the Society for such a regular despatch of the Journal and standard of papers for which you must take so much credit.... almost single handed.

There is a postscript which makes the letter so valuable to me

> 'At the age of 82 years (83 in December next) bodily ailments singly not of much consequence, but cumulatively together become somewhat restrictive in activities and must be accepted as the normal product of longevity. Next month (November) it will be 60 years since I joined the Geological Survey. Please excuse the typing but my script with a shaky hand has become illegible.'

The delivery of the Wadia Medal lecture in 1981 was probably the last public engagement Auden fulfilled. 43, Thurloe Square which was his permanent place of residence was well located and all geologists from India passing through London invariably called on him and paid their respects. He had a way of making his visitor feel important and had a beneficial effect on all.

Auden passed away peacefully on 21 January, 1991. He was cremated on the 29th after a Mass at Westminister Cathedral and as per his wishes, his ashes were immersed in Ganga at Hrishikesh.

I am thankful that I have survived so long (I am 85) to be able to pay this centenary tribute to such a lovable personality as John B. Auden, the last of the British geologists who served the Geological Survey of India with such distinction and acquaint the Fellows of the Society with glimpses of his life and many sided contributions to our knowledge of the geology of India.

B.P. RADHAKRISHNA

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Chronology

1903	Born at York, eldest son of Dr. G.A. Auden, distinguished psychologist and archaeologist.
1908	Family moved to Birmingham
1926	Graduation from Cambridge. Appointed as assistant Superintendent of Geological Survey of India
1926-1928	Raniganj coal field – mapping
1929-1931	Field mapping – Uttar Pradesh and Rajasthan
1928-1939	Field mapping of Himalaya, mainly Central Himalaya, Punjab, Uttar Pradesh, Nepal and Sikkim
	Joined the Himalayan Club; Served as Council member (1933-1944); Vice-President (1950-1953)
	Assistant Editor, Himalayan Journal for 9 years (1939-1944)
1934	Examination of Bihar-Nepal Earthquake
1938	Elected Fellow, National Institute of India (Indian National Science Academy)
1939-1945	Second World War, end of work in Himalaya; Mineral enquiries;
1939	Obtained Pilot A license; Reconnaissance flight over Vindhyan;
	Married Sheila
1940	Daughter Anita born at Calcutta
1942	Daughter Rita born at Simla
1940-1942	Teacher, Presidency College, Calcutta
1944-1945	In-charge of mica production, Ajmer
1945	Deputation to US for training in Engineering Geology (Tennessee Valley Authority)
1945-1952	Superintending Geologist in-charge of Engineering Geology and Groundwater Division
	Investigated almost all the major dam projects, Bhakra-Nangal, Damodar valley, Hirakud, Beas, Rihand, Narmada, Tapti, Koyna, Vaitarni, Mattupettai, Kali.

1947	India became Independent – Partition of India. Awarded doctorate degree, Cambridge University
1949	Acted as Director of Geological Survey of India for two months
1952-1953	Deputy Director – Mineral Development
1953	Sought premature retirement from the Geological Survey. Last British geologist to leave the Survey
1953-1955	Director, Geological Survey, Sweden (eighteen months)
1956	Review geologist – studying data coming from India, Pakistan and Burma
1960	Joined FAO, Land and Water Resources Directorate, UN in Rome (8 years)
	Geology of dam sites in Korea, Turkey, Iran and Afghanistan
1961-1962	Afghanistan. Several trips to India, Ceylon, Nepal up to 1969
1968	Retirement from active service
1981	Last visit to India to deliver Wadia Memorial Lecture
1991	Death, 21 January (87 years)

John Bicknell Auden

Family Background

ANITA MONEY*

My father's last visit to India, accompanied by my mother Sheila (this was her last visit too) and my sister Rita, was in 1981, a few years before his 80th birthday. He went to receive the INSA medal from Indira Gandhi and to deliver the Wadia Memorial Lecture. He died in January 1991 at 43 Thurloe Square where my parents had lived since 1962 – the longest stretch in one place. We held a requiem Mass for him at Westminster Cathedral and later in December that year Rita, Otto (my son) and I took his ashes to India as he had wished.

My purpose in writing this memoir is to fill in some background about our family – that is the Audens and Bonnerjees (my mother Sheila was a Bonnerjee) and to say something about my sister Rita, son Otto and myself .

My father was born on December 14th 1903 in York where his father George Augustus was a GP. George Augustus had begun work there in 1899 just after his marriage to Constance Rosalie Bicknell whom he had met at St Bartholomew's Hospital in London. He had been educated at Repton School in Derbyshire (the Audens come from the Midlands) and then studied Natural Science at Christ's College, Cambridge (where my father also went) before starting his internship at Barts. Constance Rosalie Bicknell who had taken a good degree in French at Royal Holloway, was training to be a nurse with the intention of becoming a medical missionary. Both George Augustus and Constance Rosalie had fathers who were vicars and, to some extent, they shared a middleclass professional background though the Bicknells appear to have been much better connected. On the Bicknell side there are some Indian connections.

John was one of three brothers. Bernard, the eldest, born in 1900, later became a farmer and spent time in Canada and Wystan, the youngest, born in 1907 was later to become a poet (W.H. Auden) and an American citizen. In 1908 George Augustus, leaving behind his more lucrative career as physician,

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**eldest daughter of J.B. Auden*

took on the pioneer and exacting public role of first school medical officer in Birmingham, then the major industrial city in England, and also became Professor of Public Health at the University. The family lived in Solihull, now a suburb of Birmingham but then a village.

In his essay 'A brother's viewpoint' written after Wystan's death in 1973 and published in *W.H Auden: A Tribute* (Weidenfeld and Nicholson, 1974), sadly now out of print, my father describes their background simply and clearly and it is possible to see how it shaped his choice of career. He speaks of visiting waterworks in Birmingham, studying 'menhirs and stone circles, gold and lead mines, blue-john caverns, pre-Norman crosses and churches'. Like Wystan our father always felt grateful for his parents' wide range of interests which extended beyond medicine to archeology, Icelandic sagas, the Classics, poetry, music and literature. The Auden household was full of books and their boyhood holidays, many of which were spent among hills, included biking and climbing in Wales, Bradwell in Derbyshire, and later Cumberland (not so much the Lake District for all its beauties but the bleaker Pennine areas like Alston Moor to the East) where his parents bought a small cottage near Threlkeld called Wesco of which he was particularly fond and where he spent time on his first leave back from India. This is also where my mother, Rita and I first met George Augustus in 1947 when we took a trip to England.

John went to India almost straight after Cambridge in 1926 to join the Indian Geological Survey. After a brief, unhappy marriage (the dedication to him in *The Ascent of F6* makes reference to this while the title was suggested by K2) he met our mother Sheila Bonnerjee in Calcutta in the late 1930s. She was introduced to him by her sister Minnie who was married to Lindsay Emmerson, an editor on *The Statesman*. They, like John, were friends of the poet and critic Suddhin Datta. Our mother's family was well known in Calcutta. Her grandfather Womesh Chunder Bonnerjee was the first president of the Indian National Congress and has been rather ignored in history books because he is seen as too Anglophile though historians are beginning to appreciate the extent of his involvement and work for Congress. W.C or 'greybeard' as my mother and her sisters used to refer to him, had spent time in England and his family lived in a large Victorian house in Croydon which became a meeting place for a number of Indians studying in England. He is buried in the older of the two Croydon cemeteries. His great admiration for English education and culture, an admiration shared by a number of Bengalis and others at that period, might well have made him seem one of those figures easy to satirize as a westernized oriental gentleman – a figure that both the English and Indians alike have been quick to mock – but in his case the interest ran deeper than a taste for English fashions and manners and he, like some of his contemporaries, wished to improve the situation in India with the help of the English. His children were brought up and educated in England and not only the boys but even the girls went to university. A parallel can be drawn with Constance Rosalie, our paternal grandmother who, like my Indian great aunts, was among the first women to take a degree. These great aunts included Agnes Mazumdar, Pramila (whose son Muchu became General Chaudhuri and was Chief of Staff from 1962-1966) and Suzie who became a doctor. My mother's father Ratnakrishna Curran Bonnerjee was a barrister in Calcutta after returning from England where he had read Greats at Balliol before studying law. He had a reputation as a raconteur. My sister and I knew only one of our grandparents – George Augustus – the others having died, but feel in some ways that we know them all through family stories, photographs and family myth.

Our mother studied at The Oriental School of Art in Calcutta and then went abroad with three of her sisters in the early 30s. She began a year's course at the School of Commercial Art in Munich but because of the political situation left for London and studied at the Central School of Art. Her sister Anila studied economics at the LSE under Harold Laski and Indira studied journalism. Minnie did not join them in Europe but took a 'slow boat to China' as she put it. She was later Principal of Bethune College in Calcutta. They were often referred to as 'The Bonnerjee Girls' and it is interesting that three of them married Englishmen (Anila married Tom Graham who was Head of Modern Languages at Emanuel School, London, for many years) and Indira married a Parsee (Russi Talyarkhan who became Chairman of Voltas). Neither of her two brothers, Protap and Bharat, married but we remember them with affection as uncles who spoilt us.

When my mother returned to India in 1937 she arranged to work with Jamini Roy whom she admired and liked. She held many exhibitions in Calcutta and Bombay and some of her work was also exhibited abroad. She illustrated a variety of books, wrote and illustrated numerous articles - some on fashion, some satirical and with a purpose in the form of parables which I think she and my father sometimes collaborated on. She also wrote stories for children. These articles and stories were published in *The Statesman*, *Shankar's Weekly*, *Trend* and other papers. Though she continued painting when she came to England in the 1950s events and various domestic pressures meant that she ceased to give exhibitions though Rita and I hope sometime to arrange a retrospective of her work at The Nehru Centre.

Rita and I were both born in India - Rita in Simla in 1942 and I in Calcutta in 1941. Calcutta was an extraordinary place to be brought up in during the 1940s – before Independence. We lived in 2/5 Lansdowne Road (since pulled down as we discovered in 1991) and Minnie and Lindsay also lived there. They and our parents between them had a wide and cosmopolitan circle of friends – intellectuals, diplomats, artists, businessmen, journalists. We went to a school run by Miss Higgins and as we rested on our mats on the floor after lunch she would read to us from Caesar "Gaul is divided in three parts......"

Our childhood memories include visits to the GSI in Calcutta and the monkeys in the trees who could occasionally ravage the papers, rides in our father's jeep in the maidan speeding over hollows and bumps, camping in tents divided into different rooms (though I forget where), going with our bearer nicknamed Mouse to admire all the gods and goddesses displayed in tents during festivals, travelling to school in a rickshaw, tea at Firpos, meals in Chinatown, shopping in the bazaar, train journeys both across plains and in a narrow gauge railway winding slowly up past waterfalls and orchids to Darjeeling where we spent holidays in our great aunt Agnes Mazumdar's house which was haunted. I remember the excitement of seeing clouds beneath us and the view from Tiger Hill of Kanchenjunga and Everest as well as the sound of Tibetan monks' horns. Tibet fascinated my mother and she was interested in the tanka. She also painted Himalayan mountainscapes, sometimes using some of my father's photographs for perspective. There are other memories of Howrah station, beggars, crowds of refugees and the reality of extremes of poverty and disease. My mother understood and appreciated the very visible truth in India of life and death – the juxtaposition of rituals, a marriage procession passing a funeral procession.

When we finally left Calcutta to go to school in England we went via Ischia, an island in the south reached from Naples where Wystan spent time in the Summer in the 1950s. Our father had always been close to Wystan and they corresponded throughout their lives. Early letters from India in the 1920s and 1930s show John's dislike of the attitudes of some of the English out in India and how his faith in and affection for India grew. Our parents were initially concerned about the possible problems of a mixed marriage. My father converted to Roman Catholicism in India, partly through his friendship with an American jesuit Father Anderson Bakewell but also because he felt that Anglicanism was too associated with the Raj while the 'catholicity' of Roman Catholicism made it more suitable for mixed cultural backgrounds. My mother remained a Hindu, though not a practising one, but was sympathetic towards Christianity (her aunt Agnes became a devout Christian) and often painted Madonnas and Nativities, later becoming interested in St Francis. At her cremation in January 2002, we invited a Roman Catholic priest, a Franciscan, to officiate and the prayers included the lines from the Upanishad:

'Lead us from darkness to light
From Untruth to Truth
And from Death to Immortality'

and the peace prayer attributed to St Francis which begins:

> *'Lord make me an instrument of Thy peace*
> *Where there is hatred let me sow love ...'*

Our mother dutifully accompanied us to Mass when we were young. I have a particular memory of her looking tall and elegant in a sari (she was wearing high heeled shoes) taking Rita and me by bus to an early morning mass in a mock Gothic RC Church in a then rather grim looking Burton-on-Trent (there was no Catholic church in Repton where we were staying with George Augustus) causing some curiosity in the 1950s. We were conscious of being different, though now things have changed so much that these memories are part of history.

Rita, after studying Natural Science at St Anne's College, Oxford, went on to become a surgeon at The London Hospital. She married Peter Mudford, a contemporary at Oxford (he was at Christchurch, Wystan's college) who later became a Professor of English at Birkbeck, London University. They both visited India on several occasions. I, after a brief spell at Sadlers Wells, abandoned the idea of becoming a dancer and went to St Hugh's College, Oxford, where I read English. Since then I have done a number of things: teaching both exercise and English and working in antiques as my ex-husband Lennox Money was an antique dealer with eclectic interests which included colonial furniture and Persian pottery (he enjoyed travelling and visited India a number of times and some of his Money forebears – there is a picture of three of them in the Maritime Museum at Greenwich with a map spread out in front of them - worked for the East India Company in the 18th century). I also spent seven years on a poetry magazine called *Agenda* and edited an issue in 1997 which was partly intended to commemorate 50 years of Indian Independence. The issue included a number of translations from different Indian languages (South Asian is the global term now used) as well as poems written in English (one of India's languages though showing a sea-change) by Indian poets. Currently I work in academic administration in the public sector as well as writing a few reviews while Rita, who has now retired, goes to lectures on archeology at The British Museum and has become a wizard at crossword puzzles - something she started to do with my mother during the last few years.

The trip in 1991 when we took John's ashes to scatter both in the Hooghly and in Rishikesh (where we were joined by Rita's ex-husband Peter) was Otto's first visit to India. He appreciated taking part in the commemoration at The Geological Survey in Calcutta and the Sanskrit ritual on the banks of the Hooghly as he has a strong sense of occasion and ritual and a number of interests which include astrology, an influence from my mother. He used frequently to visit Thurloe Square and when very young went with his grandfather to The Geological Museum, The Science Museum and The Natural History Museum – all conveniently close. He also played elaborate games with his grandmother: they invented a cast of characters both Indian and English composed from numerous toy animals as well as creating a wishing tree to which exotic branches were added yearly. His imaginary island of Ottya was mapped to scale by John.

Since that trip to India in 1991 Otto has taken a degree in English at University College, London, followed by an MA in Theatre Performance at Goldsmith's College (University of London) and has done some training in mime and physical theatre at a school run by Desmond Jones. Currently, in order to earn a living, he is working in financial administration at a fringe theatre called The Bridewell, near Blackfriars.

We have finally, this August, made our farewells to 43 Thurloe Square which was never owned but rented. My father spent a very active retirement there after his time with the United Nations and there are pleasant memories of visitors, including Mr. Ramachandran, a colleague of my father's from the GSI, who has become a friend of the family. It is also where my sister returned to look after my mother till her death. The letters, photographs, diaries and notebooks collected over the years will take some sorting but sadly we have had to part with various things such as old trunks and suitcases which travelled with my father to India and other parts of the world. India was home for him in many ways and the Himalayas were one of his sacred places. The ashes of his parents are scattered in a small church called St Kentigern in Mungrisdale, Cumberland, not far from Wesco. Wystan is buried in Kirschstetten in Austria. John's ashes are in the Ganges. We hope to take my mother's ashes to India as well.

We have kept a key to the gardens of Thurloe Square where we have left a bench commemorating our parents with the Latin inscription *Ubi caritas et amor, Deus ibi est.* It seems fitting that the closure to No. 43 is in 2003, the centenary year of our father's birth and occasion for this celebration.

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(Reproduced from Rec. Geol. Surv. India, v.66 (1933), pp.461-471)

On the Age of Certain Himalayan Granites

J.B. AUDEN

EDITORIAL COMMENTS

In this paper Auden has made a masterly analysis of various aspects of age of Himalayan granites and has attempted to drive the point home about the existence of Pre-Tertiary granites in the Himalaya. Earlier, there was a tendency to consider all the Himalayan granites to be intrusives during Tertiary. The discovery of a pebble of granite in 'Volcanic Breccia' of Middlemiss and its remarkable resemblance with the granites exposed in the Arwa valley of the Central Himalaya led him to suggest about the existence of pre-Tertiary granites. Incidentally 'Volcanic Breccia' yielded an excellent collection of Permo-carboniferous fenestellide bryozoa fauna (Ganesan, 1972), thereby confirming the pre-Carboniferous age of the granite pebble.

Auden reviews the views expressed by Griesbach, Hayden, McMahon and De Terra on various granites found in the thrust sheets and in the Higher Himalaya of Ladakh, Simla, Spiti, Central Himalaya. Further, Auden adduces evidences in support of the earlier orogenic activities in the Himalaya based on the presence of Aravalli trends in the Himalaya.

After referring to the two contrasting views that Tertiary movements were responsible for the thrust displacement of the Chor granite and the associated Jutogh rocks, and that of Middlemiss's idea that Lansdowne granites and the associated metasediments were autochthonous, Auden reinterprets that the Lansdowne granite and associated rocks represented a klippe on Subathu, Tal and Krols. He makes the point that the granites were Himalayan in the sense they were involved in Himalayan movements but were not Himalayan in their original intrusive condition. – S.V. Srikantia.

INTRODUCTION

In October, 1932, a small pocket of granite was found in the 'Volcanic breccia' of Garhwal, which had been previously mapped by Middlemiss

(*Rec. Geol. Surv. India*, v.20, 1887, p.33). This granite resembles granite found *in situ* in the Arwa valley of the Central Himalaya.

The object of this note is to discuss the bearing of this resemblance on the age of the inferred parent granite.

* * * * *

VOLCANIC BRECCIA

The exposure of volcanic breccia, in which the pebble of granite was found, is at the confluence of a small *nala* with the Medi Gad, at Raitpur (29°54':78°42'), in half-inch to the mile sheet 53 K/NE.

Middlemiss places this breccia at the base of his 'Purple Slate' series, at the base therefore of the sedimentary sequence belonging to his 'Outer series'. The breccia at Raitpur lies abnormally above the Tal beds, and is itself overlain by the 'Inner Schistose Series' with its capping of gneissic granite.

The real succession he gave as below. To it I have added a correlation with the rocks of the Krol belt between Solon and Chakrata.

Garhwal	Krol Belt
Tals	Tals
Massive limestone	Upper Krol limestone
	Krol B (Red shales)
Purple Slates	Krol A (Lower Krol limestone)
(Conglomerate boulder bed in Purple slates)?	Infra Krol
	Blaini
	Jaunsars
Volcanic Breccia ?	Mandhalis

The correlation of the lower part of the Purple Slates with the rocks of the Krol belt is uncertain. Along the Pauri track, ENE of Raitpur, Upper Krol limestone, Red Shales, Lower Krol Limestone and Infra Krol were all clearly recognisable. After this follow purple slates with bands of green slate, a thin conglomeratic boulder bed (distinct from the volcanic breccia), more purple slates and, finally, ripple-marked quartzites. These purple slates and quartzites are certainly to be matched with those found in the Jaunsars of the Solon-Chakrata area, and it is tempting therefore to correlate the thin conglomeratic boulder bed with the Blaini. I did not see the volcanic breccia in its normal position, but its assignation by Middlemiss to the base of the Purple Slates suggests analogy with the Mandhali boulder beds which appear to underlie the Jaunsars near Chakrata and Kalsi. The correct position of the Mandhalis is not yet fully understood. Oldham, Pilgrim and West have all tentatively correlated them with the Blaini and Infra Krol. If this is substantiated, it follows that a thrust must separate them from the overlying Jaunsars.

From the point of view of the present paper the exact correlation does not matter. It is safe to say that the volcanic breccia occurs at a horizon below the Krol limestones which is either equivalent to or older than the Blaini. The Blaini is now regarded as the same age as the Talchirs, which are Upper Carboniferous in age (*Mem. Geol. Surv. India*, v.53, p.131, 1928). It was considered by Sir Thomas Holland to be Purana, (*Rec. Geol. Surv. India*, v.37, p.129, 1908) but Pilgrim and West have given cogent reasons for reverting to the original Talchir correlation made by Oldham in 1883 (*Op. cit.*, v.21, p.130, 1888). No one has suggested an age younger than Upper Carboniferous.

It may be taken, therefore, that the volcanic breccia of Garhwal is not younger than Upper Carboniferous.

It follows that a pebble of granite which occurs in this volcanic breccia must be derived from a parent granite which can at the latest have been exposed to denudation in Upper Carboniferous times. The intrusion of this granite would probably have been earlier still.

THE PEBBLE

In the hand-specimen this is seen to be a fresh fine-grained non-porphyritic granite, with quartz, feldspar, green ferromagnesian mineral amd pyrites (specimen No. 44/543).

Its specific gravity is 2.63.

Under the microscope, the rock is seen to contain quartz, albite-oligoclase, chloritised biotite, pyrites, ilmenite, apatite, calcite (rock slice No.22171).

Quartz and plagioclase are about equal in amount. The plagioclase gives maximum extinction angles perpendicular to (010) of 15°. Its mean refractive index is equal to or just below that of balsam; in one case very slightly above. The mean refractive index is always well below that of quartz. The mineral approximates to albite-oligoclase. It is generally turbid with slight saussuritisation.

The biotite has been almost completely altered to chlorite, with liberation of iron. Shreds of brown and more birefringent biotite are occasssionally to be seen interleaved with the chlorite.

Pyrites, ilmenite and rare apatite occur. Calcite is found in considerable quantities in interstitial clusters and veins.

The rock may be called an *albitite-oligoclase-granite.*

GRANITES IN THE ARWA VALLEY

From Musapani in the Saraswati valley, six miles north of Badrinath, to

Ghastoli and up the Arwa valley, a great variety of granites and gneissic granites are found. The commonest type is a moderately fine-grained white granite, without parallelism of minerals, showing quartz, feldspar, muscovite, biotite and often abundant tourmaline. In addition, there are glomeroplasmatic gneisses with clusters of biotite, gneissic granites, feldspar augen granites and abundant pegmatites with or without tourmaline. Along the Arwa valley, from near the west end of its west to east course up to the 16,300 foot base camp established by the Kamet Expedition in 1931, there are found porphyritic and non-porphyritic granites with prevalent green ferromagnesian minerals, and often with pyrites. It was the memory of these granites which at once at Raitpur suggested a relationship with the pebble found in the volcanic breccia.

Specific gravities of two specimens, one a green granite, the other a whiter, biotite-granite, are respectively 2.66 and 2.63.

Under the microscope, these granites are seen to contain abundant quartz and albite-oligoclase. Microperthite and anorthoclase also occur and may be prevalent. In slide 22062 there is microperthite with subordinate oligoclase, the latter occurring both as fresh crystals, and in perthitic intergrowth with orthoclase. In 22064, micro-perthite is less common than albite-oligoclase, while in one slide of 22061 albite greatly exceeds anorthoclase in amount. Biotite is more common than muscovite, and is very generally chloritised, 22061. Tourmaline is seen in 22065 and 22064. In 22065 there is apatite. Sphene occurs in 22061.

These rocks vary from *albite-oligoclase-granite* to *adamellite.*

COMPARISON

It is seen from the above descriptions that there is a close similarity between the pebble found in the volcanic breccia of Raitpur, and the granites found *in situ* in the Arwa valley. The closest similarity is with rock slice 22061. The striking feature is the prevalence in both pebble and *in situ* granite of sodic plagioclase (It should be pointed out that the occurrence of albitite-oligoclase is not peculiar to the Arwa granites or to those found north of the Himalayan axis. It occurs, often extensively, in the Hazara, Chor and Lansdowne granites. Megascopically, these latter granites, even when unfoliated, are markedly different from those in the Saraswati and Arwa valleys. Microscopically there seems to be greater spreading of small crystals of primary mica, distinct from saussurite-mica, throughout the feldspars, than is found in the Arwa granites).

It may be concluded, therefore, that granites, similar to those found in the Arwa valley, were intruded before the Upper Carboniferous.

Hayden (*'Geography and Geology of the Himalaya'*, p. 219, (1907-08)) describes the presence of fragments of granite in the Kuling series of Spiti and the Agglomerate Slate of Kashmir, and therefore ascribes a pre-Carboniferous age to the parent rocks. Mr. Wadia tells me that the pebbles he has seen in the Agglomerate Slate are of white gneissic granite, very similar to that of Hazara. Hayden goes on to say:

> 'It will be seen subsequently that at this period the Himalaya did not exist and this old granite must therefore be excluded from the term "Himalayan."'

He contrasts this old granite with other granites found in the Himalaya, which have been regarded as Cretaceous or Tertiary in age. It is here that there seems to be a discrepancy, because, on the account of Griesbach and Hayden, the granites of the Arwa valley must be correlated with these later granites, and, on the account given above, similar granites should be considered as belonging to a Palaeozoic suite.

OTHER OCCURRENCES OF GRANITE

Griesbach (*Mem. Geol. Surv. India*, v.23, p.42, 1891) describes the presence of younger granites cutting through the older gneisses and schists, and traversing the overlying rocks of the Haimanta system (Cambrian and ?Precambrian). He states that the greater peaks of the Central Himalaya are all within the line of this granitic intrusion, citing those of Kamet, Mana and Badrinath. The Arwa valley lies within this line. He describes these rocks as containing muscovite, quartz and albite, with-accessory minerals such tourmaline, garnet and beryl. There can be no doubt that the Arwa rocks belong to this so-called newer granite suite of Griesbach.

He remarks that there is nothing to show that the later Himalayan granite of Kumaun and Garhwal is much younger than lower Palaeozoic, but suggest that at least some of these granites are equivalent to those in the Hindu Kush which are intrusive into upper Cretaceous rocks. He finally favours the view that the granites were intruded not long prior to the extensive basic rocks of Hundes, which are Middle Tertiary in age.

In the Spiti area Hayden (*Mem. Geol. Surv. India*, v.36, Pt.1, p.98, 1904) describes a biotite granite with orthoclase in excess of plagioclase, which is intrusive into older Palaeozoics. In Rupshu he mentions a similar granite which cuts Carboniferous and Permian schists, and must therefore be post-Carboniferous or possibly post-Permian.

In the provinces of Tsang and Ü in Tibet, (*Op. Cit.*, v.36, pt.2, p.62, 1907) he describes three series of igneous rocks:

(1) A foliated biotite-granite, associated with tourmaline-granite, intrusive into Jurassic rocks, and probably not older than Eocene. This is a continuation of the great granitic axis of the Himalaya.

(2) Series of basic dykes, possibly Eocene.
(3) The Kyi Chu hornblende-albite-sphene-granite, which is definitely not older than Upper Cretaceous.

In the '*Geography and Geology of the Himalaya*' pages 218 to 220, Hayden summarises the known occurrences of granite as follows:

(1) Pre-Carboniferous granite, found as pebbles in the Kuling conglomerate and in the Agglomerate Slate.
(2) Gneissose granite, described in detail by Lieut.-General McMahon, and thought to be early Tertiary.
(3) Biotite-granite, tourmaline-granite, hornblende-granite, which are either late Cretaceous or Tertiary.

It is the biotite-granite which Hayden states occurs at Chamba, Chor, Lansdowne, etc.

Age

This classification is open to question. Firstly, although Hayden states that the granites of Chamba, Chor and Lansdowne belong to his biotite-granite division, yet it is these granites which were described by McMahon, and which are so largely gneissic. Middlemiss (*Rec. Geol. Surv. India*, v.20, p.138, 1887) and West (*Mem. Geol. Surv. India*, v.53, p.53, 1928) have both shown the passage of massive unfoliated granite into gneissic granite, and it is probable that the biotite-granite and gneissic granite of Hayden's classification are different but intimately related modifications of the same magma. Secondly, the late Cretaceous or Tertiary age of all these rocks is not so definite as Hayden's account leads one to suppose.

It is true that McMahon was consistently in favour of a Tertiary age for the gneissic granites which he had examined. Middlemiss, (*Op, Cit.*, v.26, p.277, 1896) however, maintained that the Hazara granite, and probably also those of Chor, Lansdowne and Dudatoli, were pre-Triassic. McMahon (*Geol. Mag.*, p.304, 1897) criticised these conclusions, without, in my opinion, adding support to his own assertion of a Tertiary age. The evidence adduced by both these authors was of a negative kind.

In an important memoir, ('*Geologishe Forschungen in westlichen K'un-lun and Karakorum-Himalaya*', Berlin, 1932) De Terra has given an account of his geological reconnaissance through Central Asia in 1927-28. In the western K'un-lun (p. 47), he has discovered two main occurrences of granite; that of the K'un-lun proper (his *Hauptkette*), and that of the Kilian range. These granites are intrusive into gneisses, schists and sediments of the Karakasch and Kilian series. The latter series is Upper Silurian in part. De Terra considers that the intrusions are of Lower Devonian age. It is noteworthy that they have been strongly affected by orogenic movements of late Palaeozoic age, which have resulted in the formation of schistosity, and lamination (*plattige Absonderung*) oriented in a NW-SE direction. The modern Kilian chain strikes almost due east-west. This NW-SE direction of Palaeozoic structures may be compared with that found by Dr. Heron in the Kirana hills (31° 58':72°45') of the Punjab, to be mentioned later.

De Terra considers that the Tankse granite, of the Ladakh and Karakorum area (p.113), is definitely unconnected with the late Cretaceous and Tertiary folding of the Karakorum, but was intruded in late Palaeozoic times.

ARAVALLI DIRECTIONS IN THE HIMALAYA

In favour of the pre-Triassic age, advocated by Middlemiss, for some of the granites intrusive in ranges bordering the Peninsula, is the striking orientation of phenocrysts and of lenticular and linear structures (Flaserige (*lentikulare*) *Textur and Gestreckte (lineare) Textur,* Grubenmann-Niggli, 'Die Gesteinsmetamorphose', p.456, 1924) in the gneissic granite at Lansdowne. In fifteen observations over different parts of the granite, I found the range of direction varied from 35°-215° to 60°-240°, averaging NE-SW.

Similar directions were observed in the tectonic elongation of pebbles in the Jaunsar conglomerates along the Palor river (30°42':77°24'), which averaged 60°-240°. Fold-ripples in the Jaunsar phyllites at Shallai (30°40':77°42) varied from 80°-260° to 60°-240°. The schistosity of the quartz-schists in the Jaunsar series near Andra (30°36':77°44') strikes due NE-SW. These Jaunsar rocks are possibly Devonian in age. Idioblasts of andalusite in a hornfels by the Ramganga river (30°2'30":79°17'30") were seen to be oriented in a 50°-230° direction. This last occurrence is interesting, because the hornfels is a product of metamorphism of the Dudatoli granite, which can almost certainly be correlated with that at Lansdowne.

This orientation is at right angles to the present axis of the Himalaya, and is the same as that of the Aravalli range. If the present Aravalli range be continued across the Gangetic alluvium, it is seen to meet the Himalaya between Chakrata and Naini Tal.

No orientation along Aravalli directions has been seen in beds higher than the Blaini. The Infra Krol and the Krol Limestones are unaffected by it. Fold-puckers in the Lower Krol limestone were seen to be parallel to 120°-300°, that is, parallel to the axis of the Himalaya (Some of these fold-puckers are distinct from the fold-ripples in the Jaunsars which were mentioned above.

They appear to be original sedimentation ripple marks that have offered avenues of relief to later stress).

Accepting the Blaini as Upper Carboniferous, it follows that the dating of this Aravalli orientation is not later than Carboniferous.

This NE-SW orientation was presumably connected with orogenic activity along the Aravalli axis. It may be remarked that the linear schistosity (*gestreckte Textur*) of the amphiboles in the calc-schists of the Aravalli range of Rajputana was found to be parallel to the axis of the range, 30°-120°. The feldspar phenocrysts in the Erinpura granite, as, for instance, at 24°39':73°15' (corrected longitude), are similarly oriented. It is true that the Delhi rocks, to which these calc-schists belong, are pre-Cambrian in age, and owe their structures to an orogenic activity that was pre-Cambrian, but there is reason to suppose rejuvenation along this range (Fermor, *Rec. Geol. Surv. India*, v.62, p.391, 1929).

The Vindhyan rocks of Bundi and Karauli States are sharply folded and faulted in a NE-SW direction (Heron, *Mem. Geol. Surv. India*, v.45, p.169, 1922). Coulson, *Rec. Geol. Surv. India*, v.60, p.185, 1927). These movements were post-Bhander in age and altogether distinct from the earlier orogenies responsible for the structures in the Delhi rocks. The age of the Vindhyans is not definitely known, but reasons have been put forward to support the supposition that some of the series in the Vindhyan system may be Cambrian (Auden, *Mem. Geol. Surv. India*, v.42, pt.2). This would imply that some of the movements affecting the Vindhyans were Cambrian or later, and accords with the considerations advanced above for structures found in the Palaeozoic rocks of the present Himalaya. The movements were post-Cambrian and pre-Permian.

Middlemiss (*Mem. Geol. Surv. India*, v.24, p.125, 1890) has also recorded the presence of structures in the Kumaon which are oblique to the modern axis of the Himalaya. Basic volcanic rocks, with interbedded quartzites and slates, show folding, cleavage and crushing along a north to south strike. He states:

> 'The lines of disturbance, therefore, in *some* Himalayan rocks do not coincide with those of the Sub-Himalaya, nor with other Himalayan rocks, and must have been due to other and older directions of thrust'.

The 'Himalayan' rocks of Middlemiss and Meddlicott are pre-Tertiary. The 'Sub-Himalayan' rocks are the Tertiaries.

Dr. Heron has kindly drawn my attention to the NW-SE strike of the Aravalli rocks found in the Kirana hills, Punjab (Heron, *Rec. Geol. Surv. India*, v.43, p.299, 1913). He states that the border folds along the southeast flank of the Aravalli range tend to splay out at their extremities to the east, while the central folds of the range continue un-deflected in a NE-SW direction towards

Delhi. There is no evidence of the splaying out of the border folds along the north-west flank of the range, which might have been used to explain the NW-SE strike of the rocks at Kirana. Alluvium covers all the intervening ground.

While the existence of structures showing NE-SW, or Aravalli directions is of importance in the part of the Himalaya with which this paper is chiefly concerned, it is clear that elsewhere these earlier structures assumed different orientations. Both at Kirana, and in the Kilian chain, the earlier, Archaean and Palaeozoic structures occur in NW-SE directions, at right angles to those found in the Himalaya between Chakrata and Naini Tal, and at right angles to the Aravalli chain itself.

The important point is that signs of earlier orogenic activities are still recognisable in the present Himalaya, in structures which are often inclined to the axes of the later, Tertiary, chains. Both Palaeozoic and Tertiary chains show regional variation in direction, but the directions assumed during the two eras are not everywhere coincident. It is this lack of coincidence which is of value in determining the relative ages of intrusions.

ARKOSES

In connection with a pre-Triassic age for some of the Himalayan granites, may be mentioned the prevalence of arkoses in the Jaunsar series (? Devonian) and in the Tal series (almost certainly Mesozoic). The Jaunsar arkoses contain plagioclase feldspar and tourmaline and the Tal arkoses, microcline feldspar and tourmaline.

It may be concluded that these arkoses were derived from erosion of granites. It is true that any extensive series of metamorphic granulites (paragneisses), such as occurs between Josimath and Mana, would yield abundant microcline and plagioclase, and that the presence of feldpsar alone would not prove a granitic provenance. It is the joint occurrence of feldspar and tourmaline that suggests a granitic source for the Jaisalmur and Tal arkoses. Further, pebbles of feldspar may frequently be seen in the Tals, which are too large to have been derived from granulites.

LATER HIMALAYAN STRUCTURES

Pilgrim and West have described the thrust displacement of the Chor granite and its country rock of Jutogh schists, due to the Tertiary movements (*Mem. Geol. Surv. India*, v.53, p.128, 1928). It is quite possible that the Lansdowne granite, with its associated phyllites and schists, is similarly a thrust mass, occurring as a *Klippe* on Subathus, Tals, Krols and underlying slates. Middlemiss hinted at this in 1887, (*Rec. Geol. Surv. India*, v.20, pp.34,37,

1887) but condemned the idea with arguments that do not appear to be altogether sound. Whatever be the true explanation of the displaced situation of the Lansdowne granite, it is clear that subsequent Himalayan movements have greatly modified its position, as they did that of the Chor granite without, however, altering the Aravalli orientation due to the original intrusion tectonics. The granites may be considered Himalayan, in the sense that they have been incorporated in later Himalayan structures, but it seems that they were not Himalayan in the original intrusive condition. This was what was claimed by Hayden, for the parent granite of the pebbles found in the Kulings and the Agglomerate Slate.

CONCLUSIONS

Summarily, the evidence may be put forward as follows:

(1) In Tibet and the Hindu Kush there is indisputable evidence of late Cretaceous or Tertiary granites.

(2) In the Central Himalaya there is indisputable evidence of granites intrusive into the Carboniferous. These have been regarded as Tertiary, chiefly because of the existence of known late Cretaceous or Tertiary granites in Tibet, etc. A pebble, resembling some of the newer suite granites in the Central Himalaya, has been found in the volcanic breccia of Garhwal. The granite, from which the pebble at Raitpur was derived, must have been pre-Triassic. It is possible, therefore, that both the older and newer suites of granite in the Central Himalaya are pre-Triassic.

(3) In the border ranges, including Hazara, Chor, Lansdowne, Dudatoli, there are characteristic gneissic granites which were held by McMahon to be Tertiary, but by Middlemiss to be pre-Triassic. In the case of the Lansdowne granite, and the hornfels related to the Dudatoli granite, there are structures which accord better with Aravalli tectonics. Pebbles of gneissic granite, similar to the Hazara granite, have been found in the Agglomerate Slate. There is more evidence in favour of a pre-Triassic age for these rocks than for a Tertiary age.

It will be seen from the above discussion that there are a great number of uncertainties. But it seems definite that some, at least, of the granites of the Central Himalaya and border ranges closer to the Peninsula, which have been considered to be of Tertiary age, were originally intruded in pre-Triassic times and belonged to pre-Himalayan tectonics. These earlier granites are of diverse types, and are probably of more than one age.

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Vindhyan Sedimentation in the Son Valley, Mirzapur District

J.B. AUDEN

EDITORIAL COMMENTS

The mapping of a portion of the Son Valley was an outstanding piece of work completed within a period of less than a year with particular reference to the boundary between the upper and lower Vindhyans. As this mapping was carried out on relatively more detailed topographical sheets, Auden's geological map contains greater details than that of R.D. Oldham and F.R. Mallet. Auden adopted detailed lithostratigraphic classification and thus, the geological map has the imprint of his meticulous approach to geological mapping irrespective of the nature of terrain.

His work confirmed that a strong unconformity exists between the basal Semri and the underlying Bijawars. The basal conglomerate of the Semri has distinctive characteristics with abundance of red jaspers in addition to other rock types which are mostly derived from the underlying Bijawars. Auden brought out the differences in rock types between the Semri and the Bijawars. He brought out the distinctive characters of the Kajrahat limestone of the Semri.

Auden provided a detailed division of the Porcellanite stage and brought out its polygenetic nature and the volcanogenic character of its basal member. Similarly the division of the Kheinjua stage in different sectors of the Vindhyan belt is a welcome contribution. The top member of the Kheinjua stage is invariably glauconitic beds.

Auden classified the Rohtas stage with its abundant carbonate rocks into five members with variable limestone shale association in different geographical sectors. Every single outcrop has received his attention as exemplified by his incisive comments on each one of them.

The Kaimur Series which succeed the Semri has three distinctive stages: the Lower Kaimur sandstone, the Bijaigarh and the Upper Kaimur sandstone. Auden clarified that there are two quartzite members in the Lower Kaimur Sandstone *with an intervening unit of Susnai breccia and where the Lower quartzite is not continuous, the Susnai breccias should not be considered as the basal unit of the Kaimur. This is essentially a field geologist's approach to show that similar lithounits can repeat due to cyclic sedimentation.*

The Bijaigarh shales which intervene between lower and upper Kaimur Sandstone is essentially black shale.

Auden described various sedimentary structures with meticulous detail. He was the first to record the current direction and to determine the source of sediments. He recorded that dolerite dykes are intrusives into the Semris but not into the Kaimurs.

The aspect of tighter folding towards south was also recorded. Auden reported reverse faults in the Vindhyan suggesting a movement from SSE to NNW.

Auden attempted a detailed analysis of the significance of joints recorded in the Vindhyan rocks.

Based on the study of glauconite bearing beds Auden surmised that the formation of the glauconites in the Semris of the Vindhyan rocks was in association with organic matter. Thus the existence of life during the Vindhyan times is seen to be strong.

Auden also attempted basin analysis by collating all facts. He suggested that the Semris were largely a marine formation but he attributed Kaimur to be of fluviatile origin. However, his work brought out clearly that between the Semris and the Kaimurs there is a distinct change in facies reflecting a change in conditions from marine to fluviatile. Auden discusses the climatic conditions during the Vindhyan and suggested aridity or semi-aridity as the condition prevailed during the period.

Discussing the main objective of his work Auden presents a detailed historical account of the boundary problem between the Semris and the Kaimurs. Based on his field work he placed the boundary at the base of the Lower Kaimur sandstone. Based on entirely field facts, he stressed that the Semri and Kaimur are within the Vindhyan system representing two distinct calcareous and arenaceous facies. Auden discouraged the classification of the Vindhyan into the Lower Vindhyan comprising only the Semris and the upper Vindhyan comprising Kaimur, Rewa and Bhander. He suggested the adoption of four fold classification comprising Semri, Kaimur, Rewa and Bhander in the ascending order.

Auden recogniszed that correlation of the Vindhyans with carbonate-arenaceous-argillaceous units would remain uncertain owing to the discontinuity of outcrops of these rocks. Based on the presence of glauconite which was then considered as confined to Cambrian and younger formations and also on the prevailing correlation of the Vindhyans, or part of the Vindhyans, with the Cambrian rocks of the Salt Range, he speculated that the age of the Vindhyan rocks may be anything from Algonkian to Devonian and was inclined to suggest a Cambrian age for at least a part of the Vindhyan. The age of the Vindhyan to this day remains controversial, but the prolific presence of columnar stromatolites point more towards Neoproterozoic age for the Vindhyans. - S.V. Srikantia.

* * * * *

Topography

The Son valley is occupied very largely by thick alluvium, dissection of which gives rise to bad lands. Dense jungle covers the lower slopes along the whole length of the Kaimur scarp, and the whole of the Bijawar hills. Much of the central valley, when not occupied by alluvium, is covered with forest and shrub growth.

On account of the alluvium and jungle, exposures are far between and never extensive. Hence continuous mapping along the strike is practically impossible, especially between Agori and Bardi. This is particularly unfortunate in the present enquiry, and has been the cause of the varied interpretations put by successive workers on a series of discrete observations. Lateral change in sediments is not best proved by comparing dip sections, and good sections showing the junction of rock groups and series are hardly ever seen. In particular, this is the case with the Kaimur-Semri boundary. It should be pointed out that the conclusions based on mapping are qualified by these conditions.

Table of Formations

The formations discussed are enumerated in the following Table.

	Divisions for quarter inch map	Divisions for one-inch map	Thickness (in feet) in east	Oldham, Vredenberg, Datta, 1901	Mallet, 1871
Kaimur Series	Upper Kaimur Stage	Dhandraul quartzite	300	Kaimur Stage	Upper Kymores
		Scarp Sandstone	600		
	Lower Kaimur Stage	Bijaigarh shales	150		Lower Kymores
		Upper Quartzite Susnai conglomeratic breccia	150		
		Silicified Shales	100	?	
		Lower Quartzite	100	?	
Semri Series	Rohtas stage	Limestone and shales	400 to 700	Rohtas stage	10, 11
		Nodular limestone and shales		Kheinjua stage	
		Banded shales			
		Limestones			9
		Nodular limestone and shales			Lower
	Kheinjua stage	Galuconite beds	300+		8
		Fawn Limestone	250		7
		Olive shales	100+		6
	Porcellanite stage	Porcellanite, etc.	300+	Porcellanite stage	3,4,5 Vindhyans
	Basal stage	Kajrahat limestone	2000	Basal stage	2
		Basal conglomerate,etc			1

Pre-Vindhyan formations : ? Bijawars and Gneissose Granite

PRE-VINDHYAN FORMATIONS

The Bijawar[1] and gneissose granite rocks do not come within the scope of the present enquiry, but their general nature may be briefly indicated. That the granite is later in age than the Bijawar rocks is seen from an excellent exposure in a nala three miles southeast of Naogain, west of the area included within the published map. Here, there are irregular sills of sheared quartz-feldspar-granites, without ferromagnesian minerals, intrusive into purple phyllites of the Bijawars. Within the phyllites, also, are sheared blebs of metamorphosed dolerite. Since the granite cuts across the banding of the phyllites, parallel to which are the blebs of metamorphosed dolerite, it is probable that the granite was later also than the dolerites intrusive into the Bijawars. The same post-Bijawar age for the granite is suggested right in the east of the area, one mile west of Jhirgadandi, by the inclusion in porphyritic biotite gneissose granite of abundant xenoliths of amphibolitised phyllite. These xenoliths are up to two feet long by one foot wide, and are arranged parallel to the gneissose banding in a 120°-300° direction. Aside from slight thermal alteration, they resemble Bijawars which occur *in situ* further west.

The Bijawars themselves are made up of an extremely variable series of papery mica-schists, purple and red phyllites, slates and shales, dirty banded quartzites, cleaved shaley sandstones and current-bedded pebbly sandstones, siliceous limestones, crystalline limestones, haematite-schists, siderite bands, red jasper bands and intrusive dolerites, and exhibit and abundant permeation with vein quartz. The commonest rocks are the purple phyllites, slates and shales. It is important to emphasise the close association of rocks of the same

[1]In his use of the term Bijawar, Mr. Auden is following both editions (1869 and 1893) of the Manual of the Geology of India, as also Mr. R.D. Oldham in the 'Geology of the Son Valley', *Mem. Geol. Surv. India*, v.31, pt.1, p.4, 1901. Even in the first edition of the Manual, however, the possibility is recongnised (p.29) that the 'transition rocks' of the Bijawar basin may comprise two formations. Work during the present century has tended to accentuate this view and the metamorphic rocks of the Jubbaulpore district described by Mallet as Bijawar are now regardd as more probably related to the older Dharwars of Southern India, recognised as an older 'transition' system by Foote in 1888, i.e., after the issue of the first edition of the Manual. The only area outside the original Bijawar area of Bijawar in which rocks originally described as Bijawars are still regarded as such is the Dhar Forest area. In the Son Valley the 'transition' rocks have long been suspect, and the view that the Bijawar tract of this region includes also older rocks has been given expression to in the new edition of the geological map of India on the scale of 1"=32 miles, upon which the Son Valley strip of 'Transitions' has been arbitrarily divided into a northern strip of Bijawars and a southern strip of Dharwars. This tract has never been surveyed in sufficient detail, and it is probable that a careful survey by an officer experienced in the rocks of both the original Bijawar area and of Dharwarian tracts would lead to a further drastic reduction in the area to be shown as Bijawar. It in not unlikely on general grounds that all cases in the Son Valley in which the schistose, phyllitic and slaty rocks are intruded by granites the rocks will be regarded as pre-Bijawar in age – L.L. Fermor.

lithological type, but of higher and lower grades of metamorphism. The Jungel Red Shale series occurs, it is true, as outliers in the Bijawars, and it is possible that other smaller outliers may occur tightly pinched in within the Bijawars, but this shale-slate-phyllite association is so close as definitely to preclude the idea that every shale band represents an outlier of the Red Shale series. Even supposing that the Bijawars, on more detailed examination, should prove to be a composite formation, made up of more than one series with different grades of metamorphism, the same argument, that the association of metamorphic and non-metamorphic types is too close for this explanation everywhere to be valid, still holds. Similar associations of metamorphic and non-metamorphic types are common in the Impure Limestone and Phyllite series of the Delhi system, along the Wakal valley in Mewar, Rajputana, and also in the Jaunsar and Blaini beds of the Simla Himalaya. In the elementary stages of metamorphism, it is evident that no separation of rocks into zones marked by different metamorphic grades is possible.

The limestones are generally massive, poorly bedded, thoroughly crushed and siliceous; as may be seen by Patera, Bharari and south of Billi. In the latter locality, they might be mistaken for crushed Kajrahat limestone, of the Semri series. In the *nala* south of Khattai, purple crystalline limestone occurs strongly interbedded with phyllite bands, to the density of three or four to the inch. In this *nala* is a sill of metamorphosed dolerite cutting obliquely across the bedding of limestones and phyllites. Both dolerite and country rock are penetrated by quartz veins.

At Agori fort was seen the only example of red jasper in situ. It occurs interbedded between bands of beige-coloured siderite and of haematite. Dr. Heron has commented to me in conversation of the fact that, though red jasper is very common as pebbles in the Vindhyans, it is seldom found in the basement formations upon which the Vindhyans were laid down. This is certainly true for the present area.

The dolerites have a strong green colour in hand specimen, (43/80 – Registered numbers of rock specimens in the collection of the GSI, Calcutta), and in section show extensive chloritisation of the augite. Slice 2133, (Registered numbers of rock slices in the collection of the GSI, Calcutta) is seen to be made up of cores of pleochroic titanaugite surrounded by chlorite, of ilmenite almost completely altered to leucoxene, abundant epidote, interstitial quartz, and feldspar too altered for determination.

VINDHYAN SYSTEM

General

In the area examined, the only series seen are the Lower Vindhyans, (referred to in this paper as the Semri series), and the Kaimur series, of the Upper Vindhyans. The overlying Rewah and Bhander series are absent.

The Semri series consists in the main of limestones and sandstones. Lying unconformably on the schists, phyllites, shales, etc., of the Bijawars are the basal Semri sandstones and conglomerates, made up of material from the underlying formation. These pass up in to shales, with lenticles of limestone and finally in to a locally very thick limestone (Kajrahat) ranging from 0 to 2,000 feet thick. This limestone episode was succeeded by pyroclastic and epiclastic tuffs, shales, sandstones and arkoses, characteristically silicified to porcellanites, and without doubt a bedded, marine formation formed within the vicinity of volcanoes. These beds are followed by olive shales, a fawn limestone and a characteristic group of sandstones, pebbly grits, and sandy shales, marked throughout by the presence of glauconite. Ripple marks and sun cracks prove elevation and frequent exposure to subrerial conditions. These beds are succeeded by parallel, well bedded limestones and shales, formed probably on marine flats. The thickness of this Semri series cannot be estimated accurately owing to folding within many of the groups. In the Markundi-Chopan area, it is of the order of over 3,000 feet. Westwards, it diminishes to about 1,000 feet for the beds near Khattai. Still further west, the Semris must expand greatly. In western Rewah, Oldham mentions a probable thickness of 1,500 feet for the Rohtas stage alone (*Mem. Geol. Surv. India*, v.31, p.21, 1901).

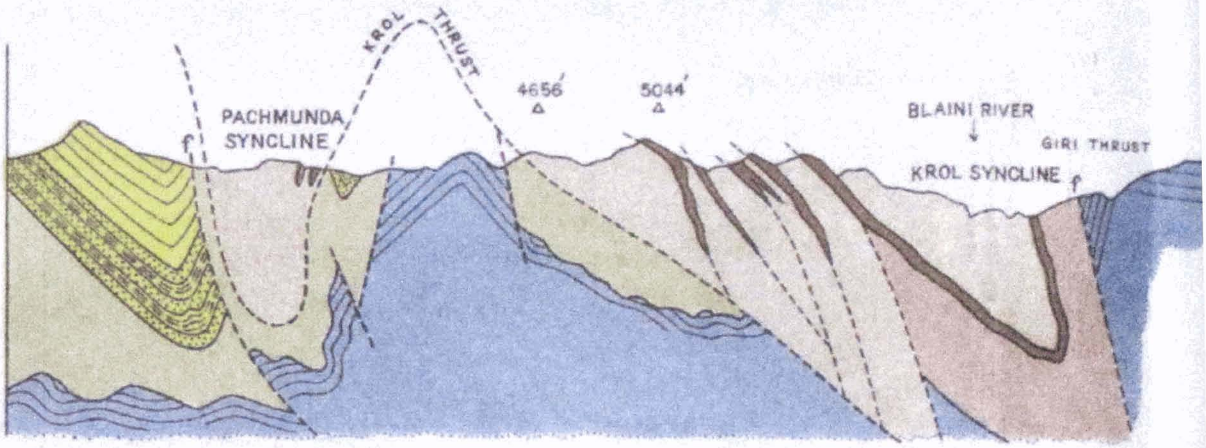
Following after the limestones, there comes the Kaimur series of sandstones, quartzites and shales, without limestones. They have every appearance of being fluviatile deposits formed under arid or semi-arid conditions. Ripple-marks, sun cracks and, locally, rain-drop impressions are all found. Current bedding is a characteristic feature, indicating first shifting currents and finally, towards the top, a more or less constant direction of origin of current from the east and southeast. The thickness of the exposed Kaimurs is about 1300 feet in the east, but westwards, within a distance of about 50 miles, it diminishes to less than 700 feet. The upper boundary with the Rewah series was probably close above the level of the present Kaimur plateau.

SEMRI SERIES

Basal Stage

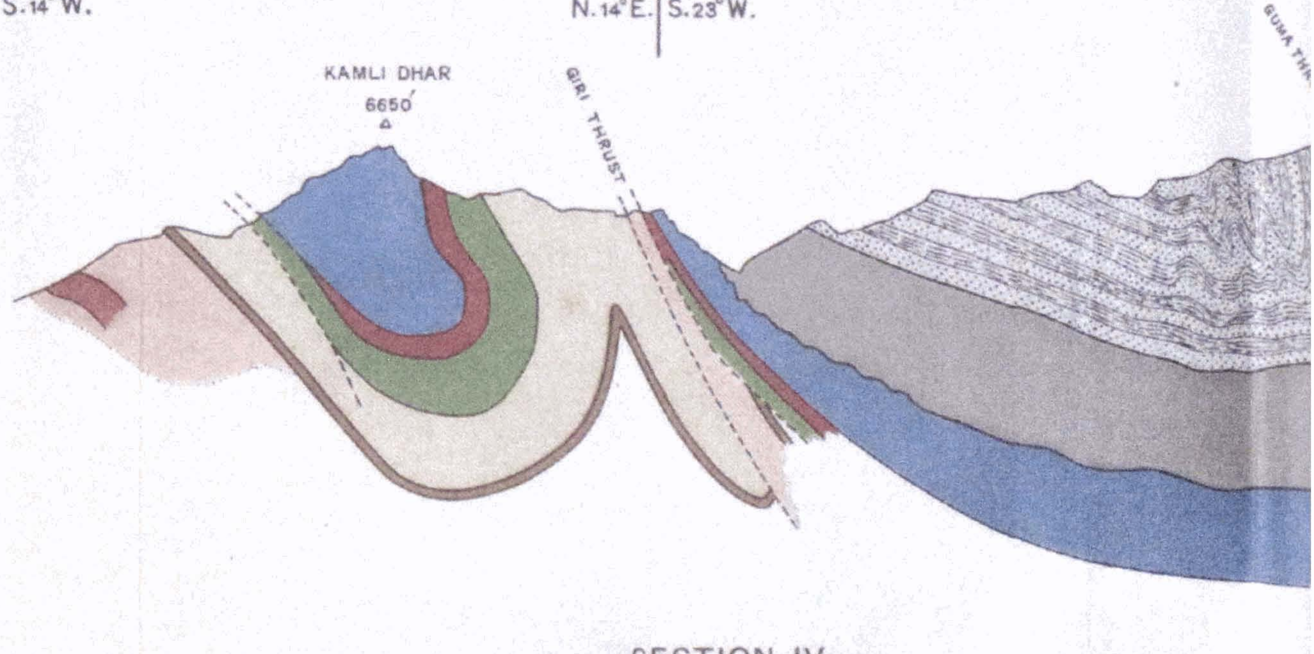
Basal conglomerate etc.

This consists of a variable series of pudding stones, conglomerates, breccias, brown quartzites, slates, bleaching shales and lenticular limestones. It is inconsistent, and the failure to crop out cannot always be assigned to faulting, but must be regarded as due to original capricious sedimentation. The



SECTION I.

Scale, 1 inch = 1 mile.



SECTION IV.

Scale, 1 inch = 1 mile.

floor upon which the Semri series were deposited. It does not follow, however, that the granite intrusive into the Bijawars along the Son valley and the granite at Karwi are of the same age.

Following above the pebble beds and quartzites is a series of black, laminated and bleaching shales, which are seen at Kajrahat, south of Billi, along the right bank of the Rihund and southwest of Gangi. South of Billi, these contain beds of earthy limestone and dolomitic limestone in pillows, and also brownish-green sandstones derived from the Bijawar phyllites.

Beds of uncertain correlation

Mention should be made of cases in which it has been difficult to determine the stratigraphical position of the rocks concerned. It was seen that in the Bijawar rocks there are associated, side by side, phyllites with slates and red shales; phyllites with crystalline limestones, unaltered current-bedded sandstone and cleaved shalely sandstones; microcrystalline limestones of Semri type with quartzite breccia. As above stated, it is not known whether there are one or more series in the Bijawars, or whether the fact that, within a few yards, the rocks are seen to have suffered variable degree of metamorphism, may not alone explain the variability of this system, when examined even over wide stretches of country. The unmetamorphosed types, which by themselves could be easily taken for Vindhyan rocks, are found however in such abundant connection with metamorphosed types, which are known to be older than the Vindhyans, that their confusion with the latter is only seldom possible. Such confusion does, however, sometimes occur along the junction between Vindhyans and Bijawars.

*   *   *   *   *

It may be mentioned here that the basal conglomerates of the Semris resemble exactly those found in the outliers of the Jungel Red Shale series, as by Titihidar. The associated red shales and phyllites of this series are not really similar to any facies in the Vindhyans, though they could be matched with many specimens from the Bijawars WNW of Obra.

Kajrahat Limestone

This limestone varies considerably in appearance. It is sometimes coarsely crystalline and grey-blue in colour (41/285), but more usually it is finely to microcrystalline and of blue, brown and white tints. It is well bedded, occurs in layers of from four inches to two feet thick, and is marked out by finer bands of varying hardness which are with difficulty recognised on a fresh fracture surface. The more outstanding of these are siliceous and non-reactive to dilute hydrochloric acid.

There is extensive permeation with silica which may segregate in amygdales made up of good prismatic crystals of quartz embedded in chalcedony, or which may cut across the limestone in veins joining sills parallel to the bedding. In the area examined, I could find no stratigraphic relation of siliceous to non-siliceous limestones, such as mentioned by Mallet (*Mem. Geol. Surv. India*, v.7, pp.33-34, 1871).

The thickness of this limestone is very puzzling. At hill 849, it is completely vertical over an outcrop width of half a mile, or 2,640 feet. Folding was naturally assumed to account for this thickness, and folding was in fact seen in the Kanhar river three miles to the east. Yet, in the plain by Billi there are at least two miles of dip section, with a minimum dip of 12° which would give a thickness of some 2,300 feet, even neglecting the continuation of this dip section in the southwest, where the dips are steeper and are sometimes vertical. The triangular outcrop of the limestone by Billi resembles in plan exactly what is so often seen on a small scale in sections of folds, namely the accumulation of material, from one particular bed out of a folded series of beds, at the apex of the fold. It is possible that, as in a vertical sense, so in the horizontal, there may be an accumulation of material in excess of the normal thickness. Even so, the minimum thickness for the Kajrahat limestone by Billi cannot be less than 2,000 feet. It is striking that, from having such a thickness, this limestone should disappear completely one mile east of Hardi, in a distance of 12 miles Northwards, also, the dying out is rapid, since limestone has not been recognized north of the Markundi Jamual fault. Vredenburg has mapped the limestone by Chatawar as Kajrahat, but this is incorrect, as will be shown later.

* * * * *

Porcellanite Stage

The term 'porcellanite' was used by Mallet in his memoir, and was retained by Vredenburg, though generally in inverted commas, since he considered that the rocks were for the most part tuffs. Present day nomenclature shows a varied use for the term. Holmes ('*Nomenclature of Petrology*', p.187, 1928) defines it as

> 'a compact thermally-metamorphosed rock of light colour and porcelain-like appearance, derived from marls and shales.'

Hatch and Wells ('*Textbook of Petrology*', p.36, 1926) on the other hand state that

> 'The hard flinty rocks produced by silicification of tuffs are sometimes described as *halleflinta* or *porcellanite*, according as their fracture is conchoidal or splintery.'

Of the two definitions, the latter seems to be the more suitable, particularly as, in the present case, the term is of long standing and there is no question of thermal metamorphism. The term 'jasperoid' is less good, since it implies the silicification of limestones (Grubenmann-Niggli, '*Die Gesteinsmetamorphose*', p.316, 1924).

Not all the rocks of porcellanite type, here included, were true tuffs; some were probably shales, but the term bas been extended here to cover those types of silicified rock, from whatever sources derived, which are now compact, flinty, strongly jointed, with splintery fracture and usually with sonorous hammer ring, and of porcelain-like appearance in weathered specimen. In addition to these siliceous types, there are more normal sedimentary types, included under the general stage heading.

The rocks present are arkoses, fine-grained sandstones with considerable proportion of clay, silts, shales, local conglomerates (at the base) and porcellanites of the following types: banded, pale and dark; thin-bedded and of transclucent green colour; pale-weathering dark opaque rocks of rhyolitic and andesitic appearance in more massive beds; the same with fragments of silicified shale scattered without orientation. They crop out in the low narrow ranges immediately south of the Son river downstream from Chopan, and on the north side of the Son, in the irregular hills to the northeast of Agori. The contrast in general aspect of this group with the overlying Vindhyans is very marked, especially if the Son river is crossed from Charkaria to Gaeghat. The dips are steeper, and there is an impression of considerably greater age, which is subjective, and due to the sudden encounter of a thick series of silicified rocks, after having just left more usual sedimentaries.

*   *   *   *   *

There is certainly no doubt about the tuffaceous nature of the beds by Hardi, Harra and eastwards to Khurdan Hill, and it seems that the eastern part of the area recently examined was sufficiently close to the eastern of the two centers of volcanic eruption to show an increase in the amount of clearly recognizable tuffs. West of the Kanhar river, these tuffaceous beds are difficult to recognize, and instead, the translucent green and the pale and dark banded porcellanites predominate.

Under microscope, the highly angular and concavo-convex fragments of quartz and feldspar give vitroclastic shapes which are quite characteristic (20567, 20568). More complete blow-hole structures are sometimes seen. These fragments, from 2 mm long down to 0.08 mm, together with minute crystals of chlorite, are sent in a matrix of quartz and feldspar which varies from being microcrystalline to isotropic. When seen between crossed nicols, recrystallisation has often caused the loss of individuality of the smaller fragments by mergence with the matrix, but their shapes are still preserved in ordinary light on account of the delicate chlorite coverings delimiting original structures. The abundance of long wedge-shaped fragments of plagioclase, whose length is perpendicular to (010), is another indication of the pyroclastic origin of some of these rocks, since, under water transport, these crystals would inevitably have broken parallel to the (010) cleavage. The plagioclase occurs almost to the exclusion of orthoclase, and varies between albite and oligoclase. The mean refractive index is either equal to or lower than that of canada balsam, and there is an extinction of from 0° to 18° perpendicular to (010). Clots of small interlocking plagioclase crystals sometimes occur (20569), which were probably blown out as such from the vents. Carbonate is rare, and has been seen only in slice (20566).

Besides the clearly recognisable tuffs, there occurs a splendidly banded series of alternately pale and dark porcellanites, and tuffaceous fine grained sandstones. These are best seen on the south bank of the Son river just to the north of Hardi (*see* Plate 1, Fig.1). The pale bands are about 0.5 to one inch in thickness while the dark bands are up to four inches, preserving excellent parallelism. Under the microscope, they show a minutely laminated structure which is made up of strings of dark shaley material, apparently pushed aside by the processes of silicification, as non-replaceable residues. Both pale and dark bands are cryptocrystalline or isotropic (20570.). In the area examined, these banded rocks are the most common of all the facies, and may be seen sporadically right to the western border, west of which they crop out in force. They are very well seen in the *nala* 5½ miles ESE. of Bardi, where they must be over 800 feet thlick. In the *nala* 2½ miles southeast of Naogain, some of these banded porcellanites are ripple-marked. Here they are interbedded with the same translucent green porcellanites so common south of Chopan and northeast of Agori, and with green nodular silicified shales similar to those found at the base of the Kheinjua group.

The characteristic feature of this group is the extent of silicification. Apart from the tuffs and tuffaceous sandstones, silicification of which does not obscure the nature of the parent rock, the origin of the other types of porcellanite is difficult to determine. There may be a convergence of product, starting probably from very different rock types, such as quartzites, shales and limestones, and ending in practically isotropic porcellanites. Such homoeomorphism may be compared with that of the hornblende-schists (without any wish to homologies processes that were very different), which may be derived from shales or from lavas, lacking initial similarity in chemical composition (Adams and Barlow, *Mem. Geol. Surv. Canada*, v.6, p.164, 1910). This silicification is almost certainly solfataric in nature, and must have extended well beyond the foci of pyroclastic deposition. To what extent the silicification of the succeeding stages

Plate 1

Fig.1. Banded porcellanites, south bank, Son river, Hardi.

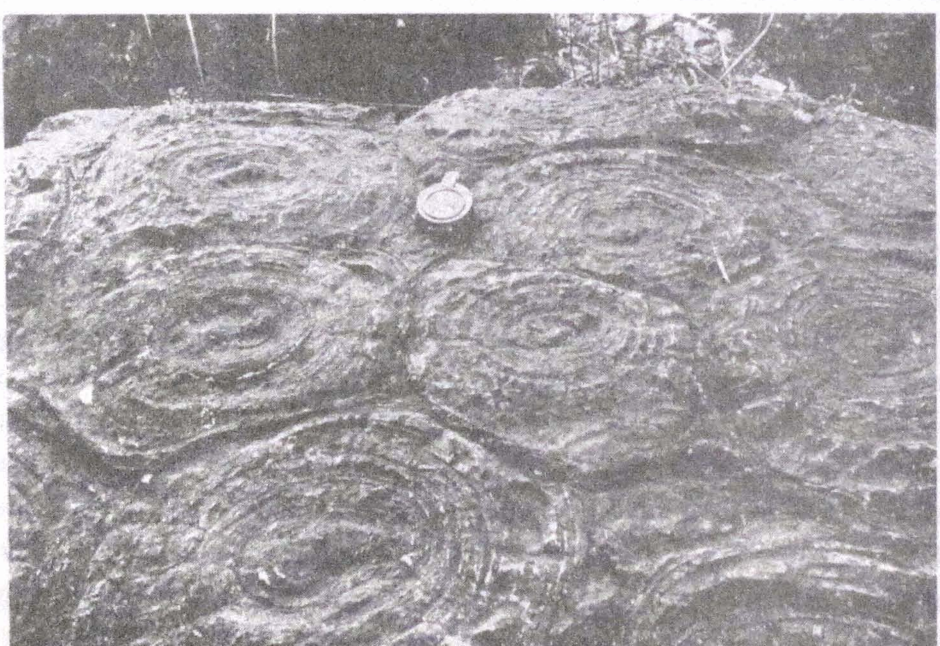


Fig.2. Spheroidal fawn limestone, Kheinjua stage, Bargawar.

was solfataric is difficult to decide. The porcellanites of the Silicified Shales, near Susnai, may represent the last bed of tuff formed by the waning volcanoes, but they might equally well be interpreted as having been derived from silicified sandstones, independent of any volcanic activity. Specimens were seen in these Silicified Shales, at Susnai, of quartzite passing laterally into pale porcellanite, with a transition zone marked by later ferrugination along the contact between the impervious porcellanite and the previous quartzite. The account by Blanckenhorn may be compared.

The two analyses made by Tween, and given in Mallet's Memoir may be quoted here:

	Porcellanite rock Per cent	Trappoid rock Per cent
SiO_2	86.81	79.35
Al_2O_3	6.25	12.23
Fe_2O_3 / FeO	3.1	2.5
CaO	0.12	0.14
K_2O	4.1	4.5
Na_2O	1.0	3.1
	100.38	**100.82**

The high percentage of silica is noteworthy. The larger percentage of potash relative to soda is surprising, considering that sodic plagioclase appear to be more common, in the tuffs examined, than orthoclase.

The succession in the Basal and Porcellanite stages, along the strike in sheets 63 P/2 and 6, 3 and 7, may be briefly tabulated as follows:

Succession in the lower stages of the Semris

Stage	Northeast of Agori Fort	Chopan and slightly eastwards	Gaeghat area
Porcellanite stage			Sandstones and shales
	(*Markundi-Jamual fault*)	. . .	Dark blue speckled porcellanite
			Sills and shaley sandstones
	Banded and translucent green porcellanites with silicified breccia	Banded porcellanites interbedded with tuffaceous quartzites	Banded ashes and porcellanites
			Arkoses and shales
		Nodular calcareous sandstones and bright green porcellanites	Dark blue silicified tuffs, with decided volcanic aspect
	Banded porcellanites	Banded porcellanites	
		Local conglomerate	
Basal stage	Kajrahat limestone	White 'chalky' rock	White 'chalky' rock.
		Kajrahat limestone	
	Bleaching shales	Bleaching shales	Green silts and blue black slates of Kon
	Sheared micaceous sandstones		
	Local quartzites	Basal quartzites and conglomerates	Quartzites

On account of the folding, there is certain to be repetition of beds in the incompetent Porcellanite stage, but this is not sufficient to bring up the underlying Basal stage on the north side of the porcellanites.

Kheinjua Stage

Olive shales

Following above the porcellanites are fine grained olive-green shales with cuboidal or pencil fracture. Their appearance is very characteristic, sometimes exactly resembling the shales above the Talchir boulder bed in the Raniganj coalfield. Silicification is occasionally found at the junction of these shales with the overlying limestone.

Over the whole of the area there is no actual junction seen between these shales and the Porcellanite stage, though west of Agori the two crop out very close together. Their fine development at Newar, below a fawn limestone, was one proof of the incorrectness of the correlation of this limestone by Vredenburg with that at Kajrahat.

Fawn Limestone

This is a fawn-weathering, siliceous and cherty limestone, with an interior which is seldom clear, but usually shows signs of dolomitisation, silicification, amygdales of agate, and segregation of lime material as calcite in vesicles and veinlets. Chert is very common, weathering out in irregular patches, and in parallel bands. Sometimes there is separation into fine grained, flinty limestone and coarser limestone, the former occurring as faulted and folded plates in the latter. Calcium, magnesium and ferrous carbonates are all present.

The weathered surface is pitted, and marked out by chert. Individual bands in the limestone may show marked folding on a minute scale, suggesting disturbance of unconsolidated material on an unstable sea floor. Bedding is coarse, being generally from two to three feet.

A very characteristic local type of this limestone is seen (1) at the northwest end of Salkhan Hill; (2) between Chatawar and the prominent north-south bend of the Son river near Agori. In this type, the limestone is often markedly spheroidal, and weathers on a flat surface to concentric alternate rings of limestone and chert (Plate 1, Fig.2)[1]. Agates are common in the Chatawar

[1]The similarity of these concentric rings to the so-called *Cryptozoon* is striking. *Cryptozoon* appears to have been found most commonly, but not exclusively, in the Cambrain. On this resemblance might be based a further argument for the presence of life in the Vindhyans, and for a Cambrian age to these rocks. The organic origin of structures called *Cryptozoon* is doubted by Seward (*Plant Life through the Ages*, p.86, 1931). It is probably unwise to do more than point out the resemblance.

locality. It is this limestone of Chatawar which Vredenburg has correlated with Mallet's No.2, or the Kajrahat of the present nomenclature. Mallet had originally correlated it with his No.7, which is what, in my opinion, it should be. The reasons for returning to Mallet's correlation are as follows:

(1) There is the very strong evidence of the constancy of the sequence of Rohtas limestone/Glauconitic beds/Fawn limestone/Olive Shales/Porcellanites. Vredenburg was in the first place misled in correlating the sandstones at Salkhan with the Basal stage, and in not noticing the Fawn Limestone below. Secondly, he did not notice the glauconitic beds above the spheroidal Fawn Limestone at Bargawan, or the Olive Shales below the strike continuation of this Fawn Limestone at Newar. The sequences are best put in tabular form.

Correlation of Kheinjua stage

Newar	*Chatawar-Bargawan*	*Salkhan Hill*	*Pataudh-Chopan*
Glauconitic beds	Glauconitic beds	Glauconitic beds	Glauconitic beds
Fawn Limestone	Spheroidal Fawn Limestone	Spheroidal Fawn Limestone	Fawn Limestone
Thick Olive Shales	*fault*	*gap*	Olive Shales
	Bijawars	Porcellanites	Porcellanites

This constancy is so striking for 40 of the 50 miles of strike section mapped, that I have no doubt that the quarter-inch map published in the 1901 memoir should be altered to Mallet's original rendering.

(2) Vredenblug was unaware of the existence of the Markundi-Jamual fault, and marked all the stages of the Semri series as swinging round the projection of Bijawar rock north of Agori. The proof of the fault near Markundi adds support to the supposition of a fault just south of Bargawan. The only exposure where there is doubt as to which stage the limestone should be assigned is actually in the Son river, three-quarter of a mile SSE of Gurdah, where the limestone which I have mapped as Rohtas does in places resemble more that of Kajrahat, Mallet's No.2. Since, however, this limestone passes northwards into what is in type and by position certain Rohtas limestone, and since the Rohtas and Kajrahat limestones frequently resemble each other, it is probable that the revised mapping is the correct interpretation.

Khattai and Hurma

I am inclined to agree also with the original correlation of the limestones found at Khattai and just north of the Son river at Hurma both with the Kheinjua stage. Oldham and Vredenburg (*Mem. Geol. Surv. India*, v.31, pp.162-163,

1901) doubted that Mallet was correct in supposing the two limestones as equivalent. While admitting that the exposures are poor, and that the limestone at Khattai is not typical of the Fawn Limestone, yet its proximity to the glauconitic beds of the small hillocks just to the west of Khattai is in favour of supposing it to belong to the Kheinjua stage. The sections north of the Son river, near Hurma, are obscure, and are complicated by a wedge of Kheinjua rocks brought into the north by a strike fault.

Splitting up of Fawn Limestone westwards

Westwards, the Fawn Limestone splits up and becomes interbedded with olive-green and blue shales. An excellent section is seen in the Gopat river, at Bardi, where beds of limestone from three to six feet in thickness alternate with shales. The limestone is heterogeneous, consisting of pellets of calcareous shale in a carbonate matrix. Calcite and quartz appear to have recrystallised side by side. The total thickness of the limestone bands, excluding the intervening shales, is less than 100 feet. Between Bardi and Barhat, agates and chert are common, and are associated with blocks of ferruginated breccia loose on the ground.

This splitting up of the Fawn Limestone is in agreement with the account, given by Datta (*Mem. Geol. Surv. India*, v.31, p.144, 1901) of the country north of the Son and west of old longitude 82°30'.

Glauconitic beds

This is a variable series of silty sandstones with the general presence of glauconite, of calcareous glaucnitic sandstones, quartzites, conglomerates, breccias, and thin limestones. The limestone bands occur near the base, just above the main Fawan Limestone, and are interbedded with current-bedded quartzites.

Bedding is markedly lenticular, and seldom over six inches thick in the silty sandstones, but reaches six feet in the quartzites and conglomerates. The whole series is abundantly ripple-marked and sun-cracked; proof of shallow water conditions. Weathering in the calcareous sandstones is often pitted, as a result of solution of lime segregations, while the glauconite at the same time oxidizes to limonite, which occurs as specks throughout the rock.

The characteristic features of this group are the presence of glauconite and the abundance of ripple marks and sun cracks.

* * * * *

Under the microscope, the sandstones in the Kheinjua stage are seen to be arkosic. They show glauconite, quartz, very common feldspar (plagioclase and microcline), tourmaline, colourless mica. The quartz in the specimens obtained is of average grain size 0.20 to 0.18 mm and is quite frequently rounded. The feldspars are both fresh and turbid, and are strikingly common, a fact which differentiates these rocks from those in the Lower Kaimur sandstone. Tourmaline is usually present, but not generally as commonly as in the Lower Kaimur sandstone. Clastic colourless mica is frequently found.

Glauconite

The glauconite occurs chiefly either in sausage shapes up to 1 mm long by 0.30 mm in width, but generally not exceeding 0.75 mm in length, or in interstitial wedges between grains of quartz and feldspar. It is of varying density in colour, which is not entirely due to variations in the thickness of the rock slices. The glauconite in slices 21345, 21349, 21351 is far darker than that in 21337, which may be taken as typical for the Son valley. The green is similar to that of chlorophyll, and is of patchy density even in a single granule. The mean refractive index, determined by emersion in liquids is between 1.600 and 1.605. The specific gravity is not constant, and lies between 2.70 and 2.75. If kept for a few minutes in liquid of specific gravity 2.80 some of the grains will sink, probably due to absorption of the liquid. Individual grains are composed of a felt of minute overlapping crystal plates, generally 0.01 to 0.02 mm long, but sometimes up to 0.05 mm. Pleochroism is in pale green and straw-yellow colours. Between crossed nicols there are aggregate polarization colours and no general extinction of the whole grain.

* * * * *

A more complete analysis made by P.C. Roy, with considerable difficulty, from one gram of picked mineral from specimen 43/88, gave the result given below, and may be compared with the mean of twelve analyses given by Dr. L.L. Fermor (*Rec. Geol. Surv. India*, v.58, p.333, 1925-1926).

	Analyses by P.C. Roy (43/88) Per cent	Mean of twelve analyses given by L.L. Fermor Per cent
SiO_2	54.30	49.11
Al_2O_3	14.01	8.03
Fe_2O_3	7.24	20.05
FeO	4.10	3.05
MgO	3.54	3.18
CaO	0.82	0.87
Na_2O	0.58	0.66
K_2O	7.56	6.97
$H_2O\pm$	7.66	8.05
	99.85	**99.97**

* * * * *

Rohtas Stage

This is the top stage of the Semri series, and was named after the rocks exposed below the Kaimurs at Rohtasgarh, 40 miles to the east of the present area. Mallet quotes a section determined by Williams in which the thickness of the Rohtas beds is given as 700 feet. Dr. Fox visited the limestone quarries near Rohtasgarh in 1928. He describes the limestones from the type locality as follows:

> 'They are thin-bedded and of a general grey colour. The composition varies very much from band to band in the vertical face of the quarry. The chemist has had to analyse each band and thus arrive at a workable group of bands of good quality, suitable for the manufacture of Portland cement. It is nearly all "fat" or pure limestone averaging 84 per cent calcium carbonate, with less than 3 per cent magnesium carbonate and roughly 10 per cent silica. This is the quality of the material transported by aerial ropeway across the Son to the cement works at Japla.
>
> The limestone beds become distinctly siliceous towards the top, under the capping of sandstone of the false scarp. The limestone itself also contains cherty layers in places and thin laminae of siderite and argillaceous matter are not uncommon in the banding of the limestone.'

In the area recently mapped, the Rohtas stage shows a considerable variety of limestone type, and of relation of limestone to shale. Certain features are common throughout:

(1) The general thin and markedly parallel bedding of both limestone and shales, in contrast to the lenticular bedding of most of the beds in the Kheinjua stage, and thicker bedding of the Kheinjua limestones.

(2) The prevalence of grey, blue, pink and orange tints in both limestones and shales, and of smooth-weathering surfaces.

The characteristic type may be taken as that exposed in the Ghaghar river by Markundi, where the beds of limestone are between three inches and one foot in thickness, and are marked by parallel, finer bands of varying composition. West of Agori, the bedding becomes thinner and almost the whole of the Rohtas stage consists of one inch bands of grey, pink and orange earthy limestones, alternating with thinner bands of coloured shale. These well bedded limestones were possibly deposited under conditions resembling those described by Field (*Amer. Jour. Sci.*, v.16, p.239, 1928). From the Bahama bank, where almost pure calcareous ooze is laid down on very shallow marine flats covering 7000 square miles. Other types exist, however, and are numerated below

(1) Limestone-nodule and shale associations occur in two horizons, one at the base of the stage where it is more or less persistent between Pataudh and Bardi, and the other near the top of the stage, found locally only near Rudauli,

Makri Bari and Markundi. The lower of these two was mapped by Mallet in his stage 8, just below the Rohtas limestone No.9, and by Oldham, Vredenburg and Datta with the Kheinjua stage. In my opinion this is erroneous. The nature of the limestone, and the fine parallel banding of shales which passes also through the limestone nodules, is far more characteristic of the Rohtas stage. Moreover, the existence of an exactly similar facies near the top of the Rohtas is a strong indication that the lower calc-nodular shales should also be included in this stage.

In this facies, large nodules of dark microcrystalline limestone, up to three feet diameter and one foot six inches in height, with shale banding which shows with difficulty on a fresh fractured surface, lie imbedded in grey and black shales. The nodules may occur isolated, or in strings, several yards long and a foot or more in height (Plate 2, Figs.1 and 2). There is an abrupt lateral termination of beds of shale against limestone, while the shale above and below the nodules has been arched. In thin section, the nodules show a slightly banded structure, in which thin lenticular areas of carbonate are separated by very thin wisps of dirt, probably clay. At least 90 per cent of the rock is of carbonate.

They are fairly certainly formed by localized addition of carbonate to already slightly calcareous shales. This is suggested by the parallel banding of the shales often passing directly through the nodules. But to what extent the addition was by replacement or by displacement, and when it happened, is less certain. The arching of the beds above and below may suggest addition by displacement subsequent to the shale deposition, but it is quite possible for mud to be deposited on the top of nodules already formed and to preserve the quaquaversal dip of their upper surfaces. The shales are themselves slightly calcareous, say with 5 per cent carbonate. If there had been growth of nodules entirely subsequent to the formation of the shales, causing displacement, there should be 90 per cent *minus* 5 per cent, that is, 85 per cent expansion. This expansion would have to be vertical, since there are no signs of lateral disturbance of the beds adjacent to the nodules. Vertical displacement to such an extent is not seen, nor are there any signs of crushing in the arches which would be expected if addition of carbonate had resulted in expansion under a load. The probability is, therefore, that the formation of the nodules took place, at least in part, contemporaneously with the deposition of the shales, and that the nodules, once formed, may have acted as centres for deposition of carbonate, which continued for a short time after the nodules had been covered up by shale. Mallet (*Mem. Geol. Surv. India*, v.7, p.41, 1871) states that the size of these nodules varies inversely as their number, and that symmetry of form increases with the distance between the concretions. This is not borne out by an exposure where the path between Gangi and Bardi crosses a *nala* due south

Plate 2

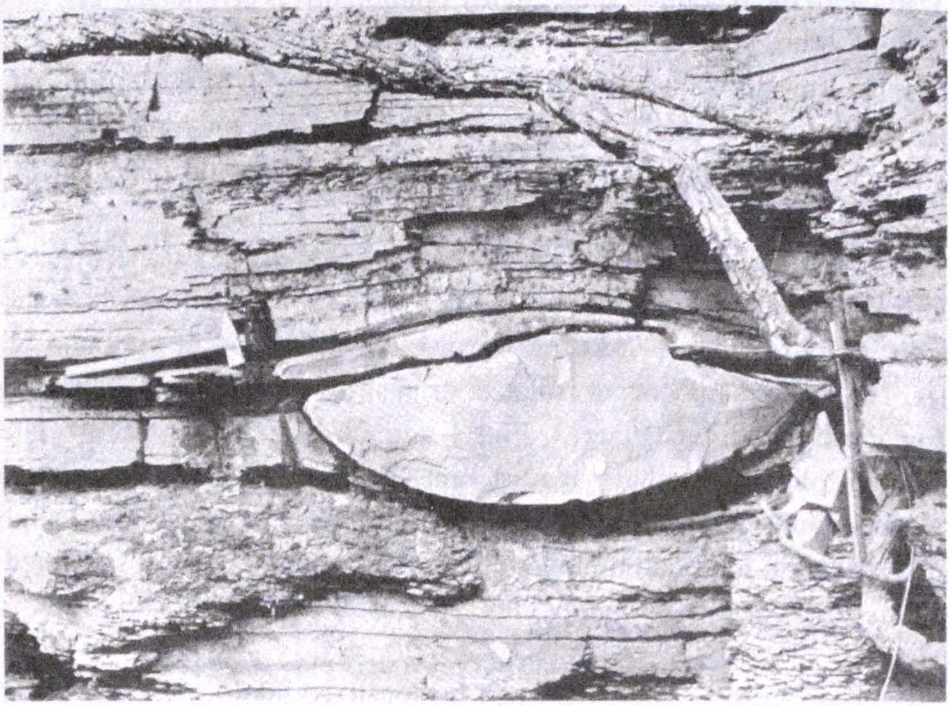


Fig.1. Calcareous nodule, Rohtas limestone, Rudauli.

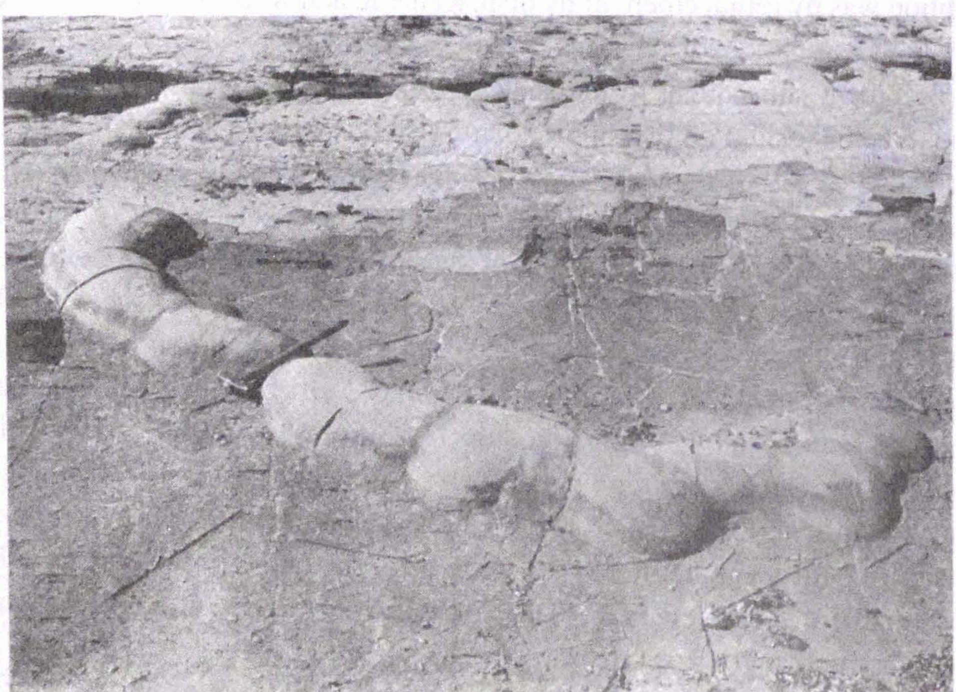


Fig.2. Line of calcareous nodules, Rohtas limestone. Path between Gangi and Bardi.

of Beechi. Here, the nodules are more abundant than seen anywhere else, and at the same time there is no loss of size. Size would vary inversely with number only when the areal supply of lime was constant and limited, but it appears that the amount of lime was areally variable, even if limited enough to prevent complete calcification of shale bands.

* * * * *

While silicification is not noticeable in the particular calc-nodule horizon, there are signs of its occurrence higher up in the Rohtas stage and in the Kaimur. The presence of vertical dykes of crystalline limestone in the main group of microcrystalline Rohtas limestones south of Markundi is also suggestive in this connection, and points to permeating solutions from submarine springs in a manner similar to that described by Ower. The conditions which prevailed may be considered to be those of wide shallow areas of warm water subject perhaps to seasonal evaporation. Both horizons of calc-nodules are close to deposits which were subject to exposure to air (Kheinjua and Lower Kaimur sandstone groups).

(2) Along the south bank of the Son, by Panwar and Chitaual, and wrongly mapped in a the quarter-inch map of Oldham etc., as Kheinjua, the thin bedded gray limestone are strongly interbanded with black shale, which crops out on a weathered surface to give excellent contour effects. The limestone contains irregular patches of darker carbonaceous limestone.

This shale-limestone facies corresponds to the variegated shales with thin limestones found in the *nala* which flows from Chakria to join the Ghaghar river at Dongahwa.

(3) North of Keotilli, and by Manchi and Bara, towards the top of the Rohtas stage, there are two to four-foot beds of coarser limestone, used locally for lime burning. Some of these bands have been strongly silicified, to result in irregular patches of pale orange-weathering porcellanite occurring outstanding from the gray limestone. Many of these limestones have stylolites, or solution effects.

One of the best localities for seeing these stylolite limestones is in the outer scarp two miles north-west of Silpi. Here, there has been extensive silicification. Later ferrugination of fallen blocks gives a pseudo-breccia, which is never found in the *in situ* rock from which the blocks have fallen. These thicker beds of silicified limestone occur within the Rohtas limestone and not quite at the top of the stage.

(4) In the east of the area, overlying the smooth-weathering limestones, and immediately below the basal Kaimur quartzites, are black, finely banded, papery, carbonaceous shales together with subordinate beds of micaceous sandstones showing ripple marks and sun cracks. These shales are rarely well

exposed, and are best seen 1.7 miles due north of the *n* of *Donai* (Plate 3) where they are 250 feet thick. This thickness is exceptional, and both to the east and west the shales appear to thin out. Mr. Bhola states that northeast of Susnai, he could trace the lateral passage of these shales into limestones, so that their thinning out may be a facies change, and not an indication of erosion in places where the shales are thin or absent. The equivalence of shale and limestone in the Rohtas stage was suggested by Mallet (*Mem. Geol. Surv. India*, v.7, p.46, 1871) and is evidently a feature characteristic of the stage, in which permeation by lime solutions was prevalent.

The summarised correlation of the Rohtas stage is given in the following Table:

Correlation of Rohtas stage

West of Agori	Markundi area	Eastern part of 63 P/3 7,2,6
Thin-bedded limestones and shales	Calc, shales and thin limestones; seen a quarter of mile north of *m* of *Makri Bari*	Black, papery, carbonaceous shales
Siliceous limestones	Calc-nodular shales; seen two-fifths of a mile NNW of *Makri Bari*	
Coloured earthy limestones and shales	Thin-bedded, highly coloured shales; Ghaghar river and Bhatti-Belach	Thin-bedded limestones and shales
Thin-bedded limestones and shales	Main limestone of the Ghaghar river	Main limestone, often siliceous
Calc-nodular shales	Calc-nodular shales;[1] Ghaghar river one mile NNE of confluence with Son river	
Thickness 400 feet, plus	Thickness 700 feet	Thickness up to 600 feet

[1]These nodules of limestone in shales were noticed by Hooker, '*Himalayan Journals*' v.1, p.55, 1854, in exactly this locality. He states: 'In the afternoon, I examined the conical hill, which, like that near Rohtas, is of stratified beds of limestone, capped with sandstone. A stream runs round its base, cutting through the alluvium to the subjacent rock, which is exposed, and contains flattened spheres of limestone.' This hill is one mile ENE of Pataudh. The capping of sandstone is the basal quartzite of the Kaimur series

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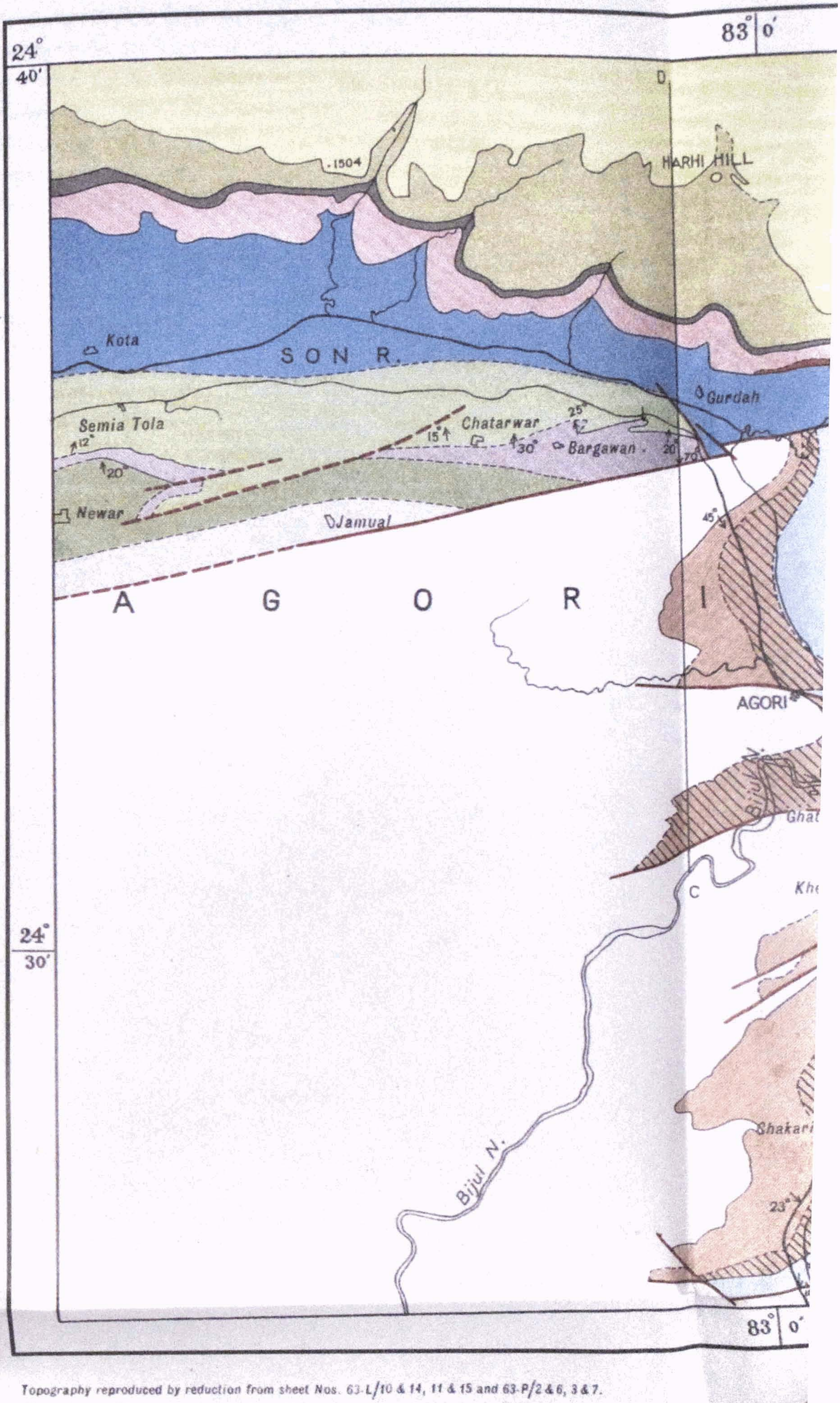
KAIMUR SERIES

Lower Kaimur Sandstone Stage

This stage consists in the east of the area of two well defined bands of quartzite, cropping out in two distinct scarps, with an intervening band of shales, containing the Susnai breccia and porcellanite beds. West of Markundi, these intervening shales die out, and in sheet 63 L/10 and 14, there is only one band of quartzite, cropping out in a single scarp.



Topography reproduced by reduction from sheet Nos. 63-L/10 & 14, 11 & 15 and 63-P/2 & 6, 3 & 7.

It is important to emphasise the tow scarps, marking the outcrop of the two quartzites in the Lower Kaimur sandstone, because this is the clearest field evidence that the Susnai breccia, which occurs at the base of the upper of the two quartzite bands, does not lie at the base of quartzites of Kaimur type. Mr. Bhola, who visited the critical locality a year after myself, is in complete agreement about this. The two scarps are best seen round the base of Mangesar Hill, between Rudauli and Susnai.

Lower Quartzite

This is generally more massive than the upper quartzite, occurring in beds up to 15 feet thick. Small pebbles occur in lenticular patches in the quartzite matrix. They are seldom above 0.5 inches in diameter and are mostly vein quartz, and sometimes of ironstone (two miles north of Donai). Current bedding is locally common, as by 1,068 hill above Makri Bari. The colour is white or gray. Microscopically, the quartzite exactly resembles the upper quartzite, and will be described under that heading.

This gritty quartzite passes upwards to thinly bedded lenticular flagstones and mudstones, which show excellent sun cracks and ripple marks. These beds are sometimes conglomeratic, containing void lumps of black shale. Good exposures may be seen 1.3 miles due south of Mangesar Hill, and one mile northeast of Pakri.

Silicified Shales

Below the Susnai breccia, and above the shallow-water top facies of the lower quartzite, there are black micaceous shales with papery lamination, together with jet black, strongly jointed, silicified, carbonaceous shales and thin bands of siderite ironstone. These black carbonaceous shales readily bleach. Interbedded with them are porcellanites.

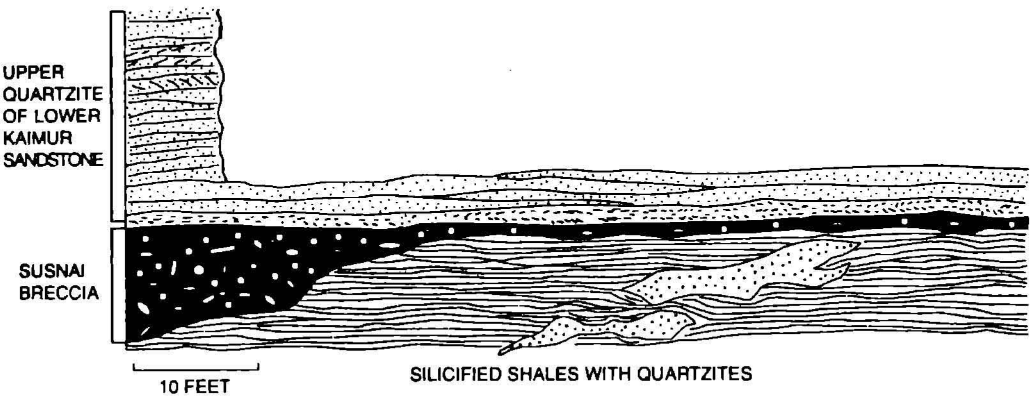
* * * * *

Susnai breccia

* * * * *

In the ravine, 0.75 mile southwest of 2025 hill, rounded and angular fragments of porcellanite lie densely and sparsely in a gritty matrix, or in a matrix of greenish quartzite. The conglomerate swells out from ten inches to seven feet in thickness, within a distance of 20 feet, occurring in a clean cut washout, abruptly removing the underlying shales.

The bedding of the conglomerate and of the associated quartzites below the upper of the two lower Kaimur quartzites is very lenticular. There is no doubt about the washout being due to currents having eroded a channel in the previously deposited shale. The rounded nature of many of the included fragments of porcellanite is also indicative of current action.



Susnai breccia in ravine, three-quarters of a mile southwest of point 2,025.

The following is the succession in the locality, half a mile ESE of 1836 hill.

Upper Quartzite (40 ft.)	Cliff of current-bedded quartzite
Susnai conglomeratic breccia (3 ft.)	Conglomerate, with scattered pebbles of porcellanite showing fair rounding (3 ins.) Sandstone Conglomerate, with current bedded matrix, (9 ins.) Sandstone Conglomerate, crammed with flat discs of porcellanite
Silicified shales (22 ft. 6 ins.)	Hard silicified sandstone Spotted green limonitic sandstone Thinly laminated blue-black papery shales; nodular micaceous shales with thin bands of current-bedded sandstone; flat nodular bands of siderite Thin papery shales, containing bands of pitchblack porcellanites *Base not seen.*

* * * * *

The provenance of the porcellanite fragments was probably the porcellanite beds from the shales immediately below the Susnai breccia. Oldham regarded the porcellanite beds as belonging to the Rohtas stage, which accounts for his explanation of a Rohtas source. Actually, they are underlain by the lower of the two Lower Kaimur quartzites, a fact which has only come to light as a result of detailed mapping. These beds were probably elevated along one or more axes, not far removed from the present outcrop, and the cherts were deposited away from these axes in the form of the breccia. The local elevation of land along axes would presumably increase the velocity of streams confined to the intervening synclinal areas, and cause the washouts seen In one of the exposures.

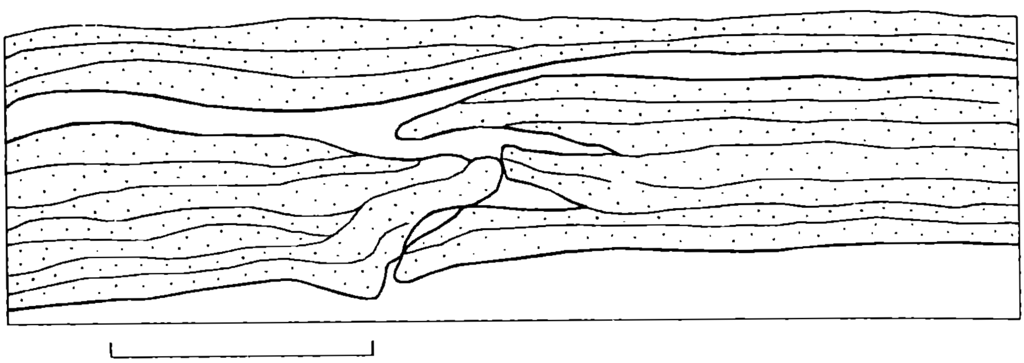
Autoclastic breccia: Mention was made of the ferruginated porcellanite two miles to the east of the Chaoki tank, and of a ferruginated Rohtas limestone in the form of a pseudo-breccia two miles northwest of Silpi. In one other locality, one mile NNW of Chirhuli, a true chalcedony-chert breacia was found as rare blocks near the Lower Kaimur sandstone outcrop. Nothing was seen *in situ*. This rock is certainly of auto clastic appearance. Normal Susnai breocia was found two miles to the west, slightly above the base of the Lower Kaimur quartzites, so this autoclastic breccia is probably an independent phenomenon.

Upper Quartzite

This forms, by its dip slopes, the excellent rim which surrounds the main cliffs of Upper Kaimur sandstones. Upon this rim are abundant sambhar. The scarp slope, forming a 40 to 50 foot cliff, is everywhere conspicuous, and easy to map.

The rock is generally a fine grained quartzite which has been strongly silicified. The bedding is seldom above three feet in thickness, and is generally markedly lenticular, as in the case of the lower of the two quartzites. Beds three feet thick will die out within 36 feet horizontal distance. Ripple marks are everywhere abundant, varying from para ripples with crests one foot apart, to wave and current ripples with crests three, two and one inches apart. Current bedding is universal, but inconsistent in direction. The basal 2½ feet often show five bands of six inches thickness, each with separate current bedding. The current bedding is often of the criss-cross type usually regarded as eolian (cf. Grabau, '*Principles of Stratigraphy*', p.704, 1924). The rounded nature of the sand grains, as well as indicating wind rounding, may be thought to suggest wind deposition of the whole of the Lower Kaimur sandstone. Yet the fact that the quartzites occur is well defined, even if lenticular beds, and the abundance of ripple marks of the type formed in water, appears to me to favour the suggestion of deposition in shallow water rather than as dune sands. Wind almost certainly was responsible for the rounding of the grains, and doubtless for the dropping of sand into deltaic waters, but the actual deposition as finally preserved was probably due to water. Moreover, many modern river sands exhibit the type of current bedding usually regarded as eolian, as, for example, in the dissected sand flats at the confluence of the Jumna river with the Ganges, where there is little question of wind action. The inference of eolian deposition from criss-cross bedding is probably valid only when such is on a scale of 50 to 100 times larger than that seen in the lower Kaimur sandstones and the Ganges sands, as is figured in Grabau's book.

The lenticular nature of the strata has favoured penetrative movement of beds (*Durchbewegung*) in places where the quartzite has been disturbed, as in the *nala* which joins the Donai *nala* from the northeast of height 982.



Penetrative movements of beds in Lower Kaimur sandstone.

* * * * *

Bijaigarh Shales

The quartzites, micaceous sandstones and shales pass up gradually to the true Bijaigarh shales, which are black, carbonaceous, fine grained, micaceous and frequently pyritiferous. They contain occasional ironstone bands. They often fracture in pencils, and when jointed, show close joint spacing. The upper ten feet of the Bijaigarh shales are recognized almost everywhere by bleached red and yellow colours, giving the impression of baking. These shales were probably more pyritic and owe their present colour to the oxidation of the pyrites and the formation of ferric oxides and sulphates. The latter are often seen as white efflorescence on the surface of the shale. The presence of iron is also manifested by the frequent seepages of hydrated ferric oxides which tend to cement loose blocks of shale to a hard modern breccia. It should be pointed out that there is not enough iron in the shale to justify any exploitation, and that every person who has examined these shales for possible coal content has given an emphatic negative answer. Vertically, the sequence is:

Upper Kaimur sandstone	Scarp sandstones and green silts
Lower Kaimur sandstone	Bijaigarh black shales, 150 feet Shales of Bijaigarh type, with ripple-marked shaley quartzite Blue shales, ripple-marked and sun-cracked shaley quartzites, quartzites Quartzites, strongly ripple-marked, cropping out in 40-50 feet cliff Susnai breccia Silicified shales, with beds of porcellanite Shaley sandstones and shales, with ripple-marks and sun-cracks Quartzites, cropping out in cliff
Rohtas stage	Rohtas limestones and shales

* * * * *

Upper Kaimur Sandstone Stage

Scarp Sandstones

Above the Bijaigarh shales is a series of thin-bedded flags of predominant green colour and very often ripple-marked. The beds comprise green sandy silts, micaceous green brown sandy shales, and contemporaneous conglomerates, with discs of green shale set in green-brown shale matrix. Bedding is seldom over six inches, and jointing is frequently in broad curves. These beds do not form cliffs but crop out in the 30° slopes at the foot of the main scarp.

Under the microscope the diameters of the grains seldom exceed 0.20 mm. Angular quartz occurs in a matrix of sericite and clay paste. Tourmaline may occur.

Main Scarp Sandstones: These form the greater part or whole of the cliffs of the Kaimur scarp from east to west of the area. The cliffs may be vertical; more often they show great bulging surfaces, and is so magnificently seen on Mangesar Hill (Plate 4, Fig.2). Bedding is massive, from five to 15 feet. Current bedding is abundant and inconstant in direction.

The sandstones are soft, and of a brown to red colour, strongly reminiscent in type of the Old Red Sandstone of the Welsh borderland. Their grain is usually fine, not often exceeding 0.30 mm. Some of the grains are rounded. There is an abundant clay matrix between the quartz grains, which is made up mostly of sericite material. Kaoline is absent since the mineral concerned has strong birefringence and straight extinction. A green or green-brown mineral is common in the clay paste interstital between the quartz. It occurs usually in

Plate 4

Fig.1. Kaimur scarp, looking east from two miles southwest of Paliari.

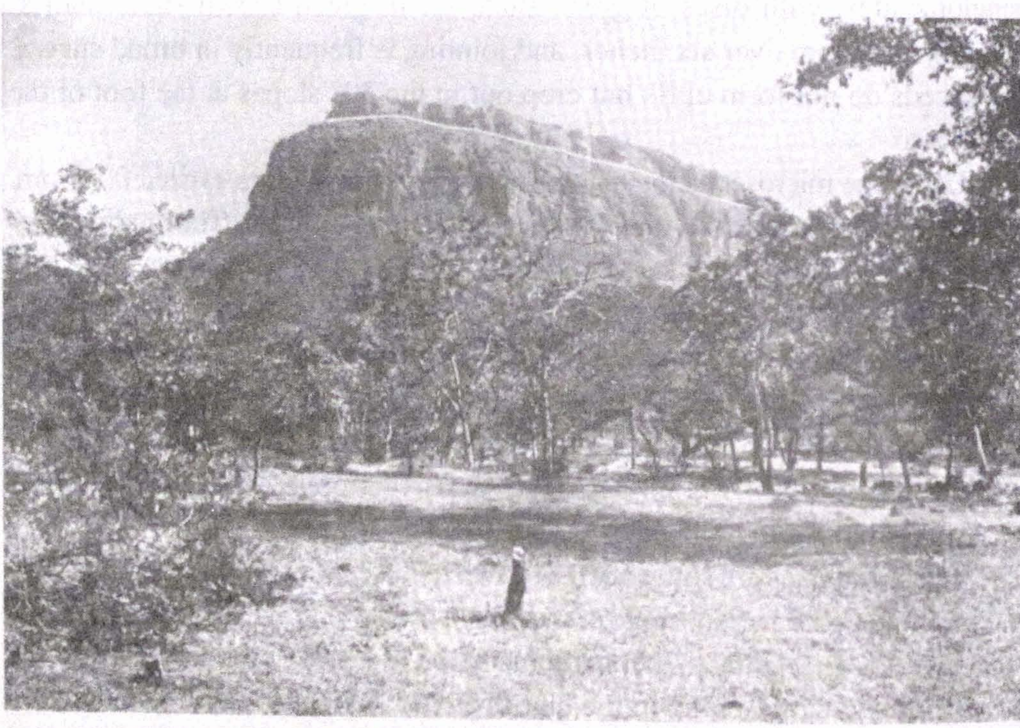


Fig.2. Mangesar hill from the west, showing Dhandraul quartzites overlying brown scarp sandstones.

vermicular shapes with the fibres at right angles to the length. The birefringence is variable, sometimes excalty resembling chlorite, and sometimes as strong as that of the green mica, which occurs in the green beds of the Dalradians in Scotland. Extinction is straight. Pleochroism is pale green for vibrations parallel to the fibres and straw-yello-green for vibrations perpendicular to these. Some of the material may be chamosite; some is possibly allied to the green mica found in the chlorite zone of the Scottish Dalradians (*Min. Mag.*, v.22, p.244 (1930). Compare also the slico lent by Mr. W.D. West from a quarter of a mile southwest of Birnum Station, Dunkeld, Perthshire). It is definitely authigenic in the rock, often occurring in vermicular shapes enveloping quartz grains, and grading off in colour to paler undifferentiated material.

Dhandraul quartzites

These form the ridge by Dhandraul Irrigation bungalow and the Ghaghar reservoir dam, and occur as a 50 to 100 feet capping to the cliffs of Bijaigarh fort, and to most of the Kaimur scarp between Kandakhot, north of Agori, and the Murwa pass, south of Paliari. They are well seen on Mangesar Hill, viewed from Chopan, forming the small, topmost, vertical cliff above the bulging cliffs of the Scarp Sandstones. Westwards and eastwards these quarzites forsake the main scarp and crop out in a minor scarp within the plateau.

The change from the coloured and impure Scarp Sandstones to the purer Dhandraul quartzites is not always abrupt, and the boundary between them becomes difficult to map in cases where the Dhandraul quartzites form neither a vertical scarp above the bulging cliff of the scarp sandstones, nor a minor scarp north of the main Kaimur Scarp.

The rock is generally a fine grained white quartzite, with grain size up to 0.5 mm and far poorer in interstitial clay paste than the Scarp Sanstones. The colur in the field varies from pure white to white stained with purple. The grains are sometimes rounded There is a strong cement of secondary silica. Limonite is usually present, in small patches, and in the field is seldom absent from the conspicuous joints within traverse the quartzite. These joints are more common and more closely spaced than in the underlying Scarp Sandstone. On account of their prevalence, there is copious discharge of water from below the dam across the Ghaghar river, east of Dhandraul. The quartzite itself is here impervious enough to prevent seepage of water.

There is a constant and universal current bedding. The dips of these bedding planes indicates directions of current from the northeast, east southeast, and south. Of these directions, those from the east and southeast very greatly predominate. A westerly direction is never seen. Ripple marks are common north of Silpi.

* * * * *

Thicknesses

The following table shows the thicknesses in feet of the Vindhyan stages and sub-stages described:

			(West) Beechi.	Bakia	Chitaul	Kolla	Chopan longi-tude	(East.) 202 hill
KAIMUR SERIES	Upper Kaimur sandstone	Dhandraul quartzites	270+	277+		180+	300+	120+
		Scarp sandstone	230	310	390	350	600	550
	Bijaigarh	Shales	70	100	130	150	150	150
	Lower Kaimur sandstone	Upper quartzites					150	110
		Silicified Shales	200	220		150	100	10
		Lower quartzites					100	100?
SEMRI SERIES	Rohtas stage		(Western Rewah, 1500)			400	400 to 700	400+
	Kheinjua stage	Glauconite beds				?	300+	
		Fawn limestones	100-				250	250
		Olive shales				?	100+	
	Procellanite stage		Thickness indeterminable.			In east over 300		
	Basal stage	Kajrahat limestone	Zero				2000	Zero?
		Basal beds						

Kaimurs	770'	in West	Minimum thickness		in East
Semris	1000?		Kaimurs	1370'	
			Semris	3000'	

* * * * *

Features of interest in this area are:

1) The presence of glauconite in both limestone and flagstones below the main Tirohan limestone.
2) The overlap of the Kaimurs to the north
3) The freshness of the granite in the floor and the feldspar fragments in the Semris
4) The easterly direction of currents during the deposition of the Lower Kaimur sandstone.

* * * * *

DOLERITES

Dolerites have been found intrusive into the Semri Series (but not into the Kaimurs) in four places: at Kajrahat, in the shales between the basal conglomerates and the Kajrahat limestone; 0.35 miles northeast of Pataudh, in the Olive Shales at the base of the Kheinjuas; 0.5 mile WNW of Manchi, near the top of the Rohtas stage; and 0.6 miles SSE of Bakia Bagawar 1627 hill also near the top of the Rohtas.

Of these localities, the last two showed rock too weathered to obtain in a hand specimen. These rocks are typical of highly weathered basic intrusives, with centripetal crusty weathering from joints to give the usual ball effect and oatmeal appearance. There is some green staining along the joints, possibly due to solubility of chlorite weathering products. Contacts with the Rohtas limestone were not seen. The limestones here are highly disturbed, but independently of the intrusions.

The dolerite at Kajrahat shows no contact effects on the bleaching shales into which it is intruded. It is fresh, and of variable texture. Some types are typically doleritic while others are more basaltic, with two mm phenocrysts in a fine grained groundmass.

* * * * *

STRUCTURE

Folding

Folding is more important than faulting. The major folds are seen to become tighter towards the south, passing from the gentle east-pitching anticline of the Biranchuan amphitheatre to the close folds of the Susnai-Jhiria tract. Further south still, there appears to have been a packing up of beds, especially of the Kajrahat limestone at Billi, corresponding, in the horizontal, to the redistribution and concentration in the crests of limbs of smaller folds seen in the vertical sense. The incompetent units such as the glauconitic flags at the top of the Kheinjua stage, and the porcellanites, besides reacting in the major folds, show a strong development of minor folds which render impossible any accurate estimation of their thickness. The increase in intensity of folds towards the south is evident from the map. It is true that the closer folds of the south are traced out in the Semri series, which are less competent as a whole than the Kaimurs, but it is probable that if the Kaimurs had not been denuded over the tract now occupied by the Son river, they would have participated to some extent in the greater degree of folding. Steep dips of 50° in the upper Kaimurs are seen in the Susnai pass, and between Markundi and Gurdah. The rising up of the Kaimur plateau like a tidal wave over the Son valley, from its horizontal condition by Shahganj or Gopalla to the more inclined slopes approaching the scarp face, is very striking.

Faulting

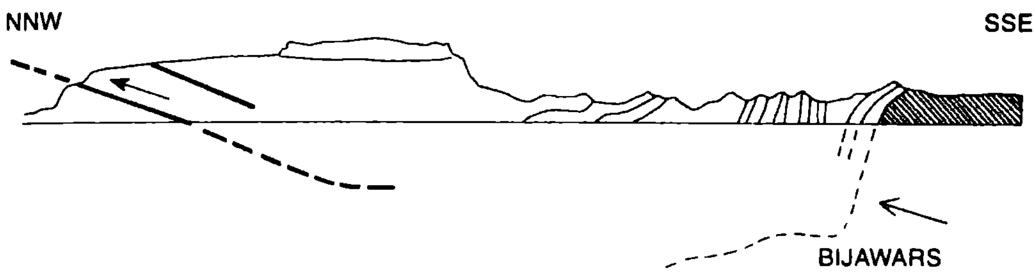
Markundi-Jamuai fault. A fault is well seen two miles east of the Markundi pass where a system of quickly replacing faults accompanies a strong monoclinal fexure, with downthrow to the northwest. Slickensides on the surfaces of the faults show movement to have been in a vertical direction. This fault continues to the west probably beyond Jamual, causing the juxtaposition of Kheinjua and Rohtas rocks against the Bijawars. Until the identification of the beds between Madain and the Son river to the east with the Kheinjua stage was re-established, no fault was considered necessary here. Vredenburg correlated these beds with Mallet's No.2, and has accordingly mapped all the stages of the Semri series as curving round the narrow wedge of Bijawar rocks in attenuated form. This structure implies a capacity for flow and attenuation which is unlikely for the beds concerned, as is shown by their wedge-like behaviour near Chakari. Now that Mallet's original correlation has been reverted to, it is necessary to assume either faulting or original failure of sedimentation or overlap to account for the juxtaposition of Kheinjua and Rohtas rocks with the Bijawars. One mile SSW of Gurdah, there is a poor exposure showing limestone, similar to the recognizable Kheinjua limestone just to the north, dipping at 70° to the south, underneath Bijawar phyllites. This would certainly suggest a reversed fault, bringing Bijawars upon to Kheinjua rocks. The indication that a cut-out fault is required on the north side of the wedge of Bijawars, with downthrow to the north, is seen by the fact that on the north and south sides of this wedge, there lie at the same horizontal level respectively, Kheinjua together with Rohtas rocks and Basal quartzites. The Basal Quartzites, assuming all the beds to be represented, should be at least 1000 feet below the top beds of the Kheinjuas, and yet they occur at the same horizontal level, dipping generally in opposite directions. The difficulty is not removed by supposing that the lower stages of the Semris were locally overlapped on the north side of the wedge so that Kheinjuas and Rohtas beds lie next to Bijawars, because in that case they should have occurred at the same level of overlap on the south side. Nor is it possible to assume a tilt down to the north to bring different horizons to the same level, because such a tilt should have converted an original slight sedimentation dip of the Basal beds on the south side to a new northward dip; which is not so. The Basal Quartzites on the south side dip southwards at 45°.

Fault south of Agori: There is a series of fault southwards from Agori, affecting the Semri-Bijawar boundary to the west of the Rihund river. The contact of Semris with Bijawars is seldom seen owing to dense jungle, but the local intense disturbance of the Semri rocks near anomalous outcrops of Bijawars is enough to warrant the supposition of their existence. Some of the faults are of reversed nature, Bijawars having been pushed northwards over Semris (or Semris southwards under Bijawars), as for example along parts of the Ghathita and Agori faults.

There are local boundary faults between the Semris and the Bijawars such as those by Kota and between Khattai and Gangi.

By Hurma, there is a wedge of Kheinjua rocks pushed into Rohtas limestones at a low angle. The fault planes are not seen, but there is considerable accompanying disturbance.

Mangesar fault: In the scarp promontory three-quarters of a mile east of Mangesar Hill, a low angle reversed fault, hading to the SSE, cuts out one limb of a sharp flexure in the Scarp Sandstones of the Upper Kaimurs. Above, and parallel to this fault is a marked oblique joint cutting the bedding of the strata at an angle of 20°; this is probably of shear nature. The hade of the fault plane suggests movement in a SSE-NNW direction. It is assumed that this reversed fault and overlying shear joint represent the effect of lateral relief to the more intense folding to the south of the scarp (Plate 5, Fig.2).



Diagrammatic section across Mangesar Hill.

Below this fault is a series of cross buckles in the lower Kaimur sandstone, radiating out from a focus just in front of the present outcrop of the fault plane.

Reversed faults in Kheinjuas: Small reversed faults are sometimes seen in the Kheinjua rocks, such as the excellent one in the *nala* one mile east of Deora (Plate 6, fig.1). Slickensides along the fault plane are in a 165-345 direction, indicating a SSE-NNW direction of movement. Such faults frequently accompany sharp folds, and die out into more gentle flexures (Plate 7 fig.1).

Joints

The Vindhyans are very strongly jointed. Measurements of joint directions were taken in the hope that some idea would be formed of the nature of the stresses which have affected these rocks.

For the most part the joints are at right angles to the bedding planes, whether these are tilted of horizontal, but there are some exceptions in which one or more sets are inclined to the bedding. Since, especially in the case of the Kaimur rocks, the dips are low, it follows that most of the joints are vertical or nearly vertical.

Plate 5

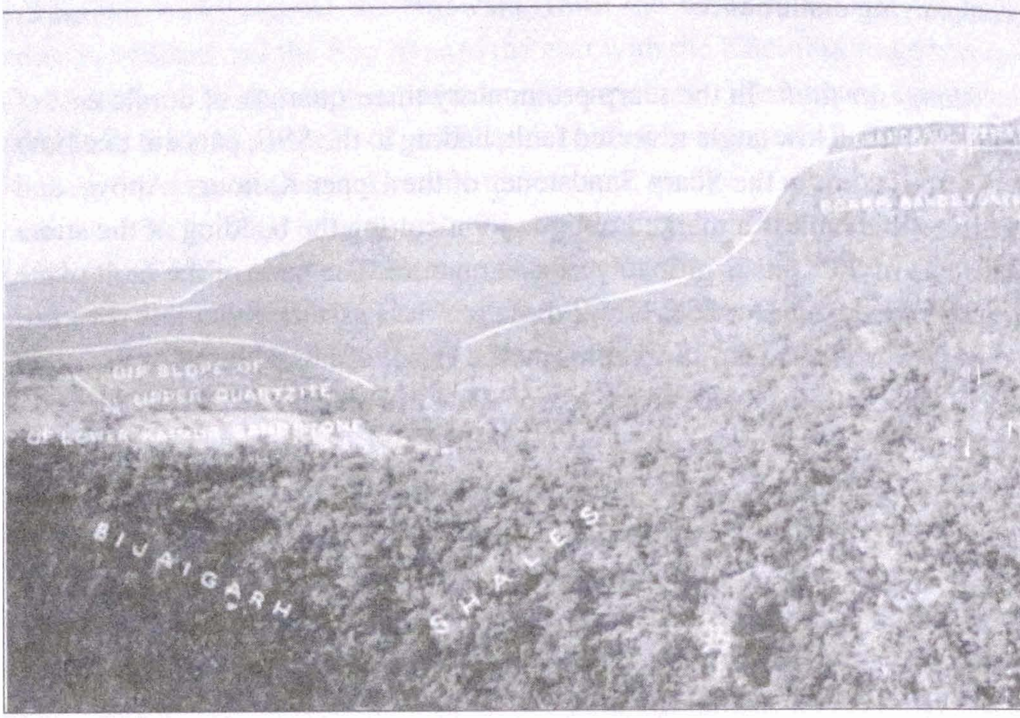


Fig.1. Kaimur scarp, looking WSW from the Gidhwa pass, one and a half miles southeast of Paliari.

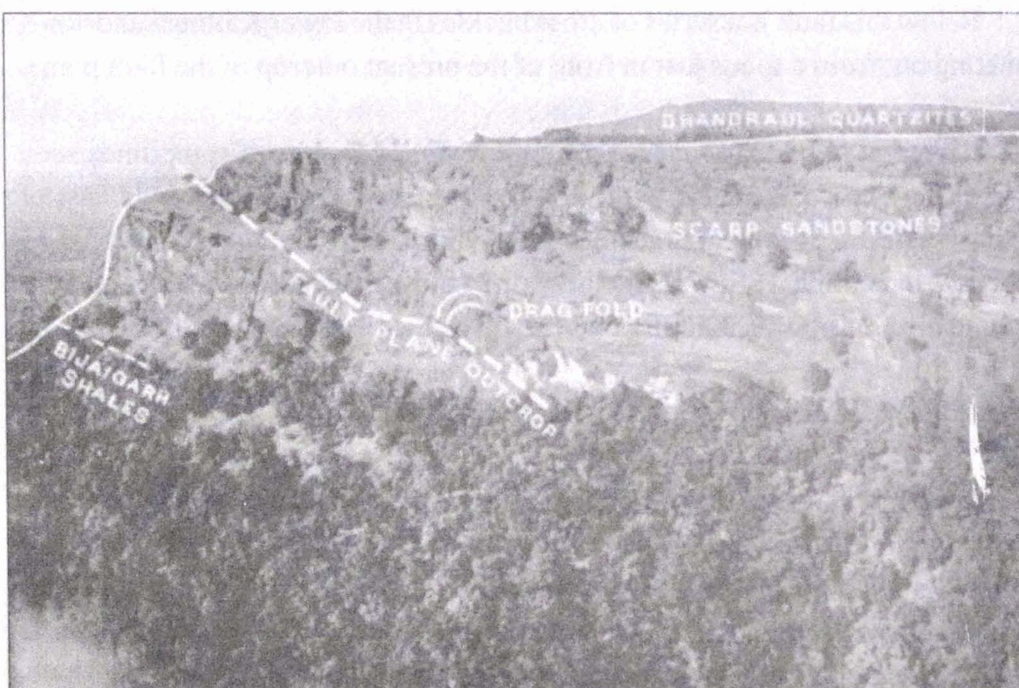


Fig.2. Reversed fault and drag fold in scarp sandstones, ENE of Mangesar hill.

Plate 6

Fig.1. Reversed fault in glauconitic beds, ¾ mile east of Deora.

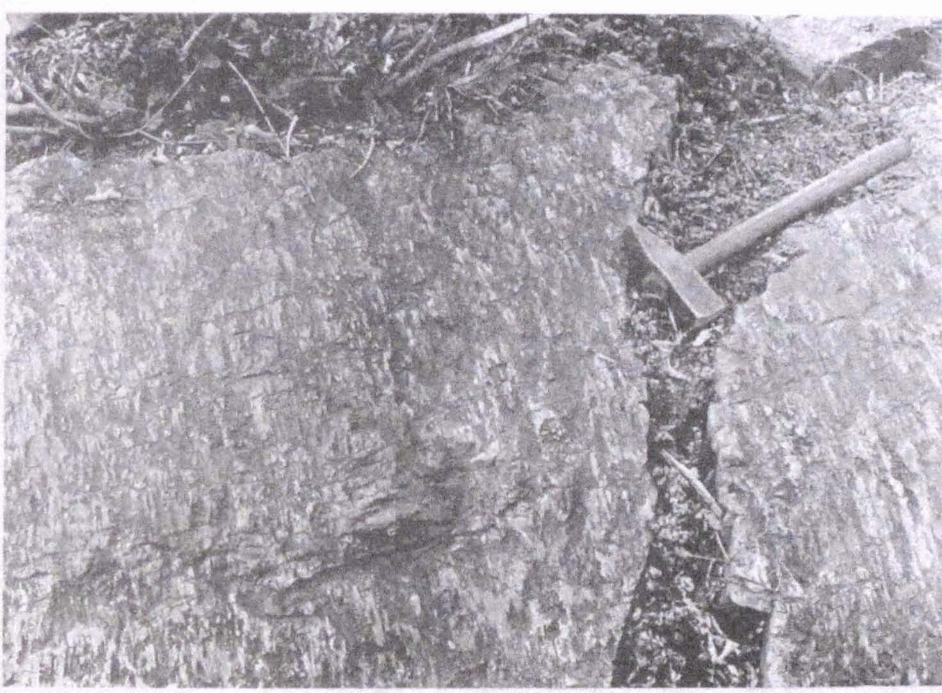


Fig.2. North-South slickensides. Glauconitic beds, ¾ mile east of Deora.

Plate 7

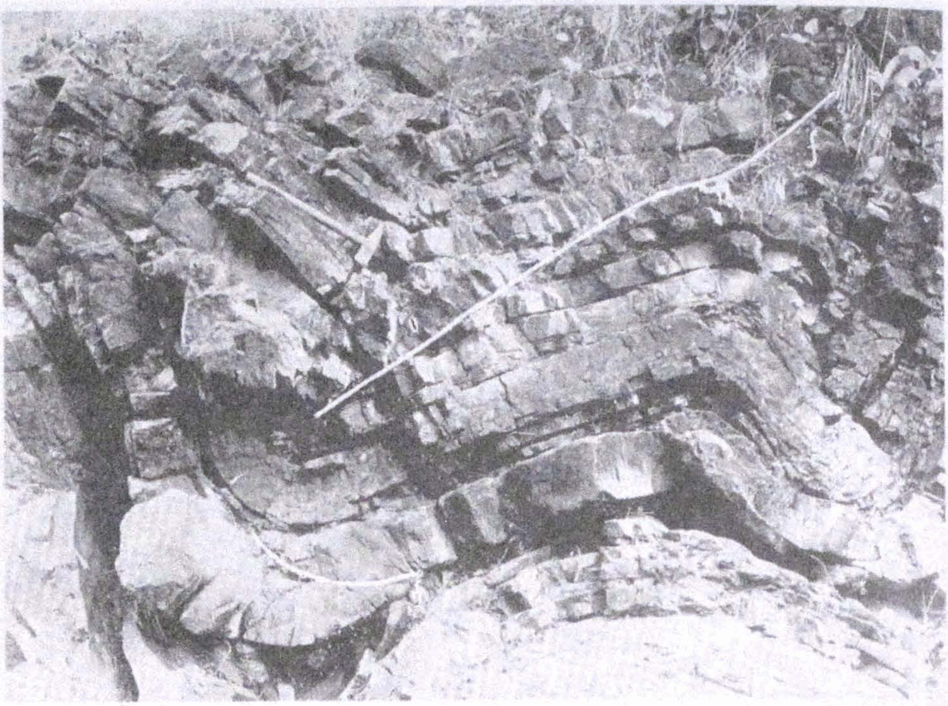


Fig.1. Fault passing into a fold, half a mile southeast of 829 hill. f = fault.

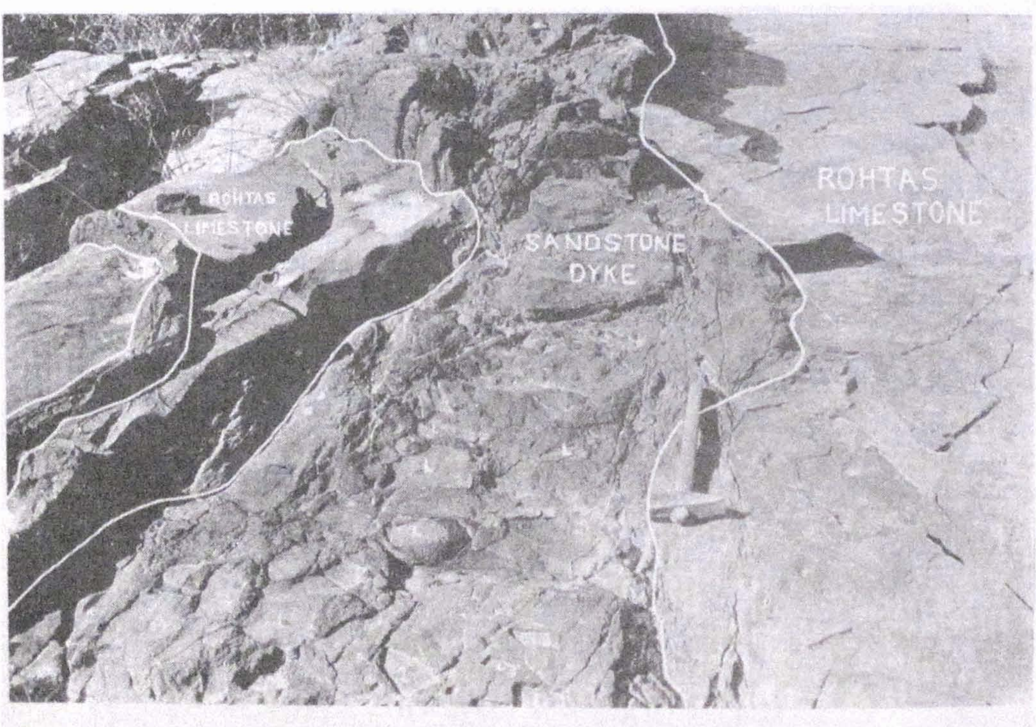


Fig.2. Blocks of limestone which have fallen into a sandstone 'dyke' in Rohtas limestone, Markundi.

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Angle of Shear and Ductility

It is difficult, however, to believe that the formation of the main sets of joints was due to tension, particularly when these joints are often found intersecting at more acute angles than is shown in the generalized diagram. Moreover, the calcareous nodules in the Rohtas stage are affected by these joints in a smooth, clean-cut manner, such as would not be expected had the stresses been tensional. It seems necessary, therefore, to consider them from the point of view of an origin under the influence of shear. Difficulties are at once evident, since, as discussed above, it is impossible to reconcile the directions of compression inferred from a study of the joints themselves, with that suggested from other inferences.

It is possible, however, that the direction of compression lay along the plane bisecting the obtuse angles between the main sets of joints, and hence that it ran NNE-SSW. Hartmann found this to be so in laboratory experiments on ductile substances, but in the field one is reluctant to adopt this explanation, when the rocks, as now exposed, are often so manifestly brittle.

* * * * *

CORRELATION

Glauconite

The presence of glauconite in the Kheinjua stage is of interest because of the bearing it has upon the origin of these beds. It is not possible within the limits of this paper to make a detailed discussion of the great amount of work which has been done on the paragenesis of glauconite, but it is necessary briefly to consider two factors; depth of formation and influence of organic matter.

Depth of Formation: Oceanic research shows that glauconite is formed 'just beyond the limits of wave and current action, or in other words, where the fine muddy particles commence to make up a considerable portion of the deposits'. It occurs 'most abundantly in comparatively shallow waters and near the mud line surrounding continental shores' (Quotation from Murray and Renard in Clarke, '*Data of Geochemistry*', Washington, p.133, 1920). The glauconite deposits of Kheinjua stage, on the other hand, show every sign of having been formed in areas of shallow water, subject to exposure to air. This is seen in the abundance of mud cracks, accompanying which are ripple marks, small-scale current bedding and penecontemporaneous conglomerates. Specimen 41/294 shows the mud cracks well displayed on glauconitic sandstone. The glauconitic rocks of the Tirohan-Karwi area, moreover, have the appearance of being a basal facies transgressional on to the Bundelkhand gneiss. Though this fact does not, by itself, indicate the depth to which the transgressing water actually attained before the Semri rocks were deposited, and the glauconite was formed, yet the lithology of the flagstones is such as to suggest a shallow water origin. Such examples have been described before.

* * * * *

It appears from the study of available literature that no specific difference according to chemical composition or to colour can be shown to exist between ancient and modern material. A slight difference, in the course of time, may have occurred in regard to depth of formation, but even in this there is uncertainty. If we accept these premises, of a probable identity of paragenesis throughout the course of time, it is not unreasonable to assume the formation of the glauconite in the Semri series of the Vindhyan rocks in association with organic matter.

Life in Vindhyan Times

It was concluded in the previous section that the rocks of the Kheinjua stage may have contained organic matter. It is of interest to recall the finding by Mr. H.C. Jones (*Rec. Geol. Surv. India*, v.38, p.66, 1909) of fossils in the Suket shales near Neemuch, from a horizon roughly equivalent to the Rohtas stage of the Son area. The identification of these fossils has resulted in a considerable difference of opinion, some English and American authorities, Bassler, Cobbold, Matley, Ulrich, and the late C.D. Walcott, supposing them to be allied to the brachiopod *Acrothele* (*op.cit.*, v.60, p.18, 1928), while Prof. Howell, of Princeton University, is in favour or their being plant remains. Whatever the final determination, it is certain that they are organic (Dr. F. Chapman has recently described these fossils as a new species under the name *Neobolus minima*, *Rec. Geol. Soc. America*, v.66, p.29, 1932).

The lenticles of vitrain matter which Dr. C.S. Fox found in carbonaceous shales near the base of the Kaimurs at Japla, indicate the existence of vegetable matter.

The case, therefore, for the existence of life during Vindhyan times is seen to be strong.

Manner of Origin of Semri and Kaimur Rocks

The Semri rocks were largely a marine formation. The marine nature of the limestones is one of fair certainty, on account of their thickness and excellent bedding. The presence of bedded tuffs, which, on analogy with present-day conditions, are probably to be considered best as offshore marine deposits formed near volcanoes along continental margins, and of glauconite, are also indications of marine conditions. The markedly parallel nature of the bedding of the main limestones indicates quiet deposition away from the influence of current and wave action, and from detritals. That the seas were shallow, certainly in the case of the Kheinjua and Rohtas limestones, is suggested by the fact that associated with these limestones are the shallow water and subaerially exposed beds of the Kheinjua and Lower Kaimur stages. To assume great depth for the formation of the limestones would involve too rapid variations in the level of the sea floor, between the periods of limestone and of sandstone deposition.

The most striking megascopic features of the Kaimur rocks are: their mainly arenaceous facies; the commonness throughout of current bedding; the abundance at certain horizons of ripple marks, sun cracks, and more occasionally of rain drop impressions; and the red colours of the Scarp Sandstones. The conditions under which the Kaimur rocks were deposited may with fair certainty be considered to have been fluviatile. Probably no better accounts have been made of such deposits than those by Barrell. For comparison with the Kaimur rocks may be recommended the critical re-interpretation Barrell made of the Old Red Sandstone rocks of Britain (*Bull. Geol. Soc. Amer.*, v.27, p.345, (1916). The characteristics he defined are so similar to those present in the Kaimur rocks, that his conclusions as to their manner of deposition may be assumed to hold good in the present case, namely: fluviatile deposits formed along flood plains in intermontane basins subject to seasonal rainfall and semi-arid conditions. The question of climate will be discussed later.

Hence, between the Semris and the Kaimurs there is seen to be a change in conditions from mainly marine to entirely fluviatile environments. It is possible to picture this change as one either of areal separation between contemporaneous environments, or of physiographical changes in areally identical regions, or of a combination of both these factors. One may imagine flood-plain deposits passing laterally to sub-aerial and subaqueous topset deposits of a delta system, and these in turn to foreset and bottomset deposits of marine formation. One is led to question momentarily whether the Semris and Kaimurs really represent series of distinct ages or whether they do not actually indicate roughly contemporaneous deposits, the one marine, the other fluviatile, both being components of a great river delta system. Age of deposition under such conditions would not be told entirely by reference to vertical sections of deposits, but laterally, by their outward growth. When dealing with topset or bottomset beds alone, the order of superposition would indicate the order of deposition; but where topset, foreset and bottomset deposits occur together in a single section, it is clear that, though superimposed, they are approximately contemporaneous. When it comes, however, to applying the theoretical, deductive case (in which the vertical scale is of necessity exaggerated relative to the beds intended to be figured, so as to enable illustration in a section), to actual examples in the field, the difficulties are considerable. The simple delta cycle may be upset by elevation, by subsidence, or by unequal tilting; may be repeated, or partially removed. Such contingencies are figured in other papers by Barrell (*Geol. Soc. Amer.*, v.23, p.377, 1912), who has applied the deductive method in considerable detail to understanding the formation of deltas. Of greater difficulty is the recognition of the individual components of the theoretical delta in actual field examples. It is admitted that every gradation may exist between flood-plain deposits and associated delta deposits, and that the deposits belonging to the different divisions of the delta are not sharply defined. This is evident also from a reading of Grabau's account, in which, after classification of river deposits into Alluvial fans, Flood Plain and Transitional Delta deposits, the actual examples, such as those of the Ganges river, are treated under the different heads without the differentiation which the headings would seem to imply. Twenhofel (footnote, p.598) mentions that Trowbridge believes undue emphasis to have been placed on these distinctions. In fact, the theoretical deductive distinctions have sometimes outstripped in clarity those that are really possible in the field. In the present instance, the absence of recognizable organisms to assist in the differentiation into marine and non-marine deposits is a further handicap.

With regard to the Semri and Kaimur series, the evidence in the field suggests entirely that only after deposition of the whole of the Rohtas stage of the Semri seriee were the Kaimurs laid down. Everywhere there seems to be parallelism of dip between the two series, neglecting those unconformities described by Oldham, due to earth movement (p.226); nowhere is there suggestion of lateral passage obliquely upwards of the marine Rohtas into the non-marine Kaimurs, which might be supposed to occur on the conception that marine bottomset beds would pass into foreset or topset beds, both of the same general age. Admittedly, the exposures showing the junction of the Kaimurs with the Rohtas are extremely poor. Oldham (*Mem. Geol. Surv. India*, v.31, p.25, 1901) has suggested that the thinness of the Rohtas stage, and the thickness of the Lawer Kaimnr sandstone near Markundi might be accounted for by lateral passage from limestone into sandstone. This statement could be used in support of the idea of lateral passage mentioned above. In my opinion, however, Oldham was mistaken in this correlation. The Rohtas limestone is now thought to be thick by Markundi, so that the necessity of explaining away its thinness is no longer required. It is important to point out that Oldham's explanation was not based on actual observation of lateral passage; there is too much jungle to render this possible. The lateral passage was, on the contrary, inferred in order to explain his difficulty, which, now removed, leaves the explanation without independent value.

If the individual groups of the Semris be regarded collectively as bottomset beds, it follows that each group should pass upwards to an areally separated topset group, and since the, by supposition, bottomset beds are distinctive and dissimilar, the equivalent topset beds should show related dissimilarities. This is not so. The marked similarity of the beds at the top of the Kheinjua stage and of the top of the Lower Kaimur sandstone imply similarity of conditions such as would hardly be expected in environments which, by supposition, were as widely separated as topset and bottomset.

No cases of inclined bedding, such as are usually associated with foreset deposits, have been seen in this area. Current bedding is abundantly found, but always between parallel-bedded sandstones. These parallel beds are often inclined, but the inclination, as now seen, is a subsequent tectonic feature, and not due to original sedimentation (with one exception; the pellet limestone in the Karwi area does appear to show its original sedimentation dip). The absence of foreset deposits would, it is true, render the differentiation between the topset and bottomset sediments one of great difficulty, the more so since contrasted marine and freshwater organisms are not present. Even allowing that the distinction between the components of the delta system are uncertain, and hence that the similarity between the Kheinjuas and Lower Kaimur sandstone is in itself no bar to the correlation of the one with bottomset and the other with topset deposits, there is still the fact that everywhere the Rohtas limestone intervenes between the two groups.

As far as can be seen there is no areal separation between the Semris series and the higher Vindhyans, beyond the fact that the Semris, cropping out at the base of the Vindhyan basin, occupy a somewhat larger total area. Each stage of the Vindhyans persists, one on top of the other in general over very wide areas and with remarkable persistence of characters.

It is necessary, therefore, to assume the second of the alternatives mentioned above, namely that of physiographical changes in areally identical environments, and to regard the single sets of fluvio-deltaic components as having been repeated many times in the course of deposition of the Upper Semris and Kaimurs. It would be more in harmony with the facts to picture the two series as representing a pile of sediments resulting from advance and retreat of the sea over fat areas, with alternate dominance in the same area of marine and fluvio-deltaic conditions.

It may be supposed that the sea advanced on to the Bijawar and granite land; that marine deposition continued until the upper part of the Kheinjua stage, when elevation resulted in alternating sub-aqueous and sub-aerial deposition. Slight subsidence followed, resulting in the deposition of the Rohtas limestone, over flats perhaps similar to the Bahama banks. Freedom from detritals implies lack of denudation, one cause of which could be due to planation of the neighbouring land. Elevation followed, and the shallow seas became flood plain areas, upon which the Lower Kaimur sandstones were deposited, with material blown in by wind from the siliceous bordering regions. Exposure to air was common throughout the Lower Kaimur succession. Local swamp conditions must have occurred to have caused the formation of the black ferruginous and carbonaceous shales associated with the Lower Kaimur stage. Finally, elevation of the whole area, with rejuvenation of the streams from the flanking mountains and consequent abundant supply of sediment, resulted in the deposition of the thick Upper Kaimur sandstones in the river reaches. The thinning of the Kaimurs to the west and the nature of the current bedding of the Dhandraul quartzites both indicate that the supply of material in the Mirzapur and eastern Rewah areas was easterly. Mr. A. L. Coulson (*Rec. Geol. Surv. India*, v.60, p.169, 1927) shows that in Bundi State, 450 miles to the west, the Kaimur sandstones are only from 100 to 120 feet thick.

That similar conditions continued throughout the course of Vindhyan deposition may be seen from the accounts given by other authors of the Rewah and Bhander series. Oldham (*Geology of India*, p.100, 1893) states that the Rewah sandstones are fairly coarse and generally current-bedded, while the Bhander sandstones are soft, fine-grained and of deep red colour, speckled with white. Mallet (*Mem. Geol. Surv. India*, v.7, p.95, 1871) in connection with the Upper Bhanders writes:

> 'Ripple marking, which is common throughout the greater part of the Vindhyans, occurs in immense profusion and variety in the upper Bundairs. Sun-cracks and water channels are also not unfrequent, but rain drops have not been hitherto observed, a rather remarkable fact, considering how common they are in the lower Vindhyans and the abundance of sun-cracks in the strata we are speaking about.'

The Rewah series and the upper stage of the Kaimur series (Dhandraul quartzites) probably mark elevation of land relative to sea, when more active deposition filled up the flood plains with quickly formed, current-bedded sandstones. The Bhander sandstones are thinner bedded, of red colour, ripple-marked and sun-cracked, and represent slackened deposition, in closer relation to marine conditions. Oscillations in level led to marine incursions with deposition of limestones, and glauconitic beds. Elevation may have led to isolation of small bodies of saline waters, the drying up of which caused sun-cracking and may have resulted in the gypsum deposits of Satna. The presence of glauconite in the sandy beds associated with the Sanchi shales, which are a local development in the Lower Bhander sandstone of Bhopal, was noticed by

Middlemiss in 1905, and mentioned by him in an unpublished report. There can be no question of the confusion of these Sanchi shales with those found in the Semri series, since these are such widely separated horizons in the vertical sequence. The presence of the mineral in both the Semris and the Bhanders, together with other features of similarity between the two series, is indication of the recurrence of similar conditions.

The quotation of Mallet, given above, shows how strongly he considered the essential unity of the beds usually called Lower Vindhyans, and the Upper Vindhyans. Other factors have come to light since Mallet's time which support this unity. Mallet continues (*Mem. Geol Surv. India*, v.7, p.95, 1871) to consider the whole system as of estuarine origin, fed, in its eastern development at least, by a river draining from the east, from over the crystalline rocks of Bihar (then included in Bengal). It may be questioned whether the conception of estuarine deposition is applicable to the bulk of the deposits, since such widespread development of sun-cracks and of red colours implies exposure of whole areas to sub-aerial conditions rather than the limited exposure which would result from the difference between high and low tides along estuarine flats. The conception put forward here is of alternating marine and predominating fluviatile conditions. Gradations, which would naturally be expected between the two sets of conditions, are here supposed to be deltaic rather than estuarine, because the sediments as now seen suggest the dominance of fluviatile deposition filling up valleys, instead of the entry of the sea into incised and depressed valleys where fluviatile sedimentation would not be active.

The crux of the question is to understand the relation of the vertical scale in delta components to the beds interpreted as deltaic, and to decide to what extent the lateral growth of the fiuvio-deltaic system occupies time as measured in the vertical sequence. That the thickness of delta deposits varies greatly is evident from two examples mentioned by Twenhofel (*Treatise on Sedimentation*, p.594, 1926) The sub-aqueous topset, foreset and bottomset components of the Nile delta, which is of great age, are given by Twenhofel as respectively 200, 800, and 1,000 metres in thickness. These 2,000 metres, or 6,500 feet, are on a scale quite equivalent to the combined Semri-Kaimur series. On the other hand, the young Frazer river delta is on a much smaller scale. The topset beds show a maximum thickness of 100 feet, while the foreset, occurring between the 3 and 30 fathom lines, approximate only to 150 feet.

In the case of modern examples of fluvio-deltaic systems, the conception of growth is almost entirely lateral. Thus, the Siwaliks may be considered to be the forerunner deposits of those now forming at the mouth of the Ganges, separated from them by some 1,000 miles. It may be possible that the Siwalik deposits occur some thousands of feet below those now forming at the mouths of the Ganges, but it is to be doubted whether a facies of this type would be deposited so far in front of the uprising Himalayan chain. If this be so, then the difference in age is accompanied by one in area. This lateral conception of growth is necessitated by the possibility of seeing only the growing end of the top of the fiuvio-delta deposits. In the case of ancient examples, however, which are no longer in a growing condition, but which are exposed in sections as a result of uplift and denudation, it is the vertical conception of growth which has been usually emphasised, regardless of the time taken for lateral growth. As stated above, with regard to the Vindhyans, it seems impossible to consider the Semri series as having formed contemporaneously with the Kaimurs, so that the vertical scale of delta components must be reduced to the stages within series, and the sequence of stages becomes a measure of the age of the beds.

Both interpretations are handicapped; the one by inability to see the beds below the undenuded growing top, except along the up-tilted margins of the deposits, the other by seeing the old system no longer in growth, but dead and dissected. If it is supposed that the growth of the Vindhyan rocks was from east to west, it follows that, since conditions during Vindhyan times appear to have become increasingly stringent, there should be more signs of aridity or semi-aridity in the sediments to the west or northwest than in the east, in addition to a similar increase upwards in anyone place in the vertical succession. Possibly, however, the area examined is so small compared to the total extent of the Vindhyan outcrop that it is unsound to extrapolate, too far, suppositions obtained from limited data.

Climate

Aridity or semi-aridity of condtions is suggested by the following facts: (1) By the freshness of the granite in the basement to the Vidhyans at Kohi, and of the fragments of feldspar in the overlapping beds of the Vindhyans when they come close to the granite. (2) By the excellent rounding of the quartz grains in many of the Vindhyan sandstones and quartzites, most marked in the Lower Kaimur sandstone stage, but present also in the Kheinjua and in the Upper Kaimurs. (3) By the red and red-brown colours of the Scarp Sandstones of the Upper Kaimur stage, a feature characteristic also of the Bhander sandstones.

Boundary between the Semri and Kaimur Series

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Present Survey, 1929 to 1931

The salient features of the Semri and Kaimur series are summarized in the table on p.46.

The most striking feature is the occurrence throughout the sequence of ripple-marked and sun-cracked beds, more particularly in the Glauconitic beds of the Kheinjuas, at the top of the lower and upper quartzites of the Lower Kaimur sandstone, and at the base of the Upper Kaimur sandstone. Further, conglomerates, pebble beds, and discs of shale are found at the base of the Basal stage; at the base of the Porcellanite stage; in the Glauconitic group; in the Lower Quartzites of the Lower Kaimur sandstone stage; and at the base of the Upper Kaimur sandstone stage. Epiclastic breccias, in which fragments of porcellanite occur in a gritty matrix, are found both in the Kheinjua and the Lower Kaimur sandstone stages.

There is seen to be, throughout the Semri and Kaimur sequence, a lack of any metamorphism, aside from metasomatic additions and looal reactions to stress at the base of the Semri series; a similarity of contemporaneous joint directions, and a general similarity in lithology of the sandstone and shaley sandstone facies, amounting in the case of the lenticular flags at the top of the Kheinjua and Lower Kaimur stages to indentity in appearance, all of which point to a general association of Semri and Kaimur series within the one Vindhyan system and which transcend those contrasts between calcareous and arenaceous facies which might suggest a separation into two different systems. Mallet's revision of the original grouping of Medlicott is certainly correct, in spite of occasional appearances to the contrary at the base of the Semri series. When, further, the similarity is considered of the Kaimur with the Rewah series in regard to current bedding, and of the Kheinjua stage in the Semri series with the Lower Kaimurs and Bhanders in regard to ripple marks and sun cracks, and when the presence of limestones and glauconite in both the Semri and Bhander series is remembered, it is seen how strong an argument exists for grouping all these series within the one Vindhyan system. Oldham did, it is true, doubt the grouping of the Lower Vindhyans with the what was held to be the Vindhyans proper in the second edition of the' Geology of India ' (*Geology of India*, p.98, 1893) though even then he qualifies this doubt by quoting from the 1st Edition, page 90, in which two features are discussed which give a deceptive idea of unconformity. Later, on visiting the Son valley he never questioned the grouping of the so-called Lower and Upper Vindhyans in one system.

Boundary: Accepting that the Semris and Kaimurs are joint members of a single system, it is still necessary to fix a boundary between the two series, the one strongly calcareous, the other mainly arenaceous. The boundary, therefore, will have to be at the top of the topmost limestone (Rohtas), or higher up.

Mallet and Oldham placed it at the top of the Rohtas limestone, but Oldham's boundary is to some extent disqualified, because no detailed mapping was done on the one inch scale, and one and the same quartzite was regarded in

Lithological types in Semris and Kaimurs

Series	Stages	Substages	Ripple marks, Sun cracks Current bedding	Conglomerates	Silicification	General characters
Kaimur Series	Upper Kaimur stage	Dhandraul quartzites	Strong current bedding Ripple marks		Secondary silica cement	Currents from east and southeast
		Brown Scarp Sandstones				Currents irregular
		Green Scarp Sandstones	Strong current bedding Abundant ripple marks	Shale discs in silt matrix		
	Lower Kaimur stage	Bijaigarh shales				Carbonaceous and with ironstones
		Quartzites and flags	Abundant ripple marks, sun cracks and current bedding	Conglomeratic breccia	Strong silicification	Marked wind-rounding of grains
		Silicified shales			Porcellanites	Some siderite bands
		Lower Quartzites	Ripple marks, sun cracks and current bedding	Pebble beds	Secondary silica cement	Marked wind-rounding of grains
Semri Series	Rohtas stage	Rohtas limestones			Often silicified near top	Rapid variation in shale-limestone ratio
	Kheinjua stage	Glauconitic group	Ripple marks, sun cracks, current bedding	Shale discs, pebble beds, breccias	Porcellanites	Probable rapid turn over of sediments by currents Pellet habit
		Fawn limestone			Agates and chert very common	
		Olive shales				
	Porcellanite stage	Porcellanites	Rare ripple marks	Fine-grained conglomerates locally at base	Strong silicification	
	Basal stage	Kajrahat limestone			Silicification	
		Basal beds		Conglomerates, pudding stones, breccias	Local silicification	

different localities as belonging to the Rohtas stage and to the Lower Kaimur sandstone.

Sir Edwin Pascoe suggested that the boundary might be drawn at the base of the Upper Kaimur sandstone, while Dr. Fox, as a result of his traverse, used the Susnai breccia as the dividing plane.

There are therefore three possible horizons to consider for this part of the Son valley:

(1) At the base of the Upper Kaimur sandstone,
(2) At the base of the Upper Quartzite of the Lower Kaimur sandstone, and at the top of the Susnai breccia,
(3) At the base of the Lower Quartzite, which is below the Susnai breccia and silicified shales group.

Of these three, the third and lowest horizon was the one accepted by Mallet and Oldham, and the one which will be reverted to in this paper.

The suggestion of Sir Edwin Pascoe would confine, in the Bijaigarh area, all the sun-cracked flags of variegated colours to a singly series below the Kaimurs, and leave the Kaimurs free from shales. In the area examined, the Kaimurs would, on this suggestion, begin with first, green and then continue to strongly red-brown sandstones. Such a boundary, however, would have little significance in relation to physiographical changes during Vindhyan times. It does not mark the beginning of fluviatile deposition, nor the oncoming of a strongly dry climate. In fact, the green ripple-marked flags, at the base of what is here called the Upper Kaimur sandstone, show rather reducing conditions and a temporary failure of exposure to drying and aeration, whatever the nature of the climate above the waters in which they were deposited. There is a further, and more practical objection, in that west of Bardi the Bijaigarh shales die out completely so that the Upper and Lower Kaimur sandstones unite in one scarp and become difficult to separate. This difficulty is not experienced by keeping the base of the Lower Kaimur sandstone (the top of the Rohtas limestone) as the dividing plane.

In the Bijaigarh area, the base of the 40 to 50 foot scarp overlying the Susnai breccia certainly appears to be a good horizon for separating Upper from Lower Vindhyans, since the scarp is easily mappable over the whole of the area east of Markundi, and participates less in folds, resulting in zig-zag outcrops, than the base of the Lower quartzite of the Lower Kaimur sandstone. But for 18 miles of the scarps below the main Upper Kaimur scarp, over the area where the Susnai breccia is best developed, there is a lower scarp formed by the Lower quartzites below the Susnai breccia. This is most pronounced above Kanch, and is the scarp actually seen from the alluvial plain. These quartzites are identical in provenance to the upper quartzites which immediately overlie in provenance to the upper quartzites which immediately overlie the Susnai breccia. To use the Susnai breccia as a horizon for demarcation would result in the separation of identical quartzites, the one to go into the Semri series, the other into the Kaimurs. Moreover, west of Markundi, where the silicified shales and porecellanites die out, the two scarps unite, so that it is impossible to separate them actually in the field. The Susnai breccia is found locally, just east of Gurdah, without the Silicified Shales, and near the base of the single scarp of Lower Kaimur sandstone. To use it as a plane of demarcation here is really to use the local conglomerate as a dividing line in the middle of a continuous sequence of quartzites (This may appear a reversal of the argument used earlier. There, the emphasis was on continuity between dissimilar lithological types being no bar to division by lithology. In the present instance, the conglomerate is local and the quartzites above and below it, in fact all round it, are of the same type. The emphasis is rather that, in this particular case, continuity of similar lithological types does not indicate the necessity of division). Westwards, where there is neither a breccia, nor intervening silicified shales, the question of boundary becomes one only of deciding between using the base either of the Upper or of the Lower Kaimur sandstones.

The breccia probably indicates no more than the explanation which Oldham and Vredenburg have given to it, namely, the local accumulation of Vindhyan debris in later Vindhyan rocks as a result of denudation along elevations formed at the time. Further, an exactly similar breccia was found in the Kheinjua stage, at places as far apart as Hurma and Barmori, in which rocks there is no question of separating beds into different series. In the area examined there seems no reason arbitrarily to pick on a single breccia and claim for it a particular importance in the separation of series. It has been mentioned above that the conglomerates and pebble beds are common throughout the Semri-Kaimur sequence. They must indicate conditions of general instability of too wide a significance to be narrowed down to the separation of one series from another. This is well brought out by the quotation from Vredenburg, who pointed out the continuity of phenomena. The same applies to the frequent irregular super-positions of stages at the base of the Semris and the dying out of shales higher up. To some extent limitation of beds is due to faulting, as, for instance, by the Markundi-Jamual fault and the fault between Khattai and Gangi. There is no doubt, however, that the basal beds die out and come in again, independently of faulting; which may be a consequence of local failure of deposition, or of local elevation soon after deposition and consequent removal of beds. This latter explanation is certainly to some extent true, for though many of the pebbles found in the Semri pebble beds are from basement beds (vein quartz and jasper), there are others of Vindhyan origin. The elevation which was responsible for the erosion of the basement formation continued and was also responsible for erosion and redeposition of Vindhyan beds.

Higher up in the succession, it has been seen that the Silicified and Bijaigarh shales die out westwards, the former near Markundi, and the latter by Bardi. West of Bardi the Lower and Upper Kaimur stages become, united into one scarp, whereas in the Bijaigarh area there were three scarps, on account of intervening shales; one due to the Upper Kaimur Sandstones and two to those in the Lower Kaimurs. Such disappearance of shales is not due to reciprocal replacement by sandstone in a westerly direction, because the Scarp Sandstones of the Upper Kaimur stage also become rapidly thinner westwards.

Whatever the cause, failure of supply of sediment, or elevation and erosion, these features of inconstancy of stages or sub-stages within series are so common throughout the Semri-Kaimur sequence, that the selection of a single overlap, or of a single breccia or conglomerate would give them an importance out of proportion to their significance. Some other factor should be chosen.

The quartzites of the Lower Kaimur sandstone, while not alone in their wind-rounded grains and their tourmaline content, show these characters in a sufficiently striking degree to be unique. This sudden deposition of wind-rounded grains on the top of a limestone, indicates a change in physiographical conditions which must be significant. Moreover, the colour of the Upper Kaimur sandstones also suggests, though by itself it may not be proof of, arid or semi-arid conditions. It has been thought best, therefore, to adopt the base of the Lower Quartzite of the Lower Kaimur sandstone (where there is only a single quartzite group in the Lower Kaimur sandstone the question is simplified) as the best horizon for separating Semris from Kaimurs, since this marks the first clear oncoming in the Son valley area of arid conditions.

Whatever line be drawn to separate Semris from Kaimurs, some criterion will be offended. The actual line now chosen marks neither the beginning of exposure to sub-aerial conditions, nor the beginning of the appearance of life. The use of the Susnai breccia as a line of demarcation was objected to partly on the grounds of separating identical quartzites into different series. Yet the line now chosen separates identical breccias and rocks of very similar facies. The breccias (Hurma-Barmori and Susnai), however, show only that instability occurred more than once, and those signs of instability were rejected for their commonness. The facies of very similar type (top Kheinjua and top Lower Kaimur sandstone) certainly indicate formation under similar conditions, but megascopically they lack significance beyond their immediate application to the nature of sedimentation. Microscopically, the quartzites associated with these lenticular flags at the top of the Lower Kaimur sandstone show the customary wind-rounded grains, which is not a feature noticed to any marked degree by the quartzites interbedded with the Kheinjua flags. The objection to separating the two quartzites of the Lower Kaimur sandstone was not for their similarity of external appearance (the lower of the two quartzites is more massively bedded than the upper) but for the indications they both yield as to the general external conditions which prevailed. The sun cracks in the flags at the top of the Kheinjua and Lower Kaimur stages indicate no more than exposure to air. The quartzites of the Lower Kaimur sandstone show the quality of the surrounding conditions.

It was stated in the description of the rocks at Tirohan, that the freshness of the granite in the basement to the Semris indicated arid conditions. This is proof that aridity began before the de position of the Kaimur rocks. From this it may be supposed irrational to claim that the Lower Kaimur quartzites in the Son valley indicate the first clear signs of the oncome of arid conditions. Further, some of the quartzites and arkoses in the Kheinjua stage of the Semri series, do show wind-rounding of grains. Arid conditions would not begin suddenly, and it is not supposed that the Lower Kaimnr quartzites mark a sudden change. They mark, however, in the Son valley, the change when it had reached sufficient intensity to be reflected in the sediments to a strong degree.

The line drawn at the base of the Lower Quartzite of the Lower Kaimur Sandstone and at the top of the Rohtas limestone, the highest ubiquitous limestone in the Vindhyan rocks below the Bhanders, is conventional. But, it is believed, it has a wider significance than the choice of a breccia, which is local. Further, it is that already accepted by Mallet and Oldham, though it was not everywhere mapped by them accurately in the field.

The Term 'Semri Series'

In this paper the term *Semri Series* has been substituted for the older term Lower Vindhyans.

*   *   *   *   *

CORRELATION

Correlation must remain uncertain owing to the discontinuity of outcrops of rocks, the general natures of which may indicate contemporaneity.

Dr. Heron has suggested, in conversation, the correlation of the Malani rhyolites of Western Rajputana with the pyroclastic rocks of the Porcellanite stage near the base of the Semri series of the Son valley. These rhyolites have been described by La Touche (*Mem. Geol. Surv. India*, v.35, p.19, 1911). They are overlain by reddish Vindhyan sandstones, frequently current bedded, ripple-marked and pebbly, and more of Bhander than of Kaimur type. The rhyolites rest unconformably on Aravalli phyllites and, although they show no bedding unconformity to the overlying Vindhyan sandstones, the occasional presence of rounded fragments of rhyolite in conglomerates at the base of the sandstones shows that some erosion had proceeded between the time of intrusion and the time of sandstone deposition. La Touche states that the rhyolites were contemporaneously intruded by the Jalor granite, and subsequently by basic dykes, which do not penetrate the Vindhyan sandstones.

In the Cuddapah area of Madras, slates, limestones, quartzites, jasper beds, and lavas belonging to the Cuddapah system, are intruded by basic sills and dykes, and are overlain with strong unconformity by the Kurnools, which are a series of limestones, quartzites and shales. Intrusions are not seen in the Kurnools.

In the Son valley, four basic intrusions have been found in the Semri series. One of them is a rhombic-pyroxene dolerite. Two occur as high up as the top of the Rohtas stage. None has been found in the Kaimurs. The granite below the Semri series is of later age than the Bijawar phyllites, but no good exposure shows its relationship with the Semri series. Since arkoses are common in the Semris, it may be supposed that deposition of the Semri series took place after the intrusion of the granite.

The failure of basic intrusives in the probable Upper Vindhyan sandstones of Rajputana, in the Kaimurs of the Son valley, and in the Kurnools of Madras may be explained by fortuitous occurrence, and need not necessarily indicate an earlier age relative to the non-intruded rocks. Certainly in the case of the Son valley area, there is no apparent reason why the intrusions should not have gone up into the conformably overlying Kaimur series, unless it be assumed that the mainly sandstone Kaimur rocks were unfavourable to the reception of igneous matter, while the Semri rocks, being more calcareous, were more favourable. The Kurnools are, moreover, predominantly made up of limestones, so that the question of environment hardly holds, on the basis of ease of intrusion into contrasted limestone-sandstone facies.

The one dolerite in the Semris, that is fresh enough for examination, appears to be neither of Deccan nor of Rajmahal type. It contains rhombic pyroxene and common pyrites. Possibly the pyrites was formed subsequent to intrusion, by the reaction of sulphide solutions, leaching from the country rock of black shales, with iron oxides originally present in the dolerite. Even if the pyrites is of no diagnostic value, it is probable that the presence of rhombic pyroxenes in this, dolerite and its absence in the Rajmahal and Deccan intrusives is significant. The next oldest basic intrusives in the Peninsula are believed to be of Cuddapah age, possibly not later than early Cuddapah (However in his memoir on the 'Barytes Deposits of the Ceded Districts of Madras' (*Mem. Geol. Surv. India*, v.64, pt.1, p.107, 1933). Mr. A. L. Coulson states that the basic sills in the Papaghnis and the Cheyairs were intruded in late or post-

Cheyair, Nallamalai or immediately post-Nallamalai times). Whether the dolerites in the Vindhyans, or in the Malani rhyolites, are equivalent to these Cuddapah intrusives is uncertain.

In two separated areas, where occur both unfossiliferous sedimentaries and intrusives, there are two unknown factors: – the age of the sedimentaries, and that of the intrusives. It is possible to correlate the sedimentaries by the rocks intrusive in them, only on the assumption that the intrusions were confined to a limited period of time. With highly distinctive igneous rocks this is perhaps possible, but with such common types as dolerites, even allowing a certain degree of differentiation by means of the nature of the pyroxene, it is hardly legitimate to claim intrusion to have occurred during a limited and unique period of time, unless the sediments themselves give a clue; which they cannot because they are themselves an unknown factor. With such latitude, the two unknown factors are not resolved by being associated together, and the argument can only be in circles. With regard to the Vmdhyan and Cuddapah rocks, it may be regarded as permissible to correlate those stages that are intruded by somewhat similar dolerites. It might equally well be maintained, however, that the Vindhyan and Malani dolerites, together with their associated volcanic phases, belong to slightly later suites, or to a single later suite, than the Cnddapah intrusions. It seems difficult to escape the uncertainty.

Lithologically, the Cuddapahs, with their richness in jasper beds, suggest an older age than the Semris, with their abundant pebbles of derived jasper. The greater general degree of metamorphism of the Cuddapahs is perhaps of little value in correlation, owing to their areal separation from the Semris, and the possibility of greater stress having acted in the Madras area at that time. On the grounds of lithology, the Kurnools seem to have more relationship to the Semris or the Bhanders than to the Kaimurs, but in this case again, the distance between the two isolated areas is probably sufficient to discount any argument on these grounds. The correlation tentatively put forward is given in Fig.1.

There is, finally, the correlation of the Vindhyans, or part of the Vindhyans, with the Cambrian rocks of the Salt Range. This was made by Dr. Fox, by analogy between the purple sandstones found in both formations. Ripple marks appear to be as common in the Purple Sandstone of the Salt Range as in the Kaimurs and Bhanders of the Vindhyans. The correlation on the basis of similarity in lithology may be objected to as unsound. Since, however, both the Cambrian rocks cf the Salt Range and the Vindhyans point to arid conditions, and since the Vindhyans are known to be pre-Gondwana, the correlation of these formations in a general way seems permissible.

It is true that aridity may have extended over a great length of time, enough

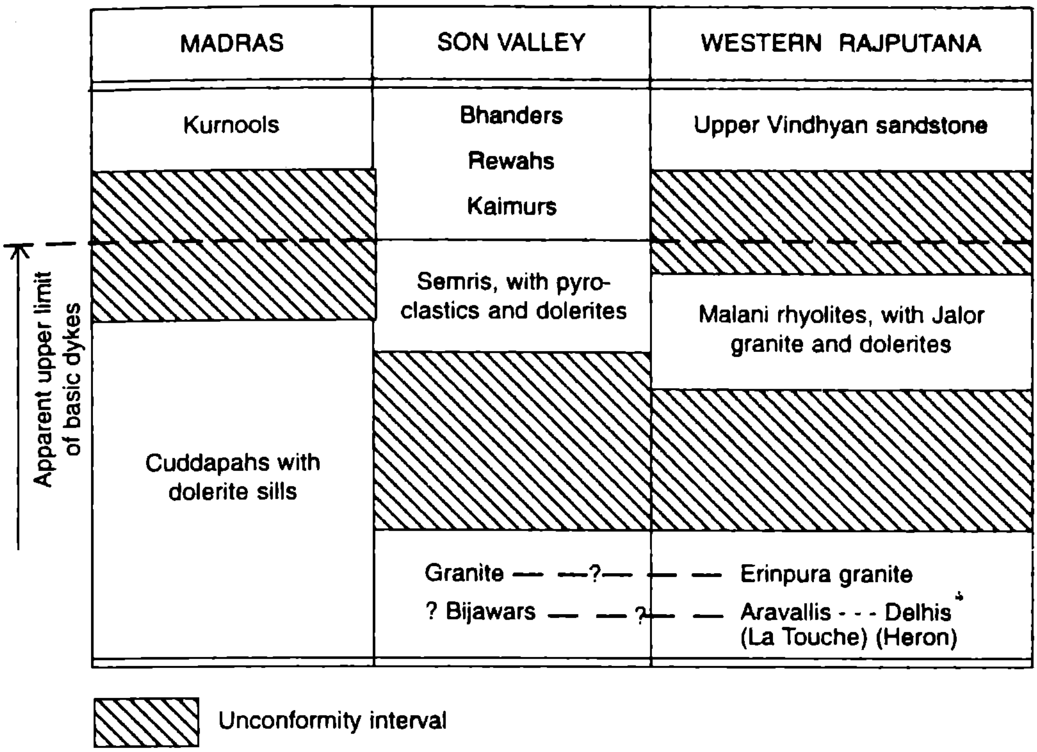

Fig.1. Correlation between Madras, Son Valley and Western Rajputana. Relative position of base of Cuddapahs unknown and therefore not indicated.

to include both the Cambrian and the Vindhyan rocks, even if these were of quite different ages, but, until this duration of conditions can be shown by reference to a time-scale given by fossiliferous sequences, the correlation of these formations may perhaps be accepted pragmatically, as useful in linking allied phenomena.

Dr. Fox regarded the Salt Marl in the Salt Range as of pre-Cambrian age, occurring normally at the base of a Cambrian sequence. The recent discovery by Mr. Gee of somewhat corroded nummulites, agreed to be *in situ*, in the Salt Marl, shows that the Marl is of Tertiary age (Cotter, *Proc. 18th Indian Sci. Congress*, (Asiat. Soc. Beng.), v.293, p.300, 1931; *Rec. Geol. Surv. India*, v.66, pp.32, 117, 1932)) As far as the correlation with the Vindhyan rocks is concerned, the existence of Salt Pseudomorph shales at the top of and as part of the real Cambrian sequence is none the less significant in connection with the nature of the climate.

The presence of life in the Vindhyans may be considered as established, though of little value in defining the age of the rocks. True glauconite appears to have been found only in Cambrian or younger rocks, Cayeux (*Introduction a l'Etuda Petrographique des Roches Sedimentaries*', Paris, p.251, 1916) mentions the occurrence of glauconite in the Huronian of North America, but it is uncertain whether he was referring to the non-potassic mineral, greenalite, found in the Mesabi iron-bearing rocks (*U.S. Geol. Surv. Monograph*, v.43, p.239, 1903) Clarke, Schneider and Twenhofel, three American authorities, all state that the mineral is first found in the Cambrian.

The age of the Vindhyan rocks maybe anything from Algonkian to Devonian. With the possible correlation of these rocks with the Cambrian of the Salt Range, and with the presence of glauconite and organic matter, it is reasonable to suppose a Cambrian age for at least part of the Vindhyan system.

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(Extracted from Rec. Geol. Surv. India, v.67, pt.4, 1934, pp.357-451)

The Geology of the Krol Belt

J.B. AUDEN

EDITORIAL COMMENTS

The Krol Belt of Lesser Himalaya of the present Himachal Pradesh and Uttaranchal, with its sequence of Blaini to Tal, occupies a stratigraphically strategic position both in the previous correlation of the Blaini Boulder Bed with the Upper Carboniferous Talchir or the present correlation with the Neoproterozoic glacial event on the basis of lower Cambrian fossils in the Tal. The geological map of the Krol Belt by Auden formed the basis of geological work in the Lesser Himalaya in the sixties. This map prepared by Auden was based on lithostratigraphic classification and meticulous field work. Auden recognized that the Krol Belt represents an important tectono-stratigraphic unit in the Simla Chakrata mountains. He described the sequence of formations of the Krol Belt in two distinct zones which he described under Solon neighbourhood comprising his Kroll Hill-Kamli Dhar Syncline and the other under Tons river neighbourhood comprising Nigali Syncline.

In the Solon neighbourhood zone he described a full sequence commencing from Simla Slate with Kakarhatti limestone upward in the order, Jaunsar, Blaini, Infra Krol, Krol Sandstone, Krol Limestone comprising Krol A, Krol B (Red shales), Krol C, Krol D and Krol E units with the Tal absent. In the Tons neighbourhood zone he described Simla Slates (Morar Chakrata beds) upward with Deoban limestone, Jaunsar (comprising Mandhali, Chandpur, Nagthat), Blaini, Infra Krol, Krol limestone comprising Lower Krol Limestone, Red shales, Upper Krol limestone, followed by the Tal constituiting Lower Tal and Upper Tal. Later work in this area by Bhargava (1976), Srikantia and Sharma (1976) not only confirmed the broad framework of Auden's grouping but recognized the clarity inherent in Auden's stratigraphic classification and structural delineation. The recognition of two structural belts, which were redesignated as the Outer Krol Belt and the Inner Krol Belt respectively for Solan neighbourhood and Tons river neighbourhood zone, with one modification in including Korgai Syncline of Krol within the Inner Krol Belt, holds the key to the understanding *of the tectonics of the Lesser Himalayan Tectogen. His lithostratigraphic classification of the Krol still remains intact though many attempts have been made later to graft different nomenclature for Auden's lithostratigraphic units.*

Auden made the first attempt to classify Simla Slate into Chhaosa Slates and Domehr Slates. He observed that greywackes predominate over slates in Chhaosa Slates and recognized beds containing pillow and kidney-shaped concretions, upto 18 inches in length, of impure quartzite and clay slate set in clay-slate matrix. These were later designated as load casts or ball and pillow structures. Though Auden was the first to explain that possibly earthquake shocks jolted partly unconsolidated material amongst overlying softer muds that had been previously deposited, their origin by similar earthquake mechanism was attributed to Kuenen (1958), by Potter and Pettijohn (1963).

Another important contribution of Auden is with regard to the classification of Jaunsar Series into Mandhali, Chandpur and Nagthat which has been well-tested by subsequent work and was later adopted, after a critical analysis by Srikantia and Bhargava (1974) under Jaunsar Group.

The study of "Jaunsar Series" of Auden is closely related to another controversial formation "Chail Series" of Pilgrim and West (1928). It was Auden who first noticed that "the Jaunsar of the Krol Belt and the Chails of the area mapped by Pilgrim and West (1928) are in places practically indistinguishable, as on Rigana Dhar and Tikar". In his comments Auden exercised great restraint without intruding into all aspect of Chail of Pilgrim and West (1928). Notwithstanding he made a pertinent comment: "It is, hoped however, to indicate that the differences between the rocks of the Krol Belt and of the adjacent northeastern area are not absolute, and that the question of age cannot satisfactorily be told by considering solely their metamorphic aspect." Auden's doubt about the status of Chail and his observation of Chail-Jaunsar gradation was further confirmed by Pascoe (1950, p.453) in his incisive and unbiased analysis of the geology of Simla area where he has commented on the possibility of Chail-Chandpur correlation. He was of the opinion that the equivalence of the Chandpur and the Chail series could be accepted with some degree of confidence. Later work of Srikantia and Bhargava (1974) brought out that the Chail of Sirmur-Chakrata area was the same as the Jaunsar of Auden.

Auden did not have much opportunity to examine the status of Simla Slate and he considered Simla Slate as older than Jaunsar more under the influence of West and correlated the so-called Morar-Chakrata beds with Simla Slates and placed Deoban stratigraphically above these formations. Later work of Srikantia and Sharma (1971), Srikantia and Bhargava (1974), Srikantia (1978), Bhargava (1976), however, brought out that Simla Group is a cover over Shali-Deoban basement and Simla Group and Jaunsar Group are homotaxial.

With regard to structure of the Krol Belt, Auden clearly stated that the structure of the Krol Belt was that of two thrust-bound synclines of Krol (and in the east of Krol and Tal) rocks resting on a Jaunsar-Simla slate foundation along Krol-Tons folded thrusts. Ranga Rao (1968) came out with an entirely different interpretation that Krol was an autochthon. He, however, overlooked crucial evidences of the occurrences of Palaeocene-Eocene (Kakara Formation, Srikantia and Bhargava, 1967) on the sub-thrust side of the Blaini-Infra Krol-Krol-Tal sequence of Krol Belt. Ranga Rao's contention was found to be not *tenable. The broad contention of Auden's interpretation of Krol-Tons thrusts continuity, however, needed modification as it was found that Krol and Giri thrusts are the traces of the same synformally folded thrust sheet of the Outer Krol Belt (i.e. the Krol-Hill-Kamli Dhar syncline of Auden) and the Chail-Tons thrusts are the traces of thrust sheet of the Inner Krol Belt (Nigali Dhar-Korgai synforms) structurally overlapping the outer Krol Belt.*

Largely the Geology of the Krol Belt represents a significant and valuable contribution to the geology of the Lesser Himalaya. Excepting for some of the modifications made by later workers as aforecited and with regard to the age of the Blaini to Tal sequence which is now proved to be Terminal Proterozoic to Lower Cambrian on the basis of unequivocal fossil find from the basal formation of the Tal Group, the main framework of the Krol Belt as delineated by Auden remains intact as a valuable contribution to the geology of Lesser Himalayan Tectogen. - S.V. Srikantia.

INTRODUCTION

The area described in this paper forms a small portion of the lower Himalaya between the Gambhar river, which flows from Simla to join Sutlej, and the Jumna river, which forms a boundary between Chakrata tahsil and Tehri-Garhwal State.

It lies in the following territories: Bharauli and Baghat divisions of the Simla Hill States, Patiala State, Sirmur (Nahan) State, and Chakrata tahsil of Dehra Dun district.

The part included in the map (Plate 1) is bounded by latitudes 30°30' and 31° and longitudes 77° and 78°. The term *Krol Belt* is taken from Kroll Hill, 7,393 feet in height (30°57':77°06'), which forms a conspicuous feature of the scenery between Kalka and Simla.

The Krol Belt occupies a narrow strip of mainly limestone country running NW-SE in its northern part, and changing in strike to nearly E-W towards the south.

* * * * *

Mapping

The area was mapped during the hot weather seasons of 1928, 1930, 1931 and 1932 and the cold weather of 1933. It is included in one inch to the mile sheets 53 F/1, 2, 5, 6, 10 and 14.

* * * * *

The present paper is a continuation of the work started by Pilgrim and West. Some of the views put forward here differ slightly from those previously expounded. Areas have been examined which had not been formerly visited, and from the study of which modified interpretations have arisen. In no sense can these present opinions be considered final. They are put forward for the purpose of crystallizing out the information and deductions before the collected data become too unwieldy. In regions of such complexity, modifications is bound to result from continued work and fuller knowledge, but the later work is only a growth from that which has preceded, and is dependent on it.

SEQUENCE OF FORMATIONS IN SIMLA-CHAKRATA HILLS

Stratigraphical sequence

<table>
<tr><th>Age</th><th colspan="3">Solon neighbourhood</th><th colspan="3">Tons river neighbourhood</th></tr>
<tr><td>Miocene</td><td colspan="3">Nahans (only at Kalka)</td><td colspan="3">Nahans</td></tr>
<tr><td>Lower Miocene</td><td colspan="3">[Kasauli
Dagshai</td><td colspan="3">Dagshai</td></tr>
<tr><td>Oligocene - Eocene</td><td colspan="3">Subathu (Nummulitic)</td><td colspan="3">Subathu (Nummulitic)</td></tr>
<tr><td></td><td colspan="3"></td><td colspan="3">never in contact</td></tr>
<tr><td rowspan="2">? Cretaceous and Jurassic</td><td colspan="3" rowspan="2">absent</td><td colspan="2" rowspan="2">Tal</td><td>Upper Tal</td></tr>
<tr><td>Lower Tal</td></tr>
<tr><td rowspan="7">? Permo-carboniferous</td><td rowspan="7">Krol series</td><td rowspan="5">Krol limestone</td><td>Krol E</td><td rowspan="7">Krol series</td><td rowspan="5">Krol limestone</td><td rowspan="3">Upper Krol limestone</td></tr>
<tr><td>Krol D</td></tr>
<tr><td>Krol C</td></tr>
<tr><td>Krol B (Red shales)</td><td>Red shales</td></tr>
<tr><td>Krol A</td><td>Lower Krol limestone</td></tr>
<tr><td colspan="2">Krol sandstone</td><td colspan="2" rowspan="2">Infra-Krol</td></tr>
<tr><td colspan="2">Infra-Krol</td></tr>
<tr><td>Upper Carboniferous</td><td>Blaini</td><td colspan="2"></td><td>Blaini</td><td colspan="2"></td></tr>
<tr><td>? Devonian and Silurian</td><td colspan="3">Jaunsar with possible Mandhali</td><td colspan="2">Nagthat stage
Chandpur stage
Mandhali stage</td><td>Jaunsar series</td></tr>
<tr><td>? Lower Palaeozoic and pre-Cambrian</td><td colspan="3">Simla slates with Kakarhatti limestone</td><td colspan="3">Deoban limestone
Simla slates (Morar-Chakrata beds)</td></tr>
<tr><td>Miocene (and older)</td><td colspan="3">Dolerites</td><td colspan="3"></td></tr>
</table>

LITHOLOGY

The lithological characters of the various rock divisions will now be described, irrespective of whether correlation will ultimately render some of them equivalent. Beginning with the base of the succession are the Simla slates.

Simla Slates

The Simla slates occur typically on the spurs between Simla and the Sutlej river. In the Krol Belt, they are seen in a stretch of country which runs from the Gambhar river, past Kandaghat and along the Ashmi-Giri rivers. They also occur in the vicinity of Subathu and Solon. After a long gap, they crop out again between Morar, Chakrata and the Jumna river, north of the Tons thrust.

The Simla slates are dark- and sombre-coloured, with grey-blue tints, and are made up of micaceous shales, bleaching shales and slates, pencil slates, clay-slates, occasional phyllites, sandstones and predominant greywackes. Except for fracture cleavage in some of the shale bands between the more massive greywackes, true oblique cleavage is never seen. Parting is parallel to the bedding planes. Bedding thickness varies from ten feet to half an inch, but is characteristically massive.

Areal Types

Northeast of the Krol thrust

Chhaosa type: The Chhaosa slates are similar to those found north of Simla. They occur in massive beds, two and more feet in thickness. Greywackes predominate over slates. The most characteristic feature of the Chhaosa slates is the occurrence of numerous beds containing pillow- and kidney-shaped concretions, up to 18 inches in length, of impure quartzite and clay-slate set in a clay-slate matrix. The difference in composition between the concretions and the matrix is often very small. Many of the pillow-concretions are too flat for their origin to be explained by rolling and concentric accretion on an inclined floor. Possibly earthquake shocks jolted partly consolidated material amongst overlying softer muds that had been just previously deposited. Wash-outs may be seen, as in the Ashmi river below Sunny. Current-bedding is common, especially in the more quartzitic rocks, and in the Gambhar river shows the beds tc be uninverted.

This division generally occurs in cliffs. The base is not seen. Its visible thickness is 1,400 feet in the excellent exposure along the Gambhar river.

Domehr slates: The Domehr slates are thin-bedded and consist of soft, green, micaceous silts, gritty slates, cindery and nodular micaceous sandstones. Ripple-marking is very common. There is a complete lack of metamorphism. This division succeeds the Chhaosa slates and has a minimum thickness along the Gambhar river of 1,200 feet. It has not been recognised east of Kandaghat.

Southwest of Krol thrust

Between Subathu and Arki, the Simla slates are richer in puckered leafy phyllites, but they exhibit as well some massive quartzitic bands, finely ripple-marked shaly quartzites and green nodular micaceous siltstones.

Kakarhatti limestone: The chief feature of these slates is the intercalation of the Kakarhatti limestone. This is pale grey, blue-grey and purple in colour. It is microcrystalline and sometimes oolitic, whence its pseudo-organic appearance. Chert is abundant, in crinkled thalloid patches more or less parallel to the bedding. The limestone has been strongly strained and has sometimes flowed. It is associated with soft, green, needle shales and bleaching slates. It has been traced by Dr. Pilgrim from Subathu to Arki and must continue for at least five miles further north.

*   *   *   *   *

Jaunsars

The Jaunsars are provisionally regarded as comprising three stages, in apparent ascending order: The Mandhali Stage; the Chandpur Stage; and the Nagthat Stage. These stages were only properly differentiated after this report had been written.

Mandhalis (Lower Jaunsar)

A discussion of this difficult group of rocks is postponed till a later section. Here I shall assume as Mandhalis those beds which apparently underlie the Chanpur stage (Middle Jaunsars), and overlie, by thrust junctions:

(a) Nahans and possible Dagshais on the south side of the Jaunsar syncline;
(b) Simla slates, with or without Nummulitics, on the north side of the Jaunsar syncline.

The apparent succession on both sides of the syncline is more or less the same, and is given below:

South limb	*North limb*
Dips north	Dips south
Chandpur stage	Chandpur stage
White massive quartzite	White massive quartzite or quartz-schist
(g) Bansa limestone, sporadic	Bansa limestone, very persistent
(f) Slates and phyllites	Slates and phyllites
(e) Dhaira (30°33' : 77°50') limestone Locally grahpite-schist	Khambroli (30°38' : 77° 50') limestone Locally graphite-slate
(d) Boulder bed	Boulder bed
(c) Quartzites, grits and conglomerates	Quartzites, grits and conglomerates
(b) Kalsi limestone or marble	Naraya (30° 39½' : 77° 50½') limestone or marble
(a) Kalsi quartzites and bleaching slates	*absent*
Krol thrust, dip north	*Tons thrust*, dip south
Nahans, possible Dagshais	Nummulitics, possible Dagshais, resting on Simla slates

(a) The Kalsi quartzites and bleaching slates may be seen on the hill half a mile WSW of Kalsi post office and on the lower slopes of the hill-sides east of the Amlawa *nala*. The quartzites are dull grey-white, and highly veined with quartz. The slates are only seen in a weathered condition, being bleached and stained with iron oxides.

(b) The Kalsi limestones are most easily seen near the foot-bridge over the Amlawa *nala*, half a mile north of Kalsi post office, and on the col between hills 6,925 and 6,658 feet, south of Kailana.

They are highly banded and interbedded with slate or phyllite. Colours are variable – grey-blue, green, purple and variegated purple-white all being seen. A sandy basis is rare. When unstressed, the limestones are microcrystalline, but stress has commonly led to the formation of fine-grained marbles, which are sometimes visibly crystalline. Specimens from the same locality may be unfolded or highly contorted.

A feature which has occasionally been noticed, as, for example, one mile ESE of Mandharsu, is that the apparent bedding-planes of this limestone are in reality joint-planes, since the composition bands, which give the true bedding; may be seen to cut these planes at high angles.

(c) The overlying quartzites, grits and conglomerates may be well seen just upstream from the footbridge over the Amlawa *nala* on the banks of the Jumna river, by mile 33 along the Chakrata-Mussoorie mule-track and at Dagura. Conglomerates are rare, but pebble beds containing pebbles of vein-quartz and purple slate or phyllite are common. Colours are pale green, grey and purple. The rocks are strongly ripped with vein-quartz, and are generally sheared to give schistose quartzites, and pebble-schists. Chlorite is the chief mineral developed, which imparts the dominant pale green colour. These schistose quartzites often weather into soft rocks that belie their real metamorphic nature, a consequence possibly of the ease of water permeation along the incipient planes of schistosity. There results an anomalous feature in that the Nummulitic quartzites, found locally at Dabra close to the Mandhalis, are vitreous, and appear superficially to show greater metamorphism than the weathered Mandhali quartz-schists.

(d) The boulder bed occurs almost invariably above these pebbly quartzites and just below the Dhaira limestone. There may be other boulder beds, but it is impossible to tell to what extent folding and faulting may have displaced the original succession and have resulted in duplication of some beds with elimination of others that were formerly adjacent.

The best localities for seeing these rocks are in the Jumna river 700 yards WSW of Bias, in the Tons river near the thrust contact of Mandhalis with Simla slates, a quarter of a mile SSW of hill 6,571 feet, and in a *nala* half a mile southeast of Makhta. The matrix is either slate, gritty slate or pure sandstone. Boulders and pebbles consist characteristically of limestone, dark slate, pale and dark sheared quartzites, and vein-quartz. Limestone fragments are invariably present in these rocks, in contrast to their rarity in the boulder bed of the Blaini. The limestones are either dark and microcrystalline, or marmorised to white, speckled, fine-grained marbles, similar to the marmorised type of the Kalsi limestone. Occasionally pink-weathering limestones are also seen. Together with these limestone fragments, there are very frequently found slivers of dark limestone that grew *in situ* in the rock. In the Tons river, these slivers may be seen to be up to 3 feet 6 inches in length. They are never over two inches thick. It is impossible to assume that such flat plates of limestone were deposited as fragments derived from erosion of pre-existing limestones, since they would have fractured in transport. Stress has certainly caused elongation of some of the fragments of limestone and quartzite, but the dimensions of these slivers are such that they cannot be accounted for solely by stress-elongation. Further, lenticles of sandstone of similar type to the limestone slivers, are also found grading insensibly into a sandstone matrix containing boulders. The whole aspect of these rocks is that of original lenticular deposition of primary and derived constituents.

Immediately below the Dhaira limestone is sometimes seen a graphite-schist or slate. The clearest exposures are in the Jumna river, 700 yards WSW of Bias, where graphite-schist intervenes between boulder bed and limestone, and in the Shwala *nala*, 0.67 miles west of Maralhau, where there is an abrupt contact of graphite-slate containing lenticles of carbonate and the overlying limestone.

(e) The Dhaira limestone is made up of thinly interbedded, dark; microcrystalline limestone and dark pyritic slate. The limestone is often lenticular and may closely resemble the Lower Krol limestone. It differs from the latter, however, in its greater degree of interbanding with slate, in its markedly angular folds, and in its frequently sandy basis. This limestone may be seen on the south side of the Jaunsar syncline at Pathna, north of Badhana, hill 3,993 feet, Dhaira, and in the Jumna river at Bias. On the north side of the Jaunsar syncline, it is to be seen between Ara and Khambrali, near Uproli, and south of Dagura.

(f) Between the Dhaira and Bansa limestones occur silvery black, sheeny phyllites and pale green, slightly talcose phyllites. These are best seen north of Udpalta.

(g) The Bansa limestone is very distinctive since it weathers to deep blue-black, granular surfaces, showing abundance of sand grains. On fracture the limestone is almost invariably eu-crystalline and blue in colour, though grey and purple colours are sometimes seen. The bedding is coarse, though the individual beds may be seen to be made up of many bands of slightly varying sand content. This sand content is far greater than that of the Dhaira and Kalsi limestones, from which the Bansa limestone is also distinguished by its more massive bedding.

On the north limb of the Jaunsar syncline, the Bansa limestone has been traced almost without interruption for 24 miles and has been an invaluable horizon. Along the southern limb of the syncline it is inconstant, though it occurs intermittently from just north of Chandni to a short distance east of the Kalsi-Chakrata motor road after which it is, for some reason, cut out.

Intimately connected with the Bansa limestone and often interbedded with it, is a pale quartzite or quartz-schist. This has been placed as the bottom member of the Chandpur stage, though the division should not be taken to imply any break in sedimentation.

Chandpur Stage (Middle Jaunsar)

The rocks of this stage form a distinctive outcrop from Chandpur, past Naga Tibba, Chorani, and extending eastwards to Nag Tibba in 53 J/N.W.

The most characteristic features of this stage are a highly banded association of quartzite and phyllite, and the presence of abundant green beds. As many as 24 bands of quartzite and phyllite may be seen in two centimetres. Although quartzite is really in excess of phyllite, the latter appears to predominate since it invariably adheres as thin films to the surfaces of the quartzite. The true ratio is seen in sections at right angles to the bedding. As a result of compression, this quartzite-phyllite association is generally thrown into striking crinkles and fold-puckers, which, together with the small-scale banding, result in simulation of fossil wood. The puckers resemble ripple-marks, but are usually too regular and of too accentuated amplitude actually to be so. True ripple-marks do occur in the quartzite bands, which impart to the later deposited muds, now phyllite, the same relief, but in such cases the amplitude is in keeping with that of ripple-marks. Later compression may, of course, fold these sedimentation ripples into puckers.

The phyllites grade into sheeny schistose phyllites, which just lack a sufficient degree of metamorphism to be called true schists. Such schistose rocks are used as roofing material at Manogi, wrongly called Dikroli, in 53 J/N W.

Besides this dominant quartzite-phyllite association, there are more massive current-bedded quartzites and an extensive series of chlorite-tuffs, slates and quartzites. These green rocks occur in distinctive homogeneous beds, showing strong polygonal jointing, and brown crusty weathering. Fracture is with a sonorous 'hammer' ring.

The majority of these rocks are metamorphosed tuffs, though occasionally amygdaloidal basic lavas are found as along the Mussoorie-Chakrata mule-path between miles 20 and 22. The differentiation in the field between tuff, lava and fine-grained intrusive rock (? contemporaneous with the volcanic material) is often very difficult. The coarser dolerites are, of course, readily recognisable.

There is no doubt about the pyroclastic and volcanic nature of the green rocks themselves. It is possible, however, that much of the so-called quartzite-phyllite association may also be tuffaceous. Many of the quartzitic bands under the microscope show little clastic quartz, but solely a fine-grained mosaic of quartz, sericite and chlorite, similar to that found in the undoubted tuffs. I am indebted to Dr. J. A. Dunn for drawing my attention to this possibility, and to references to photographs of the highly banded, recent, sub-aerial tuffs in New Zealand (*Bull. N.Z. Dept. Scientific and Industrial Research*, No.32, 1932).

The thickness of this stage near Chorani and Nagthat is at least 4,500 feet.

Nagthat Stage (Upper Jaunsar)

The Nagthat stage was only recognised as a separate group in 1933, after this paper had already been written. West of the Tons, it was not differentiated by mapping from the underlying Chandpur stage, though it is undoubtedly represented by outcrops in the Tons river below Andra, and at Minal Bag.

In the present map it is well seen on Nagthat Hill and by Lakhwar, but the best development is to the east, in sheets 53 J/N W and J/SW.

The characteristic rocks are sandstones, arkoses, quartzites, grits, conglomerates, clay-slates and phyllites showing purple and green colours. Some of the sandstones are pyritic, weathering to rusty bleaching crusts. The arenaceous rocks are strongly current-bedded and ripple-marked. The conglomerates contain pebbles of vein-quartz, often stained red or purple, purple and pale quartzites, purple and green slate or phyllite. They are typical of the Jaunsar conglomerates of the Simla area. Green tuffaceous sandstones are developed east of the area included in the map.

Boulder beds have been found in probable Nagthat beds in two places. One exposure is on the hill-side 0.4 miles NNW of Hiyun; the other exposure is in the Tons river 0.7 miles southwest of Altau. In both localities, the boulder beds are associated with quartzites, slates and phyllites, while in the Tons locality, there are also dark micaceous slates of Infra-Krol type. No limestones were seen. The boulders are angular, and consist of dark slate and greenish quartzite, types common in the Jaunsars. The matrix is gritty. Other boulder beds occur in what is definitely the Nagthat stage, south of the Aglar river in sheet 53 J/3.

In the Newali *nala*, immediately to the north-east of Khadayat, are found green tuffaceous quartzites, some of which are agglomeratic, and resemble the gritty facies of the Blaini when relatively free from pebbles and boulders.

Great variation in metamorphic condition occurs. Some of the rocks are soft clay-slates and sandstones. Others are talcose phyllites and schistose quartzites.

The rocks of this stage appear in the north to lie conformably upon the Chandpur stage, often with a basal conglomerate (Nagthat Hill). Towards the south it is probable that they overlap the Chandpur stage with marked unconformity. The significance of this unconformity is not at present fully understood.

Blaini

There are two typical rock-facies in the Blaini: the boulder bed or tillite, and the limestone. These form the most unique and striking rock association of the whole area, There is, however, no typical development of the Blaini, since no two exposures agree in character. The boulder bed may occur alone; or limestone may occur alone. There may be several boulder beds, with or without limestones, The boulder beds, and/or limestones, may lie on Simla slates, on Jaunsars, in beds of Jaunsar type, or in those of Infra-Krol type, This last manner of occurrence is particularly common in the Solan area, The slates of Infra-Krol type that are so intimately connected with the Blaini, should probably be mapped as Blaini. Since, however, the boulder beds and limestones often die out laterally along the strike, there has in many cases been embarrassment in distinguishing between Blaini and Infra-Krol slates that are lithologically identical, but, which, on account of this absence, are no longer separated in dip section. Consequently, those slates of Infra-Krol type that occur below the Blaini are mapped as Infra-Krol. Similarly, conglomerates of Jaunsar type associated with the Blaini are mapped as Jaunsar.

Boulder Beds or Tillites

The tillites are described in plural, though it is uncertain in the present area to what extent repetition of boulder beds and limestones in dip sections is due to original sedimentary repetition, and to what extent to imbricate faulting. That there must have been locally more than one boulder bed is shown by the presence of water-rounded boulders of tillite itself in tillite (Plate 2, Fig.2).

The boulder beds are generally dark grey-brown in colour, and consist of angular, sub-angular and rounded boulders set in a fine-grained matrix. The matrix may be clayey or gritty. The quantity of boulders varies, they in some exposures being absent. The boulder-free matrix in such cases is often a greenish, hard quartzite full of closely packed polygonal joints, as at Lagasan and in the Damkri *nala*. The size of the boulders varies from three feet to that of very small pebbles. Their angularity is for the most part determined by the jointing and thin-bedding of the parent rocks from which they were eroded. There is gradation from tillite to conglomerate, containing rounded pebbles of vein-quartz. Good examples of this gradation may be seen in the *nala* which flows south from Kandon to join the Giri river. The boulder beds may be strongly sheared, in which case the matrix becomes cleaved, phyllitised and eventually schistose, while the pebbles become flattened out so as to be difficult to distinguish from the matrix. This is best seen on the Juint- Chandpur ridge. Scratches are sometimes found on the boulders, but it is impossible to be sure whether these are due to internal friction or to glacial action. Certain Jaunsar phyllites north of Shallai show the presence of grooves, which were at first taken to be due to internal friction, but which, on closer inspection under the lens, are found to be corrugations or minute cross-folds running perpendicular to the strike of the strain-slip cleavage.

The boulders and pebbles are of the following types: dark slate, greenish quartzitic grit, pale quartzite, pepper sandstone, green siltstone or slate, banded slate, vein-quartz, occasional micro-crystalline limestone weathering buff-coloured. Their provenance is undoubtedly the Simla slates and the Jaunsars. The provenance of the limestone fragments is uncertain. In one case the limestone appears to be of Blaini type (19194).

Plate 2

Fig.1. Blaini boulder bed, confluence of Blaini and Gambhar rivers.

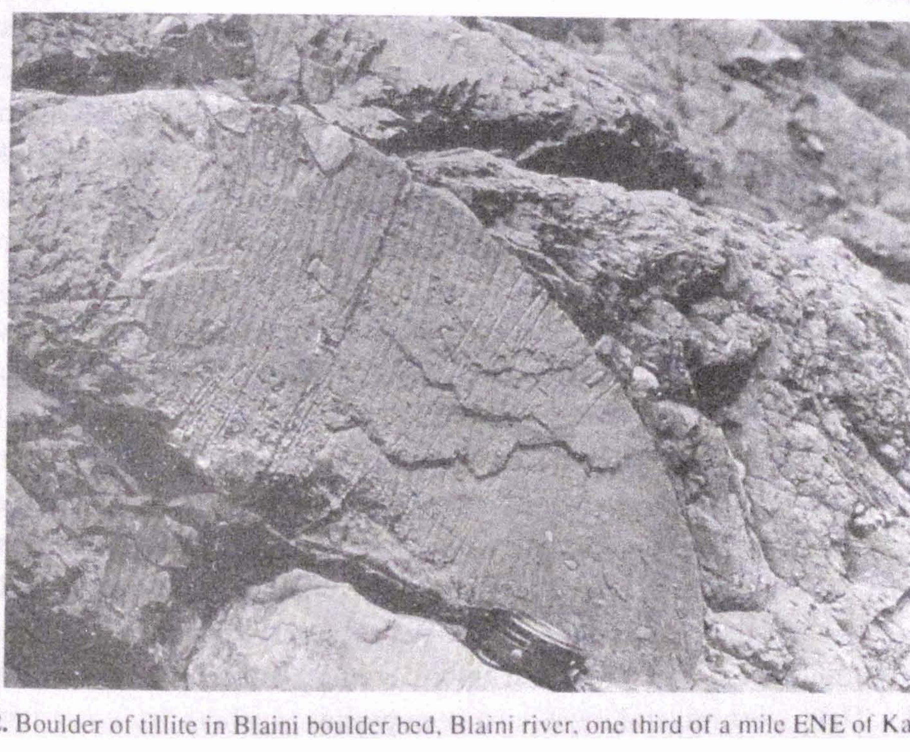

Fig.2. Boulder of tillite in Blaini boulder bed, Blaini river, one third of a mile ENE of Katiara.

Limestone

The limestone is generally pink and microcrystalline. It does not effervesce with acid or scratch with a knife. Its bedding is from half an inch to six inches and is generally contorted. Another type of limestone is one which is sandy and soft, weathering to thick dark orange-brown crusts. This is often distinctly ferruginous.

The limestone grades by addition of clay matter into calcareous shales and slates, which may be purple or pink in colour. Sometimes these are all that is seen in the Blaini, as at Barog Station, at the base of the Krol thrust.

* * * * *

Infra-Krol

The Infra-Krols are made up of highly incompetent rocks which have been so folded and inter-faulted that no representative section and no reliable estimate of their thickness can be made out. Fresh rocks of the Infra-Krols in stream sections differ so markedly from the more commonly seen weathered rocks on hill-sides that it has sometimes been difficult to assure oneself of their original identity.

The Infra-Krols consist chiefly of dark shales and slates, closely inter-bedded with thin buff-weathering a quarter of an inch to four-inch bands of impure slaty quartzite. This banding is close enough to be called of varve type. Occasionally thicker beds of pepper quartzite are found. Towards the top of the Infra-Krols (that is, in sections seen below the Krol sandstone and limestones), black carbonaceous shales or slates occur without the thin bands of slaty quartzite. The overlying of paler Krol sandstones on black Infra-Krols is well seen on the spurs south of Krol Hill and northwest of Rajgarh Hill. From a distance the dark carbonaceous beds shine in a striking manner in the reflected light of an afternoon sun.

The banded facies of dark shale and paler impure quartzite weathers on hill-sides to a very characteristic association of thin, bulbous, sheeny, gritty clay-slate, often green in colour, and concentric ring-bleached slates. The latter are ramified with irregular joints, now marked out by harder ridges as a result of liberation of iron and its precipitation as ferric hydroxide cement. On account of strong small-scale folding and recent cementation, these two rock types usually occur together in complete chaos. The commonness of iron in the Infra-Krols is seen in the universal seepages of ferric hydroxide, and white incrustations of ferric sulphate and chloride, which cover the surfaces of these rocks. The parent mineral must have been pyrites.

The Infra-Krols show great variation in the extent of metamorphism. In the Solan neighbourhood shales predominate, though at the closing end of the Krol syncline, in the lower Blaini river, the shales become true slates, with cleavage dip to the northeast. The intervening harder bands do not cleave. East of Dadahu the Infra-Krols are universally cleaved, while northwards, north of Soat and on Juin and Chandpur Hills, some of the beds turn into pearly phyllites and even become schistose. In these places they are ramified by veins of quartz. Their identification with the Infra-Krols is told by their occurrence between the Blaini and Lower Krol limestones, which also show a concomitant increase in metamorphism, and is supported by the presence of ring-bleached slates of more normal Infra-Krol type. East of Dadahu cleavage varies in dip from 35° to 70°, and in dip direction from NNW to NNE. The minimum thickness of the Infra-Krol rocks is about 500 feet, but no reliable estimate is possible.

* * * * *

Krol Sandstone

In the Solon neighbourhood, the Krol sandstone is generally seen as a soft crumbling sandstone, without good bedding and stained an orange colour with iron. Excellent exposures are found along the Kalka-Simla motor road, at the foot of Pachmunda Hill and at Salogra. North of Krol Hill, near Kandaghat, and in the *nala* which flows from Solon to join the Giri river, the sandstone is a hard quartzite in which bedding is well displayed. A conspicuous feature is the presence of bands rich in disc-like fragments of black shale, seldom over 2 mm thick but up to 5 cm long. These shale fragments readily bleach, and are almost certainly derived from penecontemporaneous erosion of the underlying Infra-Krols. Towards the southeast the sandstone ceases to be a single horizon, but splits up and becomes strongly interbedded with carbonaceous shale. Such interbanding may be seen in the Kawal Khal and at Ajga. Still further to the southeast, the intervening shale bands tend to disappear and, besides the quartzites with shale discs, there are coarser lenticular pebbly beds. The sandstone is 350 feet thick on the south face of Krol Hill above Baran, 50 feet in the southeast corner of sheet 53 F/1, two feet in the Giri river at Dadahu, and dies out on the western side of hill 3,619 feet.

In the tightly squeezed Krol syncline in the Kawal Khal, the sandstone becomes a horny quartzite, strongly veined with quartz. At Kadhar, below a local thrust, it has been highly polished by friction and has been broken down (22010).

Mr. Wadia (*Rec. Geol. Surv. India*, v.65, p.128, 1931) has suggested that some of the Krol sandstone may be metasomatised limestone. The microscopical evidence is against this supposition, since it is difficult to see how any replacement of lime by silica would result in such a striking grain structure as is shown by these sandstones. Had there been replacement, one would have expected an irregular mosaic of quartz and chalcedony. The only mosaic that has been observed is that in the crushed rock from Kadhar, where there is no question as to its mode of origin. The crumbling variety of the sandstone may probably be explained by de-silicification, and loss of the silica cement.

* * * * *

Krol Limestones

In this division of the Krol series is a great variety of limestones and shales. In the Solan area, Oldham divided the Krol limestones into three sub-stages:

Upper Krol Limestone,
Red Shales,
Lower Krol Limestone.

Between longitudes 77° and 77°25', it has been found possible to subdivide the Upper Krol limestone into three sub-stages, so that in all five sub-stages have been mapped in order the better to bring out the structure of the belt. For the most part, differentiation has been relatively easy. In places, however, on account of a basic similarity shown by some of the limestones in the three upper sub-stages, and owing to the intense folding which the eye can see to have taken place, aside from what is evinced by the mapping itself, differentiation has been more uncertain. This applies chiefly to squares A1 and B1 in sheet 53 F/6. East of 77°25', the original three divisions made by Oldham in the Solon area have been adhered to, although locally, especially near Mishwa, it would have been possible to delineate all five. Here, however, no useful purpose would have been served by subdividing the Upper Krol limestone, since the overlying Tal beds have prevented the Krols folding individually. Tals, Krol limestones, Infra-Krols and Blaini fold as a single unit. The combined thickness of the Krol limestones varies from about 1,800 feet to nearly 4,000 feet.

Krol A (Lower Krol Limestone)

In the area round Solon, this stage is made up of limestones and shales, in beds from one to four inches thick. Weathered surfaces show subdued grey-green tints. Fresh fractures are bluer. The limestones are seldom crystalline. In composition these beds show rapid alternations of shaly limestone and calcareous shale or slate; either in parallel beds (Plate 3, Fig.1), or as discontinuous, in-weathering, lenticular pillows of limestone surrounded by calcareous shale (some are seen in Plate 4). Near Solon, at the top of the stage, is a more massive 20-50-foot limestone, which is frequently dolomitised.

Small-scale current-bedding is often seen (39.800), and ill a few places, ripple-marks. Near Kotla and Dadhag, the ripples have been accentuated by subsequent compression (Registered negatives (9x12 cm) Nos. 298, 299. Rock specimen No.43.748). Discontinuous structures, once formed, appear to have acted as avenues of relief to later stress. The strike of these ripples is 120°-300°.

Fracture cleavage is universal. The calcareous shales, thus cleaved, may be seen lying about the hill-sides as pencils and needles. Towards the east, the shale facies begins to show true oblique cleavage. Between Dadahu and the Tons river, the Krol A stage is recognised by the presence of banded grey and green slates (44.91), while northwards, near Milla and Mangal, the slates become puckered, veined with quartz, and almost phyllitic. The puckering at Milla is parallel to 130°-310°. In the east, distortion of the beds and lenticles of purer limestone becomes marked (Plate 4).

Black chert is common as thin bands, or in pillows up to nine inches long and three in height. At latitude 30°33' 22": longitude 77°44'51", gypsum, with subordinate anhydrite, was found in a bed, 18 inches thick and 20 yards long, which appears to be an original deposit in the Lower Krol limestone.

In the Solon area, the apparent variation in thickness of these limestones is from 100 feet in parts of the southwest flank of the Belt, to some 2,300 feet, one mile southeast of 6,066 feet hill. The former thickness is due partly to reduction by thrust elimination, and the latter thickness to thrust multiplication. The real thickness probably varies from 300 feet on Pachmunda Hill to 700 feet on hill 6,066 feet. Within the area included by the maps, there seems to be no great variation, but further southeast, by Mussoorie and in Garhwal, these beds appear to become much thinner.

Krol B (Red Shales)

This sub-stage is characterised by soft, thinly laminated, purple-red shales, with blotches and intercalations of green shale. Thin dolomitic and cherty limestones are common. Ripple-marks are sometimes seen. Near the top of this division are parallel-bedded, shaly limestones similar to those in the Lower Krol limestone. The shales of this sub-stage are very incompetent; bedding is seldom preserved and their thickness is variable, owing to internal packing in the cores of folds and attenuation along the limbs. Slaty cleavage is never developed. Adjustment to stress takes place along countless irregular slip

Plate 3

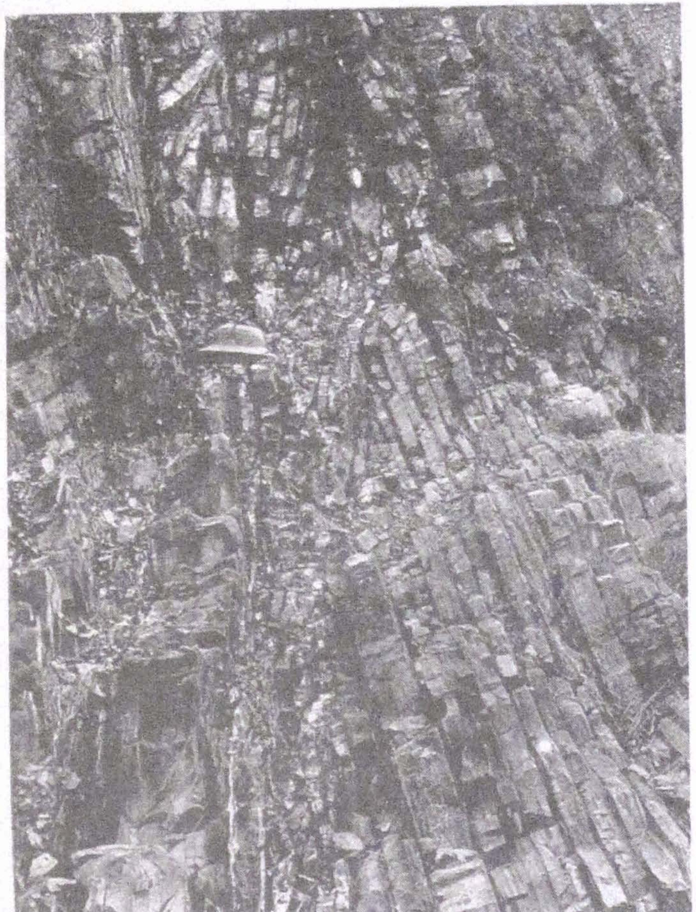

Fig.1. Fault zone in Krol A limestones and shales, Giri river, three-quarters of a mile north of Dadahu.

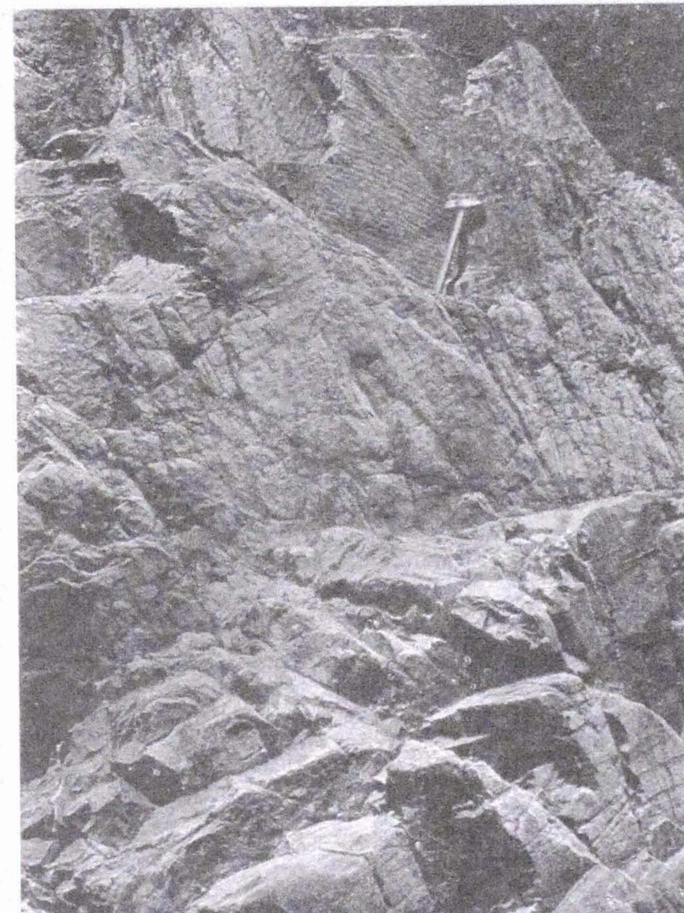

Fig.2. Steeply tilted ripple-marked Jaunsar quartzites, Giri river, one mile below Narail.

Plate 4. Deformation of Krol A limestone and shale by flow, one quarter of a mile WSW of height 3,278 feet, Nera (Newali) *nala*.

Plate 5. Overfold in Krol D stage. View of Mangarh village, with bharan, Sainbar and 6,687 feet hills in the distance.

surfaces, in the greener shales, with formation of chloritic minerals. The maximum undisturbed thickness of these shales is about 300 feet.

Krol C

This is the most conspicuous limestone on the hills round Solon, occurring in a single cliff from 150 to 300 feet in height. It is a massive, dark-blue, crystalline limestone, which usually stinks on fracture, and weathers to black 'chopping-board' surfaces. Dolomitisation is often seen.

Krol D (Chert, Limestone and Shale sub-stage)

In this sub-stage are alternations of cherty limestones and shales, with shale usually in excess of limestone. The limestones are either pale or dark and stinking, in beds from ten to 30 feet thick. The chert is pale and occurs as thin wisps and in continuous bands up to two inches thick. The shales are of black, red, green and orange colours, the darker varieties often bleaching in a manner similar to those of the Infra Krols. Rare conglomerates occur, with pebbles of vein-quartz and of chert. Soft white sandstones are often found.

Some of the limestones are penecontemporaneous breccias. The rocks of this sub-stage may be recognised on the terraced south face of Krol Hill, above the cliffs of the Krol C limestone, but their most characteristic development is between Bhaunrari and Mangarh, where the limestones readily twist into small scale overfolds in the great excess of shale (Plate 5). Gypsum was found as pockets replacing limestone near Bhaunrari. The minimum thickness of this sub-stage south-east of Narag is about 600 feet.

Krol E

The rocks of this division afford rugged scenery, since they are seldom seen below 4,000 feet. Bedding is well developed, from one to five feet. The main rock type is a banded grey and pale creamy white microcrystalline limestone. Freshly fractured surfaces of the paler varieties are white and porcellanous. Thin crinkled veins of calcite are common in the form of 'sutures' which stand out slightly on a weathered surface. These limestones pass by increase of grain-quartz first to pale sandy limestones, in which the quartz grains stick out as small millet seeds, and finally to pale calcareous sandstones. More rare are saccharoidal crystalline limestones and cream-white limestones showing tubular and ellipsoidal growths of calcite, radial to cores of calcareous mud. These growths are deceptively like corals. Red, orange and black shales are present, but are subordinate in amount to the limestones. The minimum thickness of this sub-stage is about 500 feet. Between Mishwa and Dugana, the combined thickness of the C, D and E sub-stages is of the order of 3,000 feet.

* * * * *

Tals

These beds occur in two synclinal basins completely surrounded by Krols. When first encountered in 1930, the upper stage of the Tals was regarded as Jaunsar and the lower stage as Infra-Krol. Later they were considered to be a completely new series, lying normally above the Krols, and to be equivalent to the Tal beds described by Middlemiss in Garhwal (*Rec. Geol. Surv. India*, v.20, p.33, 1887). This conclusion has been confirmed, with as much certainty as is possible in correlating between rocks of isolated basins.

Medlicott (*Mem. Geol. Surv. India*, v.3, p.45, 1864) noticed beds belonging to the upper stage of these Tals on what was then called' Kerloe' peak. This peak is in approximately the position of Giltu ka Tibba, hill 7,005 feet (30° 40': 77°29'). He was mistaken in correlating them with the Krols, and in underestimating their thickness.

The scenic changes from the rugged cream-white limestones of the Krol E stage, to the soft dark shales and greywackes of the Lower Tals, and from these to the pale cliff-forming Upper Tal quartzites, are very striking.

Sequence of Tal beds

Upper Tals	Dark limestones and calcareous sandstones; quartzites; shales. Massive arkosic sandstones or quartzites; pebble beds; shales. Alternating quartzites, often pebbly, with shale or slate.
Lower Tals	Micaceous shales or slates with a few quartzites Thick series of carbonaceous shales and dark greywackes, in massive beds marked out by finer banding and current-bedding. These pass laterally to tough slates and phyllites. Black chert beds and carbonaceous shales or slates.

The beds of the Lower Tals, particularly when converted into slates, are often very similar to those in the Infra-Krols. When uncleaved, they are usually to be distinguished by their more massive bedding, and by the abundance of dark greywacke, both features being absent from the Infra-Krols. The carbonaceous shales readily bleach, but generally as a uniformly weathering crust, and not in rings as in the case of the Infra-Krols. Many of the greywackes are strongly calcareous. Ripple-marks are sometimes seen. In the western basin, the Lower Tals vary from about 1,800 feet in the west to 3,500 feet in the east. In the eastern basin, they probably do not exceed 2,000 feet.

Quartzites form the most characteristic member of the Upper Tals (Plate 6). They are generally arkosic, and vary in colour from white to pale green. Occasionally there are found purple sandstones (7,216 feet peak). Current-bedding is universal and ripple-marks are common. Many of the sandstones are pebbly, containing pebbles of vein-quartz, green slate and pink feldspar, which is abundant and sometimes up to 10 mm. long. Pebbles of feldspar are not seen so often in the eastern of the two basins, though arkosic sandstones are common there.

Interbedded with the upper Tal quartzites are purple, red, and green micaceous shales. Some of these are striking in their irregular vermicular tubes and nodules of pale sandstone. These shales were probably sub-aerially exposed, the turned-up edges of sun-cracked mud becoming filled in with later washings of sand. Near Gubsar, where the Tals have been tilted vertically in proximity to the Guma thrust, shales have been converted to puckered phyllites. Clay-slates are common in the northern part of the western basin.

The limestones are always dark, sandy and current-bedded. No fossils have been found. Soft sandy limestone may be seen to lie on hard, highly jointed quartzite (Plate 7).

The thickness of the upper Tals, in the eastern basin, when not reduced by thrust faulting, is about 2,000 feet. In the western basin, it is probably, greater since the sandy limestone at the top are there preserved.

* * * * *

TERTIARIES

Subathus

It is not necessary to go into detail about the Tertiary rocks. The Subathus consist of olive-green and purple, oily-looking shales, ramified with minute irregular joints, and by planes of movement which are often filled in by calcite. There are also green and white sandstones, iron-stained quartzites, and rare ripple-marked shaly sandstones. Shelly limestones and unfossiliferous sheared limestones, full of veins of calcite, are common. Well-preserved fossils are rare, the shelly limestones being made up mostly of broken oysters. Nummulites are seldom seen. Two characteristic facies, of limited distribution, are a ferruginous pisolitic laterite and carbonaceous bed, one specimen of which contains over 60 per cent. of carbon. Very occasionally, conglomerates made up of fragments of pale microcrystalline limestone, set in calcareous sandy mud, are found. The provenance of the limestone fragments is not known.

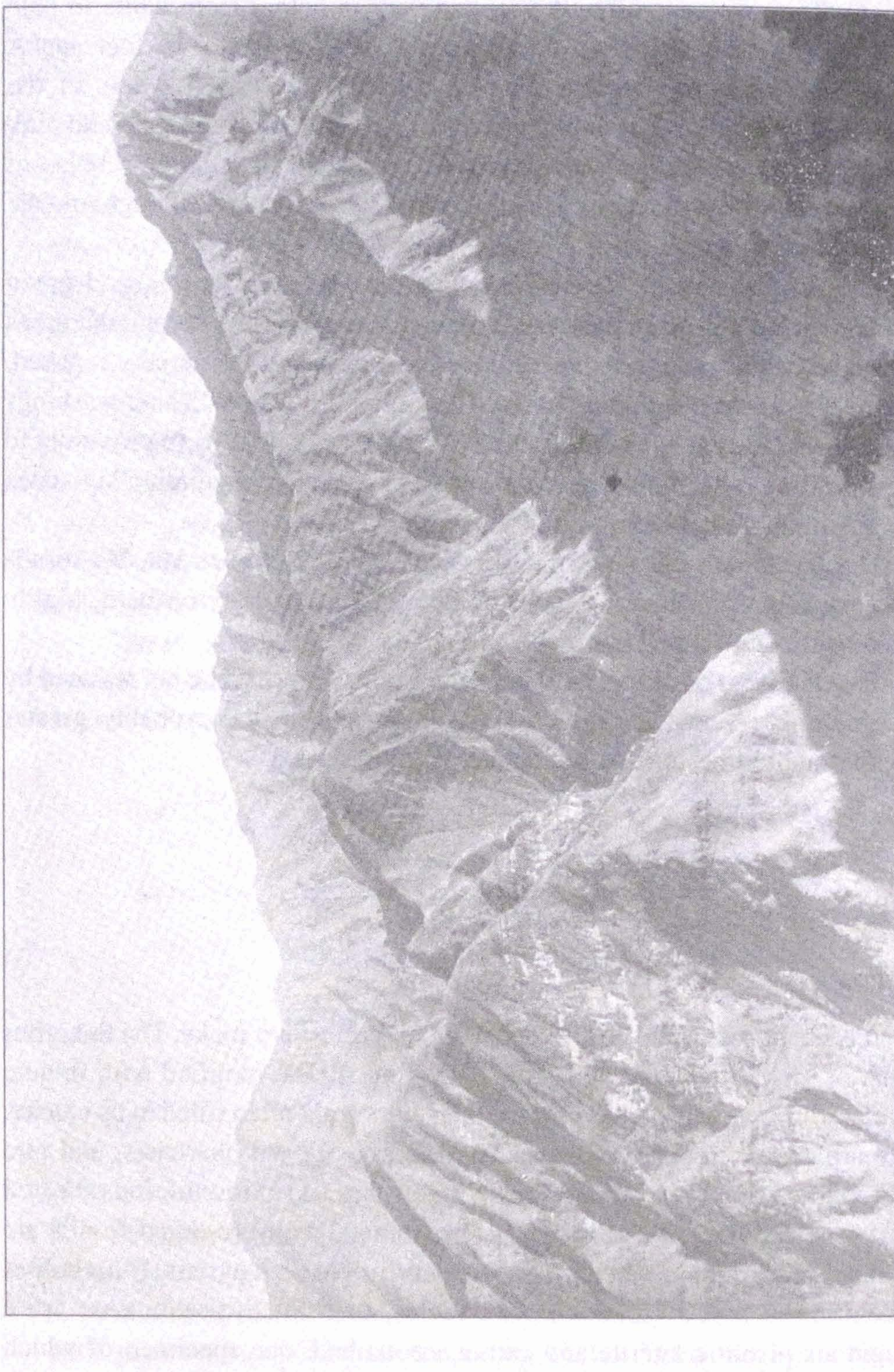

Plate 6. Guma peak, 8,098 feet, from Nigali Dhar. Syncline of upper Tal quartzite and shales, with vertical northern limb. Krol limestones on Guma.

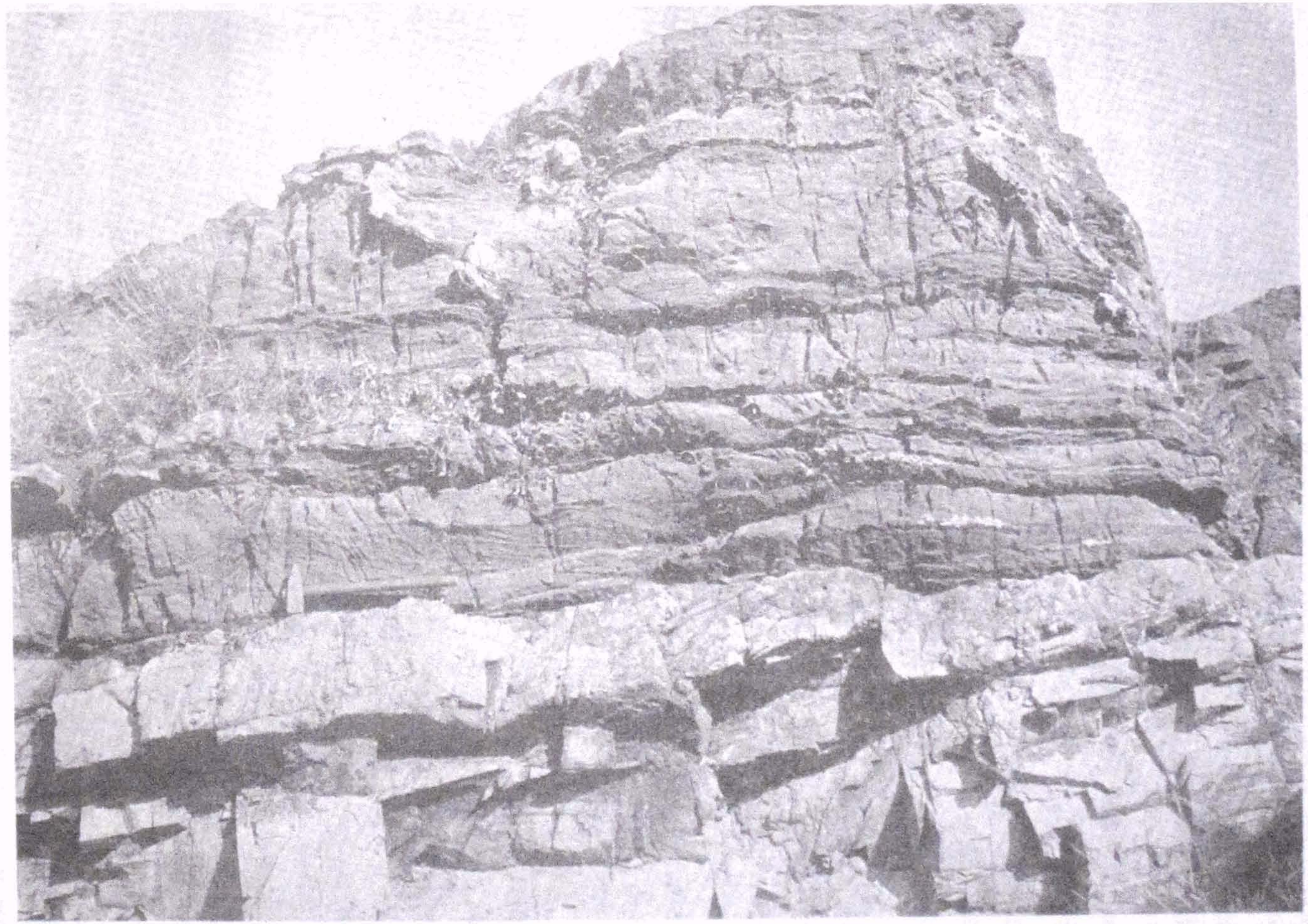

Plate 7. Dark, current-bedded, sandy limestone overlying pale quartzites, upper Tals. Current-bedding concave upwards. Nigali Dhar, three quarters of a mile northeast of Koti Dhaman.

They do not match any seen in the Krol series, nor those in the Subathu rocks themselves.

Near Kalka, along the Kawal Khal, and east of Dadahu, occurs an abnormal metamorphic facies of the Subathus. The purple and green shales become phyllitised and veined with quartz, while the carbonaceous shales are converted to dirty bleaching slates, exactly similar to those in the Infra-Krols. Greenstones are locally common east of Dadahu. A band of massive limestone, thicker than is usually found in the Subathus, is strongly developed near Sataun.

Daghshais

In the Kasauli neighbourhood, Col. Christophers has shown me a well-defined, white, quartzitic sandstone which intervenes between the Dagshais and the Subathus, and is a useful mapping horizon. The Dagshais proper consist of alternations of purple, cindery, sandy shales and purple or green sandstones, in beds up to 15 feet thick. The effect of these alternations on the scenery between Dagshai and Subathu is very striking.

Current-bedding and ripple-marks are common. Conglomerates occur, containing the same type of limestone fragments as are found in the Subathu conglomerates, and also red shale derived from contemporaneous erosion. Between Dagshai and Subathu, these beds are 2,000 feet thick.

Kasaulis

The Kasauli beds differ from the Dagshais in their general lack of purple colour, and in the predominance of sandstone over shale. The shales are less cindery, and greener. They may be either soft, or hardened to clay-slate. Some contain fragments of palm leaves. The sandstones are massive and generally hard.

Nahans

The Nahans show the same regular alternation of sandstone and shale. The sandstones are massive, soft, green-brown in colour, rudely jointed, and coarsely current-bedded. The clays are chocolate and green in colour, and usually concretionary. Both sandstones and clays are streaked with purple.

* * * * *

Dolerites and Allied rocks

Basic hypabyssal rocks have been found in the following formations:

Jaunsars, Infra-Krol, the A, B, D divisions of the Krol limestones, the Subathus and the Nahans.

The dolerites in the pre-Tertiary rocks are occasionally found fresh and not sheared, but more usually are sheared and may even be converted to chlorite-schists. Most of the specimens are green with patches of white representing saussuritised feldspars.

The basic rocks in the Tertiaries are now greenstones. Shearing, and perhaps hydrothermal action, has been intense. No schists have been produced; instead there are innumerable irregular slip surfaces, so closely packed that it is impossible to obtain a good hand-specimen.

* * * * *

DIFFICULTIES OF CLASSIFICATION

A certain experience of the rocks of the Krol Belt has impressed upon one the fact of striking similarities between rocks of different series. The series as given in the table of formations, and as shown on the map, represent the outcome of weighing-out evidence of similarity and dissimilarity, and of studying sections in localities where the rocks have not been excessively disturbed. Once established, either in the text or on the map, the dissimilarities which led to the ultimate differentiation of the rocks tend, perhaps, to obscure the similarities which also exist. Given more or less complete sections, or given continuity along the strike, there is generally little difficulty in adjudicating the importance of similarity or dissimilarity, even when characteristic rock groups are missing, since the position of the rocks with reference to other known stages, about which there is no question as to which series they belong, by itself yields information. In many places, however, thrusting and folding have been so severe that single stages occur in abnormal positions, and die out without anywhere showing, in their small outcrops, characteristic rock facies of diagnostic value. In such circumstances, neither lithology nor position can assist in determining to which group they belong, and their assignation may be extremely difficult. As examples may be mentioned:

(1) The outcrops along the Giri river from Tikari to the confluence with the Jagar ka Khala, which are mapped as Infra-Krol.
(2) The outcrops, 14 miles in length, from Chiyan to beyond Sataun, mapped as Infra-Krol.
(3) The outcrops round Rajana, mapped as Lower Tal.
(4) The outcrops between heights 2,820 and 2,795 feet on the Giri river, where an arbitrary line has been drawn between the Simla slates and the Jaunsars.

Characteristic facies of diagnostic value

Simla slates – Chhaosa slates; Domehr slates; striking at Domehr, but untypical at Kandaghat.

Jaunsars – Purple conglomerates with 'eggs' of vein-quartz; very inconsistent. Crinkled slate-blue phyllite, strongly interbanded with thin phyllite quartzite. Massive, blue, crystalline, sandy limestone (Bansa limestone),

Blaini – In its normal position between Simla slates or Jaunsars, and Infra Krol, is very striking; but see Mandhali question.

Infra-Krol – No single unique characteristic

Krol limestone – *Krol D:* some cherty limestone; of diagnostic value only in differentiating between the various Krol limestones;

Krol E: cream white porcellaneous limestones;

The sub-stages do not often occur singly and completely isolated in foreign rocks. Combination of characters and relative position is of great value.

Tals – Nature of bedding in Lower Tals and microscopic characters (microcline) in upper Tals.

Subathus – Olive-green and purple, oily looking shales, with cuboidal jointing.

* * * * *

REPETITION, CURRENT-BEDDING AND INVERSION

It has been seen that the resemblance between facies members in what have ultimately been regarded as different rock series is often striking. In the field it has led to uncertainty in mapping, since similarity might be due to two causes:

(1) Repetition in the course of time of similar sedimentary conditions; the existence, therefore, of distinct sedimentary series.

(2) Repetition of a single series by tectonic movements-
  - (a) by thrusting;
  - (b) by overfolding, with inversion.

When the beds which are now regarded as Upper and Lower Tals were first encountered in the Nigali syncline, I took them to be respectively Jaunsars and Infra-Krols. On this interpretation, supposed Jaunsars overlay supposed Infra-Krols and these, in turn, rested on Krol limestones. Close by, known Jaunsars had been found normally to underlie known Infra-Krols (with the Blaini intervening). The thought, in fact the hope, presented itself that a great overfold had been found, causing the repetition, in inverted order, of Jaunsars and Infra-Krols above the Krol limestones.

Correct succession	*Possible succession*
Upper Tals	Inverted Jaunsars
Lower Tals	Inverted Infra-Krols
Krol limestones	Krol limestones
Infra-Krols	Infra-Krols
Blaini	Blaini
Jaunsars	Jaunsars

Current-bedding

To decide if this were so, the current-bedding surfaces of the quartzites which are now regarded as Upper Tals, and of those in the true Jaunsars, were examined. The principle involved is that in undisturbed areas, the current-bedding surfaces face concavely upwards. If cases are found in which the current-bedding surfaces face convexly upwards, it may be assumed that the beds in question are inverted.

* * * * *

When applied to the Tal quartzites of the Nigali syncline (Plate 7) and to the Jaunsars of the cliffs overlooking the Tons river, it was found that both sets of quartzites were in a normal, uninverted condition. It was impossible, therefore, to suppose that the Upper and Lower Tals were inverted Jaunsars and Infra-Krols in the middle limb of a recumbent fold. The alternative explanations were either that thrusts had brought uninverted Jaunsars and Infra-Krols on to Krols, or that the rocks in question belonged to a later series than the Krols, in normal order above them. A wider experience of the rocks above the Krols showed that the two divisions graded into each other, by the increase upwards in number of quartzitic bands. The change in lithology is so gradual that it was impossible to map the boundary between the two divisions within a range smaller than 200 feet.

Further, no sign of Blaini beds has ever been seen between the two divisions. The Blaini is, it is true, sometimes eliminated from the normal Jaunsar-Blaini-Infra-Krol succession, but never extensively so. If thrusts had brought Infra-Krols over Krol limestones, and Jaunsars over both series, it would be very surprising that the Blaini, which normally intervenes, should never be seen incorporated in the thrust masses.

These facts, together with the lithological differences enumerated earlier, seem sufficient to warrant the belief that the beds overlying the Krol limestones belong to a later series. The occurrence in Garhwal of Tal quartzites overlying massive limestones, similar to the Upper Krol limestones, is enough to clinch the matter, because in Garhwal there is not the same difficulty of the existence of an underlying, highly quartzitic series with which the Tal series could be confused.

The disposition of current-bedding has further shown that the Simla slates in the Gambhar river to the south-west of Simla, the Jaunsars north of the Giri river (east of Dadahu), and the Jaunsars north of Kando, are in a normal, uninverted order.

Inversions in which strata have been folded through 120°, are fairly common, especially along the north face of Kamli Dhar. These have come to light as a result of mapping, since the stages concerned do not contain current-bedded sandstones. Further, minor flat folds are often seen from a distance in the limestone bands of the Krol D stage, but these occur on a small scale in rocks, which, taken as a unit, are in normal order (Plate 5).

As applied to the Krol Belt, the examination of current-bedding has been of most use in deciding whether or not the great outcrops of quartzites of the Tal, Jaunsar and Simla series have been completely inverted in large-scale recumbent folds.

The general structure of the Krol Belt is clearly one of uninverted, or only slightly overturned, sequences, which have been brought forward by thrusts, and not of recumbent folds.

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ORIGINAL SPATIAL RELATIONSHIPS BETWEEN DIFFERENT SERIES

Simla Slates, Jaunsars, Blaini (? Mandhali)

The sequence given by Pilgrim and West was in descending order: Blaini, Simla slates, Jaunsars.

This was based on two main considerations:

(1) The Blaini was found most usually to overlie Simla slates
(2) The Jaunsars appeared to be more metamorphosed than the Simla slates and were therefore regarded as older than them (Pilgrim and West, *op.cit.*, p.21)

Between the Gambhar and Giri rivers, Jaunsars had been found to overlie Simla slates, usually with supposed Blaini intervening. The explanation given was that Jaunsars had been thrust into an abnormal position upon the Simla slates with their capping of Blaini. Any Infra-Krol slates and Krol limestones that might originally have overlain this Blaini, were thought to have been planed off from the Blaini and pushed south over the present belt of Krol rocks.

Subsequently it has been found that over wide stretches of the Krol Belt, particularly in the east Infra-Krol and Blaini lay directly upon Jaunsars. There was also evidence that the Jaunsars which overlay the Simla slates of 6,474 feet hill and Kandaghat, without the intervening boulder bed and limestone, might in reality be in a normal stratigraphical order upon them.1 It was therefore suggested that the correct sequence might be Blaini : Jaunsars : Simla slates.

The greater general degree of metamorphism shown by the Jaunsars may be regarded as an accident of their lithological composition and of their position with reference to zones of greater stress.

This question is more complicated than was supposed in 1928. I had tended to ignore the usual occurrence of rocks resembling the Blaini between the Jaunsars and the Simla slates.

* * * * *

Blaini on Jaunsars and Simla Slates

The nature of the relation of the Blaini to the rocks which underlie it is complex. The following is a list of the main types of occurrence of Blaini which occur *in normal succession below Infra-Krol and Krol*:

(1) *Blaini on slates similar to Infra-Krol slates:*

- (a) Middle reaches of the Blaini river
- (b) Spurs northeast and southeast of hill 4,960 feet.
- (c) Kawal Khal, below height 3,241 feet.
- (d) Spurs between Jamthali and the Giri river.

  These slates should properly be mapped as Blaini but it would be impossible to separate them from the Infra-Krol in places where the Blaini boulder beds or limestones are missing.

(2) *Blaini on Simla slates:*

- (a) One mile east of Solon.
- (b) In the Kawal Kahl at Masria and Mareog.

(3) *Blaini on Jaunsars:*

- (a) Along the lower reaches of the Blaini river.
- (b) Between Rerli and Shiwa Kalan, a distance of 22 miles.

By regarding the slates of Infra-Krol type, which are associated with the Blaini, as belonging to the Blaini, no problem is involved as to their relation with the boulder beds and limestones. They may be considered simply as local intercalations of varved sediments below and between tillites.

The problem becomes one of understanding the nature of the occurrence of Blaini both on Simla slates and on Jaunsars.

Bedding discordance has nowhere been seen between the Blaini and the underlying rocks. The unconformity that exists, even though regionally considerable, is not of orogenic violence.

The Blaini boulder beds are made up almost entirely of slates and quartzites derived from the Simla slates and Jaunsars, and, clearly indicate extensive erosion of these formations.

Unconformity

Proof of unconformity has come to light as a result of mapping the great syncline of Tals, Krol limestones, Infra-Krols and Blaini which runs from Giltu ka Tibba (hill 7,005 feet) to Randera Tibba (hill 6,458 feet). The Blaini on the northern limb of this syncline lies on a great thickness of Jaunsars, of the order of 10,000 feet. The Blaini on the southern limb of the syncline rests on at most 2,000 feet (in both cases neglecting the Mandhalis). Some of this discrepant thickness is due to thrusts, since, in the eastern part of the southern limb of the syncline, Tals rest direct on Jaunsars, with Krols, Infra-Krols and Blaini all cut out. In the west, however, the whole Tal-Blaini succession is present, only slightly complicated by minor thrusts, and the Blaini still rests on a diminished thickness of the Jaunsars. It is the Chandpur stage that is almost completely eliminated.

Since the region from which the Chandpur stage was eroded appears to coincide with the southern limb of the present Tal-Blaini syncline, it follows that the original axis of uplift responsible for the erosion, must have been or less parallel to this limb. This implies that the axis had a Himalayan trend, in contrast to an Aravalli trend. Had there been an Aravalli NE-SW axis, it would have been impossible for the Jaunsars to be both attenuated by erosion, and fully preserved from erosion, along this single alignment.

In places where the Blaini rests directly on Simla slates, it may be assumed that the Jaunsars had been completely eroded away previous to the deposition of the Blaini. Such erosion must have been local, because, while Blaini rests on Simla slates along parts of the Kawai Khal, and near Solon, it is found on Jaunsars again further to the north-west, along the lower reaches of the Blaini valley. Further, across the Ashmi-Giri rivers to the north-east of Solon and the Kawai Khal, Jaunsars are found in a continuous and wide outcrop which runs without a break from the Gambhar river to south of Badgala.

Accepting that the Mandhalis occur normally between the Jaunsars and the Simla slates, it follows that an unconformity which brings Blaini, Infra-Krols and Krol limestones across the Jaunsars on to the Simla slates, must bring Blaini locally in contact with the Mandhalis. Such contact of Blaini with Mandhalis would lead to great difficulty of mapping, owing to the similarity between the two divisions. It is believed that this *a priori* case may be illustrated by outcrops between longitudes 77°40' and 77°49', along latitude 30°33'.

The position may be summarized as follows, accepting here the viewpoint taken up later in the discussion on the Mandhalis.

(1) There is at least a possibility that there are two distinct series of boulder beds and limestones, called Mandhalis and Blaini, in the following sequence:
 Infra-Krols,
 Blaini
 Jaunsars,
 Mandhalis,
 Simla slates.

(2) The true Blaini, with overlying Infra-Krol slates and Krol limestones, rests with unconformity upon both the Jaunsars and the Simla slates. This unconformity is great, but in no section has bedding discordance been seen. The folds that led to erosion of the Jaunsars must have been gentle. It is probable that these folds had a Himalayan trend.

Blaini and Infra-Krol

As previously stated, 'slates of Infra-Krol type are often intimately associated with the Blaini limestones and boulder beds.

In the simplest case, Blaini limestone appears to pass up gradually, by increase of shale matter, into pink, greenish, and finally black shales of the Infra-Krols.

The abundant bands of brown-weathering, calcareous, gritty clay-slate which occur in the Infra-Krol may be considered to be small-scale repetitions of the Blaini limestone throughout the lower part of the Infra- Krol succession.

Infra-Krol, Krol Sandstone and Krol Limestones

The typical relations of the Infra-Krol to the succeeding stages are seen round Solon. Here the dark or black shales of the Infra-Krols pass up through a transition zone of 100 feet or so to Krol sandstone, and this in turn to more dark shales, before the green calcareous shales and thin-bedded limestones of the Krol A stage set in. Viewed from a distance, as towards the northwest ridges of Rajgarh Hill from Khanog Hill, the change from the black Infra-Krol shales to pale Krol sandstone appears abrupt. When examined at close quarters, the change is found to be gradual.

The Krol sandstone has not been seen east of the western slopes of hill 3,619 feet, nor along the greater part of the northeast flank of the Krol Belt between the Kawai Khal and the Jagar ka Khala. It is only two feet thick in the Giri river half a mile north of Dadahu.

When the sandstone is absent, passage from Infra-Krols to Krol A limestones is shown by a gradual increase in the number of shaly limestone bands. Plate 3, Fig.1, shows the base of the Krol A limestones, where black shales alternate with shaly limestones and calcareous shales.

On account of the varied thickness of the Krol sandstone, Oldham (*Rec. Geol. Surv. India*, v.21, p.138, 1888) and Pilgrim and West (*op. cit.*, p.134) believed that the Krol limestones were unconformable to the Krol sandstone.

This view in my opinion has little justification. Part of Oldham's argument in any case fails, because his objection that the adjacent quartzites in his Carbonaceous series are of far greater thickness than the Krol sandstone with which they were correlated, therefore indicating that considerable erosion of the Krol sandstone had taken place, no longer stands now that those quartzites have been found to belong to a much older Jutogh series.

The intimate interbanding of shale and sandstone and the gradation from Infra-Krol, through Krol sandstone to Krol A, do not warrant the belief that any break of sedimentary conditions occurred. A truer picture is obtained by regarding the Krol sandstone as a local sandy intercalation amongst the shales and shaly limestones.

If there be unconformity at all, it should be between the Krol sandstone and the Infra-Krols, since discs of Infra-Krol shale are often found in the sandstone, and in one case a wash-out was observed at the top of the Infra-Krols. These phenomena in my opinion prove little except that currents churned up some of the recently deposited black muds.

Medlicott saw no reason for supposing the existence of an unconformity. With that view I am in agreement.

Krol D

The existence in the Krol D stage of conglomerates and pebbly sandstones, together with limestone breccias, suggests a slight break in conditions of sedimentation. The break cannot have been important, because nowhere is there any evidence of erosion of the underlying stages of the Krols. The exact relations of these conglomerates to their contemporaneously deposited limestones is obscure. Folding near Mangarh has obliterated all the original sedimentary relationships.

Krol Limestones and Tals

Over the greater part of the synclinal basins in which the Tals occur, Lower Tals rest on Upper Krol limestones.

South of Guma peak, Upper Krol limestones have been thrust directly on to Upper Tals. This is a tectonic relation.

From south of Khur to Chiyanra, the lower Tals rest on Infra-Krols. This is due probably to a combination of original unconformable overlap of Tals across the stages of the Krol limestones, and of later tectonic elimination. Middlemiss has shown that a slight unconformity exists between the Tal beds and the underlying Massive (Krol) Limestone of Garhwal.

No Tals have been seen on the Krol E limestones southeast of the Giri river, though Subathus occur there. Tals were probably never deposited southwest of the Giri river, since, in those places where they are now found on Krols, they appear to have exerted a protective influence on the underlying limestones and shales, preventing them from folding intricately amongst themselves. It is probable that the strongly folded Krol limestones southeast of the Giri formed more elevated land during the period of Tal deposition, but were submerged below the sea at the end of the Mesozoic.

Tals and Subathus

No case has been seen of Subathus resting on Tal beds. This is in contrast to the Garhwal area, where Middlemiss found the two series to be commonly associated.

Krol Limestones and Subathus

Between Janot and Sainbar Hill, there is found a collection of black, brown, olive-green and purple, splintery shales, dirty pebbly quartzites and sandstones, and lenticular, blue, shelly limestones which are wedged in the Krol D and E limestones.

At the hill one mile west and southwest of Bongli (hill 6,048 feet on the two-inch map-sheet 313 NE), the interbedding of lenticular shelly limestones and brown and green shales with the Krol E rocks is so parallel that the rocks were taken to be authentic fossiliferous Krols. The occurrence of characteristic purple and olive-green cuboidal shales with similar limestones and brown shales at Bagar is strong indication, however, that the whole lot were Subathu.

The fossils are rare and very badly preserved, They are all broken, and, like those in the Subathus, they give the impression of having been mostly oysters that had beep current- or wave-tossed on shelly marine banks.

The Floor of the Nummulitic Sea

In Garhwal, Nummunlites rest on Mesozoic Tal beds. In Sirmur State, they are seen on Krol limestones. At Subathu and at Dabra, they occur on Simla slates.

It is clear that a considerable part of the Himalayan area must have been beneath the sea during the early Tertiary, and that there must have been extensive previous erosion to allow for the occurrence of Nummulites on rock series of such different ages.

* * * * *

METAMORPHISM

General

From the foregoing lithological descriptions, it is seen that the rocks of the Krol belt show the following grades of alteration:

> Shales, slates, clay-slates, phylliltes, schistose phyllites; sandstones, quartzites, quartz-schists; limestones, recrystallised limestones; dolerites, greenstones.

The whole series is typically one formed under *epi*-conditions. Mica-schists, with index minerals of higher grade, quartzites that have been recrystallised to a new mosaic with complete loss of clastic structures, limestones with calc-silicate minerals, and hornblende-schists, have nowhere been found.

The argillaceous rocs have not been metamorphosed sufficiently for the microscope to be of much value in determination. Most of the slates and phyllites, which is hand-specimen are characteristic, are not particularly distinctive in thin sections. The differences amongst these argillaceous rocks are on the whole megascopic, rather than microscopic.

Amongst the argillaceous rocks, newly-formed quartz, sericite and chlorite are fairly universal. Blasto-biotite has not been seen.

Some of the quartz-schists of the Jaunsars are sufficiently metamorphosed for the clastic structure to be almost obliterated. Mosaics of recrystallised quartz are frequently found, but never completely throughout the body of the rock.

In the limestones may been seen idioblasts of calcite. Many of the Upper Krol limestones have been completely recrystallised, and infested with sigmoidal veins of calcite (43-758), but, even when siliceous impurities are present, there has been no sign of the formation of calc-silicate minerals. A striking feature of most of the limestones is the recrystallisation side by side of quartz and carbonate, and the frequent replacement of quartz by carbonate. It is clear that stress has acted on these rocks without the influence of any considerable temperature, since wollastonite is not formed.

The dolerites are readily susceptible to change, but, in spite of uralitisation and saussuritisation, they can always be recognized as basic hypabyssal intrusives.

*   *   *   *   *

Distribution in Space

Regarding the rocks of the Krol Belt in relation to neighbouring zones, the following divisions may be made out:

1) *Schist zone:* to the northeast; showing phyllites, schists often with index minerals; recrystallised quartzites; *epi* and *meso*-conditions.
2) *Krol Belt:* great variation in character of metamorphism; typically of epi-type.
3) *Zone of Tertiary rocks:* to the southwest; generally non-metamorphosed, but locally indistinguishable from epi-type rocks of the Krol belt

This division into three zones is not absolute. Rocks of epi-type occur in all three zones. Further, along the Krol Belt, there is longitudinal, or strike, variation in intensity of metamorphism. The Infra-Krol and Krol A stages become more altered towards the southeast.

Discussion

The metamorphic condition of these rocks is of interest in two connections, firstly, the bearing it has on correlations, secondly, the question of its cause.

One of the arguments used by Pilgrim and West in connection with abolishing the original correlation made by Medlicott of the rocks of Simla with those at Solon was based on the different metamorphic condition of the rocks of the two areas.

Referring to the Simla Slates, Blaini, Infra-Krol and Krol limestones, they state on page 6:

> 'It is noteworthy fact that none of the rocks so far mentioned is truly metamorphic. Not only are there no secondary minerals developed, but further, the Simla, Blaini and Infra-Krol series, though containing rocks often resembling slates, have no slaty cleavage and we have found no evidence of any planes of crushing which do not coincide with the planes of bedding; neither is there any crystalline structure or evidence of flow in the limestones; while the Krol sandstone is obviously not a metamorphic quartzite.'

They intended to emphasize the different grades of metamorphism between the Simla and Solon rocks, concluding (1) that the more metamorphosed rocks were the older; (2) that juxtaposition of rocks of different degrees of metamorphism must be accounted for by thrusts, that had brought rocks of different ages into abnormal association.

Had one's attention been confined to the generally unaltered rocks of the Tertiary zone, or, as that of Pilgrim and West, to the schist zone, the occasional presence of more or of less altered rocks would not have upset the broad impression of constancy in character gained from these areas as a whole. Occasional traverses from either of these areas across adjacent zones would doubtless suggest a contrast sufficient to permit the belief in differences in kind between them. Work along the Krol Belt has shown, however, its transitional character to the zones that border it, and there has proved to be so far less conviction as to the rigidity of distinction, both corrective and metamorphic, of the rocks of the three zones.

As seen from the general statement made above, the criteria assumed in the quotation just given are not valid. Viewing the rocks of the Krol Belt as a whole, there is in many places an approximation to the metamorphic grade of a considerable quantity of the rocks found in the area described by Pilgrim and West (It should be expressly pointed out that the criteria they assumed were valid for the few sections in the Krol Belt that they visited. That it has been found that these criteria do not hold, is solely the result of working in detail over a larger area than they were able to visit).

The contrast between the garnet and staurolite-schists of the Jutoghs with the shales of the Infra-Krol near Solon is undeniably great, but it must be recognized that this is the extreme contrast. Elsewhere the rocks of the Krol Belt become more metamorphosed, while the Jutoghs, away from the influence of the Chor granite, tend to lose their index minerals. The Jaunsars of the Krol Belt and the Chails of the area mapped by Pilgrim and West are in some places practically indistinguishable, as on Rigana Dhar and at Tikar.

It is not intended to imply that a correlation between the rocks at Simla and Solon should be reverted to, or that thrust-planes are not present. Pilgrim and West found definite structural features, indicative of the existence of thrust-planes, particularly at the base of the Chails. In the Deoban area, Mr. West has recently found mylonites below the Chail thrust (*Rec. Geol. Surv. India*, v.45, p.30, 1931). Moreover, these authors obtained evidence of elimination of beds by overlap, which coincided with these structural features,

It is hoped however, to indicate that the differences between the rocks of the Krol Belt and of the adjacent northeastern area are not absolute, and that the question of age cannot satisfactorily be told by considering solely their metamorphic aspect.

* * * * *

Position and Age of Granites

Granites in cores of synclines

It is a singular feature that the Dudatoli and Lansdowne granites occur synclinally at the top of a synclinal succession of slates and schists. The same relationship may obtain with the Chor granite. It is not at all improbable that, since the great series of Jutogh rocks at Simla occurs in synclinal form, they may have originally been capped by a continuation of the Chor granite, and may have owed much of their metamorphism to a granite which has now been removed. Oldham (*Rec. Geol. Surv. India*, v.20, p.148, 1887) postulated this, but the view has since been discarded (*Mem. Geol. Surv. India*, v.53, p.8, 1928), on the grounds that an intrusive mass is not capable of producing widespread metamorphic effects, such as are found in the Jutoghs. The occurrence of these gneissose granites in the cores of synclines certainly demands some connection of the granite with the general processes of regional metamorphism. It is probably nearer the truth to picture both the intrusion of the granites (or their self-generation, 'in-born', so to speak, in the cores of the folds – this is not the place to enter into a discussion on the formations of granites. It must suffice to say that the appearances in the field do indeed suggest that simple intrusion from some totally foreign source is not a complete explanation of some of these occurrences of granite. Compare Middlemiss, *Rec. Geol. Surv. India*, v.20, p.140, 1887) and the general regional metamorphism as part effects of a wider cause.

Age of Granites

I have given reasons elsewhere (*Rec. Geol. Surv. India*, v.66, pp.461-471, 1933) for believing that some of the gneissic granites of the outer Himalaya were Carboniferous or slightly older, and were connected with tectonic activity along the Aravalli axis. Further, since the Hazara granite intrudes the Dogra slates, which are Precambrian and Cambrian in age, it is permissible to regard this granite as post-Cambrian. The general similarity in character and manner of occurrence of the Hazara, Chor, Lansdowne and Dudatoli granites suggests that their correlation is permissible, and that they were intruded during the Palaeozoic era. The evidence, which is not absolute, is discussed in the paper quoted.

Difficulties arise if an attempt is made to narrow down the time limit still further. The Jaunsar arkoses indicate the presence of an earlier granite, but the Jaunsars are affected by the same Aravalli orientation that is seen in the Lansdowne granite. This orientation in the Lansdowne granite may presumably be connected with its intrusion tectonics. It is tempting, therefore, to regard the intrusion of the granite as immediately post-Jaunsar (? Post-Devonian) in age, since both granite and Jaunsars are affected along the same tectonic directions. As opposed to this reasoning, it is possible to assume rejuvenation of activity along the Aravalli axis, and to object that similarity of orientation is not proof of tectonic contemporaneity.

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MANDHALIS

Significance of Boulder Beds

The Mandhali beds have offered a problem of great difficulty.

* * * * *

There are three distinct rock facies which have to be considered in a discussion of the Mandhalis:

Limestones
Pebble beds and Conglomerates
Boulder beds

Most prominence has been given to the boulder beds, the presence of which has led to the correlation of the Mandhalis with the Blaini. The associated limestones, pebble beds and conglomerates have been variously grouped with the Mandhalis, Jaunsars and Chails according to the impressions gained from single exposures, where one or other or all of the above facies are prominent.

It is true that the boulder beds are striking rocks which at once attract the eye. Moreover, the origin of these boulder beds, whether glacial, volcanic or otherwise, is certainly one that implies somewhat abnormal conditions of sedimentation. In proportion to this abnormality of origin, it may be thought that the causal factors would be rarer. Consequently, a series of boulder beds, with an abnormal manner of origin, might be considered to be probably contemporaneous.

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In the Hazara area, Mr. Wadia has found a conglomerate, 120 feet thick, which occurs above the Dogra slates (=Simla slates) and at the base of a series of phyllites and quartzites, called the Tanols (*Rec. Geol. Surv. India*, v.65, pp.204-206, 1932). At the top of the Tanols near Talhatta, is another conglomerate, possibly equivalent to the Blaini.

The following correlation is suggested:

Hazara	*Simla-Chakrata hills*
Talhatta conglomerate	Blaini
Tanols	Nagthat and Chandpur stages
Conglomerate boulder bed	Mandhali stage
Dogra slates	Morar-Chakrata beds (Simla slates)

Boulder beds may be formed under very varied conditions. Middlemiss assigned a volcanic origin to the breccia in Garhwal. This is exactly similar in appearance to the Blaini boulder bed, which has been regarded as glacial. Later, when working in Kashmir, he was unable to decide whether the Agglomeratic Slate was of glacial or of volcanic origin.

* * * * *

I can offer no absolute proof that the view previously held, namely, that the boulder beds are glacial and all Blaini, is erroneous, because the sections now exposed are disturbed, and by themselves do not permit of certainty. But this former view has led to difficulties.

Consequences of Mandhali-Blaini Correlation

If the correlation of the Mandhalis with the Blaini is accepted, two difficulties are at once evident:

(1) The Mandhalis south of Chakrata appear everywhere to dip synclinally below the Jaunsars, and are, therefore, on this supposition, overlain by rocks older than themselves. The whole syncline of Jaunsars, normal Blaini, Infra-Krols, Krol limestones and Tals must rest as a thrust mass, or *nappe*, upon the Mandhalis.

(2) There must be two totally distinct facies of the Blaini now in close proximity:
   (a) the thin boulder bed and limestone, which runs from Chandpur peak to Shiwa Kalan;
   (b) the extremely complex series of beds called Mandhali.

Reasons against Mandhali-Blaini Correlation

There is no sign of the thrust plane that would be required to separate the Mandhalis from the overlying Chandpur beds, if the Mandhalis and the Blaini are regarded as equivalent. The quartzite associated with the Bansa limestone is, it is true, often markedly schistose, but not more so than many of the quartzites in the Mandhalis themselves and in the Nagthat stage. Thrust planes are admittedly often very difficult to locate, since they may leave little trace of their action in the rocks brought into abnormal juxtaposition. It seems irrational, however, to assume a thrust solely because of a lithological change from a series of limestones, phyllites, quartzites and boulder beds up to a series of banded quartzite and phyllites, with tuff beds, unless the ages of these contrasted rocks are known. It has just been argued that boulder beds are a common feature in the Himalaya and that age cannot be told from their occurrence.

The associations of the Mandhali and Blaini rocks may be summarised as follows:

(1) Mandhali - Characterised by a complex association of dark limestones, often sandy, and often marmorised, phyllites, grits, boulder beds, conglomerates, schistose quartzites, apparently underlying the Chandpur stage. Boulder beds full of limestone fragments and limestone of in situ growth.

(2) Blaini-Pink siliceous limestone, not sandy, associated with boulder bed in which limestone fragments are very rare. The limestone and boulder bed, if both present, are always together. Overlies the Nagthat beds, which in turn rest on the Chandpur stage.

This Blaini boulder bed, with its pink siliceous limestone, is always overlain by Infra-Krol and Krol rocks, the three stages forming the only readily recognisable sequence in the whole of the Krol Belt. East of longitude 77°30', the Tal beds form an additional and also distinctive series above the Krol limestones, the sequence eastwards invariably being Blaini: Infra-Krol: Krol: Tal.

This Blaini: Infra-Krol: Krol: Tal succession is 'normal' in the sense that it is almost certain that the stages in it are in their original order of deposition, and are unaffected by thrusts of any regional magnitude. It may be taken as the standard of reference for the Krol Belt. The relationships between the various stages in it are constant, and their mapping, apart from physical exertion, is always easy.

Contrasted with this orderly sequence, of which the Blaini is the invariable basal member, is the disorder that prevails amongst the Mandhali rocks, and the fact that the Mandhalis are overlain by a group of rocks totally distinct from the Infra-Krol to Tal succession.

* * * * *

Field Relations to Northwest

At the time of mapping the outcrops north of the Giri river, I had not seen the Mandhalis. The sections showed that a series of thin-bedded limestones and dark slates, with some soft green slates, passed up to the Bansa limestone and then into Jaunsars of Nagthat type. Boulder beds were found sporadically at the base of the succession. The occurrence of limestones did not seem anomalous, since they had been seen elsewhere in the Jaunsars, and accordingly the whole sequence was regarded as Jaunsar. The boulder beds were mapped as Blaini, and were considered to have been thrust over by the Jaunsars. Later, on acquaintance with the Mandhalis, it was realized that the beds low down in sections were probably Mandhali.

CONCLUSIONS

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Mr. West has found the Mandhalis of northern Chakrata to grade downwards into Deoban limestone, fragments of which they contain (*Rec. Geol. Surv. India*, v.66, pp.128-129, 1932). This same Deoban limestone rests on the Jaunsar series, while, in the Beshair and Gutu Gads, Jaunsars are found as well above the Deoban limestone.

The occurrence of Deoban limestone normally below the Mandhalis does not affect the argument given above, because the Mandhalis south of Chakrata are probably thrust over the Morar-Chakrata beds (Simla slates). If the interpretation given in this paper be correct, the position of Jaunsars below the Deoban limestone must be due to a thrust.

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Conclusions and Table of Correlation

Adopting the correlation of the Upper Krol limestone with the Massive limestone of Garhwal, the Krol rocks are seen to extend from the Sutlej river, near Bilaspur, to Gungti Hill (29°45':78°55') in Garhwal, a distance of some 175 miles. The limestones at Naini Tal are most probably Krol, which would bring the total length of outcrop up to 208 miles (It was stated in *Mem. Geol. Surv. India*, v.53, p.8, 1928, that the Krol limestone extends to the northwest as far as the Ravi river. This must be an accidental error, occasioned by the title of Medlicott's memoir. Between Bilaspur and the Ravi river, the rocks bordering the Tertiaries are older than Krol. At Joginder Nagar (32°0':76°47'), schists, phyllites and quartzites, together with intrusive porphyritic granite, are thrust over the Tertiaries. These are either Jutogh, Chail or Jaunsar. The Krol limestones are definitely absent. The equivalent of the Krol rocks is probably not seen until Kashmir is reached).

TECTONICS

The most cursory examination of the rocks of the Krol Belt shows their extreme complexity of structure. This complexity is seen in single exposures as well as in broad views. It becomes evident as a result of continued mapping, and may be seen at a glance in a rock-slice.

In places there is such chaos that no rational explanation is possible. Objection may be made to the adjective 'rational'. It may be maintained that with fuller knowledge, or with better exposures in the jungle-covered lower slopes of the hills, the chaos might prove to be apparent, and might resolve itself into structures more readily explicable. To some extent this objection must always hold, but it is less readily applied in describing orogenic areas of the type seen in the Krol Belt. Structure is everywhere seen by eye to be so chaotically disposed that the fear is that the map, however odd, does not adequately show it. For certain tracts bordering the thrust-planes, the only 'rational' explanation is one that does not attempt to simplify at the expense of structure; in favour of readily understandable sections. Such tracts are, therefore, difficult to represent on the map, partly because the scale demands simplification, partly because of an inherent dislike of leaving suspicious loose ends and oddly juxtaposed colours.

No thrusts or faults have been marked on the one-inch maps, since almost every plane separating rocks of different hardness, and every boundary plane between different stages, is a minor or major thrust. The major features have been traced on a separate quarter-inch map, Plate 8. It is these alone that can be here described.

Thrust-bound Synclines

Broadly speaking, the structure of the Krol Belt is that of two thrust-bound synclines of Krol (in the east, of Krol and Tal) rocks resting on a Jaunsar-Simla slate foundation.

(1) The *Nigali* syncline, named after the magnificent ridge that runs south from near Guma peak. Tal and Krol rocks occur in a wide syncline, with steep northern limb, locally inverted and severed by the Guma thrust. The southern limb is attenuated and founded on the Giri thrust.

(2) The *Krol Hill-Kamli Dhar* syncline. This is more complex, being built up of minor synclines and anticlines, often disposing the Krol limestones in outliers. The following chief individual units are recognizable, in order from northwest to southeast:

- (a) Pachmunda and Krol synclines.
- (b) Khanog and Rajgarh synclines.
- (c) Narag-Dadahu stretch of continuous Krol limestones.
- (d) Kamli Dhar and hill 3,619 feet synclines.
- (e) The easterly continuation of the Kamli Dhar syncline with enclosed Tal rocks; the Korgai syncline.

This complex of synclines is bounded on the northeast by the Giri thrusts, and on the southwest by the Krol thrust.

The two main dislocations along the belt are the Krol and Giri thrusts. The Giri thrust has caused the most havoc, since the hard foundation of Jaunsar and Simla slates has been pushed upon incompetent Krol limestones. It has produced a series of minor thrusts and inversions in the Krol rocks, which are best seen on the northern face of Krol Hill. The thrusts are generally parallel to the limbs of the folds, i.e., parallel to the bedding-planes of the beds making, up these limbs.

The folds do not call for much comment. The Kamli Dhar syncline is markedly inverted through 120°, Krol B, Krol A and Infra-Krol all dipping to the north in inverted sequence. A singular feature of the Krol belt is the nature of the folding within the Krol D stage. The limestone bands twist and overfold amongst shales in an intricate manner, as may be seen in section No.III on Plate 1.

It should be pointed out that the irregular folding of the Krol and Infra-Krol rocks is due to their incompetent nature, and cannot be considered a feature of primary structural significance, peculiar to the particular zone of rocks that intervenes between the belt of Tertiary rocks to the south-west and the phyllite-schist zone to the north-east. The rocks concerned had not been stiffened up by any previous metamorphism at the time of the Tertiary orogenies, and the rapid alternation of limestone and shale would naturally permit intricacy of folding. The major features are thrust-sheets, just as is so in the schist zone to the northeast.

Krol Thrust

The Krol thrust is the 'Main Boundary fault' of earlier writers who have described analogous areas (Middlemiss, *Mem. Geol. Surv. India*, v.24, pp.19,31, 1890). From Solon to Dadahu it brings Infra Krol and Blaini rocks against Subathus, Dagshai and Kasauli stages. Further east, Blaini, Jaunsar and Mandhali rocks override Subathus and eventually come to lie upon Nahans. It marks the approximate boundary between Krol and their foundation rocks (*Himalayan* of Medlicott) and the main belt of the Tertiaries (*sub-Himalayan* of Medlicott).

* * * * *

Recent Survey

The recent survey of the Krol belt has established conclusively the thrust condition of the contact between the pre-Tertiary and Tertiary rocks, though doubt is still left as to the importance of the thrust in the neighbourhood of Solon. Thrusts in that area are certain, but whether the Krol limestones of

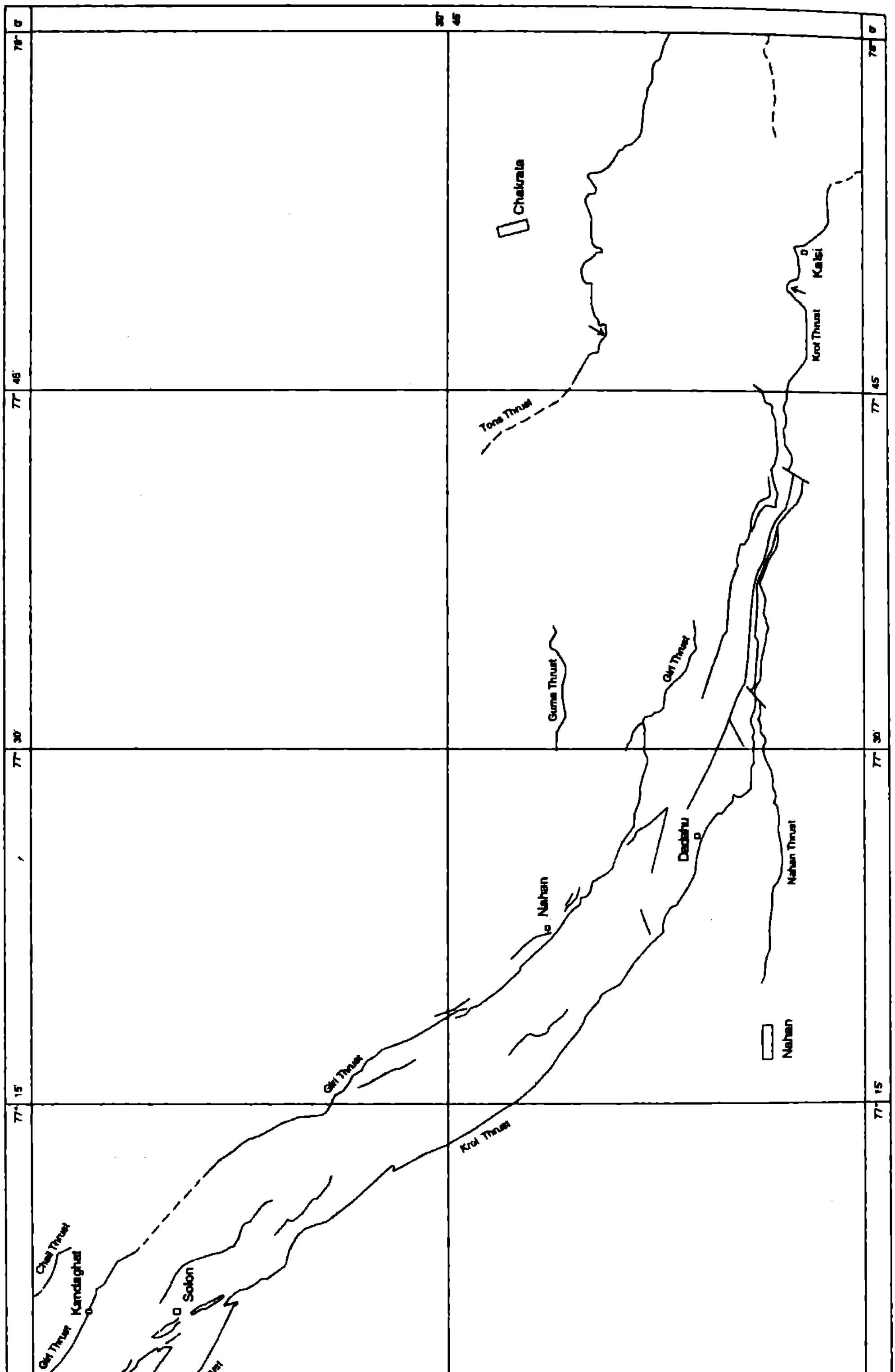

Plate 8a. Map of chief thrusts and faults.

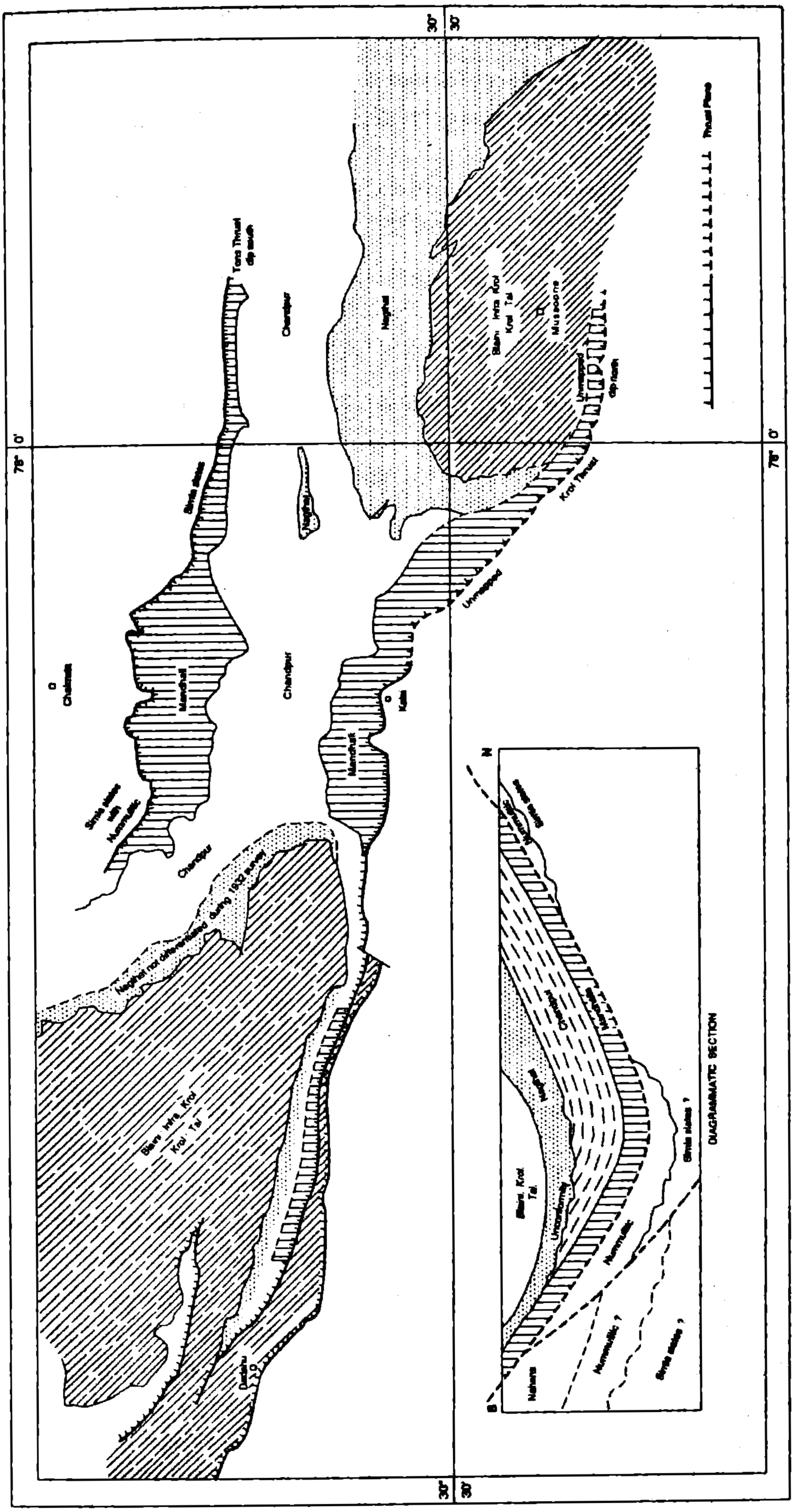

Plate 8b. Sketch map showing relationship between formations.

Pachmunda Hill form an outlier resting on an extensively thrust and folded *nappe* is not definitely proved.

The most convincing places for demonstrating the low angle of contact of pre-Tertiary rocks, with underlying Tertiaries, are the following:

(a) In the Amlawa and Tons river, near Kalsi, where Mandhalis rest gently upon hardened red shales that are either Dagshai, Nahan or Middle Siwalik.1 The dip of the thrust varies from 25 to 35 northwards.
(b) Mapping shows the low angle contact between the Infra-Krols and the Subathus between hill 4,217 feet and Dadahu.
(c) Between height 3,241 feet on the Kawal Khal river and hill 4,633 feet Infra-Krol and Blaini upon Subathus
(d) Between the Blaini river and Bharech col, Infra-Krol and Blaini upon Subathus.

The thrust is not everywhere of the same gentle hade. Northwest of Barog railway station it is even inverted for a short distance, between the motor road and the 5,800 feet contour, hading southwest. For most of the way between Narag and Dadahu, it has a very steep hade to the northeast.

The interpretation of the structure round Solon is one of great difficulty. It will be seen from the map that there is a narrow outcrop of Subathu rocks running up the Blaini river towards Solon, which is flanked by Infra-Krol rocks, and which itself has a core of Simla slates. The relations are shown diagrammatically in Fig.1. The Tertiaries are found to dip both at steep and at gentle angles, beneath the Blaini, Infra-Krol and Krol limestones.

They are known to rest at Subathu upon Simla slates. Across the Blaini valley there is the apparent succession.

Blaini, Infra-Krol and Krol limestones.

. . . .(Krol thrust, inferred).

Subathus.

. . . . (normal superposition).

Simla slates.

It is difficult to suppose that the Subathu rocks had been caught in two parallel and strongly pinched synclines amongst older rocks, because, if this were so, the enclosing older rocks of both limbs of the synclines should be the same. In reality, Simla slates are found in the middle of the Subathus, while Blaini-Infra-Krol flank them on either side. The apparent structure is that of a single anticline pitching to the southeast with the sequence given above. Only by a curious accident could the Subathus have been deposited in a bay, bounded by cliffs of Blaini-Infra-Krol (now represented by Krol and Pachmunda Hills), and with a floor of Simla slates. Under these circumstances it would be possible to imagine that subsequent movement might fold the cliffs of Blaini-Infra-Krol over Subathus, and at the same time, elevate the floor of Simla slates.

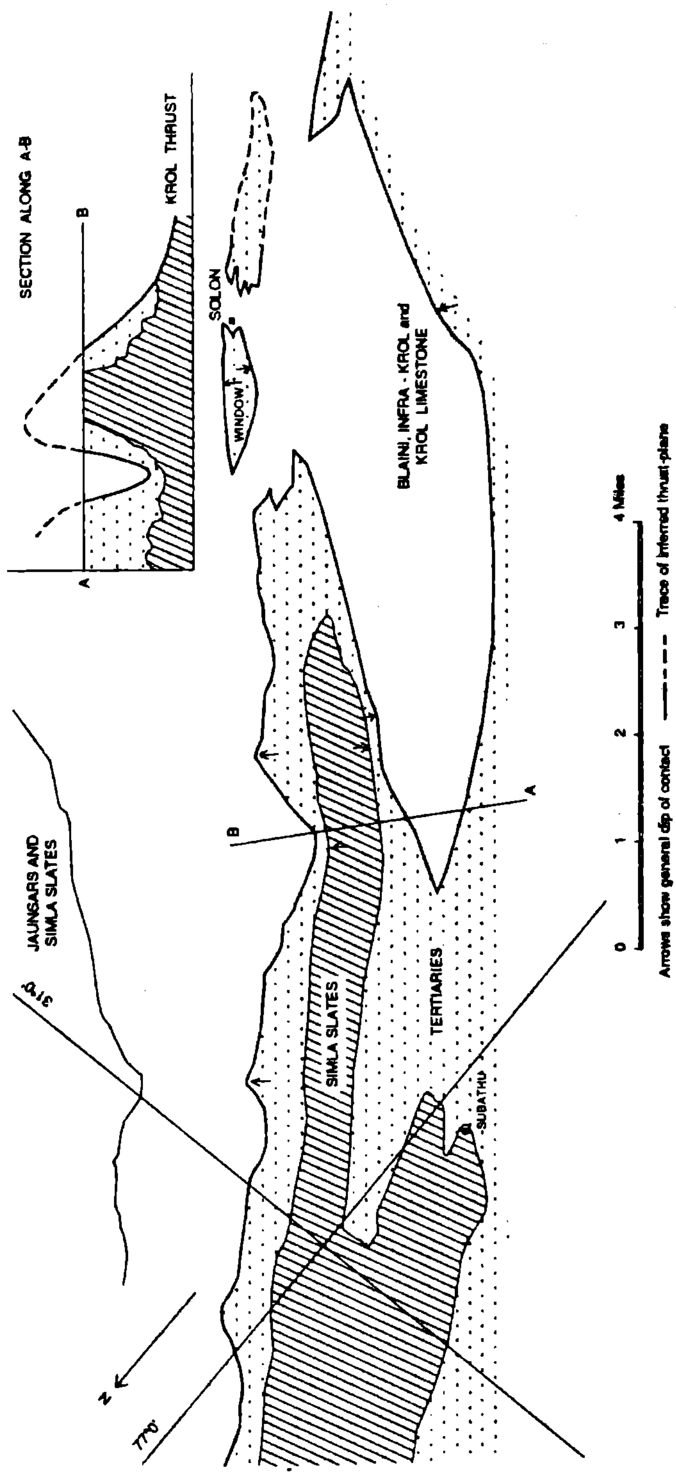

Fig.1. Diagram showing structural relationships northwest of Solon.

This is the view that Medlicott adopted. It implies that overfolding of the cliffs was negligible near Solon, but great to the northwest. It implies also that the cliffs at Pachmunda were folded on the southwest side over to the southwest, and on the northeast side over to the northeast.

There is no doubt about the normal unconformable superposition of Subathus on Simla slates. If the Blaini-Infra-Krol with outliers of Krol limestone, are found to occur above Subathus, the alternative inference may be made that their position is due to thrust faulting, subsequent folding of which has led to the formation of the Pachmunda outlier and has exposed the underlying Subathus in a pitching anticline along the Blaini river and in two *windows* near Solon. The magnitude of translation, on this inference, is great, too great probably for those who look only at the Subathu/Infra-Krol contact near Barog station.

It can hardly be doubted that the Subathu/Blaini/Infra-Krol contact, northeast of the narrow outcrop of Simla slates, is a thrust. The curved nature of the outcrop of the dividing plane, with the V pointing northeast, into the valleys, shows that the plane is gently inclined. Further, the width of the Subathus between the Blaini-Infra-Krol and the Simla slates is very variable, expanding with depth. Neither can it be doubted that the contact seen southeast of Solon, between hill 4,633 feet and height 3,241 feet in the Kawal Khal, is also the trace of a thrust-plane.

It may be held, however, that these two thrusts join up near Solon, and do not swing round Pachmunda Hill, as is here supposed. Support for the objection could be found in the occurrence of the Subathu pisolite near hill 4,819 feet, immediately below the Blaini-Infra-Krol, from which it could be argued that the magnitude of translation could not be great if the original bottom bed of the Subathus is still preserved. This bottom bed also occurs in the Kawal Khal, where there is every reason to believe the thrust to be important. Its occurrence near the 4,819 feet thrust-contact could be regarded as fortuitous.

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Some indication that the Krol thrust is more than a minor feature is given by the fact that it overlaps the Nahan thrust (which separates Subathus from underlying Nahans) in an easterly direction. At Nahan, the Nahan thrust is five miles distant from the Krol thrust. At Sataun it disappears, together with the Subathu rocks, and pre-Tertiaries rest directly on Nahans.

One of the most noticeable features of the Krol Belt is the change in strike near Dadahu from NW-SE to nearly east and west. Similarly, between the 31° and 32° latitudes, north of the area described in this report, the strike changes from NW-SE to nearly due north and south. A careful following of the boundaries between the stages in the Tertiaries might disclose the fact that the Krol thrust, and other thrusts separating the Tertiaries from the pre-Tertiaries, have caused an extensive tectonic overlap of older rocks upon younger, over a distance dependent on the amount of departure of the outcrop of the dividing plane from NW-SE. My own observations amongst the Tertiary rocks were not extensive enough to prove the point.

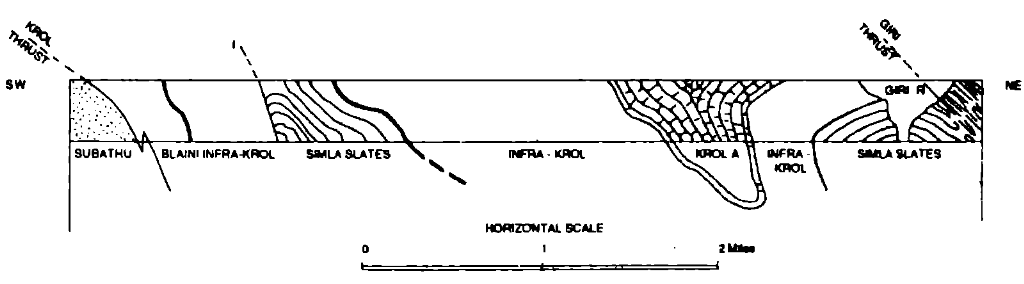
The actual fold-axes in the Tertiaries appear to follow the same general change in strike that is shown by the Krol Belt, since the folds probably arose as a result of pressures initiated by the forward movement of the belt over the Krol thrust. But a detailed examination of the fold-axes of the boundary planes between the folded stages, may well show that these are truncated by the Krol and analogous thrusts.

Giri Thrust

The Giri thrust is a well marked feature which has been traced from the Gambhar river to north-east of Chandni, where it dies out in an anticlinal fold.

It was noticed by Medlicott, who has shown a part of it very accurately.

Northwest of Kandaghat, the thrust is steep and separates Simla slates from Jaunsars. Along the Ashmi river, its dip becomes gentler. Simla slates are thrust first over Infra-Krol, and then over themselves. The thrust has not been traced between Sunnu and Gauhra, but is seen in the Giri river below the Gauhra Rest House, where two facies of the Simla slates are separated with disturbance by an inclined fault. Further southeast, the thrust truncates an anticline of Blaini with underlying Chhaosa beds belonging to the Simla slates, in the manner shown in the diagrammatic section below.



Diagrammatic section along Kawal Jhai river (Blaini shown in black). Horizontal scale, 1 inch = 1 mile. Vertical section diagrammatic.

This is a modification of the sections given on pages 12 and 13 in *Mem. Geol. Surv. India*, v.53, (1928). The Giri fault there marked is now regarded as a major feature, and its position has been changed from the southwest to the northeast limb of the anticline of Simla slates that runs along the Giri river. If the Blaini of Dudham should prove to be Mandhali, and if the Mandhalis occur normally between the Jaunsar and Simla series, there would be no need to postulate the Jaunsar thrust. The section above the Giri thrust would be a normal one.

Mapping is very difficult from height 2,820 feet down to Niwar, though the existence of thrusts is definite. Below Bongli, Jaunsars dip at 60° to the northeast upon Krol C. Two miles to the southeast the thrust is inverted, dips being to the southwest. At Milan, imbricated Jaunsars and Blaini again dip to the northeast at 40°-50° upon Krol C limestone. Eastwards the dip of the thrust varies. Northwest of Kando, uninverted Jaunsars rest at a low angle on inverted Blaini. In the Nait ka khala, the Blaini is cut out, and Jaunsars overlie an inverted succession of Infra-Krol and Krol limestones. The Giri thrust then splits up into several minor, parallel, thrusts, which eventually die out in the Barbas anticline.

Tons Thrust

The Tons thrust is a fairly well-marked feature which separates Mandhalis and Jaunsars from the underlying Morar-Chakrata beds. By height 2,206 feet, on the Tons river. Jaunsar rocks occur in the 6,000-feet scarp on the right bank, dipping southwest, while on the left bank occurs the Deoban limestone, dipping apparently to the northeast in cliffs and terraces nearly 7,000 feet in height. A great dislocation is therefore required to explain the juxtaposition of unlike rocks on the two sides of the Tons river.

In connection with the present discussion, the important point is that the Tons thrust dips to the southwest and south. Since the Krol thrust dips northwards, it is possible that the two thrusts are the same, and that the great syncline of Jaunsar rocks, with overlying Krols and Tals, rests as a *nappe* on a folded thrust-plane. Should this be so, the Krol thrust would be of premier importance in the structure of the area. No information is to hand to prove the point.

Below the Tons thrust occur Simla slates, together with soft purple sandstones of Dagshai (*see Mem. Geol. Surv. India*, v.53, p.38, 1928) type and Nummulitic beds. Definite Nummulitic limestones, associated with vitreous quartzites and green shales, are seen at Dabra. It is very probable that the lenticular limestones, shattered white quartzites and green shales that crop out between the 3,500- and 3,250-foot contours on the path from Sarog to Sayasu, are also Nummulitics.

To what extent the purple sandstones are Tertiary is impossible to determine. At Kailana and along the Seli Gad to the east, mottled purple sandstones occur interbedded with the concretionary facies so typical of the Chhaosa type of the Simla slates and may reasonably be considered to belong to the Simla slates. Moreover, Dagshai-like sandstones occur as boulders in the Blaini, boulder bed, which is without question pre-Tertiary, and is with fair certainty pre-Mesozoic, thereby proving that there must be at least two series of sandstones of similar type, one pre-Mesozoic, the other Tertiary. It does not follow that all these sandstones north of the Tons thrust must belong to the Simla slates, but only that they cannot all be Dagshai.

This occurrence of Nummulitics below both the Krol and the Tons thrusts is suggestive of the possibility that they are continuous beneath these thrusts. The centripetal disposition of Nummulitics below the Inner Schistose series of Garhwal may be recalled (*Rec. Geol. Surv. India*, v.20, pp.34, 36, 1887). It is true that Middlemiss did not favour the idea, which he himself brought forward, that the Inner Schistose series occurred as a *Klippe* upon continuously underlying Nummulitics, but a re-examination of the Garhwal area may eventually establish that this is so.[1]

The question of the identity of the Krol and Tons thrust has yet to be settled, but it seems reasonable, in view of the similar tectonic sequences on either side of the Jaunsar syncline, to regard them as one and the same thrust that has been subsequently folded.

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Age of Thrusting

In the Kalsi area, the Krol thrust brings pre-Tertiary rocks to rest upon Nahans. The thrust must therefore be of Miocene or later age.

At Bilaspur, Krol limestones are seen to rest at 30°-40° upon Upper Siwalik conglomerates. The latest movement of the thrust here cannot be older than Pliocene (This thrust has not been joined up with the Krol thrust of the area included in the map). The same inference applies to the thrust at Dhaduwala, south of Nahan, which brings Middle Siwaliks to rest upon Upper Siwaliks.

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Inclination of Thrusts

The inclination of both the Krol and Giri thrusts is found to be very

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[1]Middlemiss was aware in 1887 of the thrust structures that were at that time being discovered in the Northwest Highlands of Scotland, but he considered that the Garhwal area, examined on its own merits, did not warrant similar deductions. It is possible that the great *nappe* structures found in the Alps predispose geologists to find them elsewhere in analogous orogenic belts. Even allowing, however, for such a predisposition, and for an unconscious neglect of facts that might negative explanation of structure by *nappe* formation, the undeniable existence of such structures in many mountain chains makes it probable that another interpretation may be put on the structures present in Garhwal.

variable, in some places being only 20°, in others inverted. Mr. P. Lake (*Geol. Mag.*, p.305, 1903; op. cit., p.34 (1931); *Geog. Jour.*, v.78(2), p.151, 1931) has deduced that the thrust-plane at the base of the Himalaya must have a dip, at its outcrop, of 14°. He suggested in 1903 that the visible boundary faults of the Himalaya are probably minor thrusts, since the actual base of a modern mountain chain would be obscured by the products of its own denudation (Siwaliks and Modern Ganges Alluvium). Dr. Fermor (*Rec. Geol. Surv. India*, v.62, p.410, 1929) has drawn attention to a paper by Middlemiss (op. cit., v.50, p.122, 1919), in which the inclination of the thrust at Kotli between the Murrees (Dagshais) and the underlying Middle and Upper Siwaliks, is actually 12° to 15°. This thrust was taken by Dr. Fermor to be the Main Boundary fault, and Mr. Lake has accordingly allowed that the real basal thrust-plane of the Himalaya does in fact crop out, and at an inclination that agrees with the theoretical value. Mr. Wadia (*Mem. Geol. Surv. India*, v.51, pt.2, 1928; map at the end of Memoir) has shown that this thrust cannot be considered a boundary fault. It does not form a limit to the deposition of the Siwalik sediments, and, moreover, it terminates a short distance to the northwest in an anticlinal fold. The point at issue, however, is not the actual nature of the thrust-plane described by Middlemiss, but the variability of inclination of most of the Himalayan thrusts. Mr. Wadia agrees with me in the experience that a thrust may change greatly in dip within a distance of a few miles. The thrusts began, doubtless, with a rapid forward movement, when elastic limit was reached, but they must have slowed down as this original stress was relieved, and as resistance of the underlying and frontal foreland became greater. Cadell's experiments (*Trans. Roy. Soc. Edin.*, p.337, 1890) have shown that horizontal pressure applied at one point is not propagated far forward into the mass, and it seems legitimate to suppose that, in proportion as pressures in one part are relieved, so would new pressures and strains arise in the part to which the thrust masses have been translated. It would be expected that increase in frontal resistance would tend to cause the folding of the whole structure of overthrust mass, and overridden mass, as a single unit. The original disposition of the thrusts, that might have better accorded with theoretical inclinations required for movement along plane surfaces, would consequently be obscured.

Further, the rocks undergoing folding and thrusting are not homogeneous, and it would hardly be expected that relief from pressure would take place with mathematical perfection. The resistance offered by the Bohemian *massif* to the advancing Alpine folds may be cited as an example of the kind of deflection that is caused by the local presence of a stiff unit of the foreland.

The coincidence of the theoretical inclination of 14°, deduced by Mr. Lake, with the observed inclination of a part of the Kotli thrust must be fortuitous. It may, moreover, be questioned whether there is a single thrust, of unique importance, to which Mr. Lake's deductions can be applied. It appears to the writer that the conception of a 'Main Boundary fault', and hence of a basal thrust-plane to the Himalaya, has been carried too far. It arose at a time when the faults were thought actually to mark the successive limits of sedimentation against the uprising Himalaya, and when the structure of the pre-Tertiary rocks had not been examined in detail. Recent work by Pilgrim, Wadia, West and the writer has shown the number of thrusts that actually exist in these pre-Tertiary rocks. Some of these cannot be considered minor structures, comparable solely with the minor thrusts, as distinct from the major thrusts, of the North-West Highlands. The Chail thrust of Mr. West is of premier importance. In the Himalaya, as in the Alps, it would appear impossible to regard any single dislocation or *nappe* as having borne the whole burden of the advance upon the foreland.

Pre-Tertiary Structures

A brief note bas already been published (*Rec. Geol. Surv. India*, v.66, p.467, 1933) in which the existence of structures showing a NE-SW, Aravalli, orientation was discussed.

The observations were scattered over a wider area than that here described. Actually along the Krol Belt, the following structures may be noticed:

(1) In the Palor Ka Khala, above Siyun; conglomerates in the Jaunsar series have been crushed, so that the pebbles have been elongated to ellipsoids, the major axes of which strike 60°-240°. The elongation is seen on dip surfaces. Along one direction at right-angles to the dip surface, the pebbles appear more or less circular. Dip of conglomerates: 30° to ENE.

(2) The Jaunsar phyllites at Shallai are thrown into small-scale folds, the size of mega-ripples, the axes of which vary in strike from 80°-260° to 60°-240°. In addition, there are grooves and striae, on the bedding planes of these phyllites, which strike 35°-215°. These resemble glacial striae, but are found on close inspection to be minute cross-folds running in the direction of dip of the false cleavage. They appear to resemble the grooves described by Dr. Fermor (*Econ. Geol.*, v.19, p.560, 1924), except that they have no connection with the pitch of the synclinal fold in which they occur. Dip of phyllites and quartzites: 30° to SSW.

(3) The Blaini boulder bed on the ridge between Juin and Chandpur summits, has been made schistose. The direction of elongation of the pebbles varies from NE-SW to ENE-WSW. Dip of boulder beds : due west.

(4) The schistosity of the Jaunsar quartz-schists, in the Shamanah ka Khala, below Andra, strikes 45°-225°, the shear-cleavage dip being 70° towards 315°. Dip of quartzites: 65° to SSW.

These directions are at right angles to the strike now shown by the Himalayan range. They suggest that pressures had formerly acted in approximately a NW-SE direction, which is the same direction as that of the pressures responsible for the formation of the Aravalli range and its subsequent rejuvenation.

If the Aravalli range be produced across the Gangetic alluvium, it meets the present Himalaya in the region between Chakrata and Naini Tal. It seems a legitimate assumption to regard those structures of NS-SW orientation in the present Himalaya as having been caused by activity along the Aravalli axis. Such structures have never been noticed in the Infra-Krol and higher series, so it may be assumed that the activity responsible for them ceased in Blaini times, that is, during the Upper Carboniferous.

It has already been stated that the folding which was responsible for the unconformity of Blaini upon Jaunsar rocks probably did not have an Aravalli direction. There is therefore a certain degree of anomaly, since the Blaini of the Juin-Chandpur ridge appears to show this Aravalli orientation. Further, no unconformity of orogenic violence is seen between the Blaini and the underlying Jaunsar and Simla series.

The two sets of facts must be left together and unexplained. The commonness of NE-SW structures in the Himalaya cannot be disregarded. Moreover, they cannot be explained by supposing that their formation was due to strongly rotational Tertiary stresses, since the post-Blaini rocks all show a true Himalayan, NW-SE, orientation of structure.

Besides the structures that I have myself recorded from Garhwal, Middlemiss (*Mem. Geol. Surv. India*, v.24, p.125, 1890) mentions the prevalence in the Kumaon of folding and cleavage of pre-Tertiary rocks in a north-south direction, which he attributes to an east-west pressure.

It may be maintained with safety that the modern Himalaya contain relics of structures that were due to earlier, non-Himalayan, tectonics.

ECONOMIC

The country is very poor in minerals. It should be remarked that in no instance has any mineral been seen to occur in sufficient quantity to justify exploitation.

Barytes

Barytes occurs, or may have occurred, in the following localities. In all cases it is found in the older rocks.

(1) A discontinuous vein of barytes occurs in the Simla slates near hill 3901 (30°58' 30":77°1'15"), two miles ESE of Subathu, on the border of Bharauli and Baghat State.

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(4) In the Jagar ke Khala, Sirmur State (30°37'30": 77°28'), small veins of barytes are found in the Blaini boulder bed.

Gypsum

Gypsum is found in the Krol limestones in the following localities:

(1) Near Bhaunrari, Sirmur State (30°47':77°14'). Small pockets of gypsum occur in Krol D limestone. These are probably replacement pockets.

(2) Ridana, Sirmur State (30°33'22":77°44'51"). A lenticular bed of gypsum, 20 yards long and a maximum of 18 inches in thickness occurs in Krol A limestone.

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(Extracted from Rec. Geol. Surv. India, 1935, v.69, pt.2, pp.123-167)

Traverses in the Himalaya

J.B. AUDEN

EDITORIAL COMMENTS

During the period 1932 to 1934 Auden took geological traverses in Kashmir and Baltistan, Garhwal, Nepal and Sikkim and recorded his observations as he thought it was desirable to place such observations on record, so as to build a scaffolding for the later formulation of geological structure which would eventually emerge from detailed work, despite some danger in early generalization.

In his Kashmir and Baltistan traverse Auden examined the Trias limestones and their relationship with volcanics which he presumed to be part of the Panjal volcanics, though part of the younger Dras volcanics, and the contact is now described as the Sanko Thrust. He reported hornblende granites which belong to what we now consider as Ladakh batholith. Between Yun and Gomboro a metamorphic complex is reported extending right upto Biafo Glacier. Hornblende granites were seen upto southwest of Skardu.

In the Garhwal Himalaya, Auden has given an excellent description of lithology and structure along Ranikhet to Dwarahat, Lobah, Dewali Khal Pass, Karnaprauyag, Chamoli, Josimath, Badrinath, Mana, Ghastoli and up the Arwa valley and beyond. One important finding is his report of a thrust, from mile 158 to Josimath, between metamorphic belt and limestone belt, possibly a precursor of the Main Central Thrust.

Auden's geological account of the Nepal Himalaya is one of the earliest authentic description from that part of the Himalaya. He describes Tertiary and pre-Tertiary rocks and the existence of three thrusts, one between Lower Siwalik and Upper Siwalik, the second one the so-called Main boundary thrust that separates pre-Tertiary from Tertiary rocks and the third one between the Darjeeling crystallines and the underlying carbonate rocks. Auden also dilates on the age of granites and of metamorphism in Nepal.

In Sikkim Himalaya Auden describes Dalings and Darjeeling Gneiss. He refers to the Tethyan Lachi and Tso Lhamo series of Permian and Triassic respectively, occurring in normal position.

Auden emphasized on the relics of Peninsular India in the Himalaya and believed in the strong unity between the Himalaya and the Indian Peninsula which prompted him to propose a division of the Himalaya into Tethys Himalaya – incorporating Spiti, Tibet etc. and Peninsular Himalaya – covering most of the outer Himalaya and possibly at one time all of Sikkim.

Auden also dwells on the relationship between the Darjeeeling and Daling, the former overlying the latter and on the nature of the contact between these two units. With regard to Sikkim granite, he considered the white fine-grained, tourmaline granite of northern Sikkim as the youngest of the intrusive granites. Traverses in the Himalaya contains many thought provoking suggestions which could form good guidelines for future work. – S.V. Srikantia

The following notes are the results of traverses in the Himalaya:

(1) Kashmir and Baltistan in June and July, 1933;
(2) Garhwal in June, 1932;
(3) Nepal in portions of February, March and April, 1934;
(4) Sikkim in October and November, 1934.

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It is realized that there is often danger in early generalization from incomplete observations such as are made on traverses. The Himalaya are so vast, however, that years will elapse before they are mapped geologically in detail, and it seems desirable therefore to place such observations on record, so as to build a scaffolding for the later formulation of geological structure which will eventually emerge from detailed work. Such results may also have a bearing on the understanding of the geology of the small areas where mapping is at present in hand.

KASHMIR AND BALTISTAN

Previous Explorers

From the point of view of the present paper, the significant geological work has been done by Lydekker and by the geologists attached to the Italian expeditions of 1909 and 1929. My colleague, Mr. Wadia, has worked for many years in northern Kashmir and around Nanga Parbat and Gilgit, to the west and southwest of the area with which we are concerned. Mr. Middlemiss has mapped extensive portions of the mountainous area east of Srinagar. The full scientific results of the Italian expeditions, written in Italian, I have unfortunately been unable, to read. I have had access only to the briefer accounts in the English language.

Route Followed

The route followed was from Srinagar, *via* the Sind valley, the Zoji La, the, Dras, Shingo and Indus rivers to Narh, over a small col to Shigar, and up the Shigar and Braldu valleys to Askole and the Biafo glacier. The return journey was over the Skoro La to Shigar and Skardu, and thence by the Satpura route across the Deosai plains to Burzil and Tragbal. A narrative account of the excursion occurs in *Himalayan Journal*, v.6, p.67, and a description of the Biafo glacier in *Rec. Geol. Surv. India*, v.68, pp.400-413, (1935). The area visited is covered by Degree Sheets 43 J, M, N and 52 A, B.

Geological Notes

On the cliffs ESE of Matayan (34°22': 75°36'), Trias limestones are seen to occur in a well-developed recumbent fold (*see* Plate 1). This has escaped attention probably because the track lies just below the cliffs and true perspective is not obtained unless viewed from further away near the river bank. It is not improbable that some of the outcrop of Triassic limestone will yield, on detailed examination, structures of the type seen in the High Calcareous Alps of Switzerland, and the northern Calcareous Alps of Austria (Dachstein-Totesgebirge area).

These limestones rest upon Panjal traps, which are well seen at Pindras. The fact that such overfolding occurs close to the traps suggests that the contact between Trias and Panjals may be tectonic, though there is also the possibility that the Trias limestones have folded within themselves on a contact that may be normal, or only slightly disturbed.

Traps continue as far as Kharbu (34°33': 75°59'), after which begins a great outcrop of hornblende-granite. The granite is both banded and non-banded and is full of basic inclusions. At the confluence of the Dras and Shingo rivers, the banding was NNW-SSE. A slightly more basic type is seen at the suspension bridge near Chunagund. The granite characteristically has hornblende, biotite, oligoclase or andesine and quartz, with less constant microperthite, epidote, sphene and apatite.

After Olthingthang, the granite becomes richer and richer in basic inclusions, which increase in size until along the Indus river they are sometimes several hundred yards in length. They were originally basalts and dolerites, but have been metamorphosed by the granite to epidiorites and hornblende-granulites. Smaller inclusions have often lost their igneous structure, except for occasional phenocrysts, and consist of a granoblastic assemblage of hornblende, biotite, oligoclase-andesine and sphene (microscope slide 23345; Registered numbers in the collection of the Geological Survey of India,

Plate 1. Overfold in Triassic limestones, Matayan, Dras valley, Kashmir. Direction of view ESE.

Calcutta). Specimens from larger inclusions are mostly epidiorites, the igneous structure still being discernible (23346).

Occasional inclusions of slates and quartzites show little metamorphism except for the marginal formation of hornfels. An extensive outcrop of vertical banded slates is prominent just south of Tarkuti (34°48':76°12'), succeeded northwards by granite, which may be seen on the opposite side of the Indus river sending tongues into the slates. Near Gidiaksdo are found dark schists and gneisses, together with anthophyllite schist. Sills of granite are seen further north at Papaldo intrusive in schists, gneisses, marbles and basic rocks. Basic rocks, now hornblende-granulites, crop out at Bagicha penetrated by exogenous veins of biotite-pegmatite derived from the granite. Some of the acid material of aplitic texture is probably, however, endogenous in origin, and due to the segregation of the plagioclase from the hornblende at the time of metamorphism. It arises throughout the body or 'soma' of the rock in a manner which suggests an *in situ* source.

Earlier Granite ?

Hornblende granite and metamorphosed basic and ultra-basic rocks, together with shales (opposite Kharmang), slates and quartzites crop out down to the Indus-Shyok confluence. Here, biotite-granite, without hornblende, is traversed by a network of dykes and sills of basic rock, which have every appearance of being intrusive into the granite, but yet which have been metamorphosed to the customary granoblastic mosaic of hornblende, plagioclase, biotite, oligoclase, and quartz. It is possible that this biotite-granite is earlier than and was intruded by the basic rocks, and that the latter owe their metamorphism to the neighbouring hornblende-granite, which is known to be young. The biotite-granite is not itself metamorphosed, but neither are some of the argillaceous sediments caught up in the hornblende-granite. Metamorphism may have been of sufficient intensity to affect the sensitive basic rocks, but not those rocks whose mineral assemblages are less reactive to slightly altered conditions. It should be remarked, however, that the hornblende-granite always contains biotite and that the granite in question may be simply a variety in which hornblende is locally absent. The anomaly is that the granite appears to belong to the Ladakh-Indus hornblende-granite, but yet appears also to be intruded by rocks it cannot have metamorphosed[1].

[1]Interesting cases are recorded by L.R. Wager from Greenland of plagioclase-amphibolite injected into an earlier grey gneiss and itself injected by pegmatite derived from the gneiss at a time of later stress and reheating. Such cases of re-injection from the biotite-granite were not noticed at the Indus-Shyok confluence, and the fact that elsewhere along the Indus the metamorphism of the basic rocks to epidiorites and amphibolites is due to the hornblende-granite makes it a legitimate conclusion that the same causes may have operated at the locality in question.

Meddelelser om Grönland; udgivne af Komm. for Videnskabelige Undersögelser i Grönland. Bd. 105, Nr.2, pp.10-12, Copenhagen (1934).

Plate 1. Overfold in Triassic limestones, Matayan, Dras valley, Kashmir. Direction of view ESE.

Calcutta). Specimens from larger inclusions are mostly epidiorites, the igneous structure still being discernible (23346).

Occasional inclusions of slates and quartzites show little metamorphism except for the marginal formation of hornfels. An extensive outcrop of vertical banded slates is prominent just south of Tarkuti (34°48':76°12'), succeeded northwards by granite, which may be seen on the opposite side of the Indus river sending tongues into the slates. Near Gidiaksdo are found dark schists and gneisses, together with anthophyllite schist. Sills of granite are seen further north at Papaldo intrusive in schists, gneisses, marbles and basic rocks. Basic rocks, now hornblende-granulites, crop out at Bagicha penetrated by exogenous veins of biotite-pegmatite derived from the granite. Some of the acid material of aplitic texture is probably, however, endogenous in origin, and due to the segregation of the plagioclase from the hornblende at the time of metamorphism. It arises throughout the body or 'soma' of the rock in a manner which suggests an *in situ* source.

Earlier Granite ?

Hornblende granite and metamorphosed basic and ultra-basic rocks, together with shales (opposite Kharmang), slates and quartzites crop out down to the Indus-Shyok confluence. Here, biotite-granite, without hornblende, is traversed by a network of dykes and sills of basic rock, which have every appearance of being intrusive into the granite, but yet which have been metamorphosed to the customary granoblastic mosaic of hornblende, plagioclase, biotite, oligoclase, and quartz. It is possible that this biotite-granite is earlier than and was intruded by the basic rocks, and that the latter owe their metamorphism to the neighbouring hornblende-granite, which is known to be young. The biotite-granite is not itself metamorphosed, but neither are some of the argillaceous sediments caught up in the hornblende-granite. Metamorphism may have been of sufficient intensity to affect the sensitive basic rocks, but not those rocks whose mineral assemblages are less reactive to slightly altered conditions. It should be remarked, however, that the hornblende-granite always contains biotite and that the granite in question may be simply a variety in which hornblende is locally absent. The anomaly is that the granite appears to belong to the Ladakh-Indus hornblende-granite, but yet appears also to be intruded by rocks it cannot have metamorphosed[1].

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[1]Interesting cases are recorded by L.R. Wager from Greenland of plagioclase-amphibolite injected into an earlier grey gneiss and itself injected by pegmatite derived from the gneiss at a time of later stress and reheating. Such cases of re-injection from the biotite-granite were not noticed at the Indus-Shyok confluence, and the fact that elsewhere along the Indus the metamorphism of the basic rocks to epidiorites and amphibolites is due to the hornblende-granite makes it a legitimate conclusion that the same causes may have operated at the locality in question.

Meddelelser om Grönland; udgivne af Komm. for Videnskabelige Undersögelser i Grönland. Bd. 105, Nr.2, pp.10-12, Copenhagen (1934).

Plate 2. Biafo glacier and the main Karakoram range, Baltistan. View towards 345° from the spur above camp 12,800, showing interbedded marbles (pale bands) and biotite schists, etc. The highest peaks (22-24,000 feet) are probably of granite.

Granites continue to Ghoro-Ghone, Shigar and Tungmo (35°28': 75°43'), intrusive into basic rocks, mica-schists and biotite-gneiss.

After Tungmo, follows a metamorphosed series of pelitic and calcareous rocks. Garnet-chloritoid-sericite-phyllite, diopside-actinolite-granulite, tremolite- and actinolite-schists, marbles and calciphyres are found as boulders between Alchori and Yuno, clearly having descended from the slopes of Koser Gunge mountain, 21,000 feet.

Between Yuno and Gomboro are mostly gneisses injected by veins of quartz-muscovite-tourmaline-pegmatite. It is evidently a pegmatite of this type that bears the aquamarines at Dusso. The tourmalines are often of a large size, up to 3-5 cm in width.

The metamorphosed calcareous suite is found in force again between Pakore and Chongo (35°41': 75°45'), the rock types encountered being marbles, calc-granulites, actinolite-epidote-gneiss (23350) and amphibolites, with dips to the ESE. These rocks probably strike southwards past Koser Gunge and down to where they were met with as boulders in the Shigar valley.

At Askole, Captain Gregory found a striking rock (rock 46/439, microscope slide 23351) which is made up of large garnets set in a matrix of kyanite, staurolite and ?roscoelite. The garnet has a specific gravity of 4.20, and is probably almandine.

East of Askole, garnet-biotite-schist, calc-granulites and rarer marbles crop out, the marble increasing in quantity, however, towards the Biafo glacier. The whole series has been invaded by a network of pegmatite dykes and sills. The dips are steep to the NNE. Looking ENE to the Laskam col (35°41': 75°57') from near the southern end of the Biafo snout, there is a suggestion of a horizontal fold of marbles within the biotite-schists and gneisses; (*see* Plate 28, fig.2 of *Rec. Geol. Surv. India*, v.68, 1934).

Continuing up the Biafo glacier is found the same assemblage of biotite-gneiss, garnet-mica-schist, marble.R. amphibolites and epidosites, with dips to the southeast. A conspicuous anticline, with WNW-ESE axis, passes through camp 12,800 feet, north of which the dips are northerly as far upwards as the glacier was visited, about 23 miles from the snout, (*see* Plate 2). On the moraine descending north-eastwards from the first large side glacier above camp 13,570 feet were noticed the following rock types: marble, amphibolite, biotite-sericite-schist, biotite-schist, quartz-biotite-granulite, garnet-hornblende-biotite-granulite. At camp 14,230 feet were found banded quartz-biotite-granulites often with garnet, and injected by pegmatite. Diopside is seen in large crystals up to 8 centimetres in length, together with diopside-rock (46/441) on one of the lateral moraines which descends from the eastern slope of the so-called Mount Meru.

This metamorphic series is evidently composed of a group of altered argillaceous, calcareous and silico-dolomitic rocks, associated with basic lavas or tuffs.

The main Karakoram range east of the Biafo glacier is probably composed of hornblende- and biotite-granite, since granite forms a large part of the lateral moraine on the northeast side of the glacier, which is fed by the Latok tributary. The scenery of peaks 23,900 feet, 23,400 feet and 22,790 feet is more massive and severe than that of the lesser pinnacled mountains of 20,000 feet immediately bordering the Biafo glacier, which are unquestionably built in the main of para-gneisses, and this in itself indicates a change in the nature of the rock. Desio (*Geog. Jour.*, v.75, p.403, 1930) mentions that the Punmah basin is mostly cut in gneisses and granites, presumably in strike continuation with those just mentioned.

Between Askole and the Skoro La (16,640 feet) are found biotite-schists, quartz-biotite-granulites and subordinate marbles. On the southwest side of the pass occurs a less metamorphosed series of purplish quartzites, spotted schistose phyllites and dark banded slates, the latter with effloresences of sulphates. This is probably a younger series, in which, near Shigar, Godwin Austin found crinoid stems (? Permo-Carboniferous).

Hornblende-granite with basic inclusions is met with again just southwest of Skardu, on the way up to the Satpura Tso. Near the pass over the Deosai plains, on a hill 14,600 feet in height, occur rhyolites and tuffs. Over the pass, near a conspicuous route cairn at 14,300 feet, is a fine outcrop of porphyritic hornblende-andesite (46/430), which is not metamorphosed in spite of proximity to hornblende-granite. The volcanic rocks very probably belong to the Eocene suite of acid volcanics, serpentines, tuffs and agglomerates which Mr. Wadia has recently found on the Burzil pass. Hornblende-granite occurs throughout the Deosai plains, with occasional volcanic rocks as on the San Sangri La.

DISCUSSION

Lydekker has shown on his map a syncline of Supra-Kuling rocks crossing the Biafo glacier, running east to the Skoro La, and Ladakh bending southwest to Alchori, near Shigar (*Mem. Geol. Surv. India*, v.22, 1883). At Shigar is marked a patch of Kuling rocks, evidently those in which crinoid stems were found. He is definite that the marbles, representing his Supra Kulings, occur as a syncline conformably overlying the gneisses, which he regarded as partly Panjal in age. This view is hard to accept. Precisely where his supposed syncline of marbles crosses the Biafo glacier there is a marked anticline, with WNW-ESE axis, running through camp 12,800. The marbles do not form a separate series, but are an integral part of a system of ortho- and para-gneisses (interbedded marbles, mica-schists, garnet-mica-schists, biotite-gneisses, amphibolites), a fact which is well shown in Plate 2, in which the marbles are seen as pale bands between the darker schists and gneisses. It seems impossible to regard the marbles as a separate series lying synclinally upon the gneisses, partly because of the interbedding which is manifest to the eye, partly because of the presence of an anticline just where, on Lydekker's interpretation, a syncline is required. It is conceivable, perhaps, that intricate imbricate thrusting had caused two distinct sets of rocks to occur in an apparently continuous succession, but this is not the impression gained in the field. Lydekker himself states that marbles increase in frequency from Askole eastwards to Korofon, and yet separates them, partly into the gneissic group, partly in the Supra-Kulings by what appears to me to be an arbitrary line. In actuality, the impure calcareous suite is found more or less continuously eastwards of Chongo, which is nine miles west of the Biafo snout, and occurs at least as far as camp 14,230 up the Biafo glacier.

Italian Expedition 1909

Ing. Novarese, in describing the rocks collected by the Duke of Abruzzi in 1909 from the Baltoro region, divides the sedimentary types into two series: schists and anagenites, and a later series of dolomites, limestones and calcareous breccias. The latter he regarded as equivalent to Lydekker's Supra-Rulings, though he was in considerable doubt into which of the two series certain of the schists should be placed (Karakoram and Western Himalaya, p.433, 1912).

Italian Expedition 1929

The last work to be mentioned is that of Desio in the recent Italian expedition to the Baltoro of 1929 (*Geog. Jour.*, v.75, p.402, 1930). Only a preliminary account is available, which was given to the Geographical Society before he had fully examined his material. The succession given by Desio is:

(d) crystalline limestones interbedded with shales, amphibolite-serpentine, mica-schists and phyllites;
(c) thick shales;
(b) gneissose schists;
(a) augen-gneiss, injected by granite dykes.

Desio believes that there are two calcareous-schistose zones in the region:

(1) the normal facies, fossiliferous and generally unmetamorphosed;

unquestionably Permo-Carboniferous and found especially along the Sarpo Laggo, the Shaksgam valley and in the Gasherbrum massif;
(2) the unfossiliferous metamorphic facies of Askole and the Biaho river.

Although Desio does not actually state that he considers the two series to be equivalent, the implication, throughout the paper (as, for instance, in the succession given above, in which only one group of limestones is found in the stratigraphic table) is that the metamorphic and non-metamorphic facies of limestone are of the same age. If this be accepted, it follows that the limestones of Askole and the Biafo valley are Permo-Carboniferous. His descriptions show that there is considerable variation in the degree of metamorphism amongst the limestones which are definitely Permo-Carboniferous.

West of the Godwin Austin glacier, the limestones form an almost continuous cover to the granite gneiss of the K2 group. This disposition is similar to that thought to exist by Lydekker just east of Askole, and might be considered to support Lydekker's contention of the synclinal disposition of a limestone series upon the gneisses. While there can be no doubt as to the existence of a great group of Permo-Carboniferous limestones, both unmetamorphosed and partially metamorphosed, at the upper end of the Baltoro glacier, and in the Sarpo Laggo and Shaksgam valleys, lying upon gneiss, I am unwilling to accept that Lydekker was correct in his supposition of a similar sequence by Askole. I would suggest that, by Askole and up the Biafo glacier, the marbles belong to the gneissic series, and that this series of gneisses, both igneous and sedimentary, has been overlain by the Permo-Carboniferous limestones in the Baltoro and neighbouring region.

D.N. Wadia

Mr. Wadia (*Rec. Geol. Surv. India,* v.65, p.196, 1931; v.66, p.218, 1933, v.68, p.19, 1934), in a series of papers, has shown the presence of crystalline limestones and marbles in his Salkhala series of northern Kashmir. This series underlies proved Cambrian rocks and is therefore unquestionably pre-Cambrian. The lower Cambrian rocks of Kashmir are described as consisting of

'vast system of fossiliferous clays, slates, limestones and arenaceous beds'.

Salkhalas have been mapped by Wadia as far north as Rattu (35°08':74°48'), some 70 miles to the southwest of Askole. It seems very likely, therefore, that a formation of such extent will be found also in the Biafo-Baltoro region, together perhaps with the Cambrian and lower Palaeozoic. The Salkalhas of the type area are not very metamorphosed, but elsewhere a high degree of metamorphism is reached. The gneissic series of the Shigar and Braldu valleys and up the Biafo glacier, together with the associated marbles, may be for the most part Salkhala, and the whole suite may be overlain in the upper reaches of the Baltoro glacier by Permo-Carboniferous limestones. Subsequent metamorphism, involving both the older possibly Salkhala limestones and the Permo-Carboniferous limestones, would cause considerable convergence in aspect. If this interpretation is correct, Lydekker's Supra-Kulings of Askole and the Biafo would be in reality mostly pre-Cambrian and should not be correlated with the proved Permo-Carboniferous rocks of the Sarpo Laggo, Shaksgam and upper Baltoro, as is hinted by the Italian geologists. Some of the crystalline limestones in the upper Baltoro region may also belong to the older gneissic series as, for example, those of Crystal Peak, 20,088.

In all these accounts there is a disturbing association of rocks of varied metamorphic grade. Reference may be made to a portion of Desio's sequence which he describes as:

> 'crystalline limestones interbedded with shales, amphibolite-serpentine, schists mica schists and phyllites'.

This applies both to the rocks which are here thought to belong to the Salkhala series, and in a greater degree to the Permo-Carboniferous series.

Granites and Epidiorites

The chief feature of note along the Shingo and Indus rivers is the penetration of basic lavas and intrusives by hornblende-granite, and their metamorphism to epidiorites and hornblende-granulites. This association of granite with earlier basic rocks is found from Kharbu in the south to near Shigar in the north, and over a width from northeast to southwest across the strike of some 50 miles. Mr. Wadia has shown the same relation to exist in the southeast quadrant of sheet 43 I, and there is no doubt that the granites and metamorphic basic rocks in the two areas are equivalent (*Rec. Geol. Surv. India*, v.66, pp.222-224, 1933). Mr. Wadia has this year found an intrusive contact of the hornblende-granite with Eocene limestones and volcanic rocks, thereby proving the age of this granite to be Tertiary, a fact which had long been suspected (*op. cit.*, v.68, p.419, 1934). The basic rocks belong to the Panjal volcanic episode of Permo-Carboniferous age.

It is possible that there was an earlier biotite-granite intruded by the basic dykes of the Panjal episode (Shyok-Indus confluence). If this is established it follows that the granite would belong either to an earlier plutonic phase of the Panjal igneous suite, or to an altogether earlier and distinct period of igneous activity, Caledonian or pre-Cambrian in age.

GARHWAL

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Geological Notes

From Ranikhet to Dwarahat occurs a complex association of graphitic slates, garnet schistose phyllite, graphitic phyllitic schist, mica-schist, garnet-mica-schist and quartzite intruded by gneissose granite which is sometimes porphyritic. The same series is found again west of Lobah (30°03': 79°17'), belonging to the Dudatoli (30°03':79°12') massif mapped by Middlemiss in 1886. Middlemiss has described the abrupt fault contact of the granite and schistose series of Dudatoli with the massive limestones to the east (*Rec. Geol. Surv. India*, v.20, p.162, 1887; v.21, p.11, 1888). He states that the schistose series occurs in the form of a syncline, with dips inwards towards Dudatoli, while the rocks surrounding this series dip away from the mountain. The massive limestones crop out from Manwa Devi (29°52':79°25') to Ganpurgarh (30°05':79°20'). These limestones have been mineralised. Iron is mined near Semalkhet (29°58':79°20') and Dr. Fox has recorded that the copper mines of Dhanpur-Dobri (30°12½':79°05') are also in limestones of the same type. Overlying the limestone with unconformity, Middlemiss describes a series of acid volcanic rocks which are themselves overlain further to the northwest by basic lavas. He referred these with some hesitation to the Deccan suite but did not at that time appear to have considered the possibility of their being Panjal or Permo-Carboniferous in age.

The basic rocks are well seen between Adbadri and Karnaprayag, and again between Karnaprayag and Chamoli. Along the Alaknanda river they appear to overlie phyllites and massive quartzites bearing a strong resemblance to the more arenaceous type of Jaunsars near Chakrata. Near Mathyana (30°22':79°18') and Nandprayag the basic rocks are in the condition of chlorite- and hornblende-schists.

Massive limestone is found with northerly dips along the Alaknanda between miles 143 (30°25':79°24') and 156 of the pilgrim track, dipping for the most part to the north. This is almost certainly the same limestone as that east of Lobah. The suggested succession reading downwards is:

Volcanic suite (top),
Karnaprayag and Chamoli quartzite series,
Massive limestone (bottom).

The limestone may be compared with the Deoban limestone of Chakrata, and the quartzites with the Jaunsars. Tuffs and lavas occur in the Chandpur group of the Jaunsar series, but they are not really similar to those in Garhwal and are not so abundant. Moreover, the associations of the basic rocks in the two areas are different.

From mile 158 to Josimath is a series of mica-schists and biotite-gneisses, apparently overlying the limestones and presumably thrust upon them.

Granulite Series

Northwards from Vishnuprayag (30°34':79°37') is found a great thickness of bedded para-gneisses consisting of recrystallised quartzites, garnet-mica-schists and massive granulites containing biotite, muscovite, microcline, plagioclase, quartz and garnet. The series is characteristically arenaceous, and massively bedded. Original current-bedding structures are still preserved in spite of the complete reformation of the rocks (*see* Plate 3). The banding in Fig.2 of this plate might be explained as flow structure were it not for the fact that in larger scale views the true current-bedded nature of the cross banding is clear and certain, and flow structures are absent, as is shown by the perfect parallelism of the true bedding planes. Under the microscope, also, there is no suggestion of the rotation of garnets to form the spirals so suggestive of movement during metamorphism. The metamorphism has taken place without flow, and corresponds to the German conception of *Abbildungskristallisation*. I am not convinced, however, that the metamorphism is proved by the absence of flow structures to be post-tectonic, a corollary which is implied by Professor F.E. Suess's application of this conception (*Geol. Mag*., v.68, p.78, 1931). Massive impure quartzites, which were the parent rocks of those now found between Vishnuprayag and Painor, would probably not flow, even if lateral stress were present.

The preservation of original bedding structures in metamorphosed rocks is, of course, a well-known feature. Recently, ripple marks have been recorded in Archaean rocks from the Grand Canyon, Colorado. Maxson and Campbell state: (*Amer. Jour. Sci*., v.28, p.298, 1934. References may also be made to Sederholm, *Bull. Comm. Geol. Finlande*, no.6, p.98, 1899; Heron, *Mem. Geol. Surv. India*, v.45, Pl.4, fig.2, 1917).

> "The bed in which the ripple mark occurs is a granular mosaic of quartz grains, averaging one millimeter in diameter, which appears to have been originally a well-sorted quartz sand. As a result of metamorphism the quartz grains have recrysallised and some feldspar, biotite and hornblende have been developed."

The rock in the Grand Canyon is evidently a granulite of the same metamorphic grade as those in which the current-bedded structures are seen in Garhwal.

Plate 3

Fig.1. Current-bedded granulites, mile 170.5 on the Hardwar-Badrinath pilgrim track, just below Pandukeswar, Garhwal.

Fig.2. Current-bedded granulites, mile 168 on the Hardwar-Badrinath pilgrim track, north of Vishnuprayag, Garhwal.

The dips of this granulitic series are consistently northwards from Vishnuprayag to Painor, a distance across the strike of at least 8.5 miles. Taking the average dip to be 45°, there is implied a thickness of succession of approximately 32,000 feet. This is not an impossible thickness. Schuchert has described a succession of 76,000 feet on the Rocky Mountains of North America, remarking that the earth's crust must have subsided there 14 miles before it became folded into mountains (*Bull. Geol. Soc. Amer.*, v.34, p.191, 1923). There was no evidence of repetition of beds by folding or thrusting between Vishnuprayag and Painor, though it is possible that such might be forthcoming if the area were mapped in detail.

At Badrinath and Mana comes in a metamorphosed calcareous suite consisting chiefly of pyroxene-granulite (44/59, 22066), marbles, diopside-calciphyres, biotite-schists and granulites, amphibolite and rusty gneiss, thoroughly invaded by tourmaline pegmatite, which sometimes bears garnet (44/66, 22073).

Biotite-gneisses begin just north of the Mana falls, followed by a varied assemblage of muscovite-tourmaline-granite (fluxional and non-fluxional), muscovite-biotite-granite and streaky gneiss with biotite segregated into clusters. In the Arwa valley are found albite-oligoclase-granites, greenish in hand specimen and containing chloritised biotite. Many of the granites may be classified as adamellite. Ferruginous shales and phyllites occur on the northern lateral moraine of Glacier No.4 in the upper Arwa valley (*Rec. Geol. Surv. India*, v.66, p.393, 1933).

A pebble of fine-grained granite resembling the finer granites of the Arwa valley was found in the pre-Permian agglomerate or boulder bed (the nature of this rock has not yet been determined) at Raitpur (29°54': 78°42'). It is possible therefore that the Arwa granites are pre-Permian. It is, of course, equally possible that granites of similar type were intruded at different times and that the Arwa granites may be Tertiary, while the similar pre-Permian granite, from which the pebble was derived, has since been eroded away or covered up by later deposits.

NEPAL

* * * * *

This present, account is confined to portions of Nepal east of Katmandu. It owed its inception to the results of observations made on traverses in connection with the Bihar-Nepal earthquake of the 15th January 1934. Mention of the thrust planes which were found in Nepal has been made in the preliminary account of this earthquake (*Rec. Geol. Surv. India*, v.68, p.217, 1934).

Route

Three traverses were made in Nepal. The first was to Katmandu and the Trisuli Ganga and Indrawati rivers, sheet 72 E; the second was from Jaynagar to Udaipur Garhi, sheet 72 J; and the third from Jogbani to Dharan, Dhankuta, along the Arun river to Legua Ghat and Chainpur, over the Milke pass to the Tamur river and Taplejung, and finally up the Kabeli valley to Sabargam on the Singalila ridge and thence to Darjeeling, sheets 72 M, N, 78 A.

Geological Notes

The rocks of Nepal fall into two main divisions, the Tertiary and the pre-Tertiary. Some of the granites discussed in connection with the pre-Tertiary rocks may be Tertiary in age, but they are considered together with the rocks they intrude.

Tertiary Rocks

The Tertiary rocks are found between Amlekganj and Sanotar, over a width across the strike of 13 miles, and between Anraha (26°49': 86°23') and Udaipur Garhi, over a width of 12 miles. They were not seen at Dharan, being covered there by alluvium. The dips are almost invariably to the north.

Going northeast from Amlekganj or from Anraha, there appears to be the same sequence:

Middle Siwaliks,
Upper Siwaliks,
Nahans or Lower Siwaliks.

There must, therefore, be a thrust plane which separates Nahans from the underlying and younger Upper Siwaliks.

Nahans

The Nahans are best exposed on the Udaipur Garhi ridge, and consist of the same alternations of brown-weathering sandstones and chocolate clays as occur at the type locality of Nahan itself. In addition there are also thin inconstant beds of impure limestone, such as exposed 700 feet below the village of Udaipur Garhi on the western side. These limestones are evidently similar to those described by Mallet from the Nahan rocks south of Darjeeling (*Mem. Geol. Surv. India*, v.11, p.45, 1874).

Similar sandstones and clays occur, but not well exposed, along the road from Amlekganj to Bhimphedi, near Sanotar (27°28':85°02'). Sanotar is probably *Etoundah* of Medlicott (*Rec. Geol. Surv. India*, v.8, p.94, 1875).

Middle Siwaliks

The Middle Siwaliks form great cliffs along the Amlekganj-Bhimphedi road, near Dhukwabas (27°19':85°00'), and are found again in the neighbourhood of Muksar (26°52':86°23'). They consist in the former locality mostly of sand-rock of Dhok Pathan type, full of feldspar and mica. This must be the product of denudation of an adjacent granite or gneiss terrain, possibly the western continuation of the Darjeeling gneiss complex, which may formerly have formed a more continuous outcrop from Darjeeling westwards towards the Punjab.

The rocks north of Muksar are probably a different horizon to those of Dhukwabas. The thickness of the beds of sandstones is less, seldom exceeding 50 feet. Calcareous concretions occur, and occasionally lenticles of coal, up to 2 inches in thickness and 5 feet in length. These are not worth exploiting, being rare and highly lenticular. The beds at Muksar probably represent a lower horizon of the Middle Siwaliks.

Upper Siwaliks

The Upper Siwaliks consist of the usual conglomerates and crop out in turreted hills of the same type as in the Dun range near Dehra Dun. They are magnificently exposed at Churia Ghati (27°21'85°00') and almost as well on the pass over the Mahamanda Danda (26°54':86°24').

The following boulders were noticed in the Upper Siwalik conglomerates in a ravine 2 miles south of Churia Ghati:

Pale schistose quartzite; very common	pre-Tertiary
Purple and white quartzites	
Dark phyllites	
Arkoses	
Purple and dark pebbly quartzites	
Silty brown sandstone. . . .	probably Nahan
Tourmaline-aplite ...	age unknown

The older Tertiaries are absent from the parts of Nepal which I visited. It is probable that they are only found well developed in the foothills northwest of Naini Tal.

Pre-Tertiary Rocks

The sequence and correlation of the pre-Tertiary rocks of Nepal is one of great difficulty. The difficulty is increased by the intrusion of granite and granite-gneiss, and the metamorphism resulting therefrom. Two facts may be stated with certainty:

(1) The find by Dr. Sutton Bowman of fossiliferous limestones on the Chandragiri pass (27°40':85°11') which are Lower Palaeozoic in age. Medlicott (loc. cit., p. 97) had noticed facets of calc-spar with a central puncture, which he thought might be crinoidal. From the specimens obtained, Waagen, Palaeontologist of the Geological Survey, was unable to give a definite opinion as to whether or not they were organic.

(2) The continuation of the Darjeeling gneiss and the Daling series westwards from Darjeeling into Nepal.

The rocks of Dhankuta-Chainpur, of the Mahabharat Lekh near Udaipur, and of the Sheopuri Lekh north of Katmandu are unquestionably, in my opinion, Darjeeling gneiss. The underlying phyllites of Taplejung (27°21':87°40'), Mulghat (26°56':87°20'), Deopur (27°45':85°34') and near Nawarkot (27°55':85°11') may be regarded as Dalings. There is no doubt at all with regard to the correlation of the phyllites at Taplejung, and Mulghat, and a very fair certainty about those north of the Nepal valley.

Bhimphedi-Katmandu

A thrust plane separates the pre-Tertiaries from the Tertiaries just north of Sanotar (27°28': 85°02'). The former series consists of the following types, going northwards: Carbonaceous phyllites; schistose sericite-quartzite (one mile south of Bhainse-Dobhan), with dips to the NNE; marbles at Bhainse Dobhan, with dips northwards at 70°; phyllites at Golping. From Bhimphedi up to the Sisagarhi col is an extensive series of schistose sericite-quartzites, tuffaceous quartzites, fine-grained biotite-granulites, biotite-schists, chlorite-biotite-schists and sheeny puckered phyllites, injected with occasional veins oú tourmaline-aplite. Rock 46/414-23326 is a muscovite-tourmaline-oligoclase-quartz-aplite intruded against garnet-muscovite-biotite-quartz-granulite. Overlying this mainly arenaceous group of rocks is porphyritic muscovite-granite which is found on the path from Sisagarhi col down to Kulikhani, This granite (46/412-23324) contains tourmaline, muscovite, less common biotite, orthoclase with microperthite, and albite, and is clearly the source of the aplite veins descending into the underlying arenaceous rocks, Above the granite is found a group of quartz-biotite-granulites, schists, phyllites, calc-granulites, and marbles in beds up to five feet thick. At a height of about 5,400 feet on the path up to the Chandragiri pass may be seen large nodules of marble, up to 3 feet 8 inches in thickness, embedded in puckered talcose and chloritic phyllites. These nodules are strongly reminiscent of those found in the Rohtas limestone group of the Vindhyan rocks along the Son valley, (*Mem. Geol. Surv. India*, v.62, Pl.9, fig.1, 1933) except that the Nepal rocks have been subjected to some degree of metamorphism.

Chandragiri Fossilliferous Limestones

On the south side of the Chandragiri pass about 50 yards below the summit occur the blue-grey non-metamorphosed limestones in which Medlicott, Bowman and I found fossils. A preliminary examination by Mr. Lahiri, of the fossils in Bowman's collection shows the presence of the following organisms:

Cystoid calyx (incomplete) and detached calyx plates;
Brachiopod valves (incomplete) with radial sculpture, probably *Orthis*;
? Bryozoa, indistinct fenestellid incrustations; Crinoid stems.

These fossils are definitely Palaeozoic and probably Ordovician in age. Descending into the Nepal valley occur quartzites underlain by ripple-marked purple and green phyllites, and slightly metamorphosed banded shaly and sandy limestones, a facies again similar to some in the Semri series of the Vindhyan system along the Son valley.

Nepal Valley

Most of the Nepal valley is covered by fluviatile and lacustrine sediments: clays, sands, conglomerates and lignite beds, A fossil femur bone of an elephant has recently been found. The rocks probably range in age from Pliocene to recent. The underlying older rocks are chiefly quartzites, quartz-schists and calcareous sandstones (Dubrinipani and Pashupatinath); biotite-schists and granulites with occasional dykes of pegmatite, (Nagarkot spurs).

On the north side of the Nepal valley, five miles northwest of Katmandu, is found gneissic granite and tourmaline-pegmatite containing abundant inclusions of biotite-schist and rarer quartzite, tuffs and hornblende-schist.

Trisuli Ganga

The Sheopuri Lekh is built of a syncline of muscovite-gneiss with tourmaline, calc-granulites (Kaulia, 27°49':85°15'), quartz-biotite-granulites and

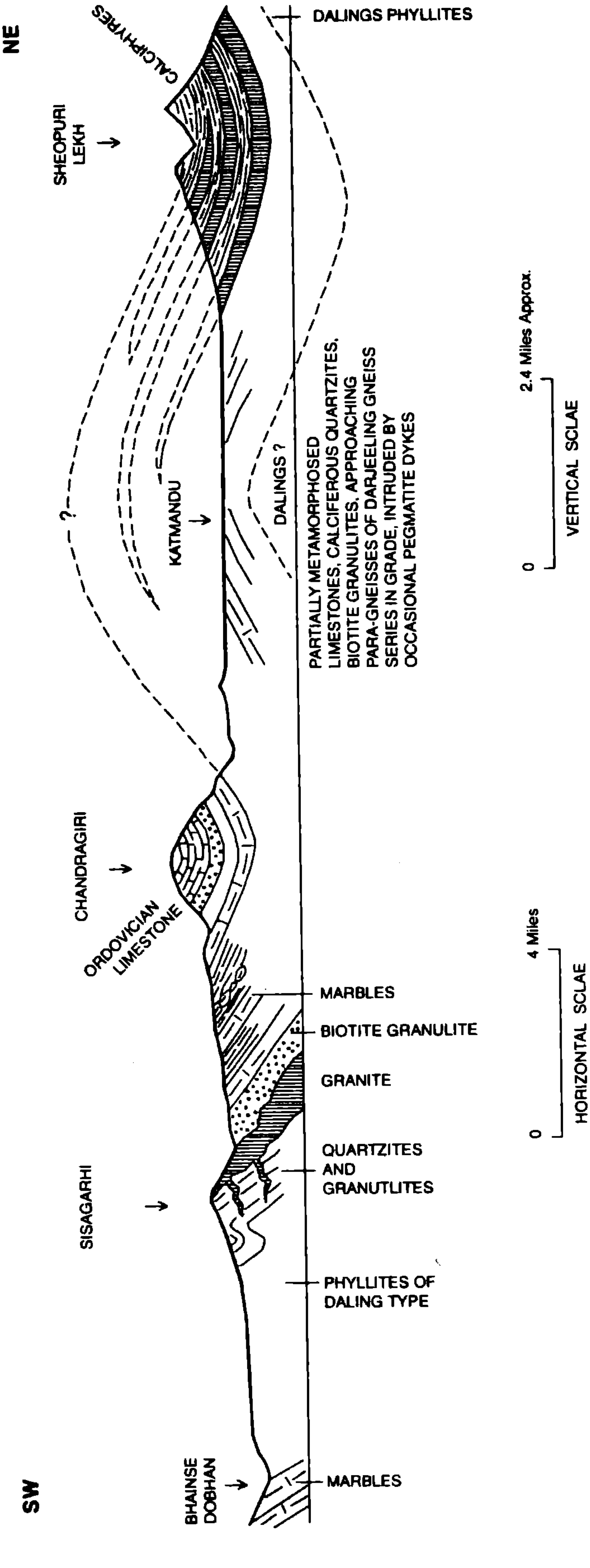

Fig.1. Diagrammatic section across the Nepal valley in sheet 72 E.

biotite-schists. Going down the spurs on the north side, the metamorphism is seen to become less. At a height of 2,850 feet, near Thansing Mukhi Jor, crinkled phyllites and thin-bedded quartzites occur interbedded with mica-schists. Still lower down, phyllites predominate. At the valley bottom almost unmetamorphosed

limestones occur in association with ferruginous phyllites (near Ganrkhar and Dhanphedi). Phyllites and phyllitic schists are found up the Trisuli Ganga as far as Betrawati (27°59':85°11').

Indrawati Valley

The eastern termination of the Darjeeling gneiss of the Sheopuri Lekh syncline is met with on the path down to the Indrawati river to Sipa Ghat (27°45':85°37'), Gneiss, biotite-schist and schistose quartzite are the chief rock types until the underlying phyllites appear near Deopur, sometimes containing garnet. Phyllites continue down as far as the Indrawati. I was not permitted to cross the river, but the rocks on the other side are darker and probably belong to a different series, perhaps faulted or thrust against the phyllite and gneiss groups.

Summary of Relationships in sheet 72 E

Summarising the relationships of the rocks seen in the traverse of sheet 72 E, the succession appears to be in ascending order: phyllites at the base; quartzites, phyllites and granulites; marbles and metamorphosed sandy limestones, together with granulites and schists or phyllites; the Chandragiri limestone of probable Ordovician age, The succession is completed by the intrusion of the Kuli-khani, granite, south of the Chandragiri pass, and of the ortho-gneisses and pegmatites of the Sheopuri Lekh, The complex of ortho- and para-gneisses of the Sheopuri Lekh is similar to the Darjeeling gneiss of Sikkim and eastern Nepal.

Udaipur Garhi; 72 J

The relationships of the rocks at Udaipur Garhi (26°57':86°2') are best illustrated by the diagrammatic section given in Fig.2. The schists, granulites, quartzites and calc-granulites are similar to those of the Darjeeling gneiss and to those of the Sheopuri Lekh north of Katmandu. Immediately above the Nahans occur bleaching carbonaceous phyllites, overlain by thin-bedded siliceous limestones and finally by dark banded limestone with patches of white marble due to low-temperature stress (the bulk of the limestone has not recrystallised).

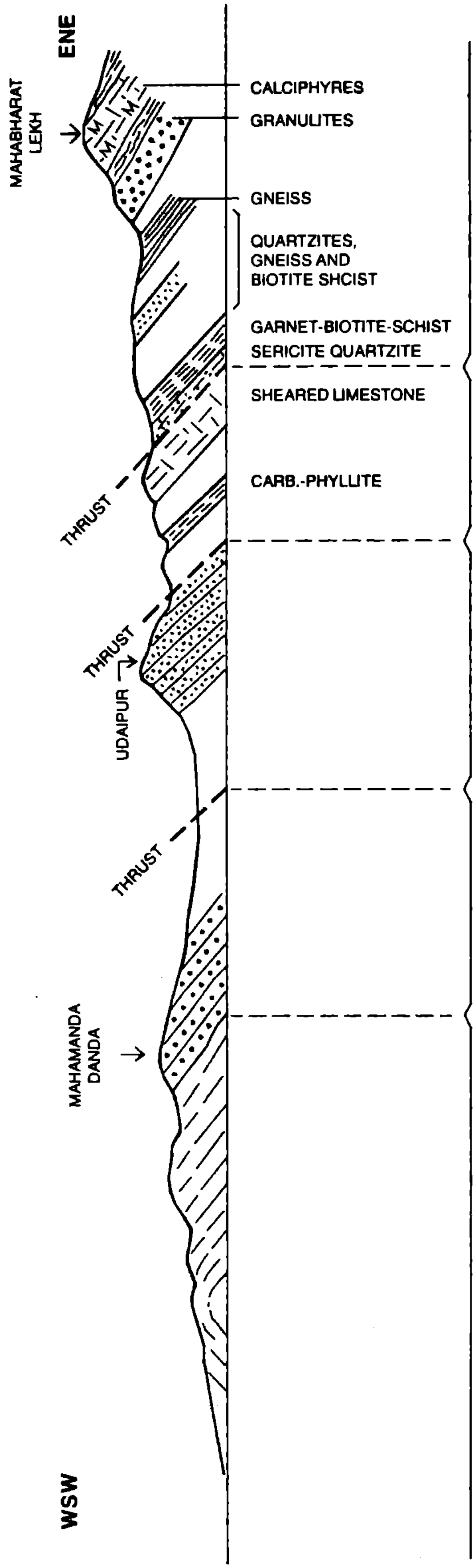

Fig.2. Diagrammatic section through Udaipur-Garhi in sheet 72 J (approximate length is 14 miles. Not to scale).

Separating the limestone from the schist-gneiss series is a graphite band, evidently marking the line of a thrust plane. This limestone is very similar to the dark stinking limestones of the Upper Krol stage. The association of carbonaceous phyllites with an overlying dark limestone recalls the similar sequence along the Krol belt of the United Provinces and it may be mentioned that their disposition relative to the Nahans is the same in the two areas.

In 1931 Dr. Bowman found crushed Gondwana coals 36 miles to the east, just south of the junction of the Sun Kosi with the Arun river (*Mem. Geol. Surv. India*, v.59, p.42, 1924) (26°5': 87°9').

Dharan Bazar 72 N

North of Dharan (26°9':87°17') are found green and purple slates and phyllites, succeeded upwards by vitreous quartzites on the Mahabharat Lekh. The phyllites crop out again north of the ridge, together with bands of ferruginous limestone, These outcrops are only some 10 miles ESE of the coal-bearing Gondwanas found by Bowman, and are in approximate strike continuation with them, Boulders of garnet-mica-schist and gneiss in the Loti Nala prove that the gneiss-schist series is found somewhere in situ near hill 6350 (26°3':87°3').

Dhankuta; 72 N

On the track up from Mulghat to Dhankuta (26°29':87°51') carbonaceous slates and sheeny phyllites, with bands of impure siliceous limestone, pass upwards to phyllitic schist containing occasional garnets (2,280 feet on path) and finally to mica schists (2,500 feet) and quartzite (3,050 feet). North of Dhankuta, mica-schist occurs associated with ortho- and para-gneiss.

Arun Valley; 72 M

Across the Buranse Dande, on the path down to the Arun river and Legua Ghat, occur gneiss at 3,700 feet and biotite-granite at 3,500 feet. Still further below occurs a conspicuous band of marmorised limestone associated with chloritoid-garnet-phyllite (46/426-23338), calc-phyllite and talcose phyllite. This calcareous band strikes down to the Mangme Khola, and crosses the Arun river about two miles south of Legua Ghat. The dips swing round from northeast to east and then to ESE. The same calcareous band is almost certainly found again four miles south of Chainpur (27°17': 87°18') in the form of saccharoidal marbles, calciphyres, tremolite-rocks, epidote and garnet-biotite-schists, and recrystallised quartzites. This band appears therefore to have passed from the phyllite or chlorite zone (chlorite is the characteristic mineral of these phyllites), into the schist zone, represented by higher-grade minerals such as biotite and garnet. Near Piple, the band would be classified in the Daling series, and south of Chainpur in the Darjeeling gneiss.

Milke Pass; 72 M

Garnet-mica-schist, quartzite, and banded ortho- and para-gneisses occur continuously from Chainpur eastwards to the Milke pass. Specimen 46/421-23333 is typical of the garnet-gneisses and contains muscovite, biotite, oligoclase, quartz and garnet. Kyanite-schist occurs near Nundhaki, but was not found *in situ*. Calciphyres, pyroxene-granulite and marbles are found as boulders in the Pilua Khola, having descended from outcrops one mile north of Nundhaki.

Tamur and Kabeli Valleys; 72 M

In the Tamur river, a return is made to chlorite-sericite schistose phyllites; typical Dalings. Such rocks are found at Taplejung and eastwards as far two miles west of Yektin (27°12':87°54') where they underlie and pass up into Darjeeling gneiss. This gneiss continues all the way to Darjeeling. In the neighbourhood of Yektin, Memeng and Pheli, the gneiss series consists of the characteristic banded garnet-gneiss (46/422-23334), with less abundant calciphyres and garnet-amphibolite. A good section is seen where the path crosses the *nala* just below Yektin.

One other feature of interest may be mentioned. Within the Daling phyllites is a thick sill of highly sheared tourmaline-granite which occurs in a dip slope from the Angbung (27°16': 87°44') ridge northwards down to the Kabeli river, (46/424-23336). This is made up of shattered tourmaline, bent muscovite, feldspars which have completely broken down to a felt of sericite and quartz, and patches of quartz mosaic with marked strain shadows. This granite has evidently been sheared in the cold, subsequent to intrusion.

There appears to have been very little metamorphic effect on the intruded phyllites.

Thrust Planes

Three thrust planes have been recognised in Nepal. One separates the Nahan, or Lower Siwalik rocks from the underlying Upper Siwalik conglomerates. It occurs near Hitaura (27°26':85°02') and again near Nepaltar

(26°54':86°32'). This thrust cannot be older than Pliocene. The so-called 'main boundary fault', which separates the pre-Tertiaries from the underlying Lower Siwaliks, is found just north of Sanotar (27°28':85°02'), again on the first col ENE of Udaipur Garhi (26°56':86°32') and probably continues through Dharan Bazar to pass below Tindharia on the Darjeeling-Himalayan Railway. A third thrust was seen 1.6 miles ENE of Udaipur Garhi, and marks the boundary between the garnet-schists of the Darjeeling gneiss and the underlying possibly Krol rocks.

DISCUSSION

Certain points may be summarised. Firstly, the Dalings and Darjeeling gneiss, which occupy a large part of eastern Nepal, owe their present disposition to large scale warping and folding, the gneiss occurring in the cores of the synclinals. North of Katmandu, the Sheopuri Lekh syncline has an east-west axis. Along the Arun and Tamur rivers the warpings have NNE-SSW axes, the Dalings cropping out in the Tamur anticline and the gneiss in the Dhankuta syncline. These broad warps may be compared with the warp mapped by Mallet and Bose in Sikkim. There are in addition minor folds, such as the anticline which crosses the Dhankuta synclinal warp with an east-west axis a little to the south of Chainpur.

Secondly, the upward passage from Dalings into the overlying Darjeeling gneiss appears to be gradual rather than abrupt, as was first noticed in Sikkim by Mallet and later by Bose. Evidence has been cited from the Arun valley of the transgression of a calcareous band from the chlorite zone to the biotite-garnet- zone. To some extent, therefore, the terms Dalings and Darjeeling gneiss may represent metamorphic grades rather than stratigraphical series. The increase in metamorphism upwards must have some connection with the occurrence in this direction of *lit par lit* intrusions of granite and granite-gneiss. Dr. A.M. Heron had independently come to the same conclusion as a result of his traverse through Sikkim with the Everest Reconnaissance Expedition in 1921. This question will be discussed again later.

Thirdly, there is the question of the age of the granite intrusions and of the metamorphism in Nepal. The Chandragiri limestone, of probable Ordovician age, occurs in a syncline resting upon rocks which show an increase in metamorphism downwards. Until detailed mapping is carried out, it is impossible to state whether the Chandragiri limestone lies conformably or unconformably upon the underlying phyllites, marbles and granulites. Should the junction be a conformable one, the Kulikhani granite would be Ordovician or post-Ordovician in age. Should there be an unconformity, this granite would be pre-Ordovician, unless an accident of intrusion resulted in a young granite just failing to reach the unconformable junction with the overlying limestones.

South of the Chandragiri pass, the metamorphism seems to be transitional in type between regional and thermal, and certainly to be connected with the intrusion of the Kulikhani granite and related aplites and pegmatites. Along the Sheopuri Lekh, the metamorphism is more of regional type, and it is more difficult in this case to assess the importance of the role played by ortho-gneiss in the metamorphism. In the case of the Angbung granite (sheet 72 M), which is intrusive into Daling phyllites, there is very little accompanying metamorphism. It remains uncertain whether all the rocks considered above were metamorphosed to varying degrees at one time, or whether later granites have caused local convergence in metamorphic type, e.g., south of the Chandragiri pass, to an earlier series of regionally altered rocks such as those of the Sheopuri Lekh.

SIKKIM

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Geological Notes

Dalings and Darjeeling Gneiss

Gneiss persists from Gangtok almost to the Penlong La. From here to near mile 20 on the Chungtang road crop out phyllites and phyllitic schists for the most part typical of the Dalings and characterised throughout by the presence of chlorite, either disseminated uniformly through the body of the rock, or in some cases both as porphyroblasts and in the ground mass. Dips are to the northeast. Wager has mapped Tertiary granite from Gangtok to near Dikchu, which is presumably the gneiss seen between Gangtok and the Penlong La. At Mangen, these chlorite rocks give place to garnet-biotite-schists and these in turn to gneiss just east of Singhik, the dips being uniformly to the northeast. Gneiss persists from near Singhik as far north as the peaks of Chomiomo, Kanchenjau and Pauhunri, and is made up of a complex: of ortho- and para-gneisses, the whole invaded by granite, pegmatite and aplite. In the igneous group may be placed the common augen-gneisses as described by Freshfield and Dyhrenfurth and many of the rusty banded gneisses such as occur some 2 miles east of Singhik, on the cliffs west of Lachung (27°42': 88°45') and near Dunkung or Deutang (28°01':88°36'). There is in addition a great variety of sedimentary gneisses including calcareous and quartzitic facies.

Calciphyres, pyroxene-granulites and biotite-granulites are found at the following localities:

(1) one mile west of Nanga and nearer Tong, dips to the northeast;

(2) one mile northeast of Chungtang, cropping out both in the Lachen and Lachung valleys, dips northeast;
(3) from the angle between the Zemu and Lachen valleys southwards to west of Chotang, dips east, west and vertical;
(4) in the Sebo Chu valley at about a height of 15,000 feet on the west side of the Khonpuk glacier (27°53': 88°50'), dips southwest.

The first three of these occurrences have been recorded by Hayden and Fermor.

Quartzites are seen most prominently at the confluence of the Lachen and Lachung Chus, at Chungtang, striking from near Latong Tenga to the neighbourhood of the Black Rock, the dips being NNE. They are also found in the Teesta valley three quarters of a mile north of Tong.

The broad distribution of the rock groups is as follows. A zone mainly of para-gneisses, including the two facies mentioned above, and approximately 11 miles in width, runs SE-NW from about Chumunko (27°27':88°48') to Lama Anden or Lamgebo (27°45':88°30'). North of Lachen a prominent syncline is seen particularly at Yatung, running north-south, so that it is clear that the NW-SE direction of strike does not persist for long. These para-gneisses are apparently overlain by rusty-banded biotite-gneiss and augen-gneiss, which are very probably of igneous origin. Such rocks are well seen for the first ten miles up the Sebo Chu valley, from Lachung to Mome Samdong and from about Potago in the Lachen valley up to Deutang and the Gayabo lake. Another outcrop of para-gneisses occurs in the upper Sebo Chu valley, with dips to the southwest, under the ortho-gneisses. Still further to the north occur what are probably interbanded ortho- and para-gneisses with a general dip to the north, as on the Tibetan Slopes of Chomiomo and Pauhunri. These rocks are clearly highly folded, as may be seen in the great overfold between what is probably Survey of India Peak No. 109 (22,960 feet) and the peak next to the southeast (*see* Plate 4). Viewed from the south, this appears to be a horizontal fold with a flat axial plane, but the impression of horizontality may be due to overfolded beds, with a northward-inclined axial plane, cropping out upon a nearly vertical precipice wall. The complexity of folding on the Sebo wall suggests that the succession will be very difficult to unravel. Broadly speaking, however, the para-gneisses dip under the ortho-gneisses.

In northeast Sikkim the general strike is NW-SE, but it is certain that this strike is local, and changes westwards, probably to east-west.

Granite, Pegmatite and Aplite

Thin veins of aplite begin to be noticeable in the gneisses at Tong bridge.

Plate 4. Wall of peaks enclosing upper Sebo Chu valley, north-east Sikkim. Flat fold in ortho- and para-gneisses; intrusive granite seen cutting across the gneisses below both the main peaks. The peak on the left or west side is probably Survey of India peak No. 109, marked as 'Round Snow, 22,960' in the older maps. View taken from the Oorrie 16,500 camp in an ENE direction.

They become conspicuous at Chungtang, one in the Lachen Chu being a foot in width, and increase in importance northwards. On the northern slopes of Chomiomo, around the Sebo La pass and on the precipices north and west of the upper Sebo Chu valley the gneisses become riddled with bosses, thick dykes and sills of fine-grained white granite. This granite cuts across the folds of the gneisses and is therefore later than the folding. The complexity of intrusion is well displayed on the flat-topped glaciated ridge of about 17,000 feet running on the north side of the uppermost Sebo La lakes. Flaggy ferruginous gneiss and quartz-granulite are easily demarcated from the white granite which weathers into large polygonal boulders. While most of the granite is clearly discordantly intrusive, there is little doubt that some of it has sometimes penetrated the gneisses in a lit par lit fashion, even in bands as narrow as one centimetre in width. One concordant contact on a large scale is seen in a corrie at about 16,500 feet on the west side of the Upper Sebo Chu valley, where the granite ends abruptly against the flat surface of the overlying gneisses. The discordant contacts are, however, the more characteristic and are proof that this granite is distinct from and younger than the gneiss series.

Microscopical

The young granite is a fine-grained white granite without flow structures (46/882-23692, 23694). Under the microscope it is seen to consist of biotite, generally muscovite, oligoclase, orthoclase and quartz, and with tourmaline, pink topaz, rutile and occasionally sillimanite as accessories. The topaz is often seen in hand specimen in small pink prisms. Hayden mentions the presence of beryl in the pegmatites of the Lachen valley (*Mem. Geol. Surv. India*, v.36, Pt.2, p.59, 1907). The only exceptional mineral in my specimens is topaz. Where tourmaline is common the biotite has generally been chloritised. In the Sebo Chu valley the tourmaline is frequently found to occur in spherical clusters, up to 5 cm. in diameter, with a biotite-free reaction rim one centimetre in width, (46/883-23693). Plagioclase is in excess of orthoclase. The aplites show the same assemblage of essential minerals, except that the orthoclase appears to be commoner, (46/884-23695).

The quartzites near Chungtang very generally contain sillimanite (46/908-23702, also Sir L.L. Fermor's slide No. C-54), and sometimes a green mica which may be fuchsite (46/888-23701).

The pyroxene-granulites contain augite or diopside, sphene, andesine or labradorite, orthoclase, microcline, and quartz. In the calciphyres occur free carbonate, together with subordinate diopside, tremolite, biotite, andesine or labradorite, orthoclase, sphene, pyrites. In 46/886-23698 the dominant ferromagnesian mineral is hornblende.

The pelitic rocks of the Dalings are best exposed between the Penlong La and Dikchu. The type rock is a green chlorite-sericite-quartz-phyllite grading into schist (23703). Nearer the overlying gneiss it develops into a coarser schistose phyllite with porphyroblasts of chlorite. Specimen 46/889-237.04 is a garnet-biotite-chlorite-sericitè-schist. It may be remarked that both in Nepal and in Sikkim garnet frequently occurs in chlorite-sericite rocks. Some, but not all, of these rocks may be retrograde. Rock 46/889 shows the marginal breakdown of garnet and the chloritisation of the biotite. Sir L. L. Fermor had previously collected, from about the same locality, an altered staurolite-mica-schist which shows the sericitisation of the staurolite and the biotite altered to chlorite (C-39). The fact that these rocks occur in the vicinity of copper lodes suggests that the retrogressive change may be hydrothermal and connected with local mineralisation. Those who postulate a thrust between the Dalings and the Darjeeling gneiss would probably claim that such changes indicate low-temperature stress and the existence of a thrust.

Lachi Series

Wager (Everest 1933, p.333, 1934) has described the finding of Lower Permian brachiopods in what he has termed the Lachi series: a complex association of quartzites, limestones, hardened shales and pebble beds. When I was on leave in England in 1933 he kindly showed me specimens of the pebble beds, which in hand specimen and under the microscope resemble the Blaini tillite of the Simla-Mussoorie foothills. The pebbles he collected from these beds were of the following kinds:

Darkish quartzite,
Quartzites, some rich in detrital tourmaline,
Pink limestone,
Sericite tuff or rhyolite,
Muscovite-granite.

This year Gourlay and I found a similar boulder bed, presumably from about the same locality (28°01':88°45'), on the west side of Lachi hill and east of the Gordamah lake. The pebbles were rare. The matrix is a dull green-brown grit, composed of completely ungraded angular quartz grains, with subordinate microcline and sodic plagioclase set in a very fine brown paste full of sericite, biotite and quartz, (46/909-23705). It shows a striking resemblance to the green silty sandstones of the Talchirs in the peninsular Gondwana coalfields. The microscope suggests that the rock is either glacial or pyroclastic in origin.

Tso Lhamo Series

At the foot of a gully on the east side of Lachi hill, at about a height of 17,300 feet, and at bearings of 74° to the northern end of Tso Lhamo, 130° to Pauhunri and 157½° to the Dongkya La, we found dark limestones and shales with a rich fauna of ammonites, lamellibranchs, and brachiopods. The position of the locality is about Lat. 28°02' N: Long. 88°46' E. (*see* Plate 5), and the dip of the strata is 200 to the ESE. This fauna has not been examined in detail, but my colleague Dr. M.R. Sahni believes it to have Triassic affinities. The final determination of age must rest on the results of a detailed palaeontological examination, but it seems clear that the fossils indicate that the beds are pre-Jurassic and probably post-Permian. They are younger, therefore, than the Lachi beds of Wager, which also they overlie in stratigraphical sequence. Underlying the richly fossiliferous beds are about 300 feet of grey gritty flags containing uncertain plant remains.

Along a ravine running NNE of Pauhunri 23,180 peak, occurs a series of flags, limestones and clay-slates. A lamellibranch resembling *Daonella* was found at about 19,400 feet. The flags are very similar to those underlying the richly fossiliferous Tso Lhamo limestones, and like them contain doubtful plant impressions. Underlying these beds, and cropping out on hill 21,000 feet, northeast of Pauhunri, are dark blue shattered limestones which are very probably the same as the Upper Everest limestone of Wager. This limestone and associated shales overlie the gneiss of the Pauhunri massif. I have little doubt that the beds on the northeast side of Lachi hill, and those of the Pauhunri ravine are equivalent. It is very probable also that the fossiliferous limestones northeast of Tso Lhamo found by Hooker in 1850 belong to the same series, and may be Triassic. I agree with Wager that Hooker's limestone is not the same as the Upper Everest limestone. We passed the former on the way down from Pauhunri, but fatigue and mild frostbite prevented us from delaying there.

I would suggest the designation *Tso Lhamo* for these probably Triassic beds, a name beautiful in itself, and given to a lake the position of which is one of the fairest in the world (Tso Lhamo = Lake Goddess). They fill a gap between the recently discovered Lachi beds and the Jurassic system which has long been known to cover so much of Tibet (*Mem. Geol. Surv. India*, v.36, pt.2, 1907).

Probable uninversion of Tibetan sedimentaries on Himalayan gneiss

Dyhrenfurth has called a succession of beds in northwest Sikkim 'von mehreren tausend Metern Machtigkeit' the *Dodang* series ('Himalaya: Unsere


Fig.1


Fig. 2

Plate 5

Fig.1. Pauhunri (23,180 feet) massif and satellite hill of 21,000 feet; Sikkim-Tibet frontier. Position of fossiliferous rooks shown by arrows. Teesta glacier on the right. Telephoto view from the flats east of Kerang, at about 18,000 feet, towards the southeast.

Fig.2. Tso-Lhamo beds, seen from the south on Laohi hill, at about 17,600 feet, north-east Sikkim. Position of fossiliferous beds shown by arrows. Northern end of Tso Lhamo visible. Moraine-covered slopes of the Sikkim-Tibet frontier seen in background. Early winter snow.

expedition', pp.301-303, Berlin, 1931). They consist of limestones, limestone breccias, calcareous shales, phyllites and sandstones, with indeterminable fossils. The age of these beds cannot be determined by reference to the fossils, but by lithological comparison with the Mesozoic rocks of the Alps, Dyhrenfurth claims to have found a complete succession of Trias, Jura and Cretaceous. He states also that this succession has been overthrust in inverted position, with the Trias uppermost, upon the Kanchenjunga gneiss. He admits that lithology is not always a safe guide, but questions whether a series of such thickness could belong to a single formation.

Only 35 miles to the east we have the following succession:

Jurassic rocks of Tibet;
Tso Lhamo series, probably Trias;
Lachi series, probably Lower Permian;
Everest limestone;
Gneiss of Chomiomo, Kangchenjau and Pauhunri.

This is a normal, uninverted succession. The Everest limestone is certainly very shattered, and may owe its deformation to a thrust between the unmetamorphosed sedimentaries and the underlying gneiss, though Wager does not accept that even a thrust is present. But the fact that a normal succession occurs in northeast Sikkim, either autochthonous or thrust upon the gneiss, is an indication that Dyhrenfurth may be incorrect in supposing an inverted sequence on the Dodang Nyima range. His conclusions are based upon uncertain evidence.

DISCUSSION

In spite of the fact that these observations are based only on traverses and not on detailed mapping, thereby lacking the greater certainty which the latter would provide, yet there are features which have appeared from them and from the observations of other geologists that require discussion. I have already discussed the observations made in the Karakoram as far as is legitimate from their cursory nature. The Karakoram form a separate geographical unit and are best considered independently from the more homogeneous outer Himalaya between Garhwal and Sikkim. What follows concerns chiefly Garhwal, Nepal and Sikkim.

RELICS OF PENINSULAR INDIA IN THE HIMALAYA

As indicated on general grounds

Gondwana relics: It has long been known that coal-bearing Gondwana rocks occur in the Darjeeling and Assam foothills. More recently Dr. Fox has been able to identify a boulder bed just above Tindharia station, which may possibly be glacial. Dr. Fox has also observed, near Tindharia and along the Teesta valley, further outcrops of the intrusive lamprophyres and mica peridotites that form such a characteristic feature of the Bokaro, Jharia and Raniganj coalfields (*Mem. Geol. Surv. India*, v.59, p.50, 1934). Sutton Bowman found coal-bearing Gondwanas in eastern Nepal at the confluence of the Sun Kosi and Arun rivers. The Gondwana rocks of Kashmir are well known through the work of Middlemiss, Bion and Wadia and they do not require further description. They afford proof that the Gondwana formation spread far to the north over part of what is now the Kashmir Himalaya, and has been involved in the Himalayan folding.

As stated above, Wager in 1933, and two of us in 1934 found boulder-bearing beds associated with Lower Permian rocks on Lachi hill, north of the Himalayan range. 35 miles to the southeast of Lachi, in the neighbourhood of the Ammo Chu and Phari Dzong, occurs the Dothak series of Hayden. This consists of a lower series of limestones with arenaceous and argillaceous beds above. Wager correlated these rocks with the Mount Everest limestone series. Dr. Fox wrote in connection with them (*op. cit*, v.58, p.62, 1931):

> 'Seeing that they occur on the Indian side of the Himalayan range and that an Anthraoolithic fauna has been discovered in the Eastern Himalaya in the Abor country it is quite possible that the Dothak series may contain representatives of the same rocks. They would then continue the line of Permian and upper Carboniferous outcrops which evidently stretch from Moulmein and the Shan Plateau through the Abor hills to the Central Himalaya and Kashmir to the Punjab Salt Range.'

Westwards of Sikkim, boulder beds are also found along the peninsular border of the United Provinces and Punjab Himalaya, including the breccia of Garhwal (? glacial or volcanic), the Mandhali beds and the Blaini boulder bed. The Talchir glacial boulder bed of the Salt Range is well known. Wadia has found striated boulders in the Tanakki boulder bed of Hazara, near Abbottabad and has therefore confirmed the suggestion put forward by Oldham, and later by Middlemiss, that the boulder bed is glacial and equivalent to that of Talchir (*Rec. Geol. Surv. India*, v.62, p.153, 1929); *Proc. 18th Indian Sci. Congress, Nagpur*, p.303, 1931).

Most of these boulder beds are of glacial origin, though there is doubt in some cases as to what extent volcanic agglomerates may not be included in that type of sedimentation (Lansdowne area of Garhwal). The association of such beds on Lachi hill in northern Sikkim with possible plant-bearing strata is analogous to the definite association of plant-bearing Gondwana rocks with the Talchir boulder bed in the Indian Peninsula, and is some indication that the origin of the Lachi pebbly grits is glacial rather than volcanic. Their resemblance to the Talchirs is certainly very striking. Accepting a glacial origin for these beds it follows that the great Gondwana ice sheet must have spread over what is now the Himalayan chain of Sikkim at least as far as Lachi (28°01':88°45'). The actual distance of expansion of this sheet would have been far greater, since the position now occupied by the Lachi series is the result of shortening due to folding and thrusting subsequent to the Gondwana period. There is an alternative explanation in the supposition that Hercynian, or embryonic Alpine movements may have initiated an elevation along the present Himalaya of sufficient magnitude to induce a local ice sheet to form adjacent to the main Gondwana ice sheet (in a manner comparable to the Alpine ice sheet in front of the larger Scandinavian sheet during Pleistocene times). Since, however, proved Gondwana rocks occur south of Darjeeling, now only some 70 miles away from Lachi, it is simpler to associate the whole series with one common cause, and assume the extension of the Gondwana ice sheet as far as what is now Tibet. The significance of this is that the northern edge of Peninsular India at that time must have been north of Lachi, and therefore that the whole of the Sikkim Himalaya belonged then properly to Peninsular India.

The glacial beds of Lachi in northern Sikkim overlie the Mount Everest limestone, which presumably was marine. They are also themselves overlain by the marine Tso Lhamo beds. It is evident that while most of Peninsular India remained almost continuously part of the Gondwana continent from the Carboniferous up to the Mesozoic era, its northern edge, such as in Sikkim, showed fluctuations between marine and continental conditions. The occurrence of marine Productus limestones in very close association with the Talchirs and continental Barakars of the Umaria coalfield (23°30':80°48') may be cited as an indication that even in Peninsular India there were local marine invasions. Such invasions do not vitiate the palaeogeographic importance of the glacial beds, wherever they are found.

Metamorphics

The nature of the Metamorphics in the Himalaya is well summarised on page 291 in the second edition of A Sketch of the Geography and Geology of the Himalaya Mountains and Tibet, from which the following passages may be quoted:

> 'Thus we may regard the crystalline belt as composed of three elements, viz., intrusive granite, metamorphic schists due probably to the action of the granite on the rooks into which it has been intruded and which it has partially absorbed, and, lastly, a series of old gneisses, schists, granulites and crystalline limestones, of which the advanced stage of metamorphism cannot be attributed merely to the Himalayan

> granite. These latter rocks, in fact, bear a marked resemblance to certain Peninsular types which are found in Madras, Burma, Ceylon, the Central Provinces . . . and Rajputana, and which are referred to the Archaean ...
>
> Thus it is difficult to escape the conclusion that the axis of the Himalayan chain and of the associated ranges to the west is in part made up of true representatives of the oldest known group of rooks, and that these are merely the northerly extension of the similar rocks of the Indian Peninsula.'

Proved pre-Cambrian sediments and metamorphics, as determined by their position relative to known Cambrian sediments, are found only in Kashmir, as Mr. Wadia's Salkhala series. Wadia and West consider, however, that the Jutoghs of the Simla Hills are equivalent to the Salkhalas, and the lithological comparisons mentioned in the above quotation suggest the strong probability that pre-Cambrian metamorphics occur further east. The difficulty of identification lies in the fact that post-Archaean granites, intruded under regional stress, may have converted Palaeozoic and even later sediments into metamorphics resembling those of the Archaean. This has, of course, been realised, and is suggested in the quotation given above, but it is a possibility which has not, perhaps, been given the emphasis it deserves. In Scandinavia, Bohemia and the Alps there are strong grounds for assuming the regional extension of Palaeozoic crystalline schists.

Aravalli Strikes

The Aravalli strikes found locally in rock structures in the Garhwal Himalaya also suggest a northward extension of Peninsular rocks into the Himalaya (*Rec. Geol. Surv. India*, v.66, p.467, 1933). These rocks have been subsequently involved in the Tertiary movements, without, it is believed, the original structures having been rotated by the later movements so as to lose their former orientation. Geodetic work by the Survey of India has shown a region of high density continuing from Rajputana into the Himalaya near Dehra Dun. Lt. Col. Glennie has consequently suggested that there may have been a buckling up of the Gangetic trough near Dehra Dun along a rejuvenated line of weakness continuing from the Aravalli range (*Professional paper No.27, Survey of India*, pp.18, 27, 1932). If this buckling originated only after the Gangetic trough had formed, it is clearly very recent, and would have no connection with the pre-Krol NE-SW structures found in the Himalaya. Some indication of recent activity along Aravalli directions is afforded by the present disposition of the Blaini-Krol-Tal sequence into three tectonic basins (west of the Tons river, between the Jumna and Ganges rivers, and east of the Ganges) which may also be due to rejuvenation in a NE-SW direction. It is difficult, however, to differentiate cause and effect, to decide to what extent rejuvenation along the Aravalli strike has been operative in contradistinction to the possible persistence of an incompletely base-levelled range projecting into the Himalaya. This question can only be decided after the distribution of rock facies in the Himalaya is better known. Factors such as the distribution of conglomerates in relation to a possible persistent NE-SW ridge, the occurrence of marine rocks such as the Krol limestone, and the dying out of the Dagshais and Subathus to the south-east, will all have a bearing on the problem (*See* Fermor, *Rec. Geol. Surv. India*, v.62, p.391, 1930).

As indicated by Palaeoclimates

The existence of rocks of Peninsular type within the Himalaya may also be considered in the light of indications afforded as to the nature of palaeoclimates. The following sequence of climatic events can be traced in Peninsular India. Dr. Fox and the writer maintain that the rocks of the Vindhyan system, in particular the series overlying the Semris, were deposited in a generally arid environment (*Mem. Geol. Surv. India*, v.62, p.223, 1933). A correlation has been suggested between some of the Vindhyan rocks and those of the Cambrian sequence in the Salt Range. Gee has established the continuity of sequence from the Neobolus shales up to the Salt Pseudomorph beds, and the Cambrian age of the latter (*Rec. Geol. Surv. India*, v.68, p.115, 1934). The existence of arid conditions during the Cambrian is therefore certain. The Talchir tillite, of Upper Carboniferous age, proves that glacial conditions prevailed at that time. By Panchet (Trias) times, however, in the Gondwana epoch, the climate had again become arid (*Mem. Geol. Surv. India*, v.58, p.104, 1932; Wadia - Geology of India, p.127, 1926).

With regard to the climatic sequence in the Himalaya, the grounds are less sure partly because metamorphism may have obscured diagnostic characters. The Chandragiri limestones of Nepal, of probable Ordovician age, afford no indications as to climate. The rocks immediately underlying the Chandragiri limestones nevertheless show a striking resemblance to the Semri series of the Vindhyan system in colour and nature of sedimentation. In the more westerly Himalaya, of the United Provinces, the Mandhali and Nagthat stages of the pre-Blaini Jaunsar series are characterised by frequent purple and green colours, by ripple-marked quartzites and by conglomerates and boulder beds. The conditions of deposition of these beds have not been properly elucidated. A closely adjacent upland or mountain terrain is implied, however; to supply the coarse clastics, and the conditions were probably in the main fluviatile and continental; in contrast to the generally marine deposition of the fossiliferous Palaeozoic sequence of the Spiti area a short distance to the north. The origin of all the boulder beds is not known. The question is rendered difficult by the obscure relationships of the Mandhali and Nagthat stages, in a manner which appears to be comparable to that of the composite Tanols in Kashmir (The whole question of the sequence of the pre-Blaini rocks is one of great difficulty. From the point of view of this paper it is sufficient to accept that the rocks mentioned are pre-Blaini and very probably Palaeozoic).

The Blaini boulder bed is regarded as glacial and as equivalent to the Talchir boulder bed of the Peninsula.

A short distance above the Blaini, and separated from it only by the Infra-Krol shales and slates, is the local Krol sandstone of the Solon area, in which wind-blown sands are a characteristic feature (*Rec. Geol. Surv. India*, v.62, p.168, 1920). These winds could have been either hot or cold.

Gypsum, in one place probably with anhydrite also, has been found in the Krol limestone (Rec. Geol. Surv. India, v.67, p.450, 1934). The inversion temperature of gypsum into anhydrite is 63.5°C (146°F) in pure water, and 36°C (97°F) in a saturated solution of sodium chloride (J.W. Mellor, *A Comprehensive Treatise on Inorganic and Theoretical Chemistry*, v.3, p.770, 1928). It may be possible therefore to postulate the existence of warm conditions; presumably with a considerable concentration of salts (since the temperature of sea water seldom rises above 35° C. or 95° F., which is far below the inversion temperature of gypsum into anhydrite in pure water) during the time of deposition of the Krol limestones. Dessication does not necessarily imply the existence of unusually warm conditions. The winter temperature of the brackish Caspian sea and the saline gulf of Karaboghaz is about 0° C. The summer temperature is about 27°C (80° F) (January and July Temperature Charts, as in the Oxford Advanced Atlas, p.16, 1931). It is unwise at present to press the occurrence of gypsum too far in this connection since the origin of the calcium sulphate in the Krol limestones is not definitely known. The gypsum may in places have been a replacement mineral though the evidence at Ridana suggested there its primary origin. Further, the inversion of gypsum to anhydrite may be due, as Dr. Fox has suggested to me in conversation, to stress: anhydrite has the smaller molecular volume and may be the stress form of calcium sulphate. Hayden has described the gypsification of Carboniferous limestones in the Spiti area, showing that the gypsum there arose out of the action of sulphurous waters on limestone (*Mem. Geol. Surv. India*, v.36, Pt.1, p.41, 1904. Fieldwork during the 1935 season has shown that gypsum found in the Upper Krol limestone of the Dehra Dun district is replacive. At Sera (30°18':78°14') replacive gypsum is found within 500 yards of a sulphur spring).

Following upon the marine Krol series are the Tal rocks (*Rec. Geol. Surv. India*, v.67, p.384, 1934). The upper Tal stage is represented by from 2,000 to 4,000 feet of white and purple quartzites, current-bedded and ripple-marked, and of intercalated sun-cracked muds. This stage was clearly laid down Junder fluvio-deltaic conditions. Proximity to the sea is indicated by the occurrence in Tehri Garhwal and Garhwal of a sandy limestone at the top of the stage full of broken lamellibranchs and brachiopods. The combined Krol-Tal sequence ranges with fair-certainty from -late Palaeozoic to the Mesozoic.

The sequence of events in the Peninsular Himalaya is certainly complicated by marine invasions. But the prevalence of fluviatile and continental conditions, and certain qualitative indications in the marine rocks, seem sufficient to suggest that both Peninsular India and the Peninsular Himalaya underwent the same broad climatic changes.

It is understandable that these climatic changes would have little effect on the faunal population of the open sea, including the Tethys for the greater part of its history. Climatic influence would be more strongly felt, however, in the region immediately to the south of the Tethys where the rocks, even though water-deposited, must have been laid down in areas frequently land-locked and shut off from the open ocean. Comparison may be made with the Germanic facies of the Trias bordering the Alpine geosynclinal facies. The almost complete absence of fossils from the rocks of the Peninsular Himalaya is a most significant feature, and may perhaps be explained by the somewhat stringent conditions which prevailed. It may be remarked, however, that in other areas which must have been subject to equally stringent conditions (Old Red Sandstone of Britain, Permo-Trias of Britain and Germany, Panchet of India) the faunas of the time survived in sufficient numbers to permit the age of the rocks being determined. This absence of fossils was discussed by Pilgrim and West (*Mem. Geol. Surv. India*, v.53, p.133, 1928), although not explained by them, and has again been recently discussed by West (*Current Science*, v.3, p.289, 1935). A satisfactory explanation has yet to be found.

Conclusions

The above considerations suggest the strong unity which must have existed between what are now the Himalaya and the Indian Peninsula, and add emphasis to the conclusions previously given by Hayden and Burrard (*A Sketch of the Geography and Geology of the Himalaya Mountains and Tibet*, 2nd Edn., p.296, 1934). The striking bands of Siwalik rocks and Indo-Gangetic alluvium, which run from the Punjab into Assam, divide off the Himalaya from Peninsular India. The rocks of the Himalaya have, moreover, been caught up in the later Tertiary folding and are in positions unlike what is known of the outcrops of their believed equivalents in the Peninsula. In spite of this present divorce of the Himalaya from the Peninsula, much of the Himalaya should be considered as made up of the foreland to the Tethys sea, and of its continental shelf. It may be suggested that emphasis should be made on the division of the Himalaya into two main types:

(1) Tethys Himalaya; Spiti, Tibet, etc.
(2) Peninsular Himalaya; most of the outer Himalaya, and, possibly at one time, all of Sikkim.

DARJEELING GNEISS AND DALINGS

Aş has long been known in Sikkim, and has now been found to obtain in Nepal, the Darjeeling gneiss overlies the Daling series. This fact is indisputable. Two explanations suggest themselves. The first is that the Darjeeling gneiss and the Dalings are two distinct series, separated by a thrust plane. This view is favoured by Dyhrenfurth and to some extent by Wager. In Wager's section, a thrust plane is marked between the two series ('Everest 1933', p.327) but in the text he states that intrusion of granite into the Dalings near Gangtok has caused the Dalings to resemble Darjeeling gneiss, remarking that 'this may one day afford a clue to the origin of the latter' (*Ibid*, p.320). The second explanation is that the granite under regional stress has invaded the upper part of a great sedimentary series converting it, where invaded, into a series of mixed ortho- and para-gneisses. This view was arrived at independently by Dr. A.M. Heron and myself. Dr. Fermor had previously adopted a somewhat similar explanation, namely that the strips of para-schists in the gneiss of northeastern Sikkim represent portions of the Daling series that have been infolded within the ortho-gneisses and rendered at the same time thoroughly crystalline. Dr. Fermor noticed that the slates of the Daling series become more crystalline as the gneiss boundary is approached (*Rec. Geol. Surv. India*, v.42, p.92, 1912).

The features observed in connection with the Darjeeling gneiss and the Dalings may be summarised as follows:

(1) It is difficult to trace an exact boundary between the Dalings and the Darjeeling gneiss. The Dalings become more coarsely chloritic and schistose upwards towards the schists and gneisses of the Darjeeling gneiss group. This transition has been noticed north-west and east of Katmandu in sheet 72 E, south of Dhankuta in sheet 72 N, along the Arun and Khabeli valleys in sheet 72 M, and along the Teesta valley in sheet 78 A. The transitional zone between the Daling phyllites and the gneiss complex is too wide to permit of any exact boundary or thrust plane being drawn between them on a large scale map. This difficulty of drawing a sharp boundary was experienced by Mallet over most of the area he mapped (*Mem. Geol. Surv. India*, v.11, pp.41-43, 1874).

(2) The transitional chlorite-sericite-biotite phyllites and schistose phyllites often contain small garnets. Some of these rocks may be regarded as retrogressive, but the cause of the retrogression is not necessarily due to shear. Hydrothermal action may have been locally operative.

(3) There is evidence, which can only be proved by detailed mapping, that a calcareous band along the Arun valley moves from what in one place must be regarded as Dalings to what further north must be mapped as gneiss,

(4) In Scotland there has been worked out by Barrow; Tilley and others the well known progressive sequence of metamorphic zones: chlorite zone; biotite zone; almandine zone; staurolite and kyanite zones; sillimanite zone (Harker, 'Metamorphism', pp.208-229, 1932). In Nepal and Sikkim it is possible that detailed mapping may establish a somewhat similar sequence, From the cursory examination that I was able to make, there is the following suggested sequence with regard to the pelitic rocks:-

(Top)	
Kyanite-schists Garnet-biotite-schists	Darjeeling gneiss
Porphyroblastic chlorite-sericite-phyllites, often with garnet	transitional
Chlorite-sericite-phyllites Slates and phyllites	Dalings
(Bottom)	

It seems possible, therefore, that the sequence may be regarded as illustrating a true progressive increase in metamorphism upwards, I do not think that there are sufficient grounds for postulating a thrust plane between the Dalings and Darjeeling gneiss as was maintained by Dyhrenfurth, and is shown in the section on page 327 of 'Everest 1933'. Locally there may be faults and even thrusts, such as the one mapped by Mallet north of Darjeeling, but the general disposition seems to be one of gradation. In view of these facts, it is possible as previously stated that the terms Dalings and Darjeeling gneiss may apply respectively to the lower and upper portions of a great sedimentary succession, the upper part of which has been injected and metamorphosed by granite magma under stress. The patterns marked on the map (*see* Plate 6), would in this case represent metamorphic facies rather than definite stratigraphical stages, or two distinct series separated by a thrust plane. In general, lit par lit intrusion by its very nature would tend to keep more or less to stratigraphic horizons, but this is evidently not everywhere so. The penetration of magma in the upper part of such a succession is certainly a remarkable feature. One may perhaps regard such an extensive magma migration as having taken the place of translation of solid rock across great thrust planes, though the factors operative in the two cases would be different.[1]

Horizontal distribution

As regards the continuation of the Dalings and Darjeeling gneiss, to the north-west, I have little doubt that both are found westwards as far as Katmandu. I would suggest also that the granites of Dwarahat, Dudatoli and Lansdowne in Garhwal may be equivalent to the igneous portion of the Darjeeling gneiss. In these cases also there appears to be the same intimate connection between intrusion of granite and metamorphism, and the same gradation from phyllites to schists, as was described by Middlemiss in 1887 (*Rec. Geol. Surv. India*, v.20, p.137, 1887). A good example may be seen on the path from Ranikhet to Dwarahat. With regard to the main Himalayan range, there is a strong similarity between the quartzitic and calcareous granulites of the Alaknanda valley and Sikkim. The Nepal ranges are not known, but specimens collected by Wager of the Lower Everest limestone resemble the calciphyres and calc-granulites of Garhwal and Sikkim. Since the geological strike of these bedded granulites (so well seen also on Kedarnath from the southwest, Trisul from the west and on Nanda Devi} coincides in general with the geographical alignment of the Great Himalayan Range, it is a reasonable conclusion that this range is built throughout a distance of some 600 miles (1,000 kilometres) of a great series of granulites with intrusive ortho-gneisses and granites.

The connection between the NW-SE extension of the Darjeeling gneiss complex in the lesser Himalaya and the similar extension of the rocks comprising the Great Himalayan range is at present hardly known. In Sikkim, the Darjeeling gneiss joins up with the rocks of the Kanchenjunga and Pauhunri massifs, but the precise differences between the gneissic complexes of the two areas in Sikkim which must exist to allow of such contrasts in topography have not been discovered. According to Wager, the contrast may be due chiefly to differential isostatic uplift. In Garhwal there is probably a thrust separating the

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[1]After this account had gone to the press there has appeared a paper by S. K. Ray on the Gneissic Complex of the Darjeeling District, which confirms the conclusions given above. *Quart. Journ. Geol. Min. Metal. Soc. India*, v.7, (1935). On page 44 he states:

> It has, thus, been shown that the gneisses and schists of the Darjeeling area are the products of regional metamorphism of an argillaceous sedimentary formation and that the whole area, particularly the sillimanite gneiss near Darjeeling, has been permeated with late magmatic emanations in the form of pegmatites, aplites, pneumatolysers and other late stage fluids.'

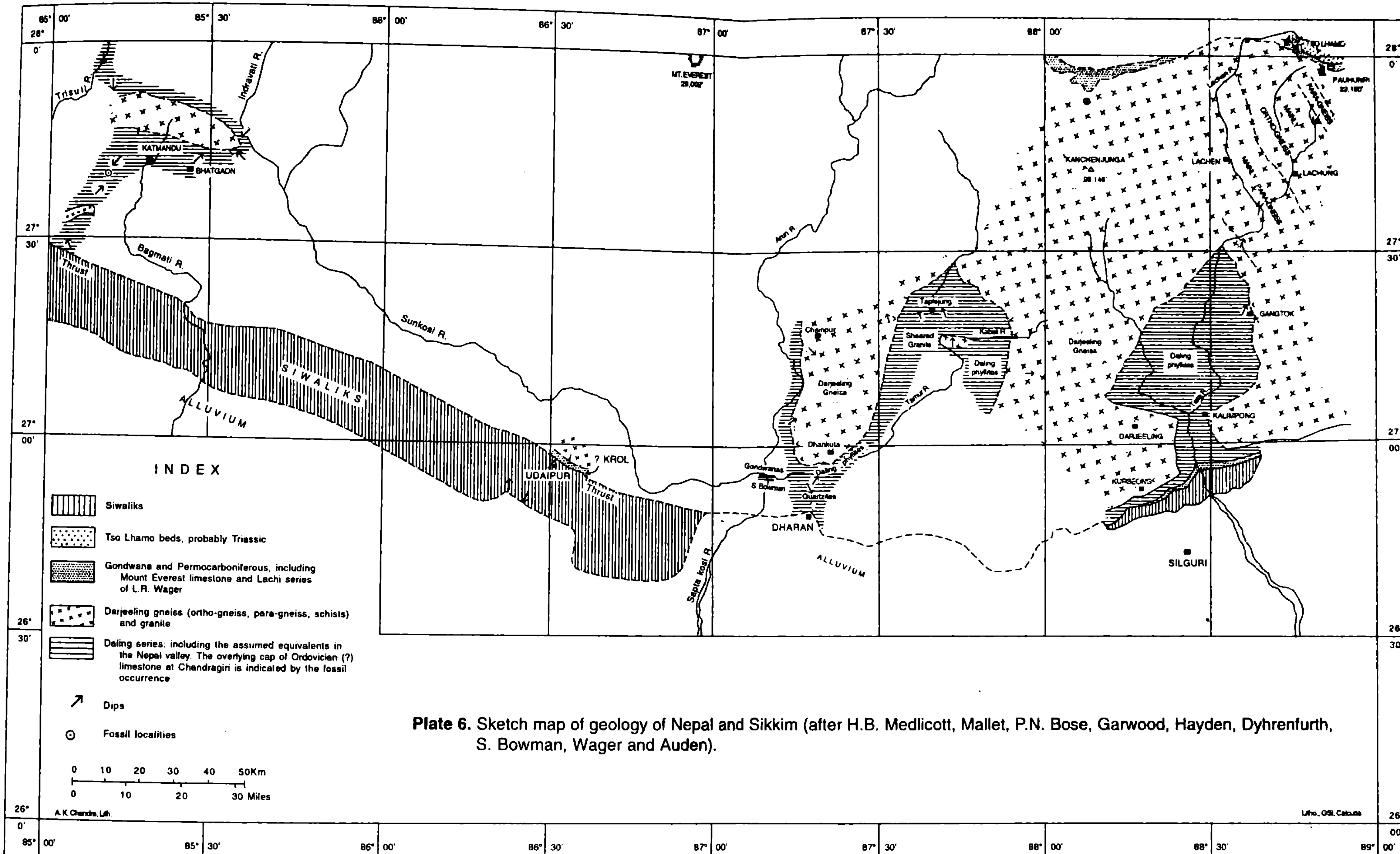

Plate 6. Sketch map of geology of Nepal and Sikkim (after H.B. Medlicott, Mallet, P.N. Bose, Garwood, Hayden, Dyhrenfurth, S. Bowman, Wager and Auden).

granulites of the main range from the apparently underlying Garhwal limestone which occurs to the south.

Significance of the Middle Siwaliks

Finally, mention may be made of the Middle Siwalik sand-rock which forms such a characteristic feature of the Siwalik outcrop from the Punjab at least as far east as about longitude 86°. This sand-rock on superficial examination might sometimes almost be taken for granite, so full is it often of feldspar and mica. Its occurrence in great cliffs without visible bedding, such as near Dhukwabas (27°19': 85°00'), tends also to belie its sedimentary origin. Such a rock must have been laid down as the result of the denudation of a granitic or metamorphic terrain. (Wadia, '*Geology of India*', p.237, 1926). The provenance of this was possibly the equivalent of the Darjeeling gneiss complex in the western Himalaya. There may prove to be a reciprocal relationship between greater erosion of this complex in the west and a more extensive development of the Middle Siwaliks.

THE SIKKIM GRANITE

Where I saw this granite in northern Sikkim it was always unfoliated, and characteristically transgressive. It is the youngest of the intrusives that were seen. Heron (*Rec. Geol. Surv. India*, v.54, p.221, 1922) noticed in the Everest region that the schorl granite:

> 'is the latest in age of the igneous rocks and occurs practically everywhere in the crystallines examined, penetrating both gneiss and metamorphics in veins and sills of all sizes. The habit of the sill is specially characteristic, namely concordance with the foliation of the rocks into which they are intruded.'

While Heron was impressed by the concordant sill-habit of this granite, he also remarks that it is later in age than the gneiss and metamorphics. In Sikkim, the transgressive habit is the more striking, especially at the northern end of the Sebo Chu valley (*see* Plate 4). In the cliffs west of the terminal moraine of the Khonpuck glacier, the granite occurs in a network of clean-cut veins and dykes which evidently bear some relation to the regional jointing. The conclusion from these observations is that this fine-grained white granite is later than the ortho-gneisses it cuts. The unfoliated granite of Sikkim and that of Chumbi are regarded by Hayden as equivalent, and doubtless also the schorl granite of Everest belongs to the same suite. Since the Chumbi granite intrudes Jurassic beds, both it and the related granites of Everest and Sikkim are probably Tertiary in age. The question remains as to whether or not the ortho-gneisses cut by the Sikkim granite are also Tertiary. Wager shows the lateral passage from the Chumbi granite into Darjeeling gneiss near Yatung ('Everest 1933' p.327).

Dyhrenfurth believes the augen-gneiss of Kanchenjunga to be younger than his Mesozoic Dodang series ('Himalaya: Unsere Expedition', p.303). Hayden grouped the foliated biotite-granite and the muscovite-schorl-granite of the Himalayan crystalline zone together, and contrasts them with the markedly different hornblende-granite of Kyi Chu (*Mem. Geol. Surv. India*, v.36, Pt.2, p.59, 1907). These views imply, therefore, that a number of granites in Sikkim and Tibet are closely related, and probably of Tertiary age. All that can be stated at present is that the white, fine-grained, tourmaline-granite of northern Sikkim appears to be the youngest of the intrusives present, and, by analogy with the Chumbi granite; is probably Tertiary, while the intrusives it cuts may be either Tertiary or older.

Wager points out the difficulty in distinguishing between the older granite-gneisses and the younger, probably Tertiary granite-gneisses. He states, however, that the former differ in being garnet-bearing, and in being associated with amphibolite bands, highly metamorphosed limestones, quartzites and shales (Loc. cit., p.320). Garnet may be seen in the pegmatites both of the Saraswati-Alaknanda valley in Garhwal (44/66) and in the Kabeli valley of Nepal. Specimen 44/66 is of a contact between garnet-tourmaline-pegmatite and biotite-granulite. It occurs in association with the more common pegmatites which do not contain garnet, and both garnet-bearing and non-garnet pegmatites are fairly certainly derived from the same magma that gave rise to the large granite and gneiss intrusions of northern Garhwal. It is these intrusions which many believe are Tertiary in age. Further, both types of pegmatite occur intrusive into the metamorphosed granulite group of Garhwal. The criterion of the presence or absence of garnet seems of uncertain value if it be used to characterise the older gneisses and if at the same time it occurs in pegmatites related to the younger transgressive granites.

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The Structure of the Himalaya in Garhwal

J.B. AUDEN

EDITORIAL COMMENTS

In this paper Auden has attempted tectonic analysis of the Lower Himalaya between the Jamuna River and Lansdowne, earlier mapped and interpreted by Middlemiss (1887, 1890) and across the Garhwal Himalaya from the plains to the Himalayan Range. This work followed the mapping carried out by Auden (1934) in the Krol Belt.

He recognized the autochthonous folded nature of the Siwaliks bound on the northside by the Main Boundary Fault (MBF) and the Krol thrust. The tectonic contact between the Siwalik and Dagshai-Nummulitic as the MBF and the Krol Thrust to be a separate tectonic entity. He has adduced sufficient evidence to suggest that the Krol belt is a major nappe which is uninverted and has not been duplicated by recumbent folding. His mapping of the Banali and Pharat tectonic windows, where Simla slate with the cover rocks of nummulities appear surrounded by traces of the Krol thrust, clearly confirms the nappe nature of the Krol Belt. He also suggested that the Simla Slate was possibly equivalent of the Chandpur although different in lithology and deposited in two distinct areas. This has been later confirmed by the mapping carried out by the GSI which brought out the correlation of the Simla Group and the Jaunsar Group.

Auden also observed that the Chandpur and Nagthat Series of the Krol Nappe (i.e. Inner Krol Nappe as per the present perception) show increase in metamorphism from southwest towards northeast.

His work assumes importance in his excellent analysis of the tectonic position of the Garhwal nappes. In Tehri Garhwal he discusses in detail the structural position of the smaller Banali and Satengal klippen. He brought out that these tectonic outliers were uninverted and not recumbent while discussing the tectonic outliers in the erstewhile British Garhwal.

In his reference to the Bijni and Amri klippen he admits the difficulty in coming to any satisfactory conclusion with regard to Volcanic Breccia of Middlemiss, comprising boulder slate and lying over the Tal beds of the Garhwal. He was not *in favour of any correlation between this boulder bed and the Blaini. The Volcanic Breccia later yielded Permian fossils.*

Auden did not subscribe to any comparision between the rocks of the Inner Schistose Series of Middlemiss and the rocks underlying the Krol Series. He found the contention of Middlemiss on such a comparision as structurally untenable.

He argued on the extensive thrust plane over the Nummulitic, Tal and Krol rocks of Garhwal and established the existence of a great system of thrusts upon the Nagthat- Blaini-Krol-Tal-Nummulitic succession in Tehri Garhwal and British Garhwal and he recognized them as the Satengal, Banali and Garhwal nappes and in this nappe system he included Amri and Lansdowne sysclines also. He considered these nappes to have travelled great distance and included the schistose rocks into which Dudatoli granite is intruded, as part of the nappe system.

Auden suggested that the Dudatoli-Dwarahat-Ranikhet-Almora region also represented a group of synclines forming part of the Garhwal Nappe System. He interpreted that there could be more than one period of movement, the stronger perhaps during Helvetian and the later during Siwalik and post-Siwalik.

In his discussion on the geological aspect of the higher snowy ranges, Auden interpreted that the ranges between the Bhagirathi and Alakanand valleys could be divided into two zones by a fairly well defined line according to him. The high grade rocks of the Main Himalayan Range rest upon little metamorphosed shales, phyllites, limestone and quartzites and this contact he considered as a thrust plane. In a way Auden was the first to recognize what is now referred as the Main Central Thrust. He identified that some granites in the high ranges as pre- or syn-tectonic intrusives.

Auden's regional tectonic appraisal brings out that the various nappes resting on the Lower Himalayan formations are part of a larger crystalline thrust sheet emerging from the base of the Main Himalayan Range. Auden displayed a sharp tectonic vision of the Himalaya which needs greater appreciation and understanding. - S.V. Srikantia.

INTRODUCTION

The object of this paper is to summarise my present views on the structure of the outer Himalaya between the Jumna River and Lansdowne, as well as to introduce a preliminary interpretation of a profile across the Garhwal Himalaya from the plains to the Main Himalayan Range.

* * * * *

Topographical and Geological Zones in the Garhwal Himalaya

Before describing the tectonics of the Garhwal Himalaya in greater detail, a brief mention may be made of the zones into which it can be divided. Topographically the following zones may be distinguished:

1. Siwalik Range and Dun.

2. (a) Outer lower Himalaya, with an intricate network of spurs and rivers.
   (b) Inner lower Himalaya, with simpler topography.
3. Main Himalayan Range, with steep scarp slopes facing towards the Plains, and gentler dip slopes facing Tibet.
4. High peaks north of the Main Himalayan Range with irregular disposition.

The structural units do not fit into this topographical classification, since, in some parts at least, three structural units are superimposed one upon the other. The main tectonic divisions for the Garhwal Himalaya are follows:

(1) Autochthonous unit. The base of this unit is probably the Simla slate series, overlying which occur Nummulitics, Murrees and Siwaliks. Thrusts occur within this unit, but do not seem to be of premier magnitude. The most important thrust is that which has long been called the Main Boundary Fault. This Autochthonous unit appears to occur well within the Himalaya, some twenty miles at least from the Dun.

(2) The Krol Nappe, thrust upon the Autochthonous unit, and corresponding to the Krol belt described in a previous paper of mine

(3) The Garhwal Nappe, thrust upon the Krol Nappe. The main Garhwal Nappe may root in the Main Himalayan Range.

(4) The Main Himalayan Range, which appears to be made up partly of elements common to one of the Garhwal Nappes and partly of a distinct group of para-gneisses and schists.

(5) The granite zone to the north of the Main Himalayan Range containing granites intrusive into the southern paragneisses and schists.

(6) The Tethys zone of fossiliferous sediments. The relationship of this zone to the granites and paragneisses is at present obscure. From the work of Hayden in Spiti it would appear that the gneissic granite, which may be Permian or Tertiary in age, has an intrusive contact with the Cambrian. The recent work of Professor Arnold Heim and Dr. Gansser may clear up this question.

The greater part of this paper will be devoted to a discussion of the Autochthonous, Krol and Garhwal units occurring in the outer lower Himalaya.

*   *   *   *   *

RECENT SURVEY (1935-1936)

During the last three seasons I have mapped east of Longitude 78°E and have joined up the succession which I had established around Solon (described in 1934) with that of Middlemiss. Before reaching the Ganges river, I found both in 1935 and in 1936 structures in Tehri Garhwal which seemed to me to settle the validity of Middlemiss' condemned impression. Now, having examined part of the Garhwal area, some of it in detail, I am convinced of the existence of great overthrusts. There are, it is true, many difficulties involved in a region almost devoid of fossiliferous rocks, except the Tal limestone, (the fossils in which are so broken that no certain age has been assigned to them) and the Nummulitics, and in which there appear to be recurrences of rock types throughout the assumed stratigraphical succession. Yet some of the features seem clear and worth recording apart from those that are less explicable.

The following tables give the stratigraphical and tectonic succession which I have determined east of Longitude 78°. To the second table has been added the succession found by Middlemiss in Garhwal in 1887.

Succession east of Longitude 78° E

Formations	Unconformities	Approx. Max. Thickness (Feet)	Probable age
Siwalik		16,000	Upper Miocene to Pleistocene
	?		
Murree (almost absent east of Long. 78°)		?	Lower Miocene
	?		
Nummulitic		?	Eocene
Tal limestone and Calc grit		200	Upper Cretaceous ?
Tal: Upper Tal quartzites		4500	Cretaceous ?
Tal: Lower Tal shales		2000	Jurassic ?
Krol: Upper Krol dolomites, limetstone and shales		3000	Trias ?
Krol: Krol red shales; Lower Krol limestone and shales		1000	Permian ?
Blaini: Infra Krol slates; Upper Blaini boulder bed and dolomite; Blaini slates; Lower Blaini boulder bed		2000	? Talchir (Uralian)
Nagthat		3000	Devonian ?
Chandpur		4000?	Lower Palaeozoic and Precambrian ?
Simla slates, possibly equivalent to the Chandpur series, although different in lithology			
Dolerites			Late Tertiary

——— Conformity; - - - - - - - - Unconformity

Tectonic Succession in Tehri Garhwal and British Garhwal

	Tehri Garhwal and British Garhwal	British Garhwal, Middlemiss, 1887
Garhwal Nappe	Chandpur (metamorphosed) ——— *Thrust* — Nagthat] Chandpur] (little metamorphosed) Boulder beds, slates and limestones of uncertain stratigraphical horizon occur in one outlier below metamorphosed Chandpurs	Inner Schistose series
Garhwal Thrust	———	——— *reversed fault* ———
Krol Nappe	Nummulitic Tal Krol Blaini Nagthat] Chandpur] metamorphosed and unmetamorphosed	Nummulitic Tal Massive Limestone Volcanic breccia in an undifferentiated group of purple Slates
— *Krol Thrust*	———	
Autochthonous	Dagshai Nummulitic Siwalik Simla slates	

AUTOCHTHONOUS

Siwaliks

The structure of the Siwaliks east of the Ganges has already been described by Middlemiss, whose illustrative sections are classics in Indian geological literature. Between the Jumna and Ganges rivers the main structure is an anticline in the Siwalik Range (the axis of which is slightly oblique to the topographical alignment of the range), a syncline forming the Dun valley, and to the northeast an overturned anticline which is truncated on the north side by the Main Boundary Fault and the Krol Thrust. The base of the Siwaliks is nowhere seen, but it is presumed that it consists of Nummulitics with attenuated Dagshai rocks resting on Simla slates; (Plate 3; Fig.1).

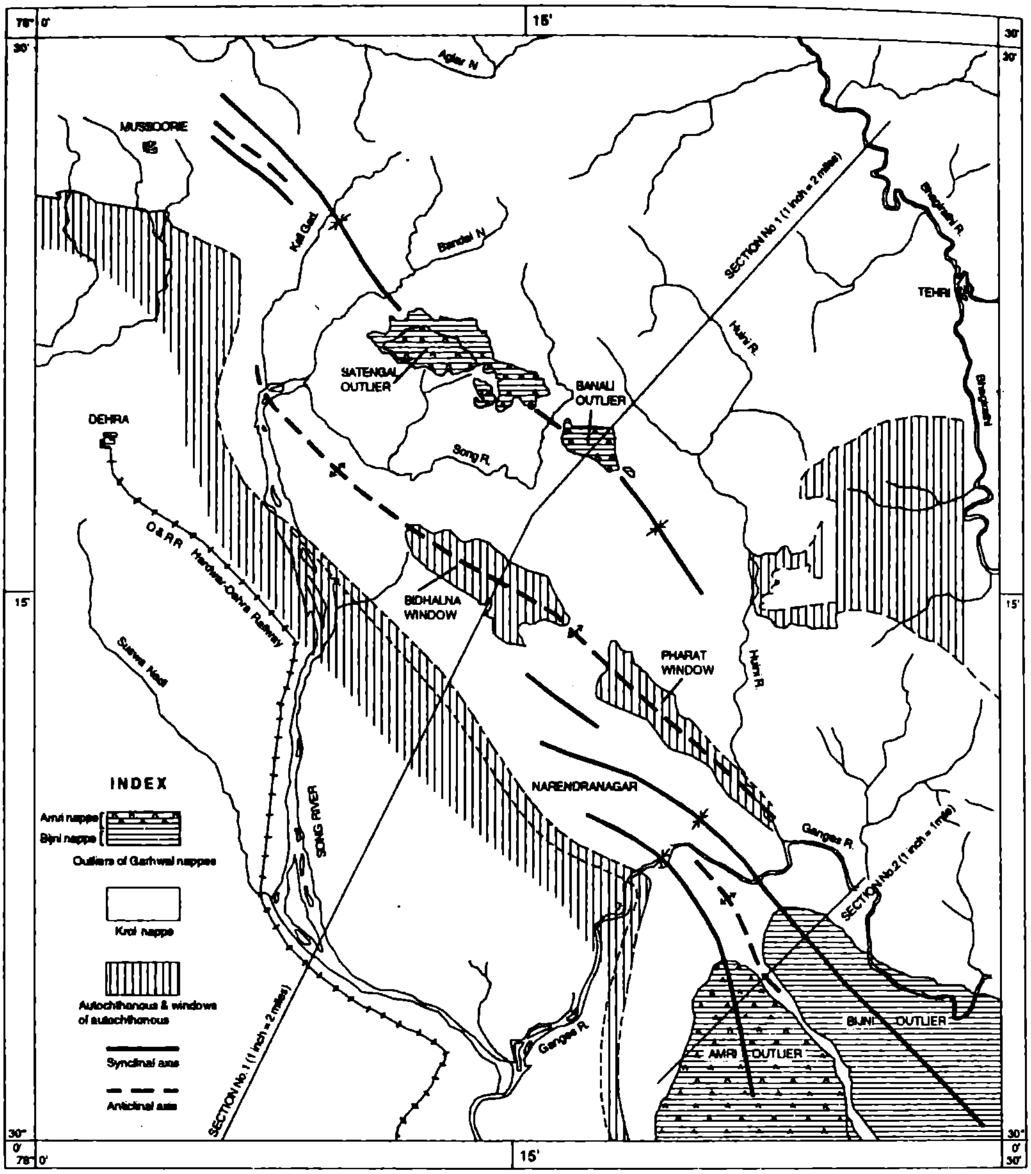

Plate 1. Map No. 53 J/S.W. showing the disposition of the main tectonic units in the neighbourhood of Dehra and Rishikesh.

Dagshai and Nummulitics

The Main Boundary Fault, in the sense originally used by Medlicott, separates the Siwaliks from the older Tertiaries which have been thrust upon them. East of Longitude 78° the Dagshai rocks (Murrees) are very seldom seen, and the chief fault is the Krol thrust which has brought pre-Tertiaries forward so as to rest directly on Siwaliks. This Krol Thrust has been called the Main Boundary Fault both by Middlemiss and myself, but, although it does in fact form the northern boundary of the Siwaliks over some of the area between Dehra and Naini Tal, it is not the same fault as that to which Medlicott. originally assigned the term (Middlemiss, C.S., *Mem. Geol. Surv. India*, v.24, pp.19,31

(1890); *Mem. Geol. Surv. India*, v.38, p.337, 1908) (Auden, J.B., *Rec. Geol. Surv. India*, v.67, p.431, 1934).

In the neighbourhood of Solon and Subathu, Dagshai and Subathu rocks (Murree and Nummulitic) rest upon Simla slates and have been overthrust by the rocks of the Krol Nappe. This is well seen around the northwest end of Pachmunda Hill and along the Blaini river (*Rec. Geol. Surv. India*, v.67, p.436, 1934).

Dagshai rocks are seen along the Tons river by Kalawar (30°32':77°49'), on the left bank of the Amlawa river at Kalsi, and as a very narrow outcrop running in a southeast direction to about Long. 78°02½'. They are thrust by a steep reversed fault (Main Boundary) upon Nahan rocks and are themselves overthrust at a gentler angle by pre-Tertiaries (Krol Thrust). Lenticles of fossiliferous limestone in the Dagshai rocks of the Tons river suggest that Nummulitics may be present there as well.

Between Dehra and Rikhikesh, Nummulitics together with cindery nodular sandstones, which are probably Dagshai, rest upon Simla slates and have been overthrust by the rocks of the Krol Nappe. They occur in two windows which will be described in greater detail in the next section. Probable Tal rocks occur, though poorly exposed, in the Chandna Rao at 30°10': 78°15' evidently to the southwest of the Krol Thrust and belonging to the same tectonic horizon as the complex Nummulitic and Tal association of Banas Talla and Banas Malla (29°57': 78°21').

Within the Himalaya, Nummulitics are seen resting upon Simla slates at Sayasu (30°42':77°44'), and from just north of Dabra (30°40':77°49') down to the Tons river. In the Tons river Dagshai rocks are almost certainly present in addition to the Nummulitics.

Numerous faults and thrusts occur in the rocks of this zone. It is possible also that the Tertiaries may have been pushed bodily over the Simla slate foundation, with the Nummulitics acting as a lubricating horizon, in a manner comparable to the anhydrite horizon at the base of the Mesozoic succession of the Jura Mountains. These movements are probably, however, of less magnitude than those involved in the Krol and Garhwal Nappes, and the term 'autochthonous' seems to be justified.

Krol Nappe

Lack of inversion

The maximum thickness of the succession in the Krol Nappe is of the order of 20,000 feet (6,100 metres). This succession is a normal one, for the disposition of numerous exposures of current bedding in the calc grit of the Tal limestone, and in the Tal and Nagthat quartzites, shows that these particular stages are not inverted, and therefore that the whole succession is in the correct order. This is important because it eliminates the possibility of repetition of certain facies by recumbent folding. Thus, the Tal and Nagthat quartzites cannot be regarded as belonging to a single horizon which has been duplicated by recumbent folding around a core of Upper Krol limestone. This conclusion is also supported by the fact that the sequence of stages above the Upper Krol limestone, on the assumption that this is the core of a recumbent fold, is not the mirror-image reverse of that below the limestone. In particular, there is no equivalent of the Blaini boulder beds in a position between the Lower Tal shales and the Upper Tal quartzites, which would be expected if the Tal and Nagthat quartzites were the same horizon duplicated in a flat overfold. Moreover, there are lithological differences between the Tal and Nagthat quartzites which, though not absolute when regarded singly, are collectively valid enough to differentiate these two stages. This point has been stressed because Middlemiss evidently confused these two quartzites. At the beginning of his survey he considered the Tals to underlie the Massive (Krol) limestone, but he was later compelled to reverse their position and to place them above the limestone. He appears also in places to have mapped the true Tal quartzites and the Nagthat quartzites that have been overthrust upon the Tals, both as Tal.

It may be accepted therefore that the sequence given for the Krol Nappe is uninverted and has not been duplicated by recumbent folding. Nor do I think it possible to assume the duplication by thrusting of uninverted stages one upon another.

The evidence for the existence of this nappe is based upon the following considerations:

(1) The most convincing evidence is the occurrence of two windows disclosing Nummulitics and Simla slates between Dehra and Rikhikesh. One of these windows occurs on both sides of the Bidhalna Rao (30°16':78°14') and is about six square miles in area. The other, window is well seen between Pharat (30°13':78°18') and Banali (30°11':78°20') and covers about seven square miles (*This Banali should not be confused with another village of the same name situated at 30°18':78°17'30". The latter village is located on an outlier of the Garhwal Nappes p.422*). They occur along the anticlinal axis which separates the Mussoorie syncline of Nagthat-Blaini-Krol-Tal rocks from the Garhwal syncline lying to the south of and *en echelon* with it. In the centres of the windows occur Simla slates, generally with steep dips. Above the Simla slates, sometimes as isolated cappings, more typically as a border to the windows, are found Nummulitic shales and limestones together with blocks of highly shattered quartzites, the surfaces of which are glazed by friction. Finally, above

the Nummulitic and associated rocks occurs the unmetamorphosed facies of the Chandpur beds, belonging to the Krol Nappe. There can be little question here of the Nummulitics occurring as outliers in pockets of a late Cretaceous erosion topography. Such a manner of occurrence would not account for the difference in type of the slates found above and below the Nummulitics. While it is admittedly difficult in some places to distinguish the Simla slates from the Chandpur series (which are possibly of the same age but deposited in two distinct areas), the difference between these two series is on the whole marked enough in this particular region, so that the occurrence of the Nummulitics between the Simla slates and the Chandpurs is significant. The upward succession in these windows, Simla slates-Nummulitics-Chandpurs, is the characteristic feature, the disposition of the Nummulitics being such as to suggest that they are part of a continuous sequence, a sequence which I conclude to be tectonic. The strong shattering of the quartzites associated with the Nummulitics, their slip-polished surfaces, and their haphazard tectonic isolation as blocks in the shales, with no signs of orderly sedimentation, suggest that these rocks have been subjected to violent stresses. Indeed, below Banali the Nummulitic shales are converted into a 'pseudo-schist' resembling biotite-schist, but in reality a highly sheared shale endowed with abundant reflecting slip surfaces. These effects must have arisen during the Miocene movements, which are known to have been a characteristic feature of Himalayan tectonics, and are indicative of shearing stress rather than simple hydrostatic pressure. On the hypothesis that the Nummulitics rest upon a pre-Tertiary erosion topography, it would, however, be necessary to assume that this topography had undergone little change throughout the Tertiary and Quaternary eras. This would hardly be expected in view both of the extent of the Miocene movements, and of the great erosion, which has taken place since then. If Miocene compression had shortened the width of the postulated valleys in which the Nummulitics had been deposited, so as to cause the infolding of the Nummulitics within the Chandpur and Simla slate series, it should have had a devastating effect on the pre-Tertiary north-south ridge separating these valleys. Yet the Chandpur beds of the narrow Diuli (30°13':78°17') ridge are neither shattered nor highly folded. The shattering occurs in the Nummulitic rocks, which dip under the Chandpurs on either side of the ridge. In the view here adopted, the Nummulitics were deposited upon a more or less peneplaned surface of Simla slates, and were later overthrust by the Chandpur series of the Krol Nappe. The valleys in which the inferred windows are now exposed are regarded as the result of recent river erosion. Young river-gravels occur 800 feet above the level of these modern valleys.

(2) Between Solon and Subathu there is a similar disposition to that just

described, except that the Chandpur and Nagthat beds of the Krol Nappe are missing. Here the sequence working upwards is: Simla slates-Subathu (Nummulitic)-Blaini. This area has already been described, being figured on page 436; and discussed on pages 434-437 of *Records, Geological Survey of India*, v.67, (1934). Near Solon there are two outcrops of Nummulitics, surrounded by Infra-Krol (Blaini *sensu lalo*) slates, which I regard as windows. The contacts between the Nummulitics and adjacent Blaini rocks are poorly exposed, and it might be maintained that the Nummulitics of these outcrops occur as eroded outliers upon Blaini. Nummulitics are known to lie infolded within Krol limestones at Bagar (30°45':77°17') evidently having overlapped the Tal rocks towards the northwest so as to rest directly upon the Krols, and it might be argued that this overlap continues in the direction of Solon across the Krol limestones on to the Infra-Krol (Blaini). The Krol limestones are, however, very well exposed near Solon, the type locality, so that this overlap could only be very local. Moreover, the same arguments apply to the Solon area as have just been given for the windows southeast of Dehra. Whatever doubts may be raised about these inferred windows, it is difficult, however, to escape the conclusion that the zig-zag disposition of the Simla slates-Nummulitic-Blaini-Krol rocks between Solon and Subathu represents the result of erosion of two tectonic units that had been brought together by thrust movements and were later folded. Here again, in a manner comparable to the windows already described southeast of Dehra, the contrasts between the Simla slates at the base of the Tertiaries and the Blaini slates above them is striking, precluding any explanation by simple infolding of Nummulitics within a single slate series.

(3) On the northeast side of the Krol syncline Nummulitics occur at Sayasu and Dabra. They overlie Simla slates and appear to underlie the complex group of Chandpurs and Mandhalis. By Koruwa (30°40':77°51'), and on the col southeast of Kailana, are found shattered and glazed quartzites exactly similar to those associated with the Nummulitics of the windows between Dehra and Rikhikesh, and around Banas Malla (29°57':78°21'), again overlying Simla slates and underlying Mandhali limestones. The thrust which separates the Chandpur-Mandhali rocks from the Simla slates dips southwards, below the Krol syncline. It has been called the Tons thrust and I consider it almost certain that this thrust joins up below the Krol syncline with the north-dipping Krol Thrust on the south side. There is evidence for this supposition along the Huinl river in Tehri Garhwal.

Considering only the first two areas, the minimum displacement of the Krol Thrust and Nappe would be about five miles. Taking into consideration the region on the north side of the Krol syncline near Kailana, the minimum displacement is likely to be 20 miles (32 km).

Metamorphism

A point which should be emphasised in connection with the Chandpur and Nagthat series of the Krol Nappe is the increase in metamorphism which is observable from the southwest towards the northeast. Along the southwest side of the Mussoorie syncline, for example near Paled (30°17':78°11'), the Chandpur series is in the, condition of banded green slates and ash beds, while the Nagthat series is made up of soft sandstones and quartzites with a secondary Silica cement. Towards the northeast both these series develop schistosity. The Chandpur slates are changed to schistose chlorite-sericite-phyllites, as at Jugargaon (30°23':78°24'), while the arenaceous beds of the Nagthat series become schistose chlorite-sericite-quartzites, such as are well seen in the neighbourhood of Kaudia (30°25':78°22'). The distance separating these contrasted grades of metamorphism is about 10 miles.

Garhwal Nappes

Outliers in Tehri Garhwal State

Ever since I had read MIddlemiss's paper on the Physical Geology of West British Garhwal, I had hoped to find a structure in the centres of synclines in Sirmur State and Tehri Garhwal comparable to the one he had described, for I was convinced that the Massive limestone and Tal beds of Middlemiss were equivalent to the Krol limestone and the presumed Tals in Sirmur State. In 1931 a sandy current-bedded limestone was found at the top of the Tal series along the Nigali Dhar of Sirmur State (30°39':77°34') but unfortunately this was the highest horizon exposed (*Rec. Geol. Surv. India,* v.67, Pl.23, 1934). It was not until March 1935 that the expected structure was found at the top of the Tal succession of the Mussoorie syncline on hill 6533 (30°22':78°12'). Between Tashla (30°22':78°11'), Satengal (30°21':78°13') and Hatwalgaon (30°20':78°16'), there was found an outlier of schistose phyllites and subordinate white quartzites overlying a group of limestones, slates and boulder beds, both of which units rest upon and are surrounded by the Tal series. The area covered by this outlier is about 7 square miles. Equally convincing is another outlier of schistose phyllites lying upon the Tal series around Banali (30°18':78°17' 30). This outlier is two square miles in area. Both outliers indisputably rest upon Tal beds with centripetal dips varying from 20° to 45°. Adjacent to the Banali outlier is a still smaller outlier, about 200,000 square yards in area, lying as a thin coating upon the Tal quartzites.

It is quite impossible to explain the position of the schistose phyllites upon the Tal series by ring-shaped reversed faults descending through the whole of the 17,000 feet of rocks of the Krol Nappe here present to its basement.

The Satengal outlier is complicated by the presence in its western part of slates, boulder beds, and a limestone identical to the Bansa limestone, which occur between the schistose phyllites and the underlying Tal. Nevertheless, whatever the stratigraphical position of these intervening beds may be, the fact of an overthrust of schistose phyllites upon the Tals is clear and beyond dispute. There is no such complication in the eastern part of the Satengal outlier or at Banali, where the schistose rocks lie directly upon the Tal series, locally with an angular discordance. I showed the Banali outlier to Professor Arnold Heim and Doctor Gansser, both of whom agreed that no doubt could be raised as to its overthrust nature.

The characteristic rock of these outliers is a green schistose chlorite-sericite-phyllite, with segregations of secondary chlorite in streaks. This type can be exactly matched with the rocks at the base of the Krol Nappe around Jugargaon. The fact that the underlying Tal and Nagthat quartzites are not inverted proves that the schistose phyllites of the outliers above them do not rest in that position as a result of duplication of the Chandpurs which occur at the base of the Krol Nappe by recumbent folding. If recumbent folding were present, either the Tal quartzites or the Nagthat quartzites should be inverted. Further indication of the lack of inversion is suggested by the presence of the limestone, mentioned above, which is similar to the Bansa limestone, and of boulder beds below the schistose phyllites of the Satengal outlier. This relationship is the same as that obtaining in the rocks at the base of the Krol Nappe between Kalsi and Chakrata, where the Bansa limestone and Mandhalis appear to underlie the Chandpur series. That is to say, both in the Krol Nappe and in the Garhwal Nappe, there is the same succession upwards of these beds. The relationship is, it may be accepted, one of a thrust contact of the metamorphosed type of Chandpurs upon normally lying Tal beds.

In these two outliers of Tehri Garhwal there are two desirable features for demonstrating the complete overthrust of the schistose phyllites upon the Tal series:

(1) Dips are everywhere centripetally inclined, but are not steep enough to bring the base of the schistose phyllites below the level of river erosion;
(2) The two areas area of a size small enough to be seen almost as a whole by the eye from neighbhouring peaks, so that the result of detailed mapping of the thrust boundary may be confirmed and integrated at a single glance.

Outliers in British Garhwal

In coming to the area mapped by Middlemiss in British Garhwal, these two features are absent. Dips are on the whole steeper, and the area is so large that it cannot be taken in by inspection from anyone vantage point. I have re-mapped that part of Middlemiss's area which lies in sheet 53 J/S.W., and have traversed along the Nayar river from Byansghat to Bhanghat, Dwarikhal, Lansdowne (29°51':78°41') and Dogadda. The correlations given in Tables are definitely proved by the results of detailed mapping. The only difference between the Garhwal area and, that of Tehri Garhwal is that Nummulitics are present above the Tal series in Garhwal, while they are almost absent from Tehri Garhwal except for very narrow outcrops along the Ganges river. The outcrop of Nummulitics in Garhwal is discontinuous, but is slightly more extensive than shown by Middlemiss.

Overlying the Nummulitics in sheet 53 J /S.W. occur two separate nappes which are disposed in synclines that are separated for some distance by the anticlinal axis running from just east of Lachmanjhula in a southeast direction past Jogyana along the Huill river; Section 2. In the western, Amri, syncline (Amri: 30°04':78°22') the rocks are characteristically green schistose phyllites with subordinate white schistose quartzites, the assemblage recalling at once that of the Satengal and Banali outliers. In the eastern, Bijni, syncline (Bijni: 30°04': 78°25') the dominant rocks arc purple, green, and white quartzites exactly resembling the Nagthat series with underlying and subordinate banded green slates similar to those of the less metamorphosed type of Chandpurs on the southwest side of the Krol Nappe. In the anticline separating these two nappes there crops out a complicated assemblage of Tal and Nummulitic rocks, obviously highly disturbed and interfolded, as may be well seen at Bagurgaon (29°58':78°29').

Between Kothar (29°58':78°34') and Lansdowne there is another and larger syncline of schistose phyllites and white schistose quartzites, similar to those of the Amri, Banali and Satengal synclinal outliers. Intruded into these rocks occurs the gneissic granite of Lansdowne.

It must be admitted at once that there are many difficulties in understanding the Garhwal area. Firstly, I have been able to come to no satisfactory conclusion about the true position of the boulder slate (volcanic breccia of Middlemiss). In the north end of the Garhwal syncline this boulder slate unquestionably joins up with the Blaini, but I am uncertain if the boulder slate so often found lying above the Tal beds of Garhwal is the same as the Blaini, thrust upon the Tals, or if it is an altogether different horizon. Secondly, as seen above, the outcrop of Middlemiss's Inner Schistose series is not made up of a single tectonic unit. These difficulties can only be cleared up by detailed mapping, but, in spite of them, I am confident that the Inner Schistose series of Middlemiss does truly overlie the Nummulitic, Tal and Krol rocks as a thrust outlier. In no other way is it possible to explain the ring-shaped boundary between the older rocks. and the

Nummulitics around Amri and Palyalgaon (30°06':78°24'). Just north of Amri, Middlemiss mapped two faults separating the older rocks from the Nummulitics. The NW-SE fault is shown as terminating westwards against the N-S fault, which is made to pass northwards towards Patna, *without displacing the Nummulitic-Tal boundary*. On the postulate of Middlemiss, this fault should have caused the Outer Formations to be thrown down below their own basement. Its throw would be enormous, and yet it fails to displace the Nummulitic-Tal boundary at all. A re-examination of this area has shown that the schistose phyllites overlie the Nummulitics round an arc of 180° and that the boundary between them is continuous and not made up of the intersection of two or more faults. The reason is clear. The faulted junction between the schistose phyllites of Amri and the Nummulitics does not cut through the Nummulitics and underlying formations, because it is a thrust plane which lies at an horizon altogether above them; Plate 1 and (Plate 3: Figs.1 and 2).

Moreover, in the Garhwal area the rock types of the Inner Schistose series are dissimilar to those underlying the Krol series along the Nayar river, both in lithology and in strike. Underlying the Krols from Byansghat to Banghat (29°57': 78°42') occur Simla slates with strikes varying from E-W to NNE-SSW. The Krol-Tal rocks, and the overlying schistose rocks from Dwarikhal to Lansdowne, have a uniform NW-SE strike. The Simla slates also differ in lithology and degree of metamorphism from the rocks of the schistose series overlying the Krol and Tal series. On the interpretation of Middlemiss, the Simla slates and the Inner Schistose series should be the same, since the reverse faulting which he postulated would have brought up the same foundation rocks upon the Tals as underlie the Tal and Krol series.

It is difficult to picture the mechanics of the reversed faulting suggested by Middlemiss, since it is necessary to assume either that his Outer series have been thrust inwards and downwards towards a centre or that his Inner series has expanded outwards on all sides from a centre over the Outer series. Cone fractures are common features in certain volcanic areas such as the western islands of Scotland, but so far as I know the displacement along these fractures is inconsiderable and is largely a consequence of infilling with magma. The whole difficulty is removed if we accept that the present basin-like disposition is a secondary feature subsequently impressed upon an extensive thrust of the Garhwal units over the Krol unit.

In connection with the question of reversed faulting, I think that Mallet had a truer grasp of the solid geometry required by geological relationships similar to those of Garhwal. When mapping north Bengal and southern Sikkim he realised that the position of the Darjeeling gneiss above the Daling series could not be explained by 'mere local inversion along the lines of contact' (Mallet, F.R., *Mem. Geol. Surv. India*, v.11, p.42, 1874). So far as I have seen these rocks in eastern Nepal and Sikkim, the Darjeeling gneiss, though truly above the Daling series, does not appear to be separated from it by a thrust plane (Auden, J.B., *Rec. Geol. Surv. India*, v.69, p.161, 1935). The point it is wished to emphasise here is that both in Garhwal and in eastern Nepal and Sikkim the observed relationship is one involving complete superposition and not local reversed faulting, even though the explanation offered for the manner of this superposition is different in the two cases.

The argument for an extensive thrust plane over the Nummulitic, Tal and Krol rocks of Garhwal may now be summarized:

(1) The Nummulitic, Tal and Krol rocks of Garhwal completely surround the Inner Schistose series (as shown by Middlemiss) and dip below them centripetally. This is well seen around Amri and Palyalgaon in sheet 53 J/S W.

(2) At Satengal and Banali in Tehri Garhwal State, schistose phyllites lie as indisputable thrust outliers upon the Tal series.

(3) At least two synclines occur within the Inner Schistose series of Garhwal (those of Amri and Lansdowne) in which the schistose rocks are identical in every respect to those found in the indisputable overthrust outliers of Satengal and Banali. In the Lansdowne outlier there is an additional element in the presence of the gneissic granite, which was intruded before the thrust movements had taken place.

4) Middlemiss argued on the grounds of metamorphism that the schistose series are older than the Nummulitics upon which they lie. Apart from the question of metamorphism, there is no known post-Nummulitic sequence to correspond to the schistose series. From both points of view the schistose series must lie with an abnormal contact upon the Nummulitics and Tal series.

(5) The Inner Schistose series is composed of two main units:-

  (a) schistose phyllites, slates, schistose quartzites and quartzites, resembling the more metamorphosed facies of the Chandpur series of the Krol Nappe;

  (b) banded grey-green slates and mainly purple quartzites, resembling the less metamorphosed facies of the Chandpur and Nagthat series of the Krol Nappe.

Neither of these two units resembles, in strike or closely in lithology, the Simla slates which occur at the base of the Outer series along the Nayar river. The more schistose rocks of the Inner series also differ from the Simla slates in metamorphic grade. These facts appear to negative the explanation given by Middlemiss of reversed faulting having brought up the basement of the Outer Formations so as to lie upon them. If reversed faulting had taken place, the basement rocks (Simla slates along the Nayar river) and the Inner Schistose series should be identical. In the solution suggested in this paper it is believed that the facts are best explained by two thrusts: the Garhwal Thrusts introducing rocks similar to those which in parts of sheet 53 J/S.W. lie at the base of the Krol Nappe, so as to rest above the Krol Nappe; and the Krol Thrust dividing off the Krol Nappe from the Simla slate foundation. This thrust is believed to be transgressive, both towards the southeast in Garhwal, and towards the northwest in Sirmur and Baghat States, with the result that it cuts out successive members from the base of the Krol Nappe.

I would suggest that the arguments given above are sufficient to establish the existence of a great system of thrusts upon the Nagthat-Blaini-Krol-Tal-Nummulitic succession in Tehri Garhwal and British Garhwal. These thrust-nappes exist now as three outliers:-

(1) Satengal outlier, covering about 7 square miles;
(2) Banali outlier, covering 2 square miles;
(3) Garhwal outlier, covering approximately 240 square miles.

The Bijni Nappe is possibly relatively local in origin, but the main nappe of the Garhwal system, which includes the Satengal and Banali outliers, and the Amri and Lansdowne synclines in the Garhwal outlier, has certainly travelled a great distance.

Further Outliers of the Garhwal Nappes

Besides working in the Lansdowne area of British Garhwal, Middlemiss also mapped a syncline of schists and quartzites intruded by gneissic granite at Dudatoli (30°03': 79°12') (*Rec. Geol. Surv. India*, v.20, p.40, p.135, 1887). He pointed out (page 40) the exact similarity between the gneissic granites of Dudatoli and Lansdowne, and also (page 136) the fact that the only synclines of importance along a line from the Plains to the Main Himalayan Range are connected with the gneissose and schistose series. I would go further in believing that the schistose rocks into which the Dudatoli granite is intruded are the same as those of Lansdowne, Amri, Banali and Satengal, which have already been described. Similarly, the gneissic granite of Ranikhet and Dwarahat is intruded into phyllites of the same type.

There is no evidence in the regions in which I have mapped or traversed for the equivalent of the Jutogh series of Simla described by Pilgrim and West. The granites of Lansdowne, Dudatoli, Dwarahat and Ranikhet appear in all cases to be intruded into phyllites of one type, corresponding to the more metamorphosed facies of the Chandpurs. These rocks may possibly be equivalent to the Chail series of West. The local increase in metamorphism to garnet-chlorite-phyllite, garnet-chlorite-schist, fine-grained biotite-schist, chiastolite schist, which is attributable to contact effects in proximity to the intruded granites, appears to take place in the Chandpur series of schistose phyllites and not in a higher and altogether distinct series such as the Jutoghs of Simla. This fact I can state with certainty to be true of the Lansdowne area where it is definite that there is no additional series above the Chandpurs of the Inner Schistose group. My briefer examination of the Dwarahat-Dudatoli area suggests the same conclusion, one which seems inevitable indeed from the observations of Middlemiss, mentioned in the passage which I have quoted in an earlier paper (Op cit., v.67, p.412, 1934). In this passage he points out the gradation in a single series from schist to ordinary slate. Mr. West, in a recent discussion of this problem, accepted that the Jutogh Thrust may not be of widespread significance towards the southeast (*Current Science*, v.111, 1935).

In all these cases, the schistose rocks, with or without intruded granite, appear to overlie in synclinal form less metamorphosed limestones and quartzites. Consequently, besides the three outliers of the Garhwal Nappes which I have discussed in detail above, I would suggest that the Dudatoli-Dwarahat-Ranikhet-Almora region also represents a syncline or group of synclines which may be outliers of the Garhwal Nappes. In the map (Plate 2) only one generalised syncline has been shown, since no detailed mapping has been done in this area, except by Middlemiss around Dudatoli.

AGE OF THE KROL AND GARHWAL THRUSTS

The maximum age of the Krol Thrust is established by the presence below it of Nummulitic and Dagshai rocks. This thrust cannot, therefore, be older than Burdigalian.

Below the Garhwal Thrusts occur Nummulitics and possible Dagshai rocks. These thrusts are therefore certainly younger than the Eocene, and are possibly, as in the case of the Krol Thrust not older than Miocene in age. This is in agreement with the recent discovery of Nummulitic and Dagshai rocks by Mr. West in the Shali area, below the Chail Thrust (*Rec. Geol. Surv. India*, v.71, p.72, 1937).

Since no Siwalik rocks are found in the windows, or below the outliers, it might be assumed that the thrust movements took place after the Burdigalian but before the Siwaliks had time to be deposited there, an assumption which would make the movement about Helvetian in age. If, however, the Siwaliks never extended so far to the northeast, this argument fails, since it is possible to imagine the thrusting, to have occurred a considerable time after the Nummulitics and Dagshais had been laid down and while the Siwaliks were being deposited elsewhere.

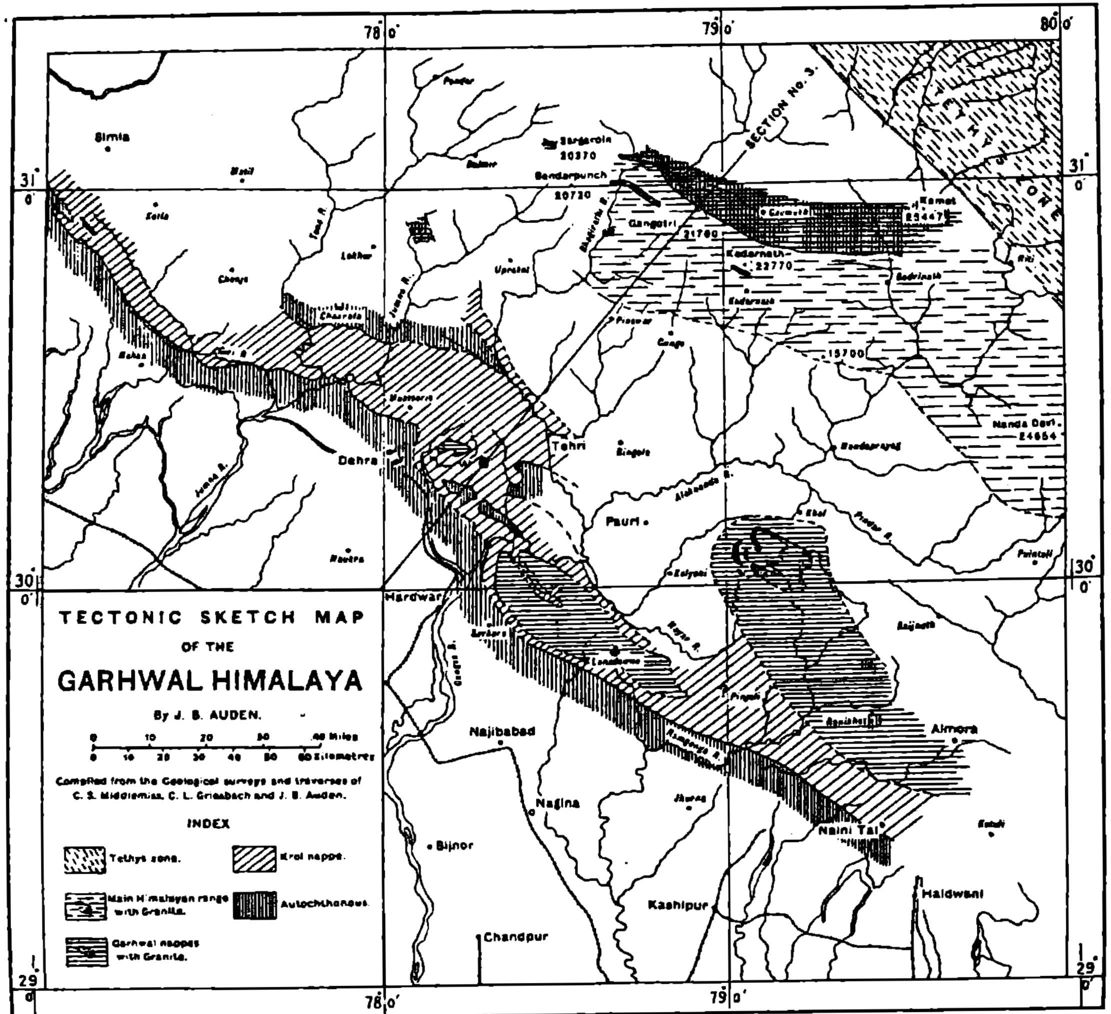

Plate 2. Tectonic sketch map of the Garhwal Himalaya, including a portion of 1:million map No.53. This map is based on the surveys and traverses of C.S. Middlemiss, C.L. Greisbach, and J.B. Auden. Auden alone is responsible for the tectonic interpretations of the geological results. The limits of the inferred Garhwal Nappe between Dudatoli and Raniket are conjectural.

That some of the movement along the Krol Thrust is more recent than Helvetian is proved by the frequent juxtaposition of pre-Tertiaries upon the Nahans between the Jumna river and north Bengal. Further, in places even the Upper Siwalik conglomerates are involved in overthrust by the pre-Tertiaries. Ten miles northwest of Dehra the boulders of these conglomerates are so shattered that it is impossible to obtain a hand specimen of them. Similar overthrusting occurs at Bilaspur on the Sutlej river (31°20':76°45') (*Op. cit.*, v.67, p.444, 1934). These movements must be of Lower Pleistocene or even of later age. Yet it is difficult to believe that the major horizontal movements of the Krol and Garhwal Nappes over a distance of several miles took place as late as this. By Lower Pleistocene times, the rising Himalayan chain must have been dissected to such an extent into blocks by deeply eroding streams that the upper nappes had already been worn away into outliers. The formation of these upper nappes can only have taken place before erosion had proceeded to such an extent that the outcrops of the nappes along an alignment in the direction of movement had been divided off into separate outliers, unable to translate the stresses as a unit. Both the Krol and Garhwal Nappes have been strongly folded, possibly as a result of the resistance offered by the floor upon which the movement was effected. There has since been erosion of these thrusts with the resulting formation of the Windows and zig-zag outcrops, and it may be accepted that the major part of the movement along these thrusts took place before river dissection had reached its present pronounced stage. It may, therefore, be assumed that there has been more than one period of movement, the stronger movements perhaps during the Helvetian, and the later movements during the Siwalik and post-Siwalik.

Snowy Ranges

I have visited the higher Himalaya of this region twice; in 1932, when a traverse was made up the Alaknanda valley to Badrinath, Mana and the Arwa valley; and in 1935, when the Bhagirathi valley was ascended up to some of its tributary valleys in the neighbourhood of Harsil, Gangotri and Gaumukh. A brief lithological description of the rocks encountered along the Alaknanda valley has already appeared (*Rec. Geol. Surv. India*, v.69, p.133, 1935). It is intended here to mention only a few points concerned with the snowy ranges of the higher Himalaya.

Two Main Zones

The snowy ranges between the Bhagirathi and Alaknanda valleys may be divided into two zones by a fairly well defined line. The southern zone, forming the Main Himalayan Range as seen from Landour and Lansdowne, consists predominantly of paragneisses and schists, dipping towards the northeast, and presenting a scarp face towards the Plains of India. The northern zone is of granite, out of which the peaks in the Gangotri and Arwa basins are carved. The boundary between these two zones is shown on the map (Plate 3). I disagree with the mapping of Griesbach, who has drawn in the neighbourhood of Harsil and Dharali what appears to me to be an artificial boundary between Haimanta slates and a combined group of granite and metamorphics (*Mem. Geol. Surv. India*, v.23, 1891).

Metamorphics of the Main Himalayan Range

The rocks of the Main Himalayan Range consist of a varied assemblage of schistose phyllites, schists, and granulites intruded by gneissic granite and pegmatite. They rest upon little metamorphosed shales, phyllites, limestones and quartzites, from which they are separated by a thrust plane. This thrust is well seen at Sini (30°46':78°36') and occurs near mile 158 on the pilgrim track from Hardwar to Badrinath. The rocks immediately above the thrust appear similar to those of the metamorphosed Chandpur series found in some places at the base of the Krol Nappe and more generally in the main Garhwal Nappe.

The main suite of metamorphosed sediments must belong to a different unit. The rocks of this suite were originally shales, shaly sandstones, sandstones, calcareous shales and limestones. In their present metamorphic condition they form a series that is characteristically granulitic, consisting of quartz-biotite-granulites, often with garnet and felspars, quartzites, hornblende-granulites, diopside-calciphyres, marbles, biotite-garnet-schists and kyanite-schists. The calcareous rocks are best developed between Badrinath and Mana, but occur to some extent up the Rudagaira valley (30°55':78°54'). It is possible that this suite is equivalent to the Jutogh series of Simla.

Granite Zone

The granites to the north of the Main Himalayan Range probably occur continuously from Dharali (31°02':78°47') eastwards to the Saraswati valley and Kamet peak. Several types of granite are present, including muscovite-tourmaline-granite, biotite-muscovite-granite and adamellite. Porphyritic types are common at Bhaironghati, Jangla and up the Nela (Lamkaga) valley.

Some of these granites are sheared and crushed. The presence of patches of granular blue quartz is suggestive of crushing, a fact which struck my colleague Dr. J. A. Dunn on being shown specimens. Shearing is well seen at a height of 10,300 feet up the Nela valley (about three miles from Harsil),

PLATE 3

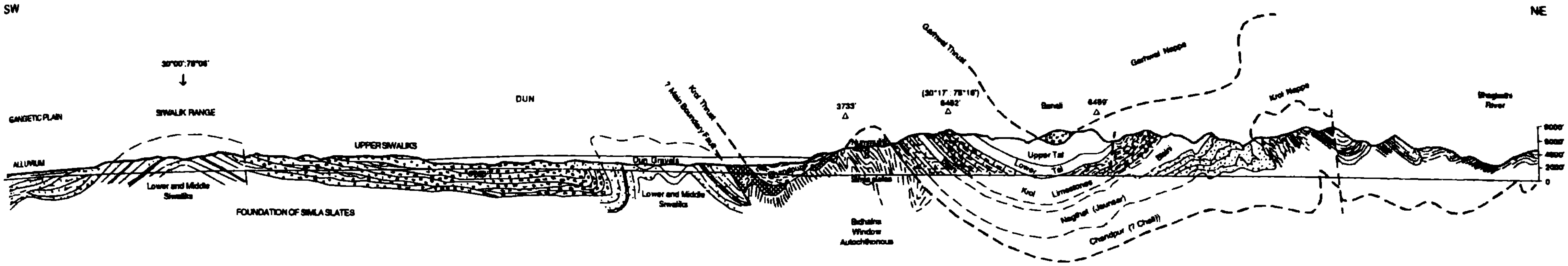

Fig.1. Section across Siwalik range and lower Himalaya in 1 inch = 2 miles map no. 53J/SW.

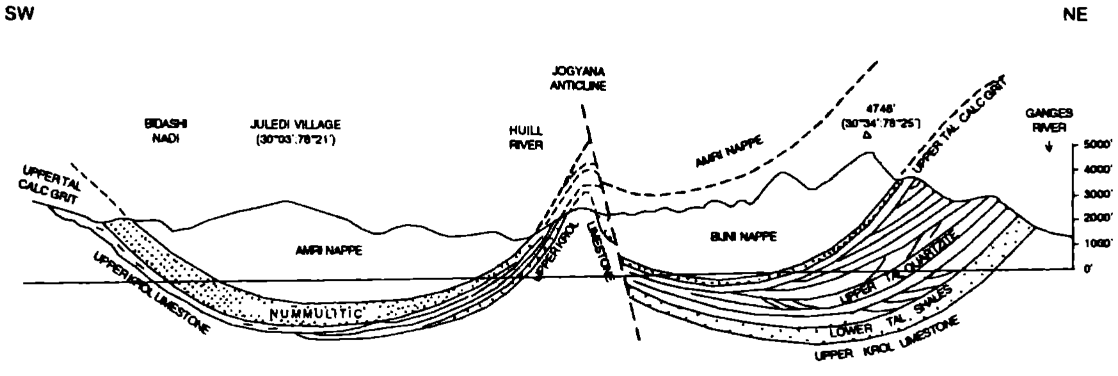

Fig.2. Section across the composite Garhwal syncline showing Amri and Bijni Nappes and the unconformity below the upper Tal calc grit.

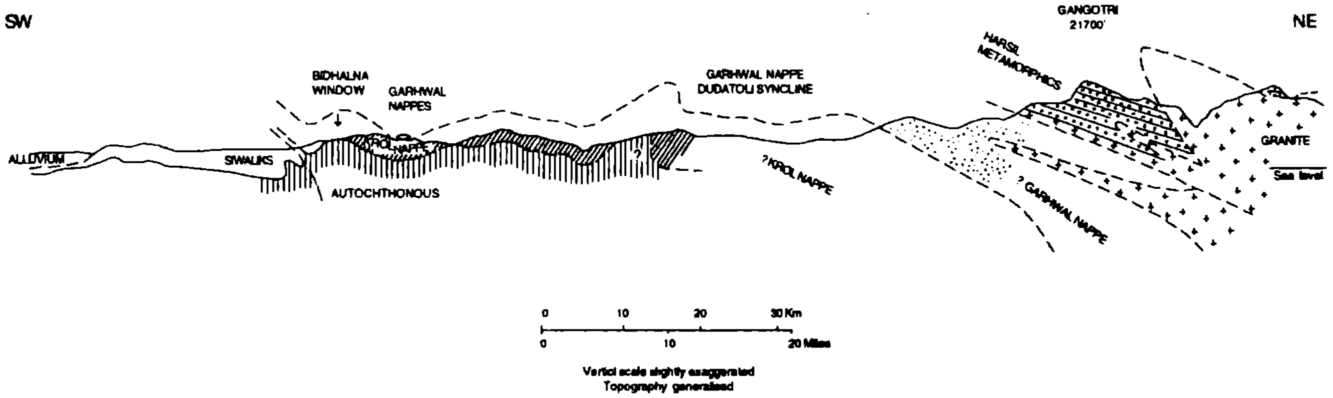

Fig.3. Tectonic section across the Garhwal Himalaya (a preliminary attempt).

where there is a contact between the granite and overlying metamorphics. The garnet of the metamorphics has broken down retrogressively to chlorite, while the granite has been sheared and mylonitised through a width of 150 feet at right angles to the plane of contact, with the development of marked schistosity and the destruction of the phenocrysts.

It would appear from these facts that some at least of these granites are not post-tectonic in the sense of the post-tectonic granites which cut across the *decken* in the Alps. These strained granites may have been intruded either during the major thrust movements, or at an altogether earlier period. It was considered above that the Lansdowne granite was intruded before the formation of the Garhwal Thrust and that it was pre-Miocene.

Possible Northward Extension of the Garhwal Nappes

It has been stated that the main Garhwal Nappe occurs as synclinal outliers resting upon less metamorphosed rocks. Reasons have been brought forward for regarding the schistose rocks and granite of Dudatoli as belonging to the same overthrust unit as those of the Satengal, Banali, Amri and Lansdowne outliers. The nearest schistose rocks to the northeast from Dudatoli occur at the base of the Main Himalayan Range, where they too appear to lie with a thrust contact upon less altered limestones, quartzites and slates. It would seem possible, therefore, that the main Garhwal Nappe joins up with the rocks at the base of the Main Himalayan Range and that the minimum distance of translation of this tectonic unit may be about 50 miles (80 km). It appears that the granites were intruded principally into the Garhwal and overlying units and were thrust with them for miles towards the southwest, over rocks which are free from granitic intrusions, but are in places considerably injected with basic magma.

Finally, comparison may be made with the eastern Himalaya. In eastern Nepal and north Bengal there are two main dislocations:

(1) the thrust causing the Gondwana rocks to lie upon the Siwaliks;
(2) the thrust separating the Daling series from the underlying Gondwanas.

These two thrusts may be analogous respectively to the Krol Thrust and one of the Garhwal Thrusts. Near Udaipur Garhi (26°57':86°32') there are bleaching carbonaceous slates and a dark crystalline limestone which resemble the Blaini and Krol series of the western Himalaya, and which, like them, rest upon Siwalik rocks (Rec. Geol. Surv. India, v.69, p.143, 1935). Further, it may be remarked that the schistose phyllites of the main Garhwal Nappe appear to be identical to the Daling series of Nepal and Sikkim. In both areas, these schistose rocks are thrust upon Gondwanas or the equivalent of Gondwanas.

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(Extracted from the Proceedings of the 38th Indian Science Congress, Bangalore, 1951, part 2, pp.109-153

The Bearing of Geology on Multipurpose Projects

J. B. AUDEN

EDITORIAL COMMENTS

In this state-of-the-art address on Engineering Geology, Auden presents a comprehensive account of geoscientific knowledge as a result of extensive work in the post war years, when emphasis was on development of irrigation and power. The different factors, that come into play in India, in engineering investigations, such as rainfall, silting tectonics, seismicity, thrusts, faults and allied factors are considered, besides basic geological data. The foundation features of the high Bhakra dam is described, with special emphasis on placing the dam base on sandstones at the heel and the toe. In the case of the Kosi high dam, adverse features such as fault in the river courses, vicinity of thrust features and the very high rate of silting, are emphasized. Occurrence of a longitudinal fault in the river course ruled out the sites at Marora and Nayar. Rocks of very low competence necessitated construction of a rockfill dam at Ramganga with a chute spillway. The geological factors of innumerable sites in the Uttar Pradesh and Punjab Himalayas are explained with lucidity, in relation to the Himalayan thrusts and their seismic susceptibility; and low competence of the foundation rocks. The significance of drainages developed along old structural lines such as shears, major joints and faults are considered in detail, in the case of dam sites in southwest India, elaborate explanations have been given about the importance of strike and dip of the foundation rocks in relation to the dam axis and ways and means of overcoming adverse features. Seismicity of the western part of India has been dealt in detail. Kutch is considered as the extension of a sedimentary basin of northern India.

The paper covered all aspects of Engineering Geological knowledge available in the country at that time and many of the conclusions drawn are relevant even today. Auden's vast experience in the Himalayan thrusts and movements have been utilized in an analysis of foundation features of high dams of north India, the only account available to engineering geologists. – B. Ramachandran.

INTRODUCTION

It is indeed a privelege to be elected President of the Geology and Geography Section of the Indian Science Congress, and a compliment to the Geological Survey of India, to which I have the honour to belong. The Survey is holding its Centenary this month, and I should like to take this opportunity of welcoming on behalf of geologists in India the geologists from abroad who have come to India for these celebrations.

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CONTRASTED ENVIRONMENTS

Modern engineering science developed mainly in northwest Europe and the eastern parts of the United States. These are regions which are geologically stable, suffer from few earthquakes, have a relatively mild and moist climate, and in general have not undergone excessive soil erosion. There have been few major problems regarding development of groundwater and storage of surface water for domestic and agricultural purposes, except in so far as the supply to large cities is concerned. Where storage of water is required by impounding dams, for hydro-electric power and municipal supply, engineering problems have arisen from structural weaknesses due to the past geological history but, except in Italy and Portugal, the stability of the region has not been called into question. While such conditions have come to be the norm for those living in environments of this type, in many parts of the world they are very far from typical. New problems were faced in the Western States of the USA. The montane zone which forms the northern margin of India and Pakistan is geologically of very recent origin, notwithstanding that old rocks have been involved in the young movements. Large-scale overthursts of middle Pleistocene, and possibly even younger, age have occurred, while the Karewa formation of late Pleistocene age has been strongly tilted in the Kashmir valley with dips as high as 40°. Destructive earthquakes are of frequent occurrence. Major glaciers occur which are actively abrading, while recent river erosion and incision is marked. About 90 per cent of the rainfall is concentrated into one-third of the year. In some areas the rainfall is less than 5 inches per annum. In many others it exceeds 200 inches. The pressure of population has driven people to widespread felling of the forests, and to unsound systems of cultivation and grazing, which have engendered disastrous soil erosion. It is true that soil erosion is prevalent in most parts of the world, but it is intense in parts of northern India and is one reason for the quite abnormal siltiness of the rivers. The softness and stability of things in northwestern Europe led Wordsworth to assume a gentle and beneficent role to nature which is scarcely in accord with the malignancy of cyclonic floods and landslides, drought, and earthquake experienced last monsoon by those living throughout the 1500 mile belt between the two Punjabs and Upper Assam.

It is with this background of young active movements, and sharp regional and seasonal variations in climate, that many of the projects have to be considered in India, and is the explanation why the geologist in this country is concerned not only with the local problems of dam foundations, but with the broader issues of regional tectonics, earthquakes, soil erosion, siltation and water conservation, matters which are of less importance to projects located on the continental shields of the temperate zone.

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SEISMICITY

Certain Objectives

Seismicity in India has already been the subject of the well-known Presidential address given by Dr. West to this Section in 1937, and was discussed at some length by Dr. Wadia and myself in Chapters 8 and 9 of the Memoir describing the Bihar-Nepal Earthquake of 1934. That it is necessary to consider it again is due to the enhanced interest arising from the many projects which are envisaged in northern India, and because the very feasibility of some of the projects has been called into question within the last few years by certain engineers and scientists.

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It has to be admitted that our knowledge of the basic conditions responsible for earthquakes in northern India is not all that clear. Major shocks have originated in such varied locations as the Makran coast, Kutch, Quetta, Kashmir, Kangra, North Bihar, the Shillong Plateau and the Assam Himalaya. Only last year occurred the great earthquake of the Upper Assam mountains. There are such manifest, superficial, and in some cases fundamental differences in the geological nature of these regions, that the picture appears to be confused. It might thus be concluded that no part of northern India is free from the possibility of being an epicentral region of major shocks, and consequently that all areas should be treated alike from the point of view of earthquake hazard and design. Moreover, accurate historical records of shocks go back only 130 years, while instrumental records are much more recent. We are thus faced with isolated events, many of them without seismographic records, which might be thought insufficient in frequency in any particular area for generalizations to be permissible about the relationship of epicenters to observed surface structure. I do not propose to cover the ground already so well discussed on previous occasions, except in so far as to introduce data not then available and to adopt a different emphasis related to engineering projects.

Kutch and Makran

The great Kutch earthquake of 1819 occurred in a part of India which is usually regarded as belonging to the peninsular foreland, and the epicentral region was over 100 miles distant from the mountains of Sind. As West remarked, if this earthquake had not occurred it is doubtful if the instability of the region would have been recognized at the present day. He concluded that the shock may have been connected with faulting and subsidence of an almost unfolded part of the foreland.

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Air-photo coverage has been carried out of Kutch in connection mainly with the water supply of the proposed major port of Kandla. The photographs reveal a very complex tectonic pattern, including domes and saddles, oblique tear faulting, and pronounced shear joints, which indicate stresses as intense as anywhere in the montane zone between the Makran coast and Quetta. Large numbers of contemporaneous sandstone dykes occur, perhaps the result of earthquakes which took place during the Jurassic and Cretaceous periods, and the Mesozoic rocks have been penetrated by numerous plugs, sills and dykes of basic magma, evidently of Deccan Trap age.

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The epicenter of the major Makran earthquake of 28th November 1945, with a magnitude of 6.7, was found by Pandse to be near coordinates 24.2°N:62.6°E (Pandse, 1946, p.106). This position is about 60 miles from the Baluchistan coastline and significantly therefore lies directly on the line of submerged ridges located by Sewell, on what may be called the Pab-Kirthar-Zagros ranges. Sondhi has described the emergence of four mud islands just south of the coast line between Gwadar and Sonmuam Bay, which he suggests is due to gas pressure released along the crests of hidden anticlines which followed this very severe shock (Sondhi, 1948, p.154).

The most pronounced topographical change which took place as a result of the great shock of 1819 occurred along the Allah Bund, 20 miles northeast of Lakhpat. This fault is located in superficial Runn deposits, which must however overlie the folded zone of Mesozoic rocks extending WNW from the Pachham group. This seismic fault is evidently close to what may be regarded as the corner of the peninsular shield.

Kutch should therefore be considered rather as a part of the orogenic zone of Sind and Baluchistan than as belonging to the unfolded peninsular foreland as has hitherto been supposed. Both the 1819 and 1945 shocks were connected with recent instability in this orogenic zone which, though now largely concealed below the Runn and the ocean by Pleistocene subsidence subsequent to folding, has all the attributes of mountain ranges. The deflections of their strikes may be related to the shape of the continental foreland, while the inferred submerged syntaxial fusion of the ranges may have been rendered possible by the absence of the shield west of about longitude 68°.

The fact, therefore, that severe earthquakes occur in this region should not be regarded as an exception to the generalization that the peninsula itself is relative stable, because the shocks occurred in an area which should not be considered as part of the peninsula, any more than the Lahore and Gangetic downwarps now so belong.

Earthquakes in Other Parts of India

We may now briefly discuss the seismic zone in other parts of India. Major earthquakes, such as the Baluchistan shock of 1935 and the Bihar-Nepal shock of 1934, had shallow foci, the first under 10 km and the second at 14.8 km. West has demonstrated elegantly the connection between 15 shocks in Baluchistan with the sharp deflection of ranges round the Quetta re-entrant, and the seismic instability of that area is clearly related to relatively superficial crustal strains.

Other seismic areas connected with sharp deflections of ranges are those of Northern Kashmir and the Hindu Kush, as well as the ranges of Upper Assam and Tibet. But the comparison between Baluchistan and North Kashmir is not at all exact since the earthquakes in the latter area have deep foci of 150-250 km (Coulson, 1938, p.143). These depths should be below the tectonic level of the downward projection of granitic crustal roots underlying the ranges which make such a swing round the Kashmir re-entrant. In contrast to the Hindu Kush area, and in resemblance to that of Baluchistan, the recent Tibet-Assam earthquake had a shallow focus (Sohoni, 1950, p.266).

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Gravity Anomalies

The Baluchistan, Kangra and Bihar earthquakes were all connected with areas of negative gravity anomalies. Reference to the G—8F anomaly maps of the Survey of India (Glennie, 1938, chart 9), and to the anomaly map prepared by Evans and Crompton after full correction has been made for surface geology and isostatic compensation (1946, p.233), shows that there are three conspicuous downwarp regions in front of the Himalayan range which are characterized by pronounced negative gravity anomalies. The western area strikes northwest from Lat.32°N :Long.76°E, and includes Kangra and Jammu. The middle area of 75,000 square miles is occupied by the plain of the Uttar Pradesh and North Bihar, while the eastern area lies in the Brahmaputra valley between Tezpur and Sadiya. The first two negative anomaly zones are connected with seismic instability, and it might seem a sound generalization to connect the seismic areas with negative gravity anomalies, and to regard the intervening areas of positive anomalies as more stable.

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However, the significant feature is not so much the actual sign of the anomaly, but the anomaly gradient regardless of sign, since a part of the crust with steep gradients is presumably subject to the greater stress. Thus, the map prepared by Evans and Crompton of geologically and isostatically corrected gravity anomalies shows a change from +75 milligals around 25°15'N:93°E to –25 milligals near Cachar, which implies a gradient of about 1.6 milligals per mile. This could be considered the explanation of the Cachar earthquake of 1869. But this suggestion fails completely to account for the 1897 and 1930 shocks, which are in a regions of gentle gradient, while the line of Burmese epicenters follows a zone virtually without anomaly change. Moreover, the Panvel Flexure of the Konkan shows the maximum gradient found in India of 4 milligals per mile, and is not characterized by seismic foci.

It should be remembered that maps showing gravity anomalies make no distinction between the ages and nature of the incidents which led to the uneven distribution of masses of different densities in the earth's crust. They represent the total effect of all orogenic, intrusive and epeirogenic processes, and of warpings in the asthenosphere, from the Archaean up to the present day. Consequently, while some regions of moderately strong anomalies may be geologically old and seismically stable, in other areas the anomalies indicate very recent changes in the distribution of crustal masses of different density and as symptomatic of newly acquired crustal strains which have not yet reached adjustment. Any anomaly properly corrected must indicate stress, but presumably regional anomalies with gentle gradients and almost circular contours are distributed and carried over wide segments of the crust, whereas the strong and markedly oriented anomalies of recent origin represent stresses confined to smaller segments which, in the process of relief, may result in seismic disturbance.

Seismic Zones and D.V.C. Projects on the Northern Edge of the Peninsula

* * * * *

The seismic zone as it concerns Bharat or India is considered to be located in the following principal areas:

1) Kutch
2) The Kangra downwarp
3) The Gangetic downwarp of the eastern districts in Uttar Pradesh and the whole of North Bihar
4) The Shillong plateau and Himalayan ranges of Assam.

These areas have been illustrated in seismic maps prepared by the investigators of the Bihar-Nepal earthquake, and by West.

Areas at the northern edge of the peninsula are certainly considerably affected by major shocks arising in the Himalayan frontal region, and feel the fringe effects of earthquake waves which actually originate to the north. This does not mean, however, as has been suggested by some scientists, that the northern part of the peninsula is itself a seismic focus that may some day give rise to an earthquake of the highest intensity. It is true that a narrow zone of high intensity, represented by isoseismals 9 and 10, lay between Patna and Monghyr during the 1934 shock. This zone is in part connected with interface conditions between shallow alluvium and crystalline basement. The devastation caused by Monghyr was certainly largely due to the fact that the town lies on alluvium immediately adjacent to hills of crystalline rocks which overlook the town, and that boundary conditions existed, involving refraction and reflection of waves, between formations of very widely different elasticities. The narrow zone may also indicate, as suggested by Dunn, the existence of a WNW-ESE stress zone parallel to the main concealed plane of failure along which the earthquake originated in North Bihar (Dunn et al. 1939, p.80). Parallel to the Patna-Monghyr line was a zone of somewhat high isoseismal 8 located in lower 8 extending ESE of Arrah, and of moderately high 7 located in lower 7 striking intermittently between Gaya and Dumka. These patches of slightly enhanced intensity, situated within areas of lesser intensity, may indicate other stress zones cutting right across the strike of the exposed geological formations, but the rapid falling off in isoseismals just to the south of the Patna-Monghyr line would not have been possible if these postulated stress zones represented principal lines of failure.

While provision must certainly be made in structural design for the fringe effects of earthquakes arising in the downwarp at the foot of the Himalaya, it does not seem necessary to allow for the highest acceleration which is

Table 1

		Assam 1897			Kangra 1905			Bihar-Nepal 1934			Baluchistan 1935		
	Acceleration mm/sec² McAdie	Area in in sq. miles	Mean radius miles	Ratio squares of radii	Area in in sq. miles	Mean radius miles	Ratio squares of radii	Area in in sq. miles	Mean radius miles	Ratio squares of radii	Area in in sq. miles	Mean radius miles	Ratio squares of radii
10	10000 to 5000	9700	56	0.33	192	7.8	0.096	1300	20	0.089			
9	2500	30000	98	0.25	2140	26	0.36	14000	67	0.45	850	16.5	0.30
8	1000	120000	195	0.49	5800	43	0.39	31000	100	0.33	2900	30	
7	500	250000	282	0.37	39000	112	0.26	94000	173	0.31			
6	250	650000	456		152000	220		300000	309	0.51			
5	100							590000	434				
Mean radius of felt area in India: in km		1400			1160			1380			295*		
Approximate limiting distance from epicentral region of landslips initiated by the shock: *in miles*		200			70			150					
Depth of focus: in km								14.8			<10		
Instrumental magnitude		Assumed to be 8.5						8.2			7.3		
Magnitude as indicated by radius of felt area		8+			about 7.8-8.0			8+			5.7*		

* These figures are too low because the shock occurred at night and potential observers were asleep

experienced only in the regions actually epicentral to the focus or focal plane.

* * * * *

Areas of Destruction in Past Earthquakes

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The intensity of an earthquake decreases according to inverse functions of the distance from the focus or focal plane. In an uniform isotropic solid the energy crossing unit area varies inversely as the square of the distance from the origin. It is true that geological formations are not isotropic and have varying elasticities, as well as capacities for absorption, while the presence of orogenic zones introduces pronounced directional features of contrasted physical properties deep within the crust. These conditions create complications, but do not invalidate the general relationship regarding the rapid decline in intensity outwards from the focus. Richter states that the trace amplitude on the seismogram varies inversely with the cube of the distance (1935, p.18). While the decline in intensity for the P and S waves may be according to the inverse second or third power, for surface waves at shallow depths it tends to be more nearly according to the inverse first power. In Table 1 is given the arbitrary ratios of the squares of the different radial distances from the epicenters. In all the cases listed the isoseismal lines showed an elliptical form with varied degrees of elongation, but it is more convenient to re-calculate the radial distance from the areas enclosed within the isoseismals, as if these had been true circles spreading out in a homogenous crust.

If distance is plotted against acceleration, the decline in intensity is seen to be roughly hyperbolic. On logarithmic paper the decline is represented approximately as straight lines (Fig.1). For the same depth of focus, and traveling through similar crustal terrain, but with different total energy or magnitude, the decline should follow almost parallel gradients, varying only with the radial distances involved for different isoseismals. Convergence of gradients towards nearly similar radial distances of felt areas might be assumed to be some indication of different depths of focus. This explanation may apply to the convergence between the 1897 and 1905 shocks, but fails in comparing those of 1897 and 1934 which have almost identical distances of felt areas. The 1934 earthquake had a shallow focus of 14.8 km certainly no shallower than that of 1897, so that the much smaller area of almost total devastation in 1934 cannot be explained by profound differences in depth of focus. Some other factor must be involved, connected perhaps with absorption in the deep and imperfectly elastic alluvium, which may eliminate differences in magnitude at distances considerably in excess of 1000 km from the epicenter.

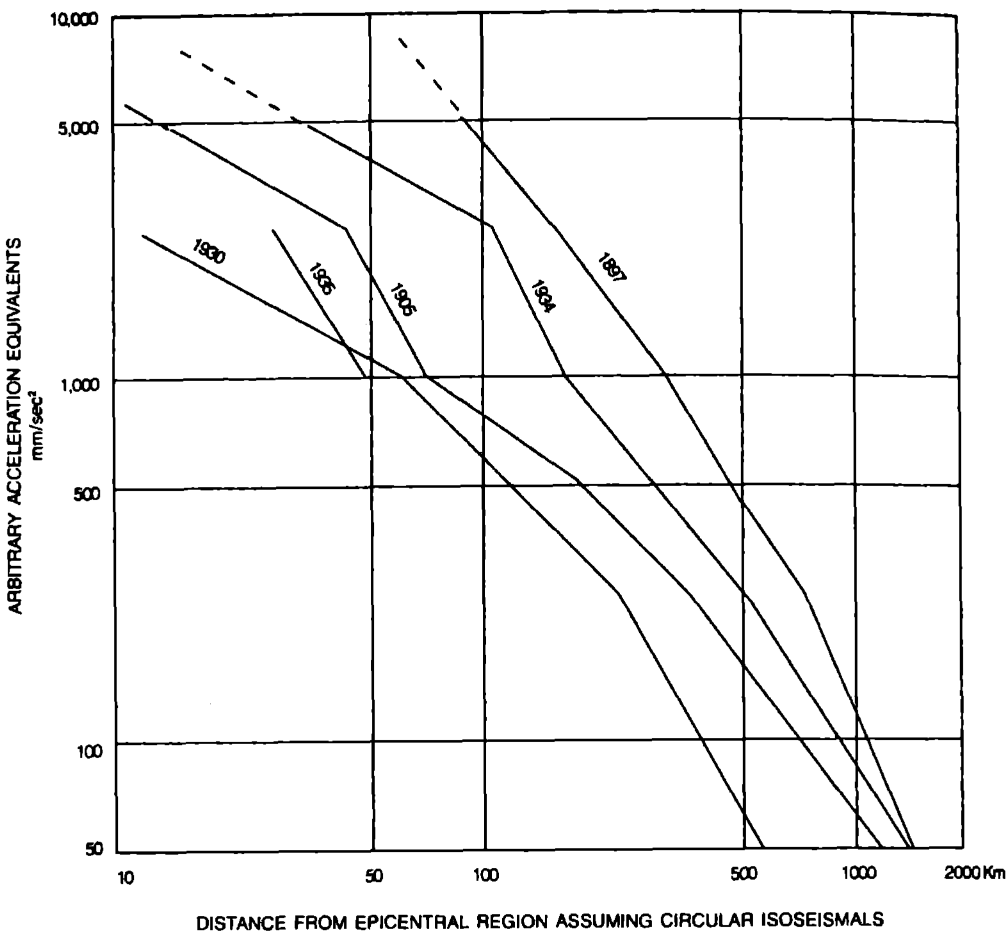


Fig.1. Diagram showing declining acceleration with distance for recent Indian earthquakes.

In all, except the 1897 shock, the acceleration drops to less than one tenth that of gravity within 100 miles of the epicenter. In the case of the Assam shock the corresponding distance is a little short of 200 miles, and it does not appear that the smoothed isoseismal ellipses shown by Oldham are practically upgraded relative to those drawn in later field studies.

*   *   *   *   *

SECULAR CHANGES IN ELEVATION

The Reported Rise of the Himalaya

*   *   *   *   *

The problem of the heights of Mount Everest and Kanchenjunga has been lucidly discussed by Sir Sidney Burrard, a former Surveyor General (1933, Pt.1, pp.53-62). Burrard tabulated the height of Everest as calculated from observations at 12 stations, 6 in the plains and 6 in the hills, whence observations were made between 1849 and 1902. The value 29,002 is the average of the observations of 6 stations in the plains with coefficients of refractions varying from 0.07 to 0.08. When, however, a coefficient of refraction of 0.05 is adopted for hill stations and 0.0645 is taken for stations in the plains, the averages of all the 12 sets of observations is 29,141 feet (8,882 m). This figure was subsequently increased to 29,149 feet (8,884 m) with further knowledge of refraction, and by applying corrections for the deflection of the plumb line. This height is in relation to various spheroidal surfaces tangent to the geoid at each station of observation. The spheroid surface, which is a geometric surface that most closely conforms to the geoid, is raised above the geoid throughout the Gangetic alluvium of eastern Uttar Pradesh and Bihar, and northwards into the Himalayan foothills. It lies, however, below the geoid surface in the neighbourhood of Kamet and probably also in the region of Kanchenjunga and Everest, where the separation of the two surfaces is thought to be not less than 70 feet. The height of Mount Everest in relation to the geoid is regarded as 29,050 feet, a difference of about 100 feet from the revised height of 29,149 feet relative to the spheroid. The Survey of India have retained the old height of Everest as it is considered undesirable, as further refinements are achieved with regard to our knowledge of refraction and the degree of separation of the geoid and spheroid, periodically to give new heights to the confusion of all Atlases.

The important point is that all three average values, 29,002, 29,141 and 29,149, are averages based on identical sets of theodolite readings, and differ from each other merely because of refinements of knowledge concerning the corrections necessary to reduce the original observational data. Consequently, the average heights prove nothing whatever about the secular rise of the Himalaya, since no new observations were involved in their estimations.

* * * * *

Slow secular movements are almost certainly taking place in the orogenic zone, with both vertical and horizontal components, though it cannot be said that these have yet been confirmed by instrumental observations. It is considered that the major geological changes which have been attributed to the Tibet-Assam earthquake, of a magnitude and areal extent sufficient to warrant changes in the design of structures so far removed from the epicentral area, have been greatly exaggerated.

Bearing on the Kosi Dam Site

Memories are short, and new disasters tend temporarily to push back recent ones too far in contemporary perspective, and almost to belittle their magnitude. Sufficient has already been said about the magnitude of the 1897 and 1934 shocks. The middle of the epicentral region of the 1897 shock, recognized as possibly the largest experienced during the last 100 years, is only 250 miles (400 km) distant from the Kosi dam site, or less than half the distance of the Tibet-Assam shock. The 1934 earthquake, with a magnitude of 8.2, had an epicenter which is only 72 miles (116 km) away from the Kosi dam site. The situation regarding the Kosi is summarized in Table 2.

Table 2. Earthquakes with epicentres close to the Kosi dam site

Year of shock	Area	Mean radius of felt area in km	Distance of epicentre from the Kosi dam site in km	Magnitude	
				Instrumental	From radius of felt area
1803	N. Bihar U.P.	?600	N. Bihar or East U.P.	-	6.7
1833	N. Bihar Nepal	?550	N. Bihar ?150		6.5
1897	Assam	1400	400	*	8+
1930	Dhubri	550	290		6.5
1934	N. Bihar Nepal	1,380	116	8.2	8+

It is considered therefore that if allowance is made in the design of the Kosi dam for its location within 120 and 400 kilometres from the epicenters of the two indisputably severest shocks in historical times, this would *ipso facto* take into account the stresses arising from the Tibet-Assam shock which originated 1000 km or more from the site. The closeness of the Kosi site to the epicentral region of the 1803, 1833 and 1934 shocks is in itself a matter of very grave concern to the engineers, requiring no additional motive from phenomena in Upper Assam for making the fullest possible allowance against future earthquakes in the immediate area of the Kosi project. It is understood that a factor of 15 per cent, gravity for horizontal acceleration and 10 per cent, gravity for vertical acceleration had already been introduced into the design of the Kosi dam before the occurrence of the 1950 earthquake.

The 1950 earthquake will be of vital concern, however, to the engineers responsible for assessing the feasibility of the Dihang project which envisages the construction of a dam over 700 feet in height on the Dihang river near coordinates 28°09':95°17'. In this region extensive mountain slopes have succumbed to devastating seismic landslips. The site is about 160-200 km away from the instrumental epicenters of the shock.

MAJOR STRUCTURES IN THE HIMALAYA

Tectonic Units

The study of the dam sites within the Himalaya mountains has shown that a number of large projected structures lie close to major thrust planes.

* * * * *

The region may be broadly classified into the following principal units:

1. Autochthonous basement with overlying folded and overthrust Tertiary rocks.
2. Para-autochthonous rocks of the major tectonic windows and the inliers of Jammu.
3. The overthrust units.

* * * * *

The following dam sites are located on these para-autochthonous rocks:

		Proposed height in feet
Dhiangarh	Chenab river	700
Larji	Beas	650
Daher	Sutlej	500

Of these sites, that at Larji is located actually within a window and very close to the major thrust plane which separates the dolomitic suite from the overlying phyllites and schists of the main range. The Riasi dolomites of the Dhiangarh site are overlain by Murree beds, but both the dolomites and the Murrees show a thrust contact against the younger Siwaliks which lie to the south.

The Keshau dam site (750 feet) on the Tons river, between Sirmur and Uttar Pradesh, is located on Mandhali rocks close to the bottom of the overthrust sheet which rests upon the Deoban dolomites. Considerable small-scale thrusts have developed within the Mandhalis of the right abutment of the dam site which perhaps arose in response to the major thrust separating the two primary tectonic units.

The Marora site (640 feet) on the Nayar tributary of the Ganga, is situated on Simla Slates which have a pronounced NE-SW strike parallel to the Aravalli axis, and are thought to be part of the autochthonous peninsular system which lies just below the tectonic units of the overthrust Krol and Lansdowne sheets (Auden, 1937, Plate 36). The site is noteworthy for the strong system of faults striking WNW-ESE, that have evidently developed in response to the

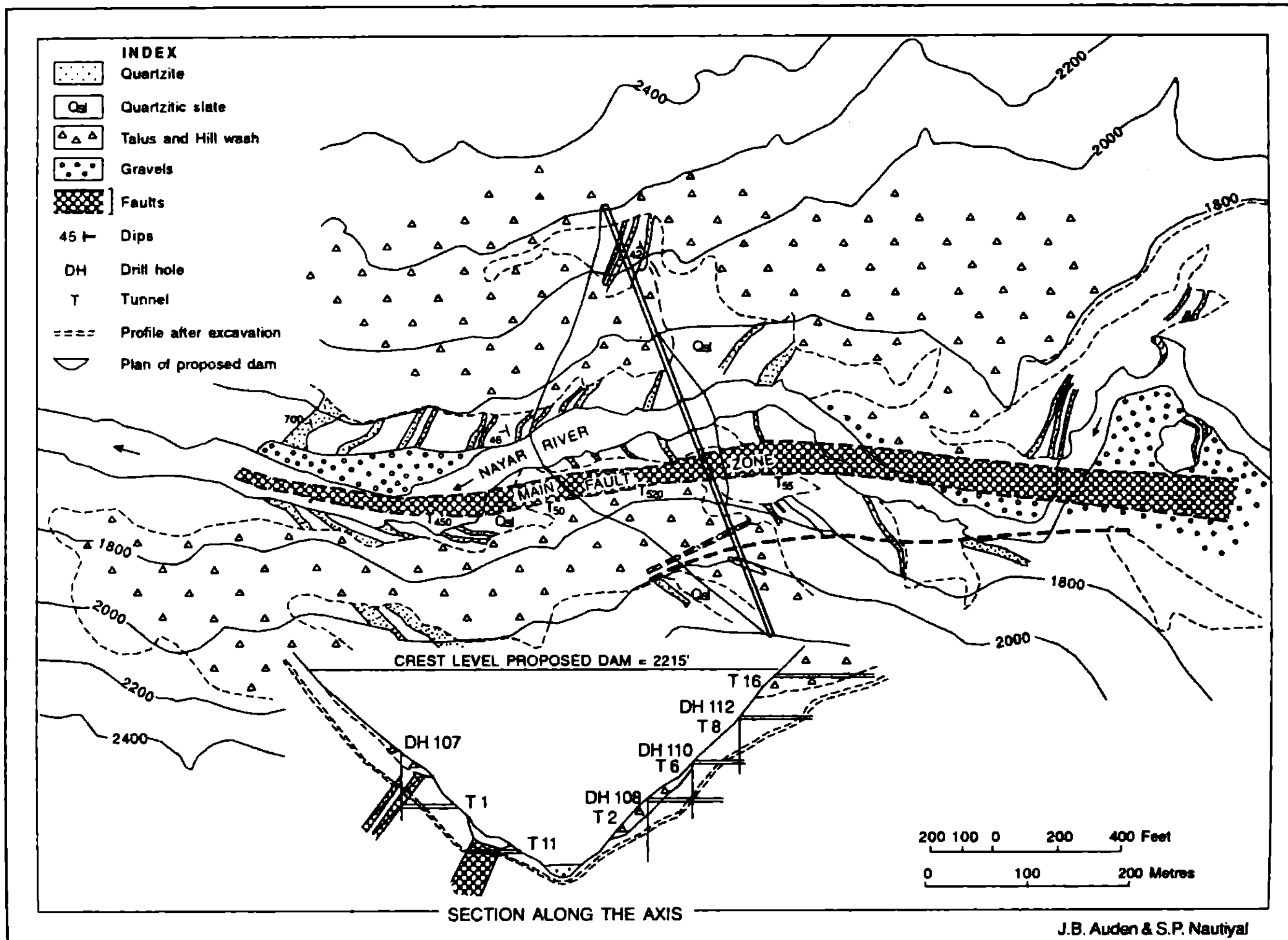


Fig.2. Geological map of Nayar river gorge, Marora dam site, district Garhwal, Uttar Pradesh.

overthrusting which took place just above (Fig.2). These were discovered and plotted by S.P. Nautiyal.

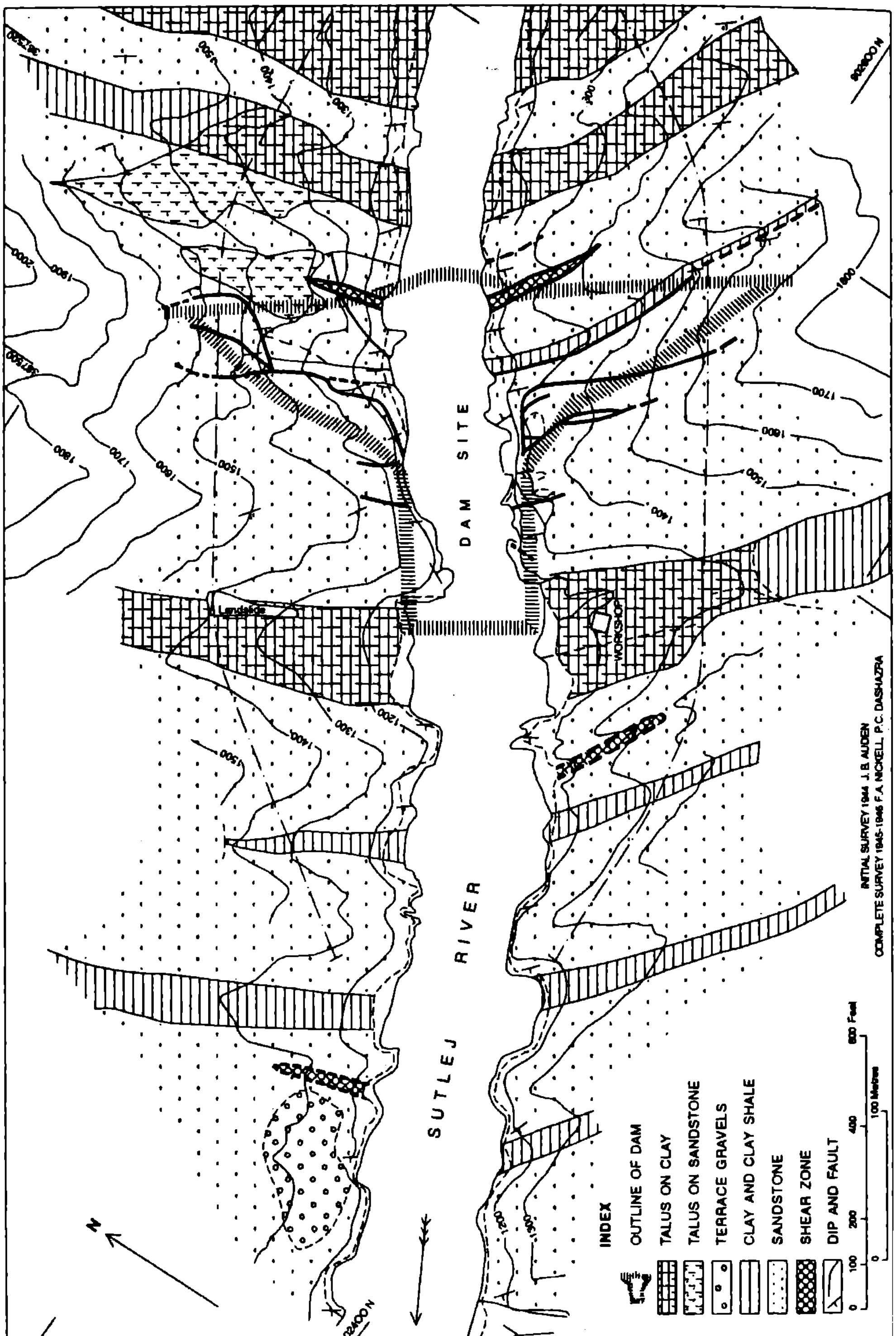
Far to the east, in eastern Nepal, the Kosi Dam site (750 feet) lies on highly forked folded and partially altered Gondwana rocks immediately below the megatectonic Daling overthrust unit. The Daling thrust occurs only 300-500 feet above the proposed crest level of the dam on the two abutments. The site also lies just north of the Krol thrust, and of recent faults in the Lower Siwaliks (Fig.4).

Thrust Planes and Stability of Dam Sites

In all these cases it has been necessary to decide to what extent proximity to the major thrust planes is likely to be a dangerous feature affecting the stability of the structures. These largest megatectonic overthrust movements, or underthrust if the emphasis is on the buckling down of the peninsular foreland into the tectogen, probably took place in the Burdigalian. The thrust planes have since been strongly folded by later Tertiary and Pleistocene movements, and subsequently eroded by rivers so that they now occur as dissected interfaces upon which rest tectonic units that are frequently isolated as outliers or klippen at the higher elevations of ridges. They have therefore been accepted as old dead structures along which it is not possible normally for further movements to originate. The thrust units have indeed become incorporated into the general body of the Himalaya, and the surface traces of the thrust planes may be regarded figuratively as old scars of healed wounds rather than as indications of anything pathological below.

* * * * *

So far as observations have been carried out in the Bhakra and Kosi areas, there is no evidence that any recent terrace gravels resting across such thrust planes have been displaced by post-terrace movements. Two faults have been found, however, which may have been active in recent times. The first is the Nahan thrust found along the Lower Giri river and listed as number 2 above. There is a suspicious set of lakelets and breaks in topography associated with this dislocation which has already been described (Auden, 1942, p.25, pl.9). Middlemiss has noted the secondary focal plane of the Kangra earthquake just south of Mussoorie, which coincides more or less with the Krol thrust (1910, pl.29). The Krol thrust does not show signs of recent instability, but the fracture on the south side of the Giri valley is along the strike extension of the focal plane. If this fracture is seismic, the main disturbance must have been prior to the 1905 earthquake, since the features referred to above are shown on forest maps of Sirmur prepared in the 19th century. The second is a fault confined to


DAM SITE
SUTLEJ RIVER
Landslide
WORKSHOP
INITIAL SURVEY 1944 J. B. AUDEN
COMPLETE SURVEY 1945-1946 F.A. NICKELL P.C. DASHAZRA
INDEX
OUTLINE OF DAM
TALUS ON CLAY
TALUS ON SANDSTONE
TERRACE GRAVELS
CLAY AND CLAY SHALE
SANDSTONE
SHEAR ZONE
DIP AND FAULT
0 100 200 400 600 Feet
0 100 Metres
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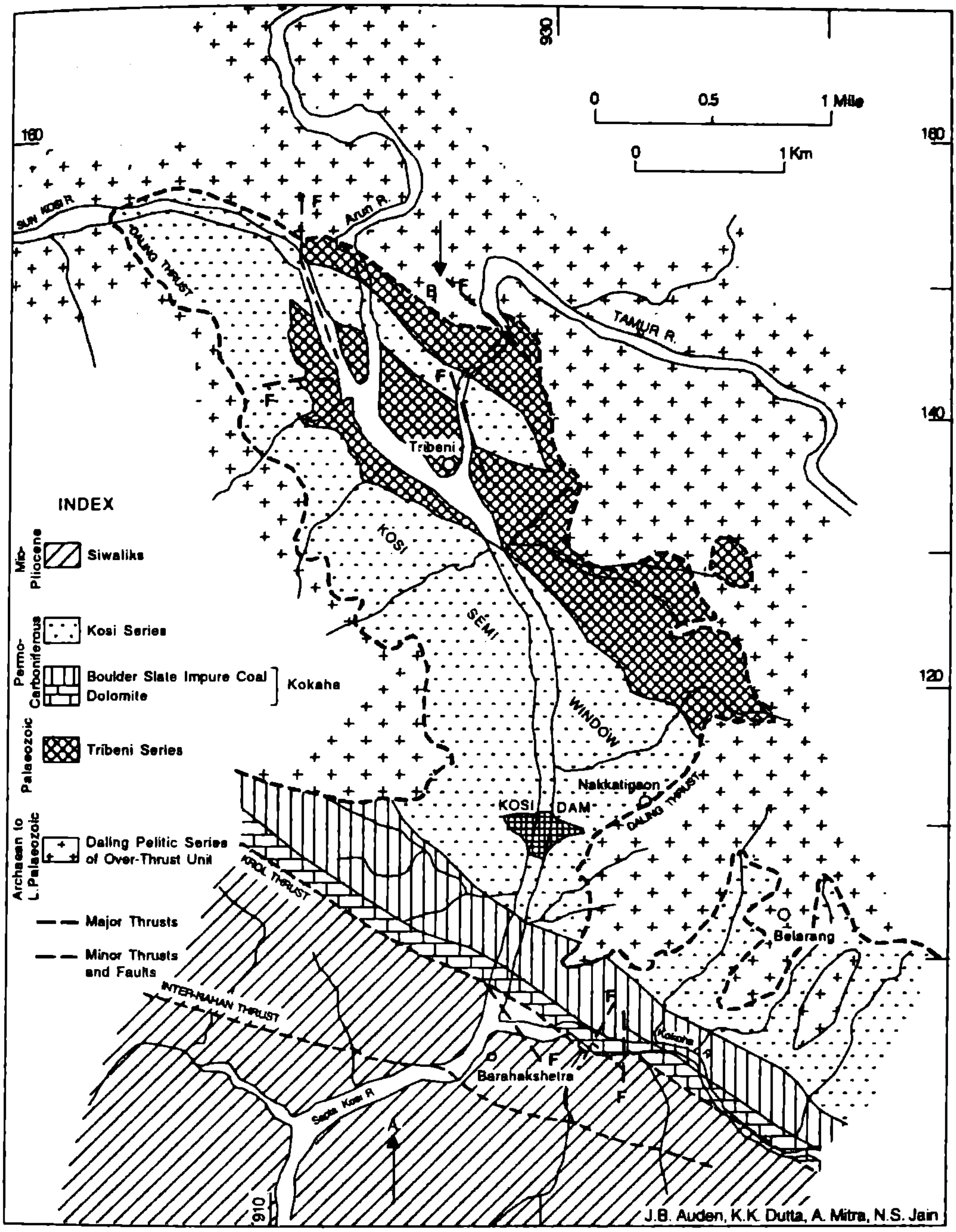

Fig.4. Provisional geological map of Kosi Gorge, Kosi dam site, Nepal.

the Nahans which runs east-west about 2000 yards south of the downstream toe of the proposed Kosi dam. From air photographs an impression is gained that this plane has undergone very recent movement, but the field evidence is somewhat equivocal.

The thrusts and tear faults which involve the Upper Siwaliks are clearly very young, being not older than Lower Pleistocene. Conspicuous tear faults are present along both the Ganga and Yamuna gaps cut through the outer Siwalik ranges, and possibly also the sharp change in strike of the Siwalik range at Chandigarh near Kalka is due to tear faulting. The alignment of the Koch dam site lies immediately to the southwest of the Yamuna tear fault, and this fact has to be considered should this site ever be finally sanctioned for an earth structure. It was considered unsound ten years ago for a concrete dam since the foundations consist of Middle Siwalik sand-rock and Upper Siwalik conglomerates, with very low strengths except for the calcified nodules.

Through the helpful cooperation of the Geodetic Branch, Survey of India, the areas bordering the Ganga and Yamuna tear faults will be the subject of periodic high precision leveling and triangulation, for the purpose of establishing whether or not slow secular movements are still taking place along them.

FEASIBILITY OF HIMALAYAN PROJECTS

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Whether or not it is advisable to start immediately with the building of really high dams of the order of 750 feet in such regions is a matter about which opinions are a little less concordant. Geologically and climatically the conditions in the Himalayan foothills create more problems probably than in most other parts of the world. Conservatism might suggest the construction of two or three smaller dams of the order of 500 feet in height rather than a single major structure but to do so involves formidable objections. The Himalayan valleys are deeply incised, with steeper declivities below kinks in the cross sectional profile which are often about 500 feet above river level. Reservoir volumes below 500 feet are generally therefore small. Further, most of the Himalayan rivers are excessively silty, so that a very large dead storage capacity has to be included in the projects. Thus, the average silt content of the Kosi river in eastern Nepal for three years has been proved by the CWINC research station to be 5.18 acre feet per square mile (2,465 m^3/km^2) per annum, and the catchment area of the Kosi river above the proposed dam site is 23,810 square miles or 61,670 km^2. It is not until dams approach a height of 600-700 feet in these regions that there is a satisfactorily large ratio between the live and dead storage capacities. These factors both indicate the desirability of starting with as high dams as is feasible, but it should be noted that subsidiary dams are in any case indicated on the tributaries to retain some of the abnormally large quantities of silt, and increase the life of the main reservoir.

The engineers are thus in a dilemma. The great destruction and misery caused by the floods and migrating courses of rivers such as the Kosi demand rectification. The geographic factors of rejuvenation and excessive silting point to the construction of high dams. But uncertainties regarding the effects of close earthquakes of the highest magnitude on structures 700 feet or more in height may for the present favour a cautious limitation in dimensions.

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Summarising, the northwest and the eastern Himalaya are subject to major earthquakes which require to be considered in the design of dams, but are not alone sufficient to vitiate their construction, provided good foundations are available. Granted that the foundation conditions are sound, and that design can allow for the future occurrence of catastrophic earthquakes close to the dams, the main criteria regarding the feasibility of projects are likely to be:

1) the duration of the live storage, even with the construction of costly subsidiary dams;
2) the lack of sales returns, from those projects situated in isolated regions, on the large quantities of power capable of development, and on which the economics of any major project must be partly based.

With silt rates as high as 5.0 acre-feet per square mile of catchment (2,380 m^3/km^2) per annum for some of the Himalayan rivers, the short life of the reservoir is a very real problem which has not yet been adequately faced. Moreover, the estimates of silt content are only of suspended load, and take no account of the manifestly large traction load transported by Himalayan rivers during periods of peak floods (Auden, 1950b). Such considerations apply to projects on the Karnali, Gandak, Kosi, Manas and Dihang rivers.

PENINSULAR STRUCTURES AND DAM SITES

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The peninsula has not undergone recent orogenic movements of the type which affected the Mesozoic, Tertiary and even Quaternary rocks of the montane zone, and the primary problems of regional stability and seismicity are not thought to be a vital consideration. But almost every dam site investigated has presented its own foundation defects which require engineering treatment.

The main features with which we have been concerned are weathering and the consequences of faulting and shearing. Weathering has proceeded to depths of 50 feet at right angles to the hill side in sites such as at Mattupatti, Tranvancore. Selective weathering of the schistose members at the Tilaiya dam site, D.V.C., has gone down to 25 feet below ground surface, and has entailed deep excavation and the removal of clay pockets in granulitic schists, with a volume in one case of over 1,000 cubic feet.

A point of great interest disclosed by dam site studies in western India is the existence of numerous regional shear zones which have influenced the drainage pattern. The Mattupatti dam site was found to have a shear zone about 70 feet in width running along the river bed. This consists of highly weathered pegmatites, amphibolites, and injection gneisses intersected with a system of clay-gouge zones with an aggregate thickness of four feet. It has had to be excavated throughout the full width of 70 feet, and down to a depth of 130 feet below original bed level, in order to provide a suitable foundation for a dam which is not to be more than 125 feet above river-bed level. There is little convincing evidence of any major fault offsets having taken place along this zone, although displacements are not easy to prove on account of the very variable nature of the injection gneisses and the lack of key formations. But a study of the 1'=1 mile topographical maps demonstrated a very striking drainage pattern, since the rivers follow remarkably straight courses. These courses have been controlled by NE-SW faults or shears, on one of which the dam site is located, and by the regional NW-SE strike of the gneissic banding. The NE-SW shear zone at Mattupatti is 35 miles long. Since the straight river pattern is developed between altitudes of 800 and 7000 feet above sea level, it is evident that not only are the structural features of great lateral extent, but that they are developed throughout a vertical height range of at least 6200 feet, and doubtless also to a greater depth. Indeed, the spacing of the shear zones at intervals of about 4 to 6 miles suggests some relationship between them and the thickness of the granitic crust. This regional phenomenon has since been found by Jacob to extend to the area of the Palghat gap between the Cardamom and Nilgiri hills.

A similar phenomenon is also noticed in the drainage pattern of the Deccan Trap outcrop of the Konkan and Gujarat, except that the second direction due to the strike of the steeply inclined gneissic banding of the Archaeans in south India is naturally absent, since the surface formation involved consists of horizontal or gently dipping lavas. Many rivers in the Konkan are aligned WNW-ESE, while in Gujarat they follow NW-SE courses. In those areas, studied on the ground, it is possible to state that faulting of the intensity sufficient to displace the flat-lying lavas is absent, and the directional features observed must be more of the nature of shears, without significant vertical displacement. Such shears are well displayed at the south portal of the northern Vaitarna-Tansa tunnel, where pronounced vertical sheeting of the lava is accompanied by zeolitisation following vertical veins. The river which most convincingly shows this straight alignment is the Karjan of Gujarat, which follows a geometrically straight course for 3¼ miles in the neighbourhood of coordinates 21°34':73°33'. The whole zone, along which different rivers adopt this particular alignment in certain parts of their courses, has a length of about 40 miles. The Gujarat shears show up clearly in air photographs as dark depressions which are in striking contrast to the high elevated ridges formed by the Gujarat dyke clusters (Auden, 1949a, p.132). The vertical dykes are not offset laterally by the shear zones, and it may be concluded from the brief studies so far made that such zones are not in general characterized by the displacements with either a vertical or a horizontal component. From an inspection of the maps the major shears in Gujarat north of the Tapi river are found to be separated by distances varying between 2½ and 4 miles, the spacing almost certainly being of significance and related to the thickness of the section of the crust actually involved in the stresses responsible for their formation. One more example which may be cited is the system of NE-SW shears which is strongly developed in the crystalline rocks of the Shillong plateau and has recently been noticed by Boileau in his study of the Um Tru Hydroelectric Project.

Horizontal shearing has cut right across some of the basaltic dykes of the Kakarapar dam site on the Tapi river. Since this set of dykes itself cuts an earlier set of composite dykes, all of which intrusions are post-lava in age, it is presumed that the shearing came at a fairly late stage in the sequence of igneous activity. But since zeolitisation has taken place along the vertical shears, the stresses were evidently developed before the Deccan magmatic cycle had completely terminated, possibly in the late Oligocene.

From an engineering point of view such planes of weakness when encountered in the foundations of dams may necessitate considerable treatment, as is demonstrated by the exceptional depth to which the foundations of the Mattupatti dams have had to be taken. In the case of the horizontal shears of the Kakarapar site, the only problem arising is the possibility of sliding taking place in the dam foundations, but it is thought that this contingency can be removed by adequate grouting in the neighbourhood of the structure.

Finally, the intense joint pattern of the Mesozoic sandstones of Kutch may be mentioned. (The Kutch shears are mentioned in this context with adjacent peninsular structures, although Kutch more properly should be regarded as part of the montane zone). This is well seen from air photographs particularly two miles north of Desalpur (23°12':69°26'), where the joints have a pronounced NE-SW trend with only occasional development of another set striking NNW-SSE. These joints are certainly connected with regional stresses. The arid climate of Kutch does not support much vegetation, which is mainly confined to irrigated tracts, but in the higher rainfall area of eastern Rajasthan the shrub vegetation follows closely the joint pattern of the Bhander sandstones, often for hundreds of yards. The joints certainly form important avenues of groundwater migration and well sites selected at prominent intersections would stand a fair chance of success. The same control of groundwater by joints exists also in the Kaimur plateau of Shahabad and Mirzapur districts. These features are convincingly displayed from the direct air routes between Bombay and New Delhi, and Calcutta and New Delhi.

DISPOSITION OF BEDDED FOUNDATION ROCKS OF DAM SITES

Coincidence of strike and alignment of dams

The statement sometimes made in text books that the strike of the rocks should be parallel to the axis of the dam has tended in this country to be somewhat uncritically adopted as a minor dogma, and one of the main criteria on which to decide the feasibility of particular sites. There are so many dams built across the strike of sedimentary and metamorphic rocks, such as Hiwassee and Fontana, that it would scarcely be necessary to stress the general invalidity of the dictum were it not for the reverence with which the generalizations has been held, and it is advisable briefly to discuss this and related matters.

There are, indeed, some locations where the rule is of importance. The case may be considered of a terrain consisting of alternating limestones and shales in which the zone of saturation, or groundwater body, lies at a considerable depth, and the limestones have been subjected to considerable solution along joints and bedding planes in the intervening zone of aeration. If a choice of locations exists, it is clearly undesirable to select a site in which an oblique strike of steeply dipping rocks so disposes the cavernous limestones that they extend underneath the dam, both far up into the reservoir basin as well as downstream out of the basin. The steep dip implies that the limestone beds full of cavities extend far to depth under the dam foundations, forming ready avenues for escape of water. Under these conditions it would be difficult to bring down any cut off deep enough below the dam to seal the leaky zones. Even with horizontal dips the treatment of such a formation presents difficulties, as was found in some of the dams on the lower Tennessee river, but the horizontality implies that there are impermeable beds at definite depths down to which treatment of the overlying cavernous limestones can be taken and terminated.

Again, rocks which strike at right angles to the proposed dam axis, and possessing dips of 20°-30° in the same direction as, but at a lesser angle than, the declivity of one of the valley sides, might create a condition liable to landslipping. This is particularly so if the sequence includes alternations of clayey and non-clayey types. Two dam sites in the Himalaya have indeed been condemned because of this disposition, which led to active landslipping. Both are in Tertiary rocks; one on the Murree series of the Jhelum river, and one on the Middle Siwaliks of the Ramganga river. In both cases the argillaceous facies was in a physical condition of clay-shale verging to clay. Under moist conditions these rocks become plastic and act as glide planes for gravitational sliding of the overlying sandstone or sand-rock into the river.

It is not possible to generalize, however, about this condition, since so much depends on the magnitude of dip in relation to the declivity of the valley wall, and also on the physical nature of the rocks in question. In the case of epi-grade slates and phyllites, alternating with quartzites, all of which rocks possess high coefficients of static frictions even when wet, the danger of landslipping under saturated conditions does not arise, unless a combination of bedding joints, cleavage-dip, slump cracks and faults with clay gouge, presents a structural pattern which favours the formation of slip circles. On the other hand, alternations of coarse mica-schists and quartzites, in a condition of meso-grade metamorphism with large crystal size, re-introduces the same tendency to slipping as exists under entirely unmetamorphosed conditions of poor compaction and consolidation.

Consequently, each dam has to be judged on its own merits, as it is only under certain circumstances that the rocks are in a physical and structural state which justifies adherence to the generalization that the strike of the bedded rocks should conform to the axis of the dam.

Dip of formations in relation to dam structure

Another generalization, which is dependent on the previous one of coincidence of strike and dam alignment, and has tended to become fixed, is the belief that an upstream dip is better for a dam foundation than one which is downstream. The reason for this opinion is that, if any permeable beds exist under the dam and reservoir basin, it is better that the water percolating into them should be so directed by the disposition of the dip that it is not allowed to escape out of the reservoir. Taking the reservoir perimeter as a whole, it is certainly desirable that the dips of any permeable rocks on the downstream side should be towards the reservoir rather than out of it. But for the dam foundation itself there is little to recommend the generalization as an invariable rule, in view of the treatment which is possible by grouting.

From another point of view, considering the resultant stresses under a dam with full reservoir load, the ideal disposition for sedimentary strata would be a downstream dip of about 60°. Such a dip is of significance with regard to stress distribution in the case of alternations of lithological types with markedly different physical properties, such as the clay-shales and sandstones of the Lower Siwalik or Nahan rocks. A surprising number of dam sites exists on outcrops of the Nahans, extending from the Sutlej river as far as Eastern Nepal, the Bhakra site being the principal one. This structure will be 680 feet in height. The Siwaliks dip downstream, at 70° near river level and 50° on the upper abutments. The thick sandstone members lie orientated at an angle not far divergent from the resultant stress, and virtually behave like bearing piles. The site would not have been condemned had the dip been upstream at a correspondingly high angle, but with that orientation the major joints perpendicular to the bedding would have had a gentle dip downstream, and there might have been a tendency for sliding of the sandstones to take place along the joints, causing displacement into the more plastic clay-shales which are also present in the foundations. Out of the total true thickness of 2520 feet of Nahan rocks present in the gorge, the sandstones aggregate 1904 feet or 75 per cent, and the clay shales 616 feet or 25 per cent. The average thickness of sandstone beds is 272 feet, and of clay shales 103 feet. It follows that in such a formation the individual beds, with sharply contrasted physical properties, have an appreciable thickness relative to the base-width of the dam which will be about 600 feet. Consequently, the geological relationships are significant for a structure which spreads over three alternations of such rocks, and is close on the upstream side to a fourth member (Fig.3).

Geological relationships are less significant, however, in the case of virtually monolithic formations such as the Delhi quartzites of Rajasthan, which may be hundreds of feet thick without intervening slates, and in which the jointing perpendicular to the bedding is so pronounced that it is often difficult even with close inspection to differentiate joint dip from true dip. On such a formation it is clearly immaterial which way the dip is disposed, since one set of joints has entirely the similitude of bedding and the net effect is that there are two equally prominent sets of divisional planes, one dipping upstream and one downstream.

CONCLUSION

This discussion is based on the assumption that alternative sites are available, one of which possesses the most favourable structural conditions. It often happens that no alternative site exists and the engineer is faced with having either to abandon the project because of manifestly unfavourable conditions which would require extensive treatment, or to construct the dam regardless of cost. Under such circumstances theoretical considerations have little influence and the duty of the geologist is not concerned with locating the best out of several alternative sites, but is confined to demonstrating the structural and physical conditions of the single available location, and what features require special treatment in the foundations. It is indeed a fact that the engineers can design structures adaptable to most geological circumstances. If the foundations are such that they will not support a high concrete or masonry structure, the alternatives of rock-fill or earth dams are present. One of the ruling considerations then becomes the availability of rock fill or earth materials suitable for construction.

With the exception of actively landslipping abutments, it is useless for geologists to condemn sites which are within the scope of modern engineering practice. There are unfortunately many sites in the Himalaya which appear marginal between being feasible and unfeasible and it is in these cases that the geologist is most concerned to assess all the factors. Here we have to learn from hard experience, for our understanding as geologists is likely to be conditioned by investigations of major slips and seismic disasters, while the engineers are alive to what great designs have already been accomplished and stood the test of time in other countries. One thing is certain that, since geological terrains can be radically different, projects must be assessed by a comprehensive study of tectonics, seismicity, siltation and economics. Uncritical adoption of what has been done with success elsewhere may not serve the best interest of the country.

This brings the address to an end. I hope that the close connection between so-called academic geology and applied geology has been demonstrated from some of the problems which we have had to face. Our Survey has not been without critics who have assumed that we have been wasting our time and the tax-payer's money on geological matters without any bearing on the welfare of the people. Such objections, when not actually motivated by malice, are based on ignorance of the close relationship which exists between all branches of science, and between the academic and practical sides. As to which is first, the chicken or the egg, is a quibble with which we need not be concerned. Prof. Hogben, following the Marxist interpretation of history, maintains that most advances in theoretical knowledge have arisen from the need of practical solutions to everyday problems such as navigation, mining and ballistics. The converse also most definitively holds that knowledge gained in the cloisters and laboratories, and by regional surveys, has been fundamental to practical applications.

In India at any rate we owe an immense debt to the always small band of devoted workers, Indian, British, Irish, German and Austrian who sustained the Survey for its first 90 years and made such significant advances in different aspects of our science. Upon that foundation all our recent work, with the greatly expanded department which the National Government has fostered, whether academic or applied, is based. The attainment of Independence has followed naturally without discontinuity to our heritage which, with few exceptions, recognized little of the racial and communal barriers and disfigure so much of contemporary politics. Let it be hoped that the nest century of growing collaboration, between geologists, engineers and other scientists, will lead to the fulfillment of some of the economic projects hitherto studied, and to the greater prosperity of the people of this land.

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Geological Report on the Seismicity of Parts of Western India, Including Maharashtra

J.B. AUDEN

EDITORIAL COMMENTS

After the occurrence of the Koyna earthquake of December 11, 1967 (December 10 according to the Universal time), Government of India requested UNESCO for Technical and Scientific advice of experts. Dr. J.B. Auden was one of the UNESCO experts who visited in 1969 to examine geological and seismological data and advise on geological aspects of seismicity. This has been done in a systematic manner by Dr. Auden in the report, as far as comments on geological data are concerned. However, his comments on "the question of water load" were not appropriate. He observed:

> *"A series of articles emanating from Professor Rothe of Strasburg has emphasized the connection between the filling of reservoirs and the occurrence of small seismic shocks. These views are naturally acceptable to those in India who had already considered that the small shocks in the region of Shivasagar which occurred between 1962 and 1967 were caused by the filling of the reservoir."*
>
> *and*
>
> *"When the small extra water load at Koyna (density 1) is considered in relation to the much greater thickness of volcanics that has been removed in geologically recent times by erosion from the plateau (at least 300 m density 2.8-2.9), it is likely that the unloading by erosion would be more effective in causing crustal movement than the loading due to the reservoir."*

That artificial water reservoirs can trigger earthquakes under appropriate geological conditions has been well established. The load of water has little or no part in triggering the earthquakes. The basic causative factor is the change in pore fluid pressure. Also, unloading due to erosion over millions of years cannot *be compared with annual cycles of loading and unloading of reservoirs. By now, triggered earthquakes are established to have occurred at over 100 artificial water reservoir sites globally and Koyna is the most remarkable site of triggered earthquakes.*

Dr. Auden has made useful recommendations for future work. - H.K. Gupta.

Origin of Investigation

The present investigation of the seismicity of parts of Maharashtra State, India, is a sequel to the study of the Koyna earthquake of December 1967 which was undertaken in 1968 by four consultants appointed by UNESCO in collaboration with several members of the Indian and Maharashtra State Governments.

On 10-11 December 1967, an earthquake of magnitude 6.5 and intensity approaching IX took place with an epicenter only 3-5 kilometres from the Koyna Dam. This dam is a concrete gravity structure 85 m in elevation above the river bed and 103 m in elevation above the deepest foundation. The lake impounded at full supply level contains 2,780,000,000 m^3 of water, which is diverted through a tunnel under the continental divide to a power house at the foot of the Western Ghats. The power generated is 540 MW. A second dam and power house are under construction utilizing the tail-race water from the original power house. This hydroelectric project is vital to the economy of Bombay city and Maharashtra State.

The Koyna Dam was severely stressed but survived, in spite of its proximity to the epicenter of the earthquake, on account of excellent workmanship. In January 1968 Professor S. Okamoto and Professor Tamura from Tokyo, Dr. Igor Gubin from Moscow and the author were invited by UNESCO to visit India to study the Koyna earthquake. The foreign group worked in collaboration with several departments of the Government of India and Maharashtra State. A report was published by the Government of India on the Koyna earthquake of 10-11 December in two volumes in September 1968.

It was considered, however, that the question of the seismicity of Maharashtra required further study, particularly in connection with design co-efficients of several dams, some already constructed, and others under construction. Accordingly, Dr. Igor Gubin and the author were invited to India in 1969.

1969 Investigation: Terms of Reference

The principal task was to examine the geological and seismological data already collected concerning the western part of Maharashtra and to advise on what further data are required in order to assess the degree of seismic risk in the west of the State. For this purpose Dr. Gubin, a seismo-geologist was appointed as Consultant in Seismology, while the author was recruited mainly in connection with the geological aspects of the problem of seismicity.

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Itinerary

Using Bombay as the base, the following excursions were made during April:

(a) Konkan south of Bombay, Alibag, Mahad, Srivardhan, Chiplun, Pophali, Koyna, Poona.

(b) Air reconnaissance from Juhu airfield to the Tapi and Narmada valleys, landing at Baroda. Visit to Oil and Natural Gas Commission. Return to Juhu.

(c) Konkan north of Bombay to Ankleshwar, Surat, Rajpipla, Nawagam, Dhulia, Shahada, Toranmal and back to Bombay.

(d) Cochin, Indian Naval Research Station, Idikki, Munnar, Udumalpet, Coimbatore, Ootacamund, Salem and back to Bombay.

(e) Belgaum, Radhanagiri, Phonda, Sawantwadi, Belgaum and back to Bombay.

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INTRODUCTION

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It has commonly been stated that the prevalent geological opinion maintains that the Indian Peninsula is seismically stable. This is not strictly correct, as may be seen from the map published in 1938 by W.D. West in which the Peninsula is classified as being "comparatively stable". Moreover, Oldham's Catalogue of Indian Earthquakes, which was published in 1882, is testimony of the occurrence of shocks in the Peninsula.

Nevertheless, it is true that the investigation during the period 1897-1950 of major earthquakes in the northern orogenic belt of India, extending from the Makran through Kashmir to Nepal and Assam, five of which had magnitudes between 8.2 and 8.6, has tended to put the feebler seismicity of the Peninsula into the background.

No epicenters were shown, for example, in the Peninsula south of the Narmada-Tapi zone, in the map of the seismicity of Asia published by Gutenburg and Richter, who regarded the Peninsula as a stable shield. The result has been that geologists and seismologists have tended to overlook the evidence of the somewhat distant past. This includes the author who, as a then member of the Geological Survey of India, was concerned 20 years ago with engineering projects in western India. It was not anticipated by the Survey that a shock of a magnitude approaching 6.5 might occur in the Koyna region. Even during our field trip in April 1969, a shock with magnitude about 5.7 occurred on 13 April 1969 on the eastern side of the Peninsula, near coordinates 17½ N, 80½ E, which was felt in Bombay 800 km distant.

On page 42 of the 1968 edition of the Geology of India and Burma published by M.S. Krishnan, it is stated:

> "The peninsular part of India is a region of high stability as the mountain building movements therein have ceased to be active long ago. Occasionally, however, very feeble shocks are felt in some parts of the Peninsula, particularly around the margins".

Although published in 1968, this statement had been written long before the Koyna earthquake. It reflects, however, an attitude which had become fairly general.

The Koyna earthquake of 10 December 1967, has indeed required an overhaul of our attitude to the seismogenic characteristics of the Peninsula, particularly in connection with the practical problem of seismic coefficients in the design of dams. This has been the function of the present inquiry, which has been primarily concerned with Maharashtra as the State most intimately concerned with Koyna and the construction of other dams in western India. We should however stress that Maharashtra cannot be considered in isolation from the rest of the Peninsula, and that in fact the whole Indian sub-continent should be regarded as a unit requiring detailed investigation.

The Koyna earthquake was a crustal shock with an extension of focal depth estimated between 10 and 30 km below surface. Since the Deccan volcanics in their greatest development are not thought to exceed 3.5 km in thickness, and are probably less than 2 km thick at Koyna, the tectonic movements responsible for the shock developed in the Basement, some 8 km or more below the base of the volcanics. The highest peak in the Basement, Annaimudi, is 2695 m above sea level, which is the thickness of the crust that is exposed for inspection. Even allowing for a reasonable extrapolation to depth of the folded Dharwar schists and gneisses which are exposed in Mysore, it is improbable that these relatively surface structures in the Basement shield can on present knowledge be applied to the range in focal depth which is involved by the Koyna earthquake.

Nevertheless, although the focal range is at considerable depth within the crust, the more superficial crustal structure within the uppermost 5 km are of importance in the problem of seismicity because they may be related to deeper concealed fractures. Moreover, while the faulting, both observed and inferred, is confined to certain zones, the epeirogenic vertical movements and gentle warping of the shield involve extensive areas and the whole thickness of the crust.

* * * * *

FRACTURES AND FAULTS IN THE PENINSULA

Uncertain extrapolation of the faults to the surface

Various faults have been mentioned in the description of different areas of western India. Since the existence of faults is of vital importance to the subject of seismotectonics it is necessary briefly to recapitulate the present knowledge of faulting in this part of the Peninsula.

The small-scale published maps of the Geological Survey of India do not often show the presence of faults. Thus, the very important Gawilgarh fault near Ellichpur is not featured in the 1:2 million map. It should be stressed however that even though much of the regional work in the Peninsula was done during the last century, the existence of major faults was clearly recognized. Thus the faults bounding the coalfields, those in the Aravalli Range, the boundary fault separating Vindhyans from Aravalli-Delhi rocks, have been long recognized and mapped. Moreover, the progressive study of the Himalayan region has led to the recognition of major thrust planes, tectonic windows and transcurrent faults. Hence, although much of the geological work is old, it should not be automatically concluded that faults were missed simply because geologists had singularly failed to notice them.

In more recent times, the fracture pattern that affects much of the western part of the Peninsula has been studied from the Cardamom Hills to Gujarat, and on the Shillong plateau as well. This was suspected from a study of the excellent modern 1:63360 topographical maps and was subsequently confirmed on the ground in the Konkan and Cardamom Hills. The fractures are abundantly clear on many air photographs which have subsequently become available. Yet in these same regions neither the maps nor the air photographs which have so far been studied indicate the existence of major faults which are likely to have a seismic connotation.

Dr. Tandon, of the Indian Meteorological Department, and more recently W.H.K. Lee and C.B. Raleigh in the United States, have undertaken fault-plane solutions of the Koyna earthquake. Lee and Raleigh used 86 stations and gave alternate directions for the fault plane, which was determined to be either NNE-SSW, dipping 72° WNW, or WNW-ESE dipping 84° SSW. These studies indicate that in the Koyna region itself the concealed seismic fault does not strike north-south, even though there is a generally north-south alignment of historically determined epicenters running down the western ghats of India. Neither solution of the fault-plane direction coincides with the observed NW-SE grain of the Dharwar Basement rocks which were seen south of Belgaum. If a hade of 20° from the vertical is assumed for the fault plane, the surface zone vertically above a focal range of 10-35 km, would be 9 km, and the inclined fault would come up to the top of the Basement some distance on one side of the epicentral zone. It does not necessarily follow, however, that the seismic fault comes up to Basement surface.

If the fault were to come to surface south of Belgaum, it should cause some lateral displacement or disturbance in the Dharwar schists, which would be evident to the geologist in air photographs and on the ground. On the other hand, the Koyna seismic fault may come to the surface of the shield under the Western Ghats in the Phonda area and may thence strike out into the Arabian Sea. It could indeed be postulated that the height difference of 430 m between the Kaladgis at Radhanagiri and Phonda is connected with such a fault. Yet this fault, by hypothesis is still active, has not had any visible effect on the Deccan volcanics which overlie the Kaladgis in this region.

These uncertainties illustrate the difficulties which are involved in correlating surface geology with deep crustal faults. It is true that the structure and tectonics of the peninsular shield are not as yet well known. It is suggested however, that a major fault, which seismic evidence indicates must traverse the surface grain of the Basement at an angle, is likely to be apparent especially on the air photographs. That the postulated seismic fault has not so far been recognized on the surface may indeed by the result of incomplete surveys and study. On the other hand, the lack of recognition could be explained by the fact that the fault, important though it is in the lower part of the peninsular crust, does not come to the surface of the shield.

A complicated rectilinear system of faults has been indicated by Eremenko and Gagelganz over the southern part of the Indian Peninsula and in the Arabian Sea as far as the Laccadive islands. This system of faults has clearly not had the support of field work, and appears to be an exercise in pedagogic imagination. Undiscovered faults must certainly be present in the region, but the circumlocution of faults around every topographical expression requires confirmation by rigorous mapping and inspection of air photographs.

* * * * *

THE QUESTION OF WATER LOAD

A series of articles emanating from Professor Rothe of Strasbourg has emphasized the connection between the filling of reservoirs and the occurrence of small seismic shocks. These views are naturally acceptable to those in India who had already considered that the small shocks in the region of Shivsagar which occurred between 1962 and 1967 were caused by the filling of the reservoir.

The problem is not a simple one, and is up to the present open to the subjective views of different scientists. The matter was incompletely discussed in the 1968 Koyna report, in which it was concluded that there was probably little causal connection between the filling of the Shivsagar reservoir and the occurrence of small shocks. It was indeed concluded that the small shocks which occurred between 1962 and 1967 were probably foreshocks to the two main earthquakes of September and December 1967.

It should be mentioned that there are several important reservoirs located on the Maharashtra plateau, all based on Deccan volcanics. No shocks have been recorded at the Bhatgar and Radhanagiri reservoirs which are on identical basalt terrains as at Shivsagar. It is true that the mean depth of the Bhatgar reservoir is 6 m less than that of Shivsagar, but it is suggested that this 6 m difference is not likely to be significant. In none of the Maharashtran plateau reservoirs is the mean depth at all great.

When a small extra water load at Koyna (density 1) is considered in relation to the much greater thickness of volcanics that has been removed in geologically recent times by erosion from the plateau (at least 300 m density 2.8-2.9), it is likely that the unloading by erosion would be more effective in causing crustal movement than the loading due to the reservoir.

In the table below, three of the Deccan Plateau reservoirs are listed, together with other large reservoirs in America and Africa, in particular regard to mean depth. It is evident that the mean depth and water load are not related to the incidence of tremors, and that other factors such as the geology must be taken into account, especially in the proximity of seismogenic zones. There is no doubt that the Koyna area is seismogenic, and lies in a north-south zone extending along the western edge of the plateau. It could be maintained, therefore, that the extra water load at Shivsagar was sufficient to trigger off shocks in a zone which is seismic. Yet, no trigger action occurred during the filling of the Bhatgar and Radhanagiri reservoirs in the same basaltic terrain.

Reservoir	Volume at full supply level in cubic metres x 10^6	Area at F.S.L. km^2	Volume / Area mean depth in metres	Incidence of small earthquakes during filling
Shivsagar (Koyna)	2,789	115	24.1	Yes
Bhatgar	685	38	18	None
Radhanagiri	240	18	13.4	None
Lake Mead	37,700	593	63.6	Yes
Grand Coulee	11,900	332	35.8	None
Kariba	160,000	5,180	31	Yes
Akosombo	148,000	8,500	17.5	None
Aswan	157,000	4,000	39	None

According to the seismic regionalization map of Richter, Lake Mead is situated in a narrow zone 150 km wide, which is liable to occasional shocks with a maximum intensity of IX. It is possible to criticize certain aspects of Richter's seismic regionalization map of the USA, particularly in the eastern part of the country, but the north-south zone liable to intensity IX is valid, and indicates that the region of Lake Mead is seismic.

The Kariba Lake lies within the African rift zone, which is subject to minor shocks regardless of the existence of the reservoir. The Kremasta reservoir located in Greece (about which the volume area data are not available) is located within the seismic belt.

It is suggested, therefore, that before making sensational deductions about the production of earth tremors by reservoir filling, more information is required about the relationship between large reservoirs and the local terrain, in regard both to geological structure and intrinsic seismicity.

The addition of a relatively small water load, of density 1.0 must be considered in relation to the removal of rock, with density 2.6-2.9, by erosion within recent times, and of ice from the major ice caps during the last 10,000 years. Since the ice caps can exceed 3000 m in thickness it is necessary to take a broad view about the positive and negative translations of water from particular areas of the crust, and to consider the small areas involved by addition of reservoir water, not more than 70 m mean depth and not greater than 8500 km^2 in area, and 160 km^3 in volume, with the great regions from which ice caps up to 3000 m in thickness, have melted, and rock has been eroded, during the Quaternary and Recent periods.

CONCLUSIONS

An attempt has been made to study the geological history and structure of western India in relation to seismicity. It must be confessed that the surface geology and geomorphology as at present understood offer little evidence of the existence of seismic faults.

Large transcurrent faults, such as are responsible for the seismicity of California, are missing from this region, although they occur along the south side of the Shillong Plateau, and in Pakistan and Afghanistan (Auden and Pallister, 1965, pp.16-23). There is no evidence that the transcurrent faults of Afghanistan are seismic.

The recent major faulting which bounds the Cambay Graben cannot be considered to be responsible for major seismicity. Indeed, the macroseismic epicenter of the great Kutch earthquake of 1819 lies 300 km WNW of the Cambay Graben, and the seismicity of Kutch is related to the folds and faults of that region, which the writer placed some years ago in the orogenic belt (1951, p.116).

Important faults exist in the Narmada-Tapi zone. Other faults have been postulated in this report along the Purna-Tapi valleys. However, the seismicity of this zone is only in a broad sense related to the faulting. Indeed, the important shock, of magnitude 6½-7 with epicenter at 24°N, 82¼°E, occurred south of the fault zone.

In southern India the connection between seismicity and faults is even less certain. The discrepancy between the fault patterns devised in references and 8 and 10 shows the uncertainty which exists about the delineation of faults in that area, and suggests caution in attributing the seismicity and zones of intensity to a system of triangular faults which is deduced from geomorphology not yet fully studied.

In Maharashtra the structures in the shield are almost entirely concealed by the cover of Deccan volcanics. In this area it is necessary to assume provisionally the existence of faults within the Basement to account for the linear development of earthquakes and of hot springs. Until, however, deep seismic sounding has been undertaken, accompanied by the normal refraction and reflection seismic profiles, gravity determination and aero-magnetic observation, it is not possible to delineate the possible faults other than by a posteriori induction from the observed seismicity. It cannot be maintained that such inductive reasoning, in linking faults with seismicity, is always convincing. Nevertheless, in western Maharashtra the linearity of the macro-seismic epicenters certainly indicates a linearity of some causal feature within the basement, even though this is not manifested where the Basement is exposed.

Consequently, the degree of seismic risk in structures such as dams located in western Maharashtra must be inferred from the macro-seismic epicenters, as well as from the instrumental epicenters, regardless of our ignorance of the geological structures in the crust, and of the relationship between the crust and the mantle.

It is possible that the western coastal region of India forms part of an arc, 7000 km in length, which lies between the Carlsberg ridge and the Indonesian-Himalayan orogenic zone. Seismicity along this arc is less than that which is associated with the Carlsberg ridge undergoing expansion and the Himalayan zone undergoing compression and elevation. The arc crosses very varied surface topography and geology, and it is difficult in the wider context of the arc to attribute the Maharashtra seismicity entirely to local manifestations of crustal disposition.

Up to now special tectonic, geomorphologic and geodetic investigations on recent and modern tectonic movement have been carried out along the western margin of India; and relative data are not available. These data are needed for understanding the geological circumstances of earthquake and the regularities of their occurrence. The incidence of the two important earthquakes, at Koyna, in 1967, has demonstrated the necessity for a further understanding of crustal behaviour in Western India. This will involve a long-term coordinated research, combining the work of several departments. The following lines of research may be indicated.

Topographical Surveys

(i) Air photography over large parts of Western India with special attention to the area of important reservoirs from Mulshi south of Radhanagari and the Konkan.

(ii) Preparation of new-style topographical maps on a scale of 1:63360, or nearest metric equivalent, and on 1:25,000 of certain limited areas considered to be critical.

Geodetic Studies

(i) Repeated first-order triangulation over the area between the concealed seismic fault and the coast

(ii) Levelling: Precise leveling should be undertaken across several sections of the Western Ghats, and repeated after periods of 5-10 years. This should be carried out from the coast eastwards to localities, such as, Karad and Satara.

Geological Studies

(i) Geological mapping of lava-flows and associated intertrappeans, dykes and fracture zones, with particular reference to their spatial occurrence and tectonic relationships. In areas, where the lavas have low dips between 1/2° and 1°, the use of levels will be required.

(ii) Photo-geology.

(iii) Periodic study of the temperature and flow of the line of hot springs.

(iv) Information from the Oil and Natural Gas Commission regarding temperature gradients in the oil wells.

(v) Geomorphological studies should be undertaken over the western plateau and Konkan between Bombay and Goa.

Geophysical Studies

(i) Seismic refraction studies at sea by the Indian Navy, continuing those already undertaken by I.N.S. Krishna and the Oil and Natural Gas Commission.

(ii) Seismic refraction studies should be undertaken on land from the coast, to the eastern edge of the Deccan volcanics, including east-west and north-south profiles.

Physical

(i) Dating of the lavas and dykes by Potassium-Argon and other isotope methods.

(ii) Geomagnetic studies are desirable in the same manner as have been carried out in the Matsushiro region of Japan.

Seismic Studies

(i) Collection of historical data.

(ii) Periodic publication of seismographic data from near and distant stations.

(iii) Tide-gauge observations.

(iv) Installation of tiltmeters for observation of crustal deformation.

Strong motion seismograph

Strong motion seismographs shall be installed in the Western part of the Deccan plateau at least at 3 stations in order to obtain data for future construction work in this area.

Coordination of research

It is clear that such a programme of investigation work as has been discussed will require the collaboration of other departments and institutes, such as the Survey of India, Geological Survey of India, Oil and Natural Gas Commission, India Meteorological Department, School of Earthquake Engineering, Roorkee, Indian Navy and the Tata Institute of Fundamental Research, as well as Irrigation and Power Departments of the Central Government, Maharashtra and Gujarat States. In addition, it will be necessary to associate scientific departments of the universities with these investigations.

It may be stressed that our terms of reference are concerned with the problems which have arisen from the incident of the Koyna earthquake. It is immediately evident, however, that a programme such as envisaged for Western India is also most relevant to other parts of the country, in particular to the region of orogenic earthquake extending from Kashmir to Assam. In this region has already been constructed, the Bhakra High Dam (225 metres) and several dams of 100-220 metres in height are either under construction or scheduled to be built in the near future. Moreover, other dams are envisaged on rivers such as Narmada, which has a similar seismicity to that of the Konkan and Western plateau.

Not only will it be necessary, therefore, to increase the net of seismic stations in the Koyna area, but some stations should be installed throughout the whole of the Himalayan arc and other parts of India. Such a programme will require direction and coordination.

In this report, it is not possible to enter into this matter in any detail. In the view of the Committee, however, it is suggested that seismological investigations are required not only in the Koyna area, but in other more seismic regions of India and the creation of a Seismological Research Institute is very desirable. This institute would coordinate the various lines of investigations.

In this connection, it may be desirable to invoke the collaboration of the UNESCO, Japanese and USSR institutes, experienced in the research on these lines.

Deep Seismic Sounding

It is very clear in regard to Maharashtra that the Deccan volcanics conceal the underlying Basement shield almost throughout the whole terrain. Indeed, the boundary of the State almost coincides the outcrop of the main area of Deccan Traps south of the Narmada. Moreover, over most of the region the volcanics are flat-lying, show little structure, and effectively conceal the crust below. Yet the present study of the seismicity of the region has shown that earthquakes occur along two well-defined zones, which must be related to faults or other structural discontinuity within the underlying Basement shield.

It is necessary therefore, to undertake geophysical profiles of the region in order to penetrate below the cover of Deccan volcanics. The normal refraction and reflection seismic profiles, such as are employed by the oil industry, do not descend deep enough in the crust, seldom exceeding 10 km. In the proposed seismic study it will be necessary to penetrate the whole of the outer crust to a depth of 40 km or more.

The study of the earth's crust and upper mantle has been carried out in several regions, in particular Soviet Asia, the Alps, western Germany and the United States. The principal methods have been well discussed by Kosminskaya, Riznichenko, Pakiser and Steinhart in a publication of the MIT Press, entitled Research in Geophysics: Vol.2, Solid Earth and Interface Phenomena, 1964. The Deep Seismic Sounding method (DSS) is that which is recommended for use across the Indian continent and continental shelf. This method employs explosions with 2 to 10 tonnes of chemical explosives, and seismometer arrays which may be as long as 110 km and located 100-200 km from the shot point.

Some of the results so far obtained are briefly discussed. The point of immediate interest for the proposed deep seismic sounding is the structure of the seismogenic zones along the Western Ghats of Maharashtra. It should be stressed however that the seismic study must be extended so as to include the following profiles.

(a) East-west profile along latitude 19°15'N from longitude 70°E to longitude 74°E.
(b) East-west profile from the continental shelf through Koyna to Hyderabad. This will include both the cover of Deccan volcanics and the concealed basement.
(c) East-west profile across the exposed Basement shield from Mangalore to Madras.
(d) North-south profile down longitude 78°E from Dehra Dun to near Hyderabad
(e) North-south profile along longitude 84°E from the Nepal foothills to Sambalpur.

The DSS method should pick up the faulting in the Basement below the Deccan volcanics, especially if this involves a sudden change in level of the Moho surface, and presumably also of the Conrad surface which is more likely to be disturbed by the seismogenic faulting of western Maharashtra.

The significance of the strong positive Bouguer gravity anomalies in Bombay Island is not at present understood. A mass of high density has been postulated by Takin at a small depth below surface, but it is possible that there may be a sharp and local rise of the Moho surface and mantle. As stated earlier there is a rise of the Moho approximating to 23 km vertically between the Malabar coast and the channel between the Laccadive and Maldive islands. This rise may be gradual, and of the order 1:15. On the other hand there may be a more abrupt change which is not recorded through lack of observations from deep seismic sounding.

Normal Seismic Profiles

In addition to the deep seismic profiles, which will require a team of specialists from abroad, it will be necessary to undertake normal seismic work, both reflection and refraction, in several parts of India:

(a) Across the Narmada valley as an elaboration of geophysical work undertaken by the Geological Survey of India (Kailasam)
(b) Across the Purna valley from the Ellichpur and Akot scarps southwards.
(c) East-west profiles in the Konkan
(d) Profiles near the edge of the plateau between Koyna and Radhanagiri to study the interface between the volcanics and the underlying Kaladgi

series. If feasible, the Konkan and plateau profiles should be continuous, but the Ghat topography may present difficulties.

(e) Across the Palghat Gap

(f) An extensive series of profiles from the coast line to the edge of the continental shelf, in continuation of that already undertaken by the Oil and Natural Gas Commission and the Indian Navy. At present there is a gap of 1,000 km between the two profiles made opposite Cochin and Calicut in the south, and those carried out in the study of the Gulf of Cambay.

This list is intended only as a guide. The final selection and exact location of the profiles will ensue from the Plan of Operations, and inevitably new profiles will later be required to verify information obtained by the profiles which may be initially proposed.

Gravity Survey

As has been discussed, numerous gravity anomalies have been found by the ONGC in the Cambay Graben, and other workers have detailed a major gravity anomaly just north of Bombay. Gravity anomalies are subject to many correlations such as the effect of known geology on distribution of crustal masses of different density. Moreover they can be misleading in certain areas if taken as a guide to surface structure.

The regional study of gravity anomalies often, however, yields important information about the crust. Taken in conjunction with the deep seismic soundings, the gravity anomalies along the west coast of India may be important for an understanding of the coastal region and Western Ghats. It is suggested that the gravity studies should be continued towards the south, extending beyond the limits of the Deccan Volcanics to the shield in Mysore. This will establish if the localised, almost circular or elliptical, gravity highs are confined to the area of lavas and Tertiary intrusions, or are associated with juxtaposition of crustal masses of different densities which are unconnected with intrusions and may be due to faulting.

Aero-magnetic Survey

An aero-magnetic survey would be of value in determining changes in composition of the Basement, especially if the change is abrupt and connected with a fault zone. It is recommended that a few east-west flight lines be chosen across the Konkan and Western Ghats in the Koyna-Phonda area. This information will be of value when correlated with the results obtained from the seismic and gravity observations.

Such an aero-magnetic survey would presumably be undertaken under contract. Large areas in Indian have already been surveyed by this method, which has determined the depth to Basement in the Gangetic plain.

Geomorphology

Apart from the recent writings of a few workers such as Radhakrishna, the geomorphological characteristics of India have not received the attention which is necessary to understand the recent movements that have affected the continents. The following suggestions are given concerning some of the studies which are desirable.

(a) Examination of the plateau surface throughout the Peninsula in relation to the Cretaceous and Eocene floors of sedimentary deposition.
(b) Systematic field and statistical study of plateau surfaces in order to correlate the successive periods of erosion, and the elevation and tilting of the surfaces. Surfaces which require examination are, for example, Cardamom and Nilgiri (together with the high surface of Nuwara Eliya in Ceylon); Mysore; Shevaroy; Simlipal (Megasini); Netarhat; Ranchi; the isolated mass of Parasnath; Aravalli; southeast Mewar.
(c) Study of river systems with particular reference to superposed and antecedent drainage patterns.
(d) Plotting of the profiles of all the major Indian rivers. This investigation has been neglected since Vredenberg's work undertaken in 1906. With modern-style topographical maps, and the detailed surveys of individual reservoir projects undertaken by the CWPC and State Irrigation Departments the accurate delineation of profiles should provide important data on individual irregularities due to warping and rejuvenation.
(e) Study of waterfalls.
(f) The extent to which the ocean covered the present plains on either side of the Palghat gap, and extended through the gap, before the Plio-Pleistocene uplift.
(g) The problem of the western and eastern Ghats in relation to the central plateaux, such as that of Mysore.

Improvement in Seismological Observatory Network

It will be necessary to improve the existing observatory network in the Peninsula and Himalaya. In this section we have been guided by UNESCO document No. SC/CS/21/2, dated July 1968, which refers to seismic studies in the Balkan region. It would be premature to decide at present how many seismological stations should be added to those already in operation in India and to give the precise locations of the new stations, but it may be suggested that five new stations would be the minimum that will be necessary.

In regard to the Peninsula it is suggested that the following zones require instrumentation.

(a) Western edge of the Maharashtra plateau and Konkan
(b) Narmada Tapi zone.
(c) Coimbatore region.

In the Himalayan region of India and Nepal it is presumed that the stations would be connected with the several reservoir projects that are now under construction.

The distribution of first order stations with short-period and long-period three component seismographs; second-order stations with medium-period seismographs; and stations with strong-motion accelerographs; will have to be decided after discussion between UNESCO and Indian seismologists. It suffices to emphasize that strong-motion accelerographs will be required particularly along the seismogenic zones of western Maharashtra and the Narmada Tapi.

Seismo-Tectonic Studies

Seismo-tectonic maps have already been prepared in India by collaboration between the Indian Standards Institution, Indian Meteorological Department, Geophysical Institute, Hyderabad, Roorkee University and the Geological Survey of India. It is realized by these institutions that such maps are provisional and require modification as the knowledge of the seismicity increases.

As a result of studies which have been undertaken since the Koyna earthquake of December 1967, including the present investigation, it is possible to delineate more specifically the two parallel north south seismic zones which are present on the west side of Maharashtra, in spite of the virtual absence of geological data. In other areas, with a paucity of instrumental and historical data, there is a wider scatter of inferred epicenters, and the correlation between epicenters and crustal structure and movement is more ambiguous. The purpose of the investigations which have been proposed above is precisely to provide new information on crustal structure and movements which will assist in a realistic delineation of seismogenic zones.

Long-term Project Proposed

The urgent need to obtain more data about the seismogenic zones in India, and to assist the engineers in their designs, is evident. It is clear that in order to undertake the investigations which have been proposed, both by the Koyna earthquake report of 1968 and in the present report, a long-term project will be required to cover India and Nepal. Such a project would last 4-5 years and might be carried out under the auspices of the United Nations, together with such bilateral assistance as may be possible under existing agreements between India and other countries.

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Darasha W. Nosherwanji Wadia Medal Lecture - 1980

India's Former Crustal Neighbours

J. B. AUDEN

EDITORIAL COMMENTS

After superannuation from the Geological Survey of India, for over a decade, Auden had the rare privilege of serving in a few International Organizations, on problems connected with groundwater and engineering geology in different parts of the world. It is this experience that has enabled him to have a global perspective on the geodynamics of different sections of the earth. The present lecture can be said to be an eloquent presentation of the state of our knowledge, as it then existed, particularly on the evolution and disposition of the Indian subcontinent and the adjoining regions, as presented by different workers, with his own comments on the credibility of those views. It should be emphasized, that being a field geologist, while appreciating the distinct contribution of geophysics, geochemistry and geochronology in unravelling the mystery of the disposition of various parts of the earth over time, he wished that "stratigraphical and palaeontological data, much of it not expressible in mathematical terms, are also of critical importance" and should not be brushed aside, if they are at variance with geophysical data.

In the lecture, he presents the conclusions arrived at by different workers on the relative positions of the Indian subcontinent, Madagascar, Sunda Arc, Australia and Antarctica, and by critical appraisal shows to what extent each of them support or oppose the known geological data. He is particularly surprised that a majority of the presentations do not effectively deal with the Sunda Arc and ignore such a conspicuous belt of 3500 km long and a width varying from 500 to 700 km and deal only with Madagascar, Australia and Antarctica. He also draws attention to the evidences against Madagascar being close to the west coast of India, as envisaged by some, in spite of certain stratigraphic and geomorphic evidence supportive of the above contention. Another point he could not reconcile to, is the apparently conformable relationship between the 'migrating' Indian plate and *the 'stationary' Eurasian plate, as according to him, the 'docking' of the Indian plate should have produced great disturbances, which to him are not quite evident. While conceding that evaporite deposits right from Iran in the west to India in the east (in the Vindhyan) may not be exactly contemporaneous, yet to him they signify a physical contiguity of landmass, not perhaps permissible on geophysical data. Towards the end he seems to feel that perhaps an "expanding earth" may explain some of the relative disposition of plates better than migration of plates, even though one degree of latitude 600 m.y. ago would then have been 107 km, only 4 km less than the present value.*

Beauty of science is its freedom from finality, to a great extent. It should be noted that a scientist's evaluation is always constrained by the then available data, prevailing concepts and technological advance in the instrumentation aiding collection of data of features, not observable by the naked eye. This lecture was delivered in 1981. In the earlier days, sometimes mutually contradictory data were obtained about location of poles based on palaeomagnetic studies. However, during the past two decades, after considerable refinement in techniques, palaeomagnetic and rock magnetic studies, made of Precambrian to Siwalik Group of formations in India, seem to support migration of the Indian subcontinent from its earlier position as a part of Eastern Gondwanaland, to where it is today. As a matter of fact the Memoir 44 of the Geological Society of India (1999) contains a number of contributions in this field to substantiate the above contention. Besides the above, the concept of 'hot plume' shot into prominence, evidences for intraplate deformations and rotation of Indian landmass came to light and the role of heat flow studies is better understood. Extensive use of seismic profiling led to the recognition of overriding of continental crust over oceanic crust.

All of these will now explain some of the anomalies pointed out by Auden between geological observations and geophysical data. However, it should be accepted that there are still quite a few grey areas which need convincing explanation to arrive at the real "crustal neighbours" of India during different geological periods. His lecture will continue to be a pointer to some of the geological observations not yet properly explained vis-à-vis geophysical data, particularly the role of some parts of Eastern Gondwanaland in our understanding of the global geodynamics. – R. Vaidyanadhan

SUMMARY

Some of the various attempts at reconstructing the configuration of crustal masses in relation to India during the Phanerozoic are discussed. On the basis of radiometric ages of the pre-Vindhyan and pre-Raipur metamorphic and granitic basement, the Cis- and Trans-Aravalli Vindhyans and Raipur limestone are regarded as late Pre-Cambrian to Eo-Cambrian in age. The evaporites common to both wings of the Vindhyans indicate a similar climatic environment of deposition to that in which the Saline Series of the Karampur well, Salt Range, Mandi, Iran and Oman were deposited. The existence of an extensive province of arid sedimentary formations, involving the close association of India with neighbouring areas to the north and west, as long ago as 600 m.y., is suggested. The Mascarene submarine plateau, which includes the 600 m.y. old granite of the Seychelles, probably always existed between India and Madagascar, and renders improbable the widely held proposition that, during late Mesozoic, Madagascar lay in contact with the present edge of the continental shelf and only 70 to 300 km from the west coast of India. Similarly, it is suggested that the Gaussberg submarine plateau, which includes the island of Kerguelen, was probably present during the Mesozoic between India and Antarctica in a manner which would not allow the presence of the Napier peninsula of Antarctic within 200 km of the Indian coast as has been shown in some reconstructions. The concept which places the Indian peninsula 6500 km from Eurasia during the Mesozoic, and then migrating as a solitary crustal unit across a wide Tethys ocean over a period of 70 m.y., is contrasted with the more probable interpretation of F. Ahmad, Owen and others, who regard India as having been separated from Eurasia during the Permian by a shallow epi-continental sea of no great width. The plate boundary of India which has been proposed by Kaila and Hari Narain is discussed in the light of difficulties in drawing boundary limits in complete discordance with the structural grain of the Hindu Kush and tri-junction region of India, Burma and China. The Sunda Arc, 7500 km long, with its extremities linked to India and the Sahoul shelf of New Guinea-Australia, and zonal continuity throughout its length, is considered to render the supposition of the proximity of Australia to Tibet improbable. The lecture ends with a discussion on the conflict of evidence regarding horizontal crustal movements between palaeomagnetism and palaeontology, and suggests that considerable areas of continental crust may have sunk in the Indian Ocean in contrast to the phenomenal rise of continental crust in Tibet and the Himalaya since the Pliocene.

INTRODUCTION

First let me thank you for the great honour you have given me in the award of the D.N. Wadia medal. Wadia was a colleague of mine, 20 years older, but unfortunately we seldom met working as we were in different parts of the continent. We did, however, collaborate in writing two chapters together of the Memoir on the 1934 Bihar-Nepal earthquake. He left the Geological Survey of India with the permanent legacy of extensive work in the western Himalaya. His textbook on the Geology of India was the principal source of general information for many generations of students including myself.

In my case I like to think of the medal as an award for joint work with colleagues of the Survey and Irrigation Departments. First with Professor West who introduced me to his area around Simla in 1928. Then Dr. Wadia in our collaboration 46 years ago over the Memoir on the 1934 earthquake, and finally, from 1941 to 1953 to the geologists who were part of our Engineering Geology and Groundwater Divisions, as well as to the engineers throughout India who presented us with their problems and were with us in the field. Of these I shall only mention one, Dr A. N. Khosla, who made northern India conscious of the importance of dams for irrigation, flood control and generation of hydroelectric power. The Bhakra Dam is his monument 225 m in height

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The majority of plate reconstructions around the Indian Ocean date back only to the Cretaceous (135 to 65 million years), but in regard to India it will be necessary to consider possible neighbours during the Eo-Cambrian to Cambrian (600 to 500 m.y.), and also from near the end of the Palaeozoic (300 m.y.).

INDICATIONS REGARDING FORMER PROXIMITY OF CONTINENTS

The indications which have led to the conclusion that many of the now separate continents may once have formed a vast single continent, or Panjaea, may be briefly summarised:

1. Similarity between the coast lines, edges of continental shelves and other bathymetric levels, of now distant continents. The fit between South America and Africa led Wegener in 1912 to suggest an original proximity and to discuss geological similarities. The fit between these two continents has been subject to successive refinements, including computer study.
2. The similarity of geological formations when now distant continental crustal units are brought into what is thought to have been the original juxtaposition. Formations of special interest are: glacial tillites; characteristic coals; desert-type formations, evaporites such as gypsum, anhydrite, sodium chloride; and distinctive metamorphic types such as Charnockites and Khondalites.
3. Comparable assemblages of rocks with similar radiometric ages. For example, rocks with radiometric ages between 500 and 800 m.y., flanked by rocks over 2000 m.y. in age, may show a common symmetrical distribution when continents are joined.
4. Faunal and floral assemblages, a whole subject in itself, and ably discussed by Ahmad (1961, 1978).
5. The fit of the gold-ore and rare-earth provinces in South Africa, Madagascar, India and Australia if these crustal units are brought close together.
6. Apparent continuation of alignments of tectonic zones between distant blocks when placed in contiguity.
7. Palaeomagnetic positions of poles, and systematic movement of poles during geological time.
8. Particular oceanic ridges marked out by incessant minor seismicity now monitored decade by decade.
9. Zebra strips of normal and reversed magnetism disposed symmetrically on either side of the active oceanic ridges.

There are so many variations in the arrangements of the crustal plates *vis-a-vis* India that it is difficult to make any simple classification. Broadly, however, the reconstructions may be divided into four groups:

1. The attempts which consider that an immensely wide Tethyan ocean occurred between India, Africa, Australia and Antarctica in the south and Eurasia in the north. Different versions have Antarctica and Australia close to the Madras coast of India. Some versions have Cape Comorin at 30° south latitude opposite Durban 80 m.y. ago. Others place Cape Comorin near latitude 10° S. close to the Tanzanian embayment. India leaves its neighbours Africa, Australia and Antarctica and migrates as a solitary unit some 6500 km since the mid-Cretaceous across the Tethyan ocean, and has recently joined up by collision with Eurasia (*see* Fig.1).

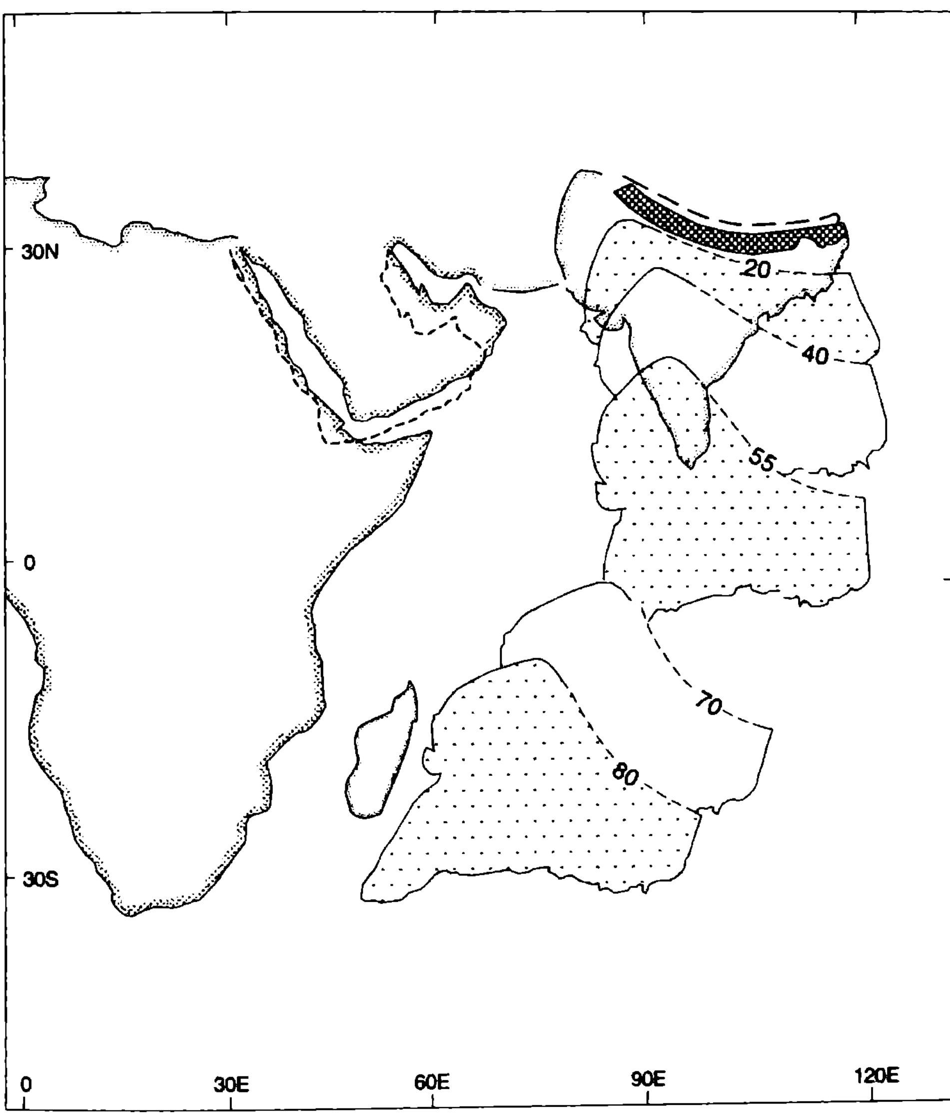

Fig.1. Northward migration of India since the Cretaceous (after C. McA. Powell, 1979). Figures in millions of years. See also Figs. 13 and 14.

2. In other reconstructions India is placed during the Cretaceous near Somalia and Arabia. A much narrower Tethys area is suggested which is part open ocean and part epicontinental sea. Australia is regarded by some authors as filling the Madras embayment, while other authors place Australia adjacent to Tibet, and consider Antarctica to have been in the Madras embayment (*see* Figs. 2 and 8).
3. Some authors ignore the Mascarene Ridge, the Chagos-Maldive Laccadive ridge, and the Gaussberg Ridge, in their attempts to bring continental masses together. A few authors recognise the probable existence of these ridges during the Mesozoic (McKenzie and Sclater, 1971, 1973; the Termiers, 1977; Stoneley et al. 1974; and Kamen-Kaye and A. A. Meyerhoff, 1980).
4. In regard to the northern limit of India many reconstructions indicate that India terminated northwards near modern Chitral, Swat and the Himalaya. The tendency now is to extend it into Tibet, and even as far north as the Kun Lun-Astin Tagh (Veevers et al. 1971, 1975) and the Tien Shan (Kaila and Hari Narain, 1976).

Before attempting to consider some of these reconstructions it is necessary to go back in time to the Eo-Cambrian and Cambrian, and to discuss the probable connection between the Vindhyans, the rocks in the Salt Range and those of Iran and Arabia.

VINDHYAN INDIA

The Vindhyans may be divided into the Cis-Aravalli and Trans-Aravalli groups. Because of the then apparent thinness of the Trans-Aravalli Vindhyans, Heron suspected that they may represent a different series, but this was before subsurface data became available, and a greater thickness of the Trans-Aravalli Vindhyans was established than had hitherto been suspected.

Trans-Aravalli Vindhyans

1. They rest on granites with a radiometric age of 750 m.y. and are not likely to be older than 600 m.y.
2. The Geological Survey of India has established the presence of 930 million tonnes of gypsum-anhydrite in Vindhyan-type rocks at Nagaur within an area of 74 km^2, around coordinates 27°12' N : 73°43' E.
3. In the Rajputana Desert Symposium of 1952 published by this Academy (it was then the National Institute) Dr. P. K. Ghosh described a boring in Bikaner City which went through 544 m of Vindhyan-type sandstones,

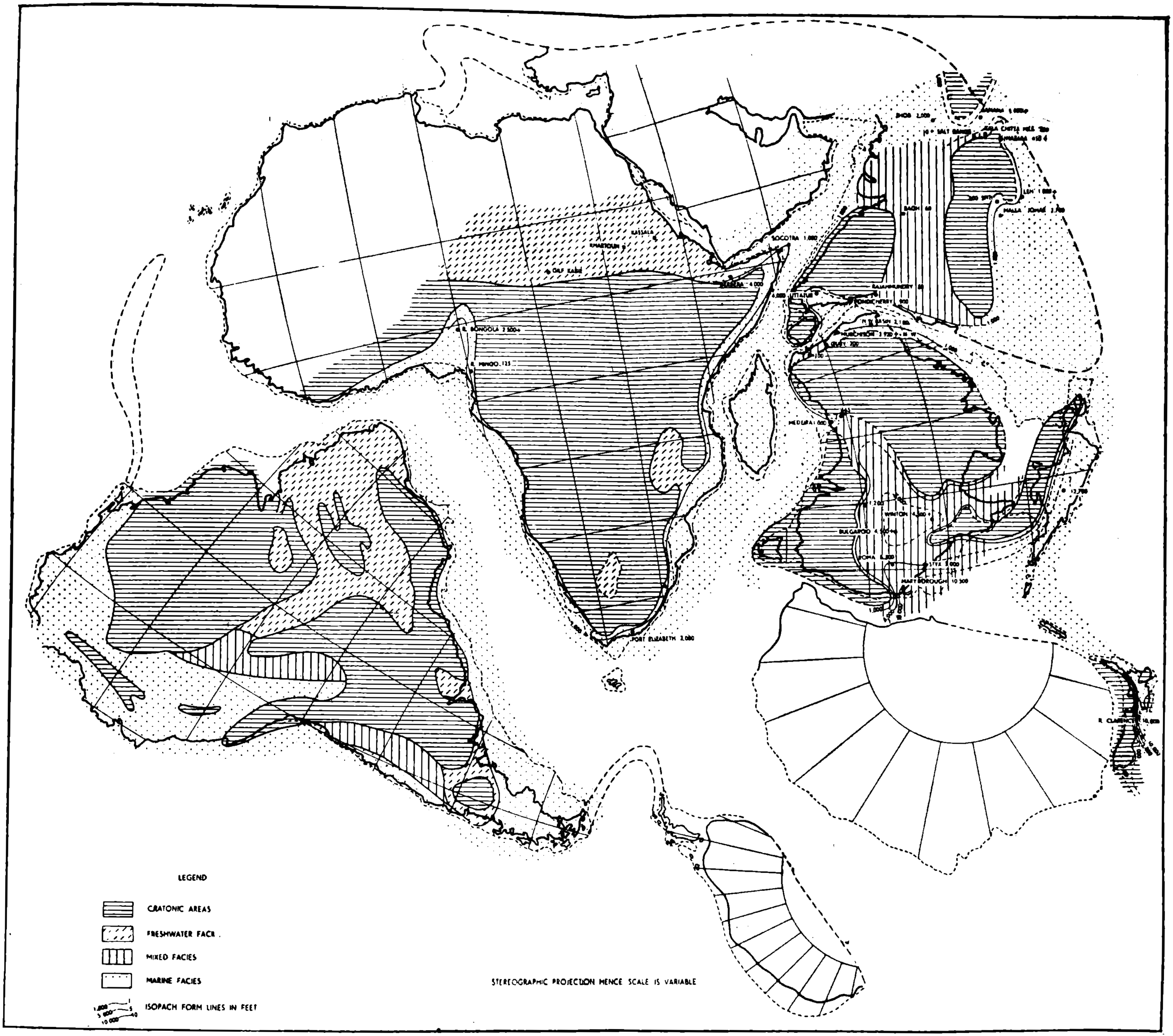

Fig.2. Palaeogeographic map of Gondwanaland, Middle to Upper Cretaceous (after F. Ahmed, 1961). Northwest Cape of Australia located within the Godavari-Krishna embayment, which is approximately 7000 km distant from the Napier Peninsula of Antarctica.

limestones and shales, with minor seams of gypsum. Near the bottom were found more gypsum as well as efflorescences of sodium chloride and magnesium chloride (1952; p.109).

4. At Karampur, near Multan, Pakistan, a deep boring penetrated the Mesozoic and Palaeozoic, and then went through 884 m of saline series, with gypsum and salt, underlying the Productus limestone and overlying Basement at 2860 m below sea level. This series is similar to that exposed in the Salt Range, 270 km to the north. On the reasonable assumption that the whole sequence at Karampur is autochthonous, with no thrust between the Purple Sandstone and the underlying saline series, which are Cambrian or Eo-Cambrian in age, this is strong evidence against the concept widely held that the Punjab Saline Series is Eocene and separated by a thrust in the Salt Range from the overlying Cambrian.
5. The saline series of Mandi in the Himalayan foothills, which occurs along a belt 110 km in length, has been dated as Permian on the basis of some sulphur isotope studies of uncertain reliability. This series is more likely to be Cambrian or Eo-Cambrian since, so for as I know, no evaporites have hitherto been found of Permian age in Indo-Pakistan.

There is, therefore, a virtually continuous series of rocks characterised by evaporites in the 600 km between the Salt Range and Nagaur. The Salt-Range and Karampur rocks are Cambrian. The exposed Jodhpur sandstones are not older than about 600 m.y. As far as the Trans-Aravalli formations are concerned, it may be assumed that they range in age from the latest Pre-Cambrian to Cambrian. The area covered by these rocks is possibly of the order of 400,000 km^2.

Cis-Aravalli Vindhyans

The main Vindhyan area southeast of the Aravalli Range covers an area of approx. 200,000 km^2. About 50 years ago, C. S. Fox, followed in 1933 by myself, discussed the possible relationship between the Vindhyans and the Cambrian of the Salt Range, and I had adduced evidence for the deposition of the Vindhyans under arid conditions. Adopting that view, the Cis-Aravalli Vindhyans would be roughly of Eo-Cambrian to Cambrian age. All this was knocked on the head when Soviet radioisotope studies were made of the glauconite obtained from the group which I had mapped along the Son Valley. The Russian studies on the basis of Glauconitic ages suggested an age for the Lower Vindhyans of 1,400 m.y., some 800 m.y. earlier than the Cambrian.

Crawford and Compston (1970) also discussed the Rb-Sr data for samples of 1,000 to 1,140 m.y. These results, therefore, favour a much older age for the

Lower Vindhyans than we had supposed, and much earlier than the Eo-Cambrian to Cambrian. On the other hand, there is a considerable amount of evidence to indicate that the Cis-Aravalli Vindhyans may be younger than the age suggested from glauconite and Kimberlite samples.

1. Eight samples from pre-Vindhyan metamorphic rocks in the Chhota Nagpur area around Hazaribagh and south of Patna give radiometric ages which range between 880 and 955 million years and an average 932 million years. Since these rocks are not metamorphosed Vindhyans but pre-Vindhyan, the strong presumption is that the Vindhyans must be younger than the metamorphics upon which they were deposited by an interval of years involving an erosion cycle, and the Lower Vindhyans might be of the order of 700 m.y.
2. Metre (1978) states that the age of the metamorphics underlying the Vindhyans in the Ujhani exploratory well at a depth of 2,115 m gave a K-Ar dating of 1,045 m.y. Again, it may be assumed that the Vindhyans at Ujhani are at least an erosion cycle younger than the metamorphics.
3. It may be noted that the Basement rocks of the Kirana Hills, which are inliers within the Indus alluvium and possibly an off-shoot of the Aravalli Range, are dated at 870±40 m.y. by Davies and Crawford (1971, p.235).
4. Anhydrite occurs in the Vindhyans of the Kasganj well. Salt Pseudomorph beds occur in the Sirbu Shales over an area of about 4,000 km^2 around Panna. While these occurrences of sulphates and chloride pseudomorphs are on a much more subdued scale than in the Trans-Aravalli Vindhyan rocks, they point to conditions of evaporation, in conjunction with other signs of arid conditions which I attempted to show 50 years ago.
5. S. N. Sarkar and three Russian workers (1967, p.538) have found that the Raipur limestone near coordinates 21°15' N : 81°00 E overlies Dongargarh granite with a radiometric age of 710 m.y. This limestone is usually considered to be late Cuddapah, but is stated by Sarkar and co-workers to be not older than 600 m.y. The Dongargarh and Erinpura granites are evidently contemporaneous, and the Raipur limestone becomes homologous with the Trans-Aravalli Jodhpur Vindhyans. On radiometric evidence, with a somewhat wider time interval, the Raipur limestone appears also to be equivalent to the Cis-Aravalli Vindhyans to which it is geographically more closely situated.
6. The fossil *Diplocriterion* was found in Vindhyans in the Tilhar exploratory well and is indicative of a Palaeozoic age (Metre, 1968, p. 46).
7. Salhuja, Rehman and Arora (1971) have described microplankton, trilite spores, and discoidal bodies from 238 samples of shales, sandstones and

limestone in the Semri, Kaimur and Rewa sediments of the Son Valley. However, they do not indicate whether these plant microfossils are pre-Cambrian or Palaeozoic.

These data all point to an age for at least some of the Vindhyan sediments southeast of the Aravalli Range not older than Eo-Cambrian, and to the broad equivalence of the formations on both sides of the Aravalli Range.

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The purpose of this discussion is not solely to stress the view that the Cis- and Trans-Aravalli arid formations are indeed contemporaneous and Vindhyan, but also to renew the suggestion that at least part of the Vindhyans is equivalent to the Cambrian of the Salt Range. Stocklin (1968, p. 1233) and the Meyerhoffs (1972, p. 293) have demonstrated the similarity of the Salt-Range Cambrian to the Cambrian of Iran and in the Afar region of Oman (approx. 22°N: 58°E). There are also important deposits of Cambrian evaporites in Somalia. It is evident that evaporite rocks and arid-type formations were deposited over a very wide area, now extending from western Iran, through Afghanistan, to Bihar, a longitudinal distance of 40°, and from the Salt Range to Somalia, separated by 22° of latitude, and involving an area of about 4 million square kilometres.

It is possible, therefore, that some 500 to 600 m.y. ago India was, in fact, a part of this great area of evaporites, and strongly current-bedded red sandstones, and was consequently linked even then to Asia, although separated by epicontinental seas.

It does not follow, of course, that all arid formations at any given period were part of a single desert region, with associated saline waters. The Kalahari desert of southern Africa has no connection whatever with the Takla Makan desert of Sinkiang and the Dasht-i-Margo in Afghanistan. Hence, it may be considered that the particular resemblance and proximity between the Indian system (between the Salt Range and Bihar) and the Iranian and Oman formations, is fortuitous, and only became evident when India, under the prevalent hypothesis, joined up with Asia some 400 to 500 m.y. after the beds in question had formed in once widely separated continents. Of these alternative hypotheses, the first would appear to explain more satisfactorily the coincidence of geographical distribution of Cambrian arid deposits, and the similarity in stratigraphical and faunal sequence, covering an area which would be somewhat smaller than the present Sahara and Arabia Deserts. If this view is adopted it would require, as indicated by the Meyerhoffs, a modification of concepts involving a long migration of India to its Motherland, and would bring India into close association with the present neighbours on the northwest side long before the Gondwana ice caps and later characteristic coals, flora and fauna raised more problems of continental distribution.

GONDWANA INDIA

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There is abundant evidence for the occurrence of terrestrial Gondwanas, intermixed with marine beds, in the central and eastern part of the Himalayas, comparable to the long-known Gangamoptreris beds of Kashmir, and extending north of the main range into Tibet. The most continuous exposures are allochthonous and thrust upon the Tertiaries along the main boundary fault. Other exposures, also allochthonous, are definitely located within tectonic windows in the heart of the Himalaya. A third category lies north of the main range and may have been carried on the backs of the overthrust sheets of Peninsular Himalayan rocks.

Pamela Robinson (1967, p.217) has produced a palaeogeographic map of the early Permian Talchirs, which she had divided into four types: *Continental facies; Craton shore facies; Marginal marine facies, Tethyan facies.* It is evident that there were considerable oscillations of the shore position, between Umaria and Tibet, a distance of 700km or say 6° of latitude.

The Indian craton thus extends north of the Himalaya, but uncertainties exist in regard to how far north. The Chinese claim that the Tsango-po follows a barrier between a cold terrestrial and marine environment to the south, and a warm marine environment to the north. Ahmad (1978) depicts a shallow epicontinental sea between India and Eurasia during the Permian, approximately 1500 to 3000 km wide. The Termiers show the presence of a Fusulina Sea flanked on the south by Iran and the Tien Shan. Fusulina occurrences are shown in the Tien Shan area and western Tibet but not in the Tethys Himalaya (1977, p.319).

The Tsang-po feature is an extension of the Indus, and the Indus fault has for some time been termed the Indus suture which is claimed to be the plane of collision zone between India and Eurasia. The Indus fault zone is unquestionably, with the Tsang-po, a megatectonic feature, but lacks, however, any sign of subduction and is relatively aseismic. Like the Chaman fault in Pakistan and Afghanistan, it is a deep crustal fault, but its role in demarcating independent continental blocks is uncertain. As will be mentioned later, Veevers, Powell and Johnson (1975) consider that the Indus-Tsang-po ophiolite belt is the surface expression of the suture between Gondwanaland and Asia, but that India has penetrated at deeper crustal level as far north as Kun Lun, Astin Tagh and the Nan Shan.

It should be stressed that the assemblage of continents suggested by Ahmad and the two Termiers place India close to Eurasia during the Permian system (240-280 m.y.), whereas the advocates of a far travelled India start the long migration from the southern hemisphere towards Eurasia during the late Jurassic to late Cretaceous, not less than 100 m.y. later than the Permian.

MESOZOIC INDIA: WEST COAST (Figs. 3 and 4)

Several authors have placed Madagascar against the continental shelf of western India. Katz and Premoli (1979) have given two positions. In one of these, the coastlines are 130 km apart at modern latitude 16° and 70 km at latitude 9°. In an alternative position the coastlines are 280 km apart at latitude 19° and 100km at latitude 9½°.

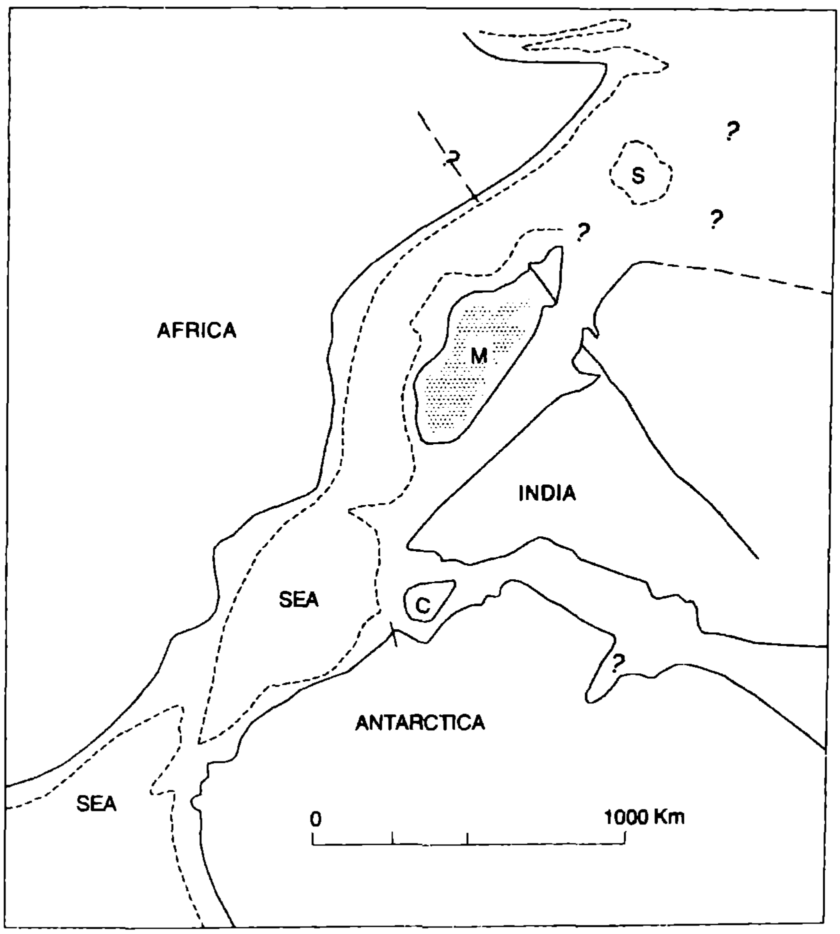

Fig.3. Assembly of India, Madagascar, Africa and Antarctica (after A.C. Crawford, 1978) Napier Peninsula is located within the Godavari-Krishna Embayment.

A re-assembly of India, Madagascar, Africa and Antarctica based upon available palaeomagnetic data (see text for references) and other criteria. Areas of sea include some submerged or partly submerged areas of probable continental crust north and south of Madagascar. Full black lines, represent coasts. **M** - Madagascar; **C** - Ceylon; **S** - Seychelles group of granitic islands. Thick black line, Narmada-Son lineament and its probable and possible extensions.

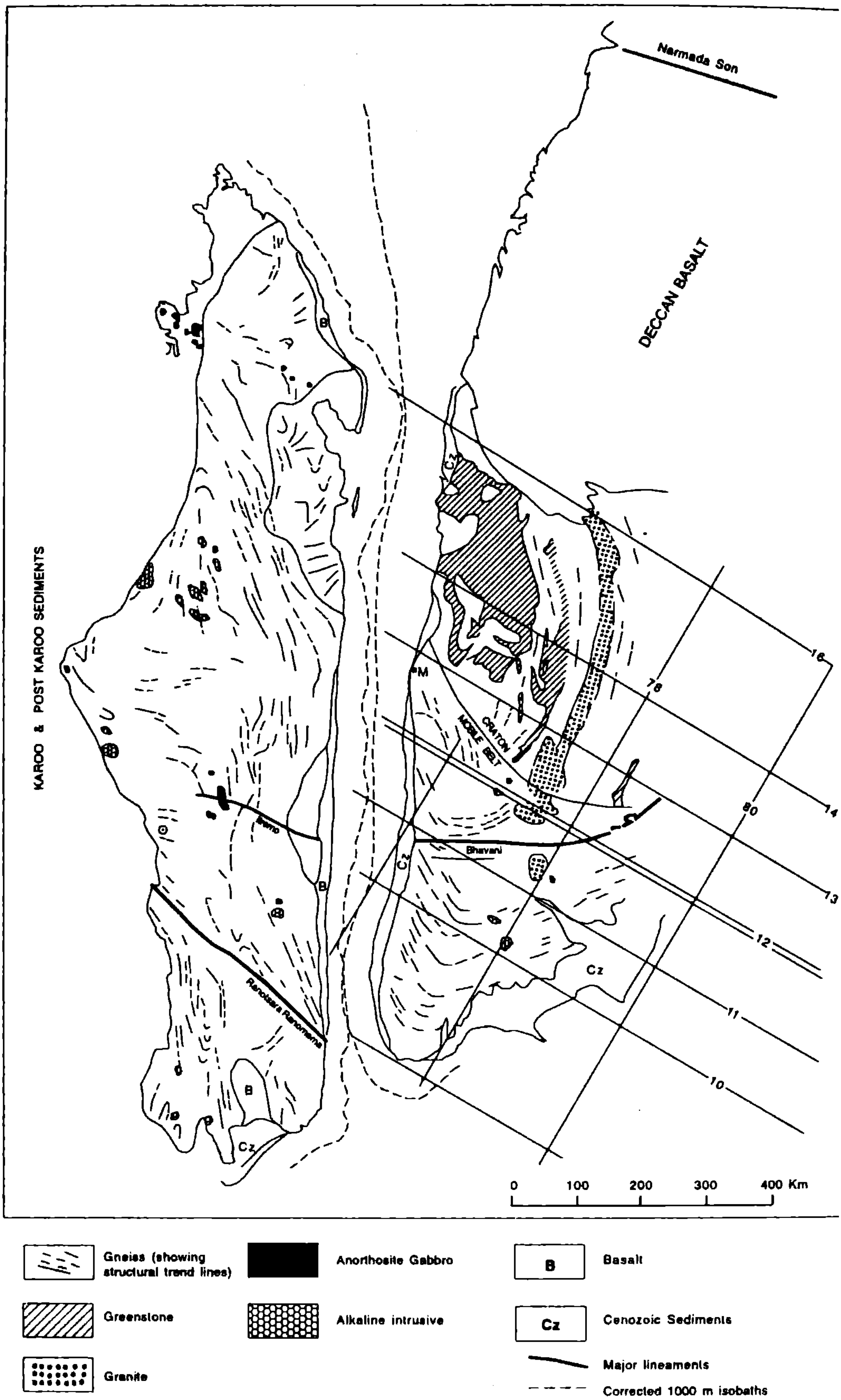

Fig.4. Madagascar located adjacent to India, with only 100 km separation opposite to Kera (after M.B. Katz and C. Premoli, 1979).

Crawford (1974, 1978, 1979a, b) adopts a third position, with the Antalaha peninsula of Madagascar opposite Saurashtra and 200 km distant. Madagascar is not however drawn to the same scale as India, and its representation should be reduced by a factor of 1.2.

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Work by the Oil and Natural Gas Commission has shown that the Narmada structures cut the continental shelf just south of Saurashtra and, even if allowance is made on Crawford's interpretation for the change of scale between Madagascar and India, it would be difficult to extend the Narmada faults and folds into Madagascar without a major rotation of orientation. It was suggested by the author in 1975 that the WSW-ENE Narmada fault and fold zone has a dextral transcurrent movement on the continental shelf, with a westward shift on the south side of the Cambay Graben amounting to approximately 150 kilometres (Auden, 1975 (Fig.1), cf. Fig.7). There is nothing like this feature in northern Madagascar, and the supposed extension appears to be mainly a zone of pyrochlore mineralisation with a modern NW-SE orientation.

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Reflection Seismic Work

Reflection seismic work has shown that 2500 m of Palaeogene and Neogene sediments exist between Indian and the Laccadive Islands which are 400 km distant from the west coast of India. Whatever the nature of the Chagos-Maldive-Laccadive ridge, it is shown by ONGC work to have a floor of Basement rocks at 4-5 km b.s.l. The presence of this thickness of Cenozoic sediments resting on Basement indicates that by the end of the Cretaceous Madagascar cannot have been closer than 400 km to India. DSDP 219 (9°05'N:72°50'E) is 380 km WSW of Cochin and located shallow-water Palaeogene at the bottom. With its distance of 380 km from the west coast of India, the boring would be located, on the assumed Cretaceous positions of Madagascar suggested by Katz and Premoli, near the west coast of the island where there is a thick Cenozoic and Gondwana succession. With the southern alternative position of Madagascar *vis-a-vis* India, which is figured by these authors, the coordinates of DSDP 219 bring it within Basement in an as yet unrifted Madagascar. Rifting from India is considered to have taken place during the Cretaceous, and must be supposed on this hypothesis that DSDP 219 encountered sediments which had been formed in the newly created oceanic gap left by separation of India from Madagascar. The boring did not go deep enough to establish if Mesozoic sediments were present below the Palaeogene.

On the above hypothesis no sediments older than topmost Cretaceous could be present, since rifting began during the Cretaceous.

The continental shelf in the Bombay area has 6,000 m of Cenozoic sediments at a distance of 200 km from the coast. This large sedimentary column rests on Cretaceous-Palaeocene Deccan volcanics as far west as the edge of the continental shelf, where seismic reflection work by Harbison and Bassinger located anticlines even 300 km west of Bombay (1970). D. N. Basu and co-workers (1980, 212-214) have shown that along one NNW-SSE zone on the Bombay shelf Tertiary sediments lie directly over Pre-Cambrian, without intervening Deccan volcanics. To what extent the Basement existed as a topographical ridge, which was too high to be over-topped by Deccan lavas, or was uplifted and eroded subsequent to lava extrusion, is not clear. S. Ramanathan, in an as yet unpublished report, has shown that some of the igneous rocks encountered in the Basement are probably Tertiary plutonic centres related to the Deccan volcanic province, in the same manner as the Barda Hills and Mount Girnar of Saurashtra, and Amba Dongar. Examples are the syenite found at a depth of about 1700 m in a test boring at Kadi (23°18':72°20'), and a granodiorite in one of the Bassein structures about 80 km offshore from the Bombay coast.

In a later work Harbison and Bassinger (1973) have indicated the existence of a ridge of continental crust running 400 km off the west coast of India between the Laccadives and latitude 20°N. This discovery, and the continental crust known to occupy the side shelf west of Bombay, suggest that Madagascar, if it had ever been near India, was probably never closer than 400 km from the coastline. Not only is the Laccadive archipelago floored with basement, but this basement evidently extends north to the 20° latitude. No deep crustal element, such as must be allowed for Madagascar, could have been located on the area of the Laccadives where basement is at such a shallow depth.

Madagascar Ridge

Those attempts which have been made to position Madagascar against the west coast of India have adopted the present exposed length of the island, which is 1560 m. The Madagascar ridge however, extends southwards below sea level as far as the Walters Shoals which are only 18 m from surface and the full length of the ridge is in fact about 2500 km. It is this full length which must be shifted to the west coast of India if attempts are made to indicate proximity of the two crustal masses, and the Madagascar ridge exceeds the 2300 km coastline between Karachi and Cape Comorin.

Mascarene Ridge

The principal objection against the suggested juxtaposition of India and

Madagascar is the existence of the Mascarene Ridge, which is over 2000 km in length, has an area of approximately 350,000 km^2 at the 2000 m bathymetric contour and lies between India and Madagascar. The existence of a granite of late pre-Cambrian age on Mahe and Praslin Islands, 50 km apart, in the Seychelles has been known for some time. This part of the Mascarene Ridge has been regarded as a microcontinent which became detached from other continental masses when Gondwanaland broke up.

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Kamen-Kaye and Meyerhoff based on the study of this region conclude that the history of the Mascarene Ridge and that of Madagascar are closely related and the two areas, with intervening ocean basin, must be treated as a geological entity. It is significant that the late pre-Cambrian granites of Mahe and Praslin are comparable in age to many of the granites of Madagascar.

The existence of this Madagascar-Mascarene entity would preclude any close contact between India and Madagascar, since the Mascarene Ridge, or sub-marine plateau, must have intervened in arcuate form between the two crustal units. The Mascarene arc has a radius of curvature of approximately 1200 km, in contrast to the straight edge now displayed by the Bombay-Cochin continental shelf. To attempt to fit the Mascarene arc against the Indo-Pakistan coastline requires placing Seychelles opposite to the Makran coast and the middle of the arc within the 125° angle in coastline near Karachi. This has in fact been attempted by McKenzie and Sclater (1973) to whom reference is made below. Madagascar lies west of the chord of the Mascarene arc, and any position of the arc would be a barrier between Madagascar and India (Fig.5 is omitted in this extract).

Chagos, Maldive, Laccadive

Next, there is the problem of the Chagos-Maldive-Laccadive Ridge 2600 km in length regarded by Powell as a recent excrescence. This ridge also lies between India and Madagascar but geological details are scarce. The Laccadives, 400 km off-shore from India, are known to rest on Basement which is continuous with south India. Termier and Termier (1977) indicate its existence during the Permian, but on what grounds is not known.

According to the Oil and Natural Gas Commission, about 2500 m of Cenozoic sediments extend for 400 km out from the Mangalore-Calicut shore, resting on Basement, but so far as is known the Laccadive Islands have not been studied and may all be coral atolls. Harbison and Bassinger have located a NNW trending Basement ridge extending from the Laccadives northwards to latitude 20°N and 400 km offshore. These features surely vitiate the concept of a Madagascar lying immediately adjacent to the edge of the Indian continental shelf (1973).

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Lester King

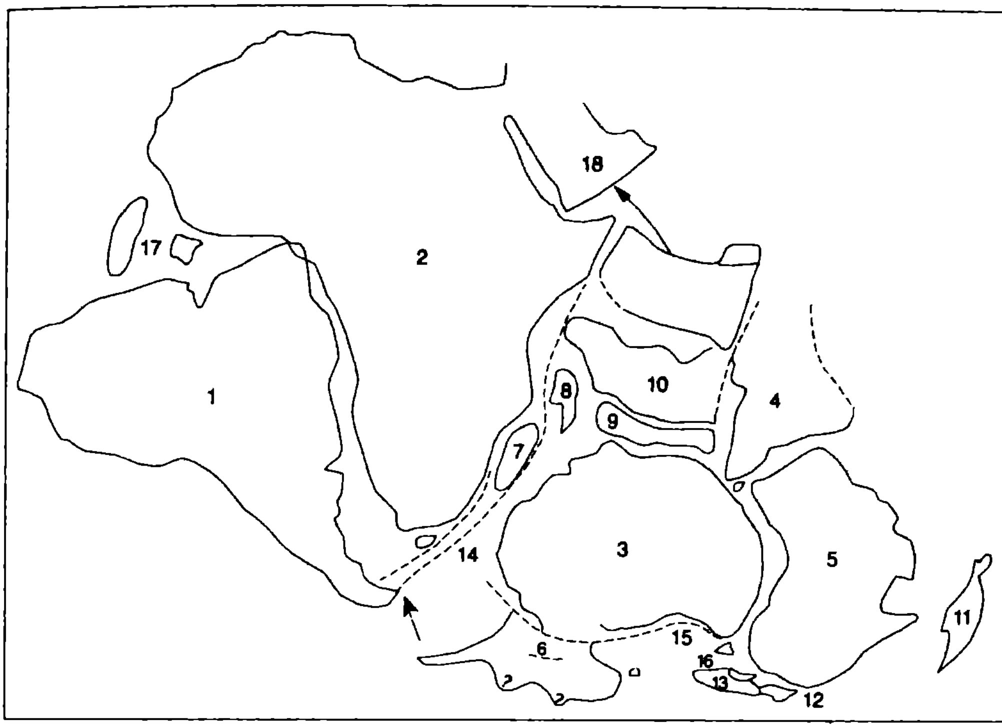
One more attempt at continental grouping may be mentioned. Lester King (1980) places Cape Comorin against Queen Maude Land of Antarctica, while the west side of India is flanked by the Kerguelen-Gaussberg Plateau Ridge and a block termed Iran-Afghanistan, west of which is the Mascarene Plateau. Madagascar is given its present position opposite Mozambique, and over 3300 km from India. Australia lies close to the east coast of India. The complete divorce of Iran-Afghanistan from Arabia, and their southern position facing Kutch and Mangalore, do not appear to be realistic. Eurasia is not included, and Burma and the Sunda Arc must evidently be regarded as belonging there notwithstanding a long-standing connection with India. This attempt at the continental jig-saw is of interest in including the Kerguelen-Gaussberg Ridge, which is ignored in most of the reconstructions (cf. Fig.6).

MESOZOIC INDIA: EAST COAST [Fig.8]

The two principal contenders for a place during the Cretaceous adjacent to the east coast of India are Antarctica and Australia. The Napier peninsula of Antarctica is shown by several authors including Crawford as located within the Godavari/Krishna bend on the east coast at present-day latitude 16° N, at a distance of as little as 200 km between the coasts. It may be remarked that in the attempts to fit Antarctica into the Madras embayment, the Napier peninsula is placed by some authorities opposite to the Krishna-Godavari delta, but in other reconstructions it is rotated by 90° to 180° from that position. The broadly circular coast line of Antarctica over a distance of 8500 km, between the Antarctic circle and 70°S, lacks marked topographical expression, and the criteria for placing any particular part of the Antarctic coast line within the Madras embayment are not of a definitive nature, since detailed geological information is lacking over much of the Antarctic coast line. Others place the North-West Cape of Australia in that position, and in the reconstruction of Ahmad, Australia lies between India and Antarctica, with the Napier peninsula being some 8,000 km distant from the Godavari-Krishna deltas. Crawford places the west coast of Australia against the Tarim basin, Tibet and the south coast adjacent to Antarctica.

Kerguelen-Gaussberg Ridge

First in regard to the placing of the Napier peninsula against the Godavari-



Supercontinent of Gondwanaland reconstructed from stratigraphic structural data. 1 - South America, with broad continental shelf in southeast. 2 - Continent of Africa, with Agulhas submarine plateau. 3 - East Antarctica Shield. 4 - Peninsular India. 5 - Australian continent. 6 - West Antarctica, part of orogenic girdle of Gondwanaland; broad continental shelf of western Weddell Sea corresponds to similar shelf of South America. 7 - Madagascar, position assigned here is in accordance with structural and stratigraphic comparison with Mozambique (Flores, 1970; Kent, 1972; Tarling, 1972). 8 - Mascarene submarine plateau, with granite on Seychelles. 9 - Kerguelen submarine plateau (with schists and siliceous slates). 10 - Iran-Afghanistan with Gondwana stratigraphy and structure. 11 - New Guinea (united with Australia by continental shelf) forming part of orogenic belt about Gondwana. 12 - New Zealand, formerly an arc structure about southeast Australia. 13 - Campbell submarine plateau. 14 - Falklands-Agulhas and Prince Edward fracture zone. 15 - Monoclinal fault front of Transantarctic Mountains. 16 - Alpine fault of New Zealand. 17 - Azores submarine plateau with coarse gneisses and granites, red sandstone, and other rocks of continental affinity. 18 - Arabia. Reconstruction is now left with one gap, between Africa (2), Iran-Afghanistan (10), and India (4). This hiatus may well have been occupied by Arabia, with ancestral geosyncline of Zagros mountains as part of Gondwana orogenic margin. If so, withdrawal of Arabia to its present position must date from Early Permian time, and Red Sea Basin must be of different origin from modern African rift valleys.

Fig.6. Gondwanaland reunited (after Lester King, 1980). The Kerguelen and Mascarene ridges separate southern India from Madagascar. Lester King prefers the term "submarine plateau" to the word "ridge" in describing Seychelles-Mascarene and Kerguelen-Gaussberg features.

Krishna bend of India, with the modern coast lines only 200 km apart, it would appear that the Kerguelen-Gaussberg ridge in the South Indian ocean has been overlooked by almost all authors.

This ridge is 2,200 km long and covers an area of about 250,000 km^2 at a depth of 1,000 m. The Kerguelen Islands at the northwestern end of the

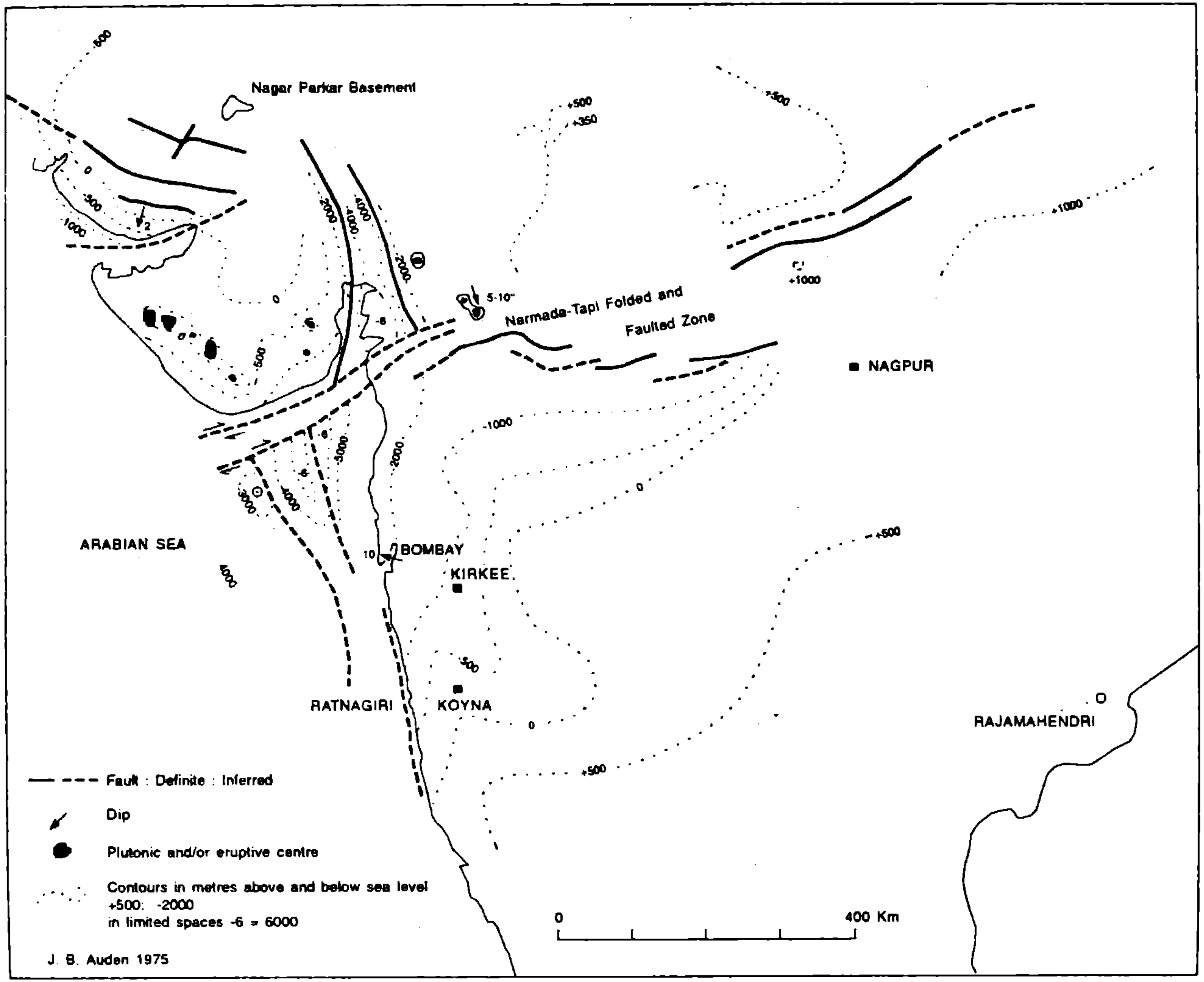
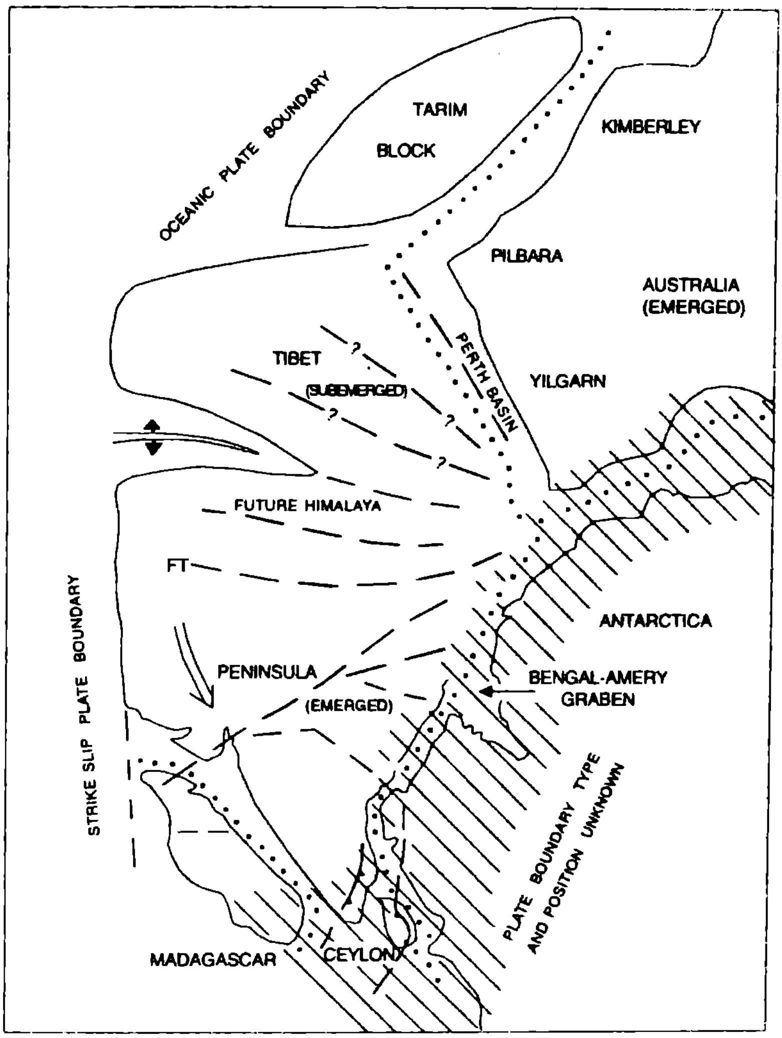


Fig.7. Major faulting in Western India (J.B. Auden, 1975). The Narmada-Son Lineament is a Major feature, but over a distance of 400 km appears to lack distinctive topographical expression, its place possibly being taken by the important fault zone of the Tapi (Tapti) valley, especially Gwailgarh. The western existence of the Narmada fault system is regarded as transcurrent, with dextral displacement.

Gaussberg ridge have an area of 6,232 km^2, surrounded by an area of 64,000 km^2 at the -200 m bathymetric contour. They are 2200 km distant from the Napier Peninsula of Antarctica. Recent studies by a French Mission have shown that the Kerguelen islands comprise a series of volcanic rocks, with one major plutonic mass of granitosyenite covering 380 km^2, and 4 minor outcrops not exceeding 4 km^2 in area. The greater part of the lavas are plateau basalts, but rhyolites, trachytes and phonolites are also present. Thin beds of lignite occur in four areas, associated with Araucaria, Angiosperms and Pteridophytes.

Radiometric dating indicates lava ages from the Oligocene to Recent, while



Part of Gondwanaland during the Permian, Triassic and Jurassic (after Crawford, 1974). Area now Indus Suture Line is suggested to have been a temporary narrow opening in which oceanic type crust developed as the Peninsular part rotated away from Tibet about a pole near the southwestern tip of Australia. This opening closed later as the rotation reverses in direction as Gondwanaland broke up. Broken lines: major rift zones. Hatching: Late Precambrian-Early Palaeozoic zone of mobility. Final crustal separation took place along dotted lines.

Fig.8. The Napier Peninsula of Antarctica is placed 100 km distant from the Godavari-Krishna embayment, while Australia is adjacent to Tibet and the Tarim Basin.

the syenite is 8.6 m.y. The lignite is associated with lavas of lower to middle Miocene age.

While no rocks crop out with a radiometric age earlier than the Oligocene, it is inferred that the basal basalts may be of Eocene age. Moreover, according to Lester King (1980), schists and siliceous slates have been found on the Kerguelen-Gaussberg submarine plateau which would imply that the floor of the volcanics may be Palaeozoic or older.

In several areas the plateau basalts have regional dips of 10° to 20°. The lavas are cut by a prominent series of fractures, extending up to 40 km in length, with a predominant NW-SE trend. In the Ile Foch, the fractures are 500 m apart and strongly recall those which I have described cutting the Deccan volcanics over a distance of 500 km between the Koyna Project and the Narmada (Auden, 1954, p.94; 1975, p.12). Near the Monts Ballons, the fractures form a triangular pattern and have acted as avenues for the intrusion of trachytic magma. The major fractures, some almost straight, as in the Val Studer 19 km in length, others spreading out in arcuate form, eastwards from the Cook Ice Cap, exert a significant control over the topography, which is immediately manifest in the excellent 1:200,000 topographical map prepared by the French.

The beds of Miocene lignite are only a few centimetres thick and of no economic importance, but they are of geological significance in indicating that Kerguelen was periodically above sea level and supported a complex land vegetation.

The Gaussberg Ridge is aseismic, like those of Mascarene, Chagos, and 90° East, in contrast to the Carlsberg Ridge. No doubt minor seismic activity occurs during periodic volcanic disturbance on Kerguelen and Heard Islands, but such seismicity is of a different category to that associated with the Carlsberg and Mid Atlantic ridges which is manifest, although seldom of large magnitude, throughout the decades of monitoring.

The aspect of the Kerguelen Island group is reminiscent of parts of Newfoundland, but more particularly of the coastlines of the North Atlantic Tertiary Thulean igneous province, as in northwest Scotland, the Faeroe Islands, and the Bardastrunda peninsula of Iceland. The volcanic terrain is not like that of recent volcanic islands, such as Reunion and Heard Island (a recent volcanic mass rising from the Gaussberg Ridge), which are essentially endogenous circular cones with radial lava outpourings from a vertical axis. The terrain has more the aspect of a regional volcanic complex, characterised by plateau basalts and plutons, in many areas displaying significant dips not due to radial outpourings on a central volcanic cone. The widespread fracture pattern points to the imprint of a diastrophism that has influenced the whole island complex. The Gaussberg Ridge is, therefore, no recent excrescence, but has the character of activity throughout the Cenozoic and probably long prior to the Eocene. This ridge, standing out obliquely from Antarctica, may have developed only after Antarctica, by supposition lying within the Madras embayment, had been left isolated by the northward migration of India. It would appear more probable that the Gaussberg Ridge existed between India and Antarctica from Mesozoic time. If that be so, India and Antarctica may never have been such close neighbours as has been maintained.

Some workers, including several Russian geologists, regard the Kerguelen-Gaussberg Ridge as an intumescence of oceanic crust, arched up during the Cenozoic. Others consider the ridge to be a thalasso craton, or micro-sialic fragment of recent continental crust. On either hypothesis at least part of the Gaussberg Ridge must have been dry land during the Miocene to allow for the development of a forest cover and the formation of lignite.

According to McKenzie and Sclater (1973), Kerguelen was originally joined to the Broken Ridge (South-East India Ridge attached at 30° S to the 90° East Ridge) from which it is thought to have become separated by the fissiparous Carlsberg Ridge splitting the pair of twins. This view is also expressed in the explanatory notes to plate 21 of the World Geological Atlas (UNESCO, 1977).

On that assumption the twin Gaussberg and Broken Ridges, at one time joined together, should have been an even wider obstruction between India and Antarctica.

Sunda Arc

There is another line of argument by which the postulate of the former juxtaposition of India, Antarctica and Australia may be questioned as of doubtful validity.

*   *   *   *   *

The northern part of the Sunda arc as now developed, lies between India and Burma. The southeastern end of the arc as just discussed, lies close to the West Irian extension of the Australian craton. If Crawford's hypothesis of the juxtaposition of Australia and Tibet between the Permian and late Jurassic is accepted, there would have to be a complete distortion of the Sunda arc for the Banda end of this arc, structurally linked with Western Irian and Australia, would then have been in the region of modern central Asia, while the northern end of the arc between present-day India and Burma would imply an inversion of relative position. Since, however, in the same reconstruction Crawford places Antarctica immediately adjacent to the east coast of India, and spreading over what is now Burma and the Bay of Bengal, there would in fact be no place for the northern end of the Sunda arc (1974, p.374).

The reconstruction of Lester King (1980) does permit of the existence of the Sunda arc without reversal of end positions, while Australia slipped away from India although preserving its cratonic status in relation to the Sunda Arc.

It is necessary to stress the characteristics of this extraordinary four-fold arc, with a Basement of Permo-Carboniferous and older rocks extending 3,500 km from Upper Burma to Billiton island between Sumatra and Borneo, and continuing eastwards as the Sunda Shelf. The next element is the sedimentary basin of the Pegu Yoma, Sumatra, Java, characterised by thick Tertiary deposits, hydrocarbons (coal, oil and natural gas) and volcanoes. The third element forms the Arakan Yoma axial zone of west Burma, Chin Hills, Manipur, Nagaland continuing southwards to the Andaman, Nicobar and Mentawai islands. Finally there is the western Tertiary zone of thick flysch deposits and hydrocarbons (oil, natural gas and coal), which extends for 1100 km in a series of Jura-style folds from Ramree to Chittagong, Tripura, Sylhet, Cachar, up to Digboi.

The width of the arc is 500-700 km. While the component zones remain parallel and of fairly uniform width, there are systematic variations along the strike. The Arakan Yoma in Burma for example forms a continuous range 1400 km in length, and includes mountains such as Victoria (3053m). Further south this zone changes to a series of islands along an arc 2600 km in length and spaced 90 to 130 km apart. In the volcanic zone, the spacing of the volcanoes in Java is approximately 60 km, whereas in Sumatra it is about 110 km and in Burma there are 6 volcanic centres between north latitudes 21° and 26° or approximately 1: 100.

The changes are, however, systematic and there is a remarkable regional unity and symmetry of homologous zones in the compound arc over a distance which is almost one fifth of the present circumference of the earth.

* * * * *

Arc Development

As Van Bemmelen showed, the Sunda Arc has developed from a series of geanticlines and geosynclines migrating progressively south-westwards from Natuna island and the Semitan ridge in Borneo during the Permo-Carboniferous, to the Jurassic tin-bearing granites of Malaya, Bangka and Billiton which are part of the Sunda Shelf, the Laramide to Quaternary orogenesis of the Barian Range, and the Mentawai islands off the south-west coast of Sumatra. This regional activity was taking place simultaneously with the supposed separation of Antarctica and Australia from the east side of India.

The present-day condition of the arc is indicated by the presence of a Benioff Zone. In Indonesia, this zone extends from northern Sumatra to Jamdena, a distance of 4500 km, with northward to NE dips of 50-60° from the horizontal, down to a depth of 600 km. In Central Burma, a more subdued Benioff Zone occurs between latitudes 21° and 26°, the dip being to the east.

North End of Sunda Arc

At the northern end of the Sunda arc the structural units of Wizo, Manipur, Tripura, Cachar, Meghalaya and Upper Assam are linked to India. The Lower Cretaceous Rajmahal-Sylhet traps are continuous below the Bengal deltaic deposits, overlain by the Eocene Sylhet limestone. The Disang series of the Arakan Yoma and Upper Assam are found south of the Shillong plateau as far west as 25°03'N :92°27' E, associated with the full Tertiary succession of Cachar and Sylhet. A gap of only 60 km separates the detailed seismic reflection survey work of Bogra from that undertaken over the most westerly anticline of the Tripura-Comilla group of folds at Bakhrabad (23°37' N :90°52' E) which is 50 km ESE of Dacca. There is a virtually continuous record of geological formations, from the Cretaceous to the Quaternary, between India, Bangladesh and Burma, not only along latitude 25° but also 170 km further south.

At the one end of the Sunda arc, therefore, the Sahul Cratonic mass of Australia and New Guinea formed a crustal unit opposed to the Sunda shelf, between which plates the most extreme convolutions of the Sunda arc units took place. At the other end of the Sunda arc, 7,000 km distant from present-day New Guinea, the formations among India, Bangladesh and Burma were in process of development from before the Eocene. The whole arc in between these ends has geographical continuity and an inter-related diastrophism throughout the Cretaceous and Tertiary. It is difficult to imagine that during the Cretaceous the extremities of this mega-tectonic arc could have been condensed into about 1500 km. On Crawford's construction, with western Australia adjacent to Tibet and the Tarim Basin, Antarctica would have lain where the modern Sunda arc now curves, and New Guinea, without any attached arc, lay some 5,000 km northeast of India (adopting India's present orientation), instead of as it now is 6,000 km to the southeast.

Where Was the Sunda Arc?

On the hypothesis which places Antarctica next to Madras, with Australia wedged between Tibet, the Tarim Basin and Antarctica, there is no place for the Sunda arc in the postulated surroundings of India. The landmass which was necessary to provide the thousands of metres of Cenozoic sediments, together with the coal deposits ranging in age from Eocene to Pliocene, would have had to be Antarctica.

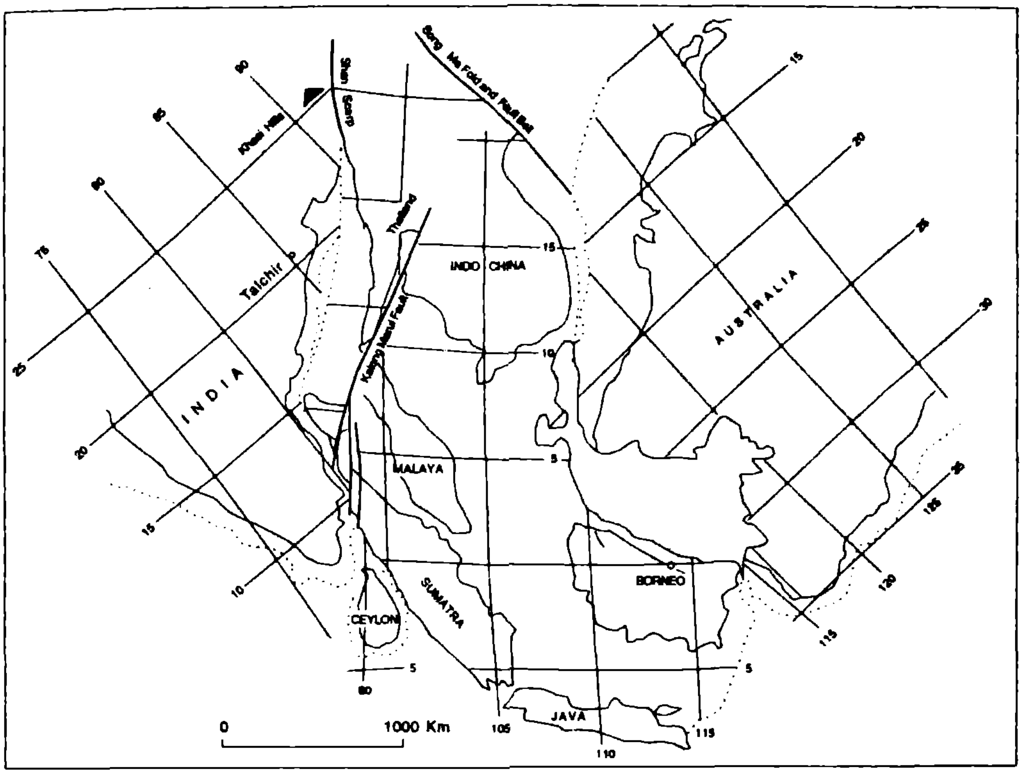
There is a less drastic distortion of the surroundings of the Sunda arc in the reconstruction favoured by Ahmad, in which Australia lies next to Madras and New Guinea is located about 1500 km east-north-east of Bengal (adopting the present-day orientation of India). New Guinea now lies 6,000 km distant in a southeast direction. This would involve an excessive, indeed seemingly impossible, lengthening of the arc, realising that all the elements of the arc were in existence throughout its length at the very time that Australia and its northern satellite New Guinea are assumed to have begun to split off from India during the Cretaceous.

It may be noted that the whole of this extraordinary Sunda arc developed within the wide Panthalassa ocean postulated by Dietz and Holden, which they figure as 7,500 km wide at the mean longitude of India and 10,000 km wide at the longitude of their *Sinus Australis*. Within this inferred ocean there were the coal-bearing fluviatile deposits of Eocene, Oligocene, Miocene and Pliocene age and extensive forested land masses to provide the coal-forming vegetation.

Smith and Briden (1977) recognise part of the Sunda arc as belonging to the Eurasian mass, but leave it disconnected with India and Burma at one end, and New Guinea at the other end, right up to the early Miocene. Before then, India and New Guinea could have had no influence on the development of the arc, whereas the evidence is that the Sahul and Sunda shelves were vital factors in the formation of the structures at the southeast end, while in the north the basement formations now represented by the Shillong and Shan plateaux were a controlling influence.

Interpretation of M. F. Ridd

Ridd (1971) (cf. Fig.9) has produced a totally different reconstruction for the Jurassic period before the break-up and continental drift. This obliterates western Burma and brings the Shan plateau next to Bengal and the Khasi Hills. The northern 250 km of Sumatra, separated from the rest of that island by a fault, lies in the Godavari-Krishna embayment, and most of Sumatra is placed against the South Indian peninsula and Sri Lanka. Western Australia overlaps northern Borneo. In this interpretation, the greater part of the Sunda arc did not exist in the north, where the Irrawady basin and Arakan Yoma had by supposition not been formed. Yet Pre-Alpine metamorphics occur intermittently over a distance of 1200 km along the line of the Arakan Yoma, and exotic blocks of limestone with *Globotruncana* and small *Assilina* occur at various levels in the flysch (Pascoe, 1964, p.1607; Brunnschweiler, 1974, p.284), suggestive of orogenic activity at least as far back as the Eocene. The complex system of arcs east of modern east longitude 115° is not figured by Ridd but his drawing (1971, p.533) indicates that this part of the arc would have been 35° of latitude,



Reconstruction of India, South-east Asia and Australia before break-up and continental drift. The stippled areas are bounded by the continental slope which, for India and Australia, has been taken as the 1000 m bathymetric contour; for South-East Asia the equivalent boundary varies in depth from abut 400 m on the east to 2800 m in the Andaman Sea. Black area is overlap of Australia and South-East Asia (see text), Maps are on Bonne Projection.

Fig.9. Eastern side of India during the Mid-Trias to Jurassic (M.F. Ridd, 1971). Northwest Sumatra lies within the Godavari-Krishna embayment, while the Shan plateau is placed next to the Khasi Hills, with no intervening Arakan Yoma, Naga and Patkai Hills.

are about 4000 km, south of New Guinea, and hence lacking the very Sahul cratonic mass which, with the Sunda craton, is regarded as responsible for the convoluted formation of the islands of the Banda sea.

These ideas have since been modified (Weissel et al. 1980) and the author now suggests that the Thai-Malay peninsula was once part of Gondwanaland, from which it was rifted away during the late Palaeozoic, leaving a Palaeo-Tethys sea which eventually closed up as the Thai-Malay unit joined up during the late Jurassic with the southern China Block.

On neither view would it have been possible for Australia or Antarctica to have been adjacent to India during the mid-Mesozoic. In his later reconstruction, oceanic crust is shown as dipping under the Andaman-Nicobar-Mentawai island arc from the Cretaceous to the Present, whereas in the 1971 concept it would have been an extension of the Indian continental crust which was subducted towards the east.

Position of Sri Lanka

In one reconstruction, by Veevers, Jones and Talent (1971, p.385), Sri Lanka is placed in the Godavari-Krishna embayment, 900 km from its present position relative to India. A test boring near 10°41' N:79°47' E about 47 km to the north of Point Colimore, went through 2300 m of Cenozoic, and 1700 m of Cretaceous, without reaching the bottom of the Cretaceous or the Basement (Metre, 1968, p. 36). Unless Sri Lanka had moved from the embayment to its present position before the Cenomanian it would have had to plough through part of the column of sediments found in the test boring. Bearing in mind the widely held view of the extensive northward migration of India from the southern hemisphere since the Cretaceous, Sri Lanka was on this supposition left lagging behind peninsular India, hugging the coast. It is difficult to see the grounds for supposing that Sri Lanka, which is so well attached to India, and went through the same erosion cycles involving the Nuwara Elya, Cardamom and Nilgiri plateaux, could have been a mere floating excrescence with such a tenuous connection with India that it was unable to keep pace during India's northward Odyssey.

MESOZOIC INDIA: NORTHERN EXTENT

The majority of reconstructions in which the Indian plate is figured suggest that the north-south length from modern Cape Comorin was 3,000 to 3,200 km, which implies a northern limit to the plate in the region of Chitral, Swat and latitude 35°N. Even if that limit is accepted, it is impossible to select any particular ligation line due to the complexity of the arcuate fault pattern present in the western Karakoram, such as figured by Ebblin and Desio. The region where one might expect the collision zone to occur is surely associated with and north of the 700 km long arcuate zone of intermediate focus earthquakes in the Pamirs extending from near Faizabad to south of Kashgar. This zone implies the existence of an approximately 30° south-dipping Benioff subduction belt, the surface expression of which should lie to the north in the region of major shallow focus shocks, close to latitude 40°N. Such a position is some 600 km north of the limit given in many of the representations of a migrant India, and is in agreement with that of Kaila and Hari Narain, although I must express reservation, about other aspects of their Indian plate boundary (cf. Figs.10 and 11).

North-East Plate Boundary

These authors have extended the Indian plate northwards to about latitude 42½°, north of the zone of intermediate focus earthquakes. I would suggest,

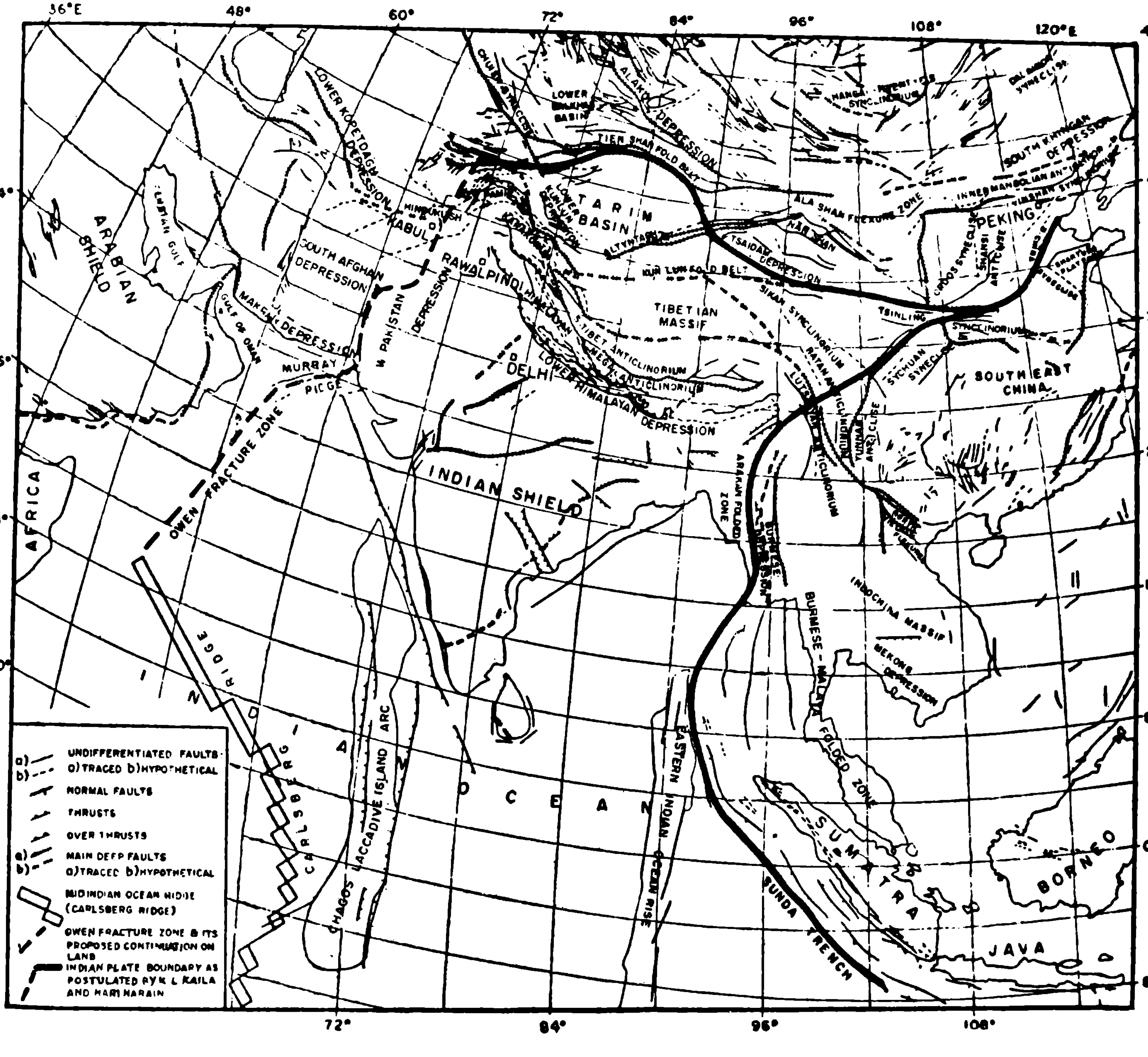


Fig.10. The Indian Plate Boundary suggested by K.L. Kaila and Hari Narain (1976). The Indian plate includes Tibet and extends north as far as the southern edge of the Tein Shan. On both the east and west sides, the boundary cuts across existing structures without displacement.

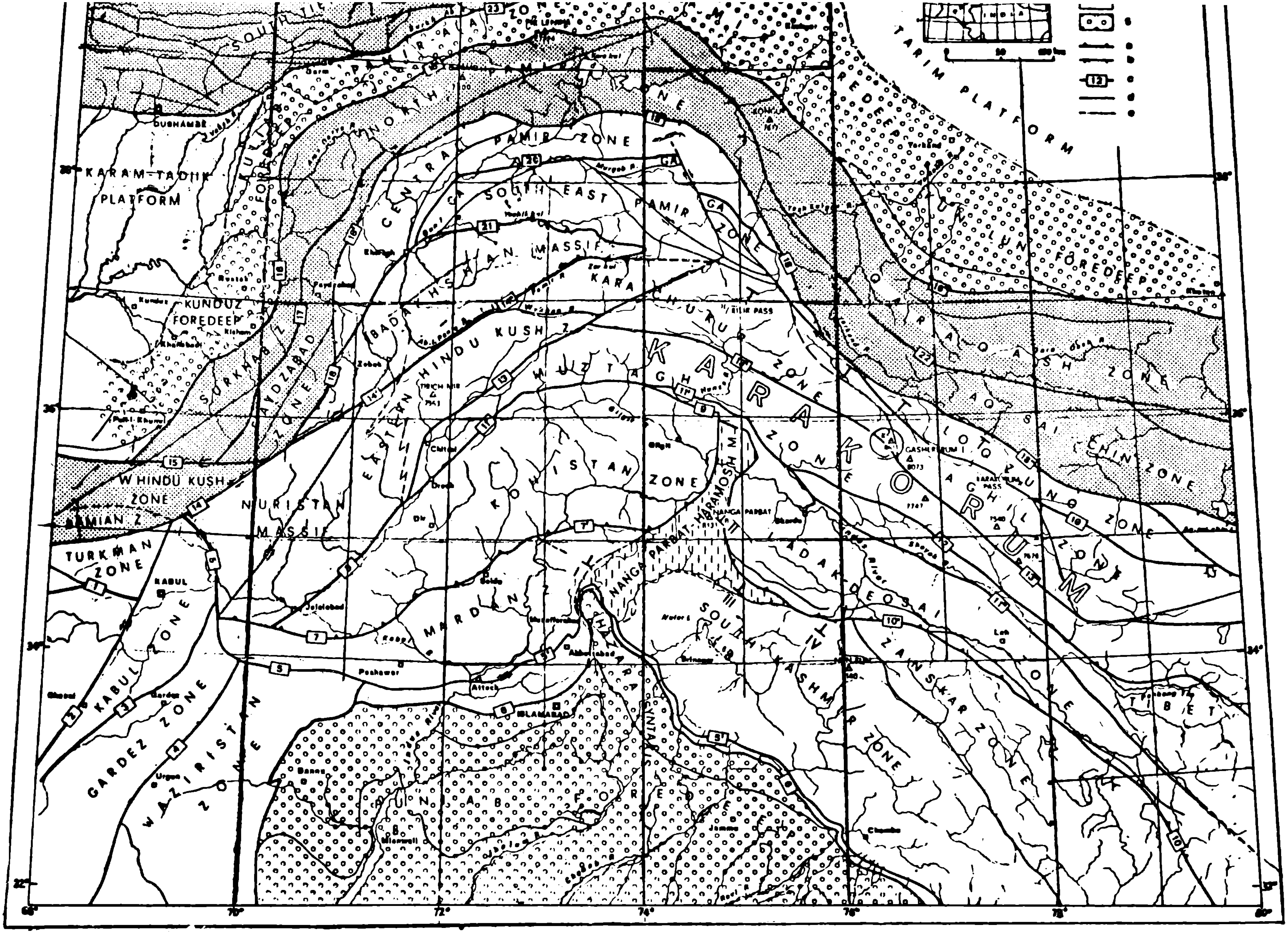
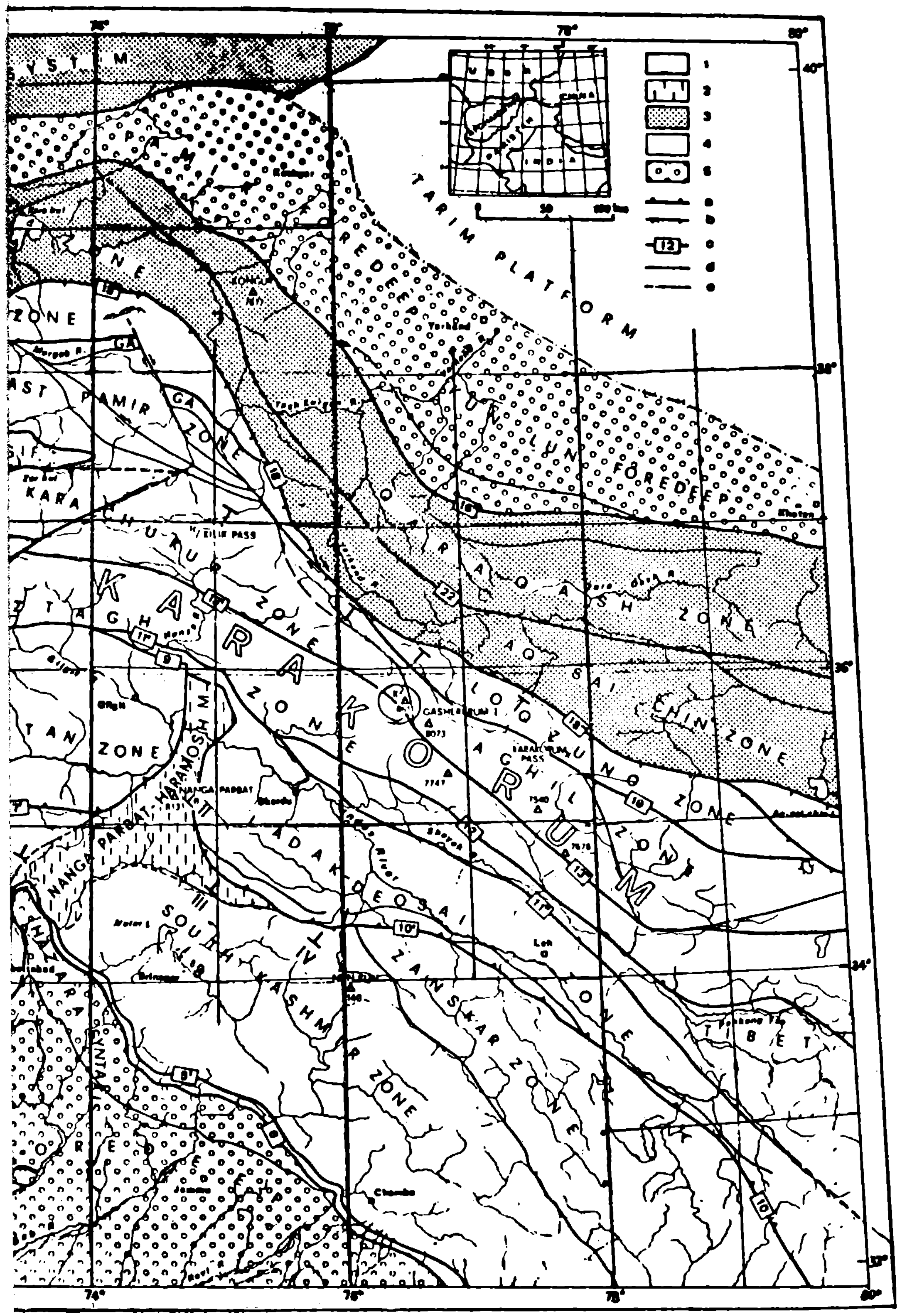


Fig.11. The highly faulted region between Attock, the Karakorum and the Pamirs, according to Ardito Desio (1979). On present evidence, it is difficult to select a likely northward termination of the Indian Plate, from such a complexity of arcuate faults.



's. according to Ardito Desio (1979). On present evidence, it is difficult to select a likely northward however, that certain parts of the plate boundary run counter to the known geology and topography. On the northeast side, from 29½°N: 101°E to 27°N: 97°E, the suture cuts right across the structural trend. The postulated boundary in China and Burma over a distance of 500 km crosses major north-south oriented topography, and within a mere 70 km transacts three world-order north-south rivers, the Yangste, Mekong and Salween (close to 28½°N: 99°E), with intervening ridges rising from 5,000 to 7,300 m in elevation. The rivers follow the tectonic grain of the country, and the postulated contact of the Indian plate with its Eurasian host would surely have created a major line of rupture oblique to the grain. The ridges, however, follow their course on both sides of the proposed suture line without any indication of a zone of megatectonic collision which, had it been in existence in that area, would inevitably have interrupted them.

In the reconstruction of Kaila and Hari Narain (1976, p.18), the southern part of the eastern boundary of the Indian plate passes within and then east of the Arakan Yoma, indicative of a fundamental geological divide which is not, however, manifest in the zonal disposition of Brunnschweiler (1974). Stoneley et al. (1974) on the other hand draw the boundary right across the well-mapped folds of the Tripura, Lushai and Cachar Hills. Here, there is no question of any mega-tectonic oblique fault dislocating the 150 km wide zone of Jura-type folds in Miocene sandstones, shales and flysch over 3,000 m thick. There are indeed thrust faults bounding the western sides of many of these anticlines, which have been drilled for oil and natural gas, but these thrusts are part of the local structural development, and have no megatectonic significance.

North-West Boundary of Plate

The same geological objections apply, in my opinion, to much of the western boundary of the Indian plate suggested by Kaila and Hari Narain which follows the 70° east longitude over a distance of about 400 km without effect on the complicated structural grain of the Hindu Kush and Badakhshan, the Sibi-Quetta re-entrant and down the Poralai zone. The really significant fault zone, along which I have suggested a transcurrent movement of some 300 km, is the Chaman fault, which may well be a suture line. This fault, which is 900 km in length, *runs, however, 150 to 200 km west of the plate boundary indicated by these authors*, and is a conspicuous feature manifest on the air photographs by the abrupt truncation of formations on either side.

Inferred Northern Island Arc

Another interpretation regarding the northern limit of the north-migration Indian crustal mass is provided by Tahirkheli, Mattauer, Proust and Tapponnier

(1979, pp.125-130). These authors propose that the Kohistan sequence covering 30,000 km^2 of amphibolites, metagabbros and volcanics between Gilgit, Kalam and Dir in western Kashmir, represent an island arc which has been underthrust by the Indian crustal unit. The angle of this Main Mantle Thrust, which is shown as passing through Patan (35°07':73°01'), is considered to be 20-30° northward from the horizontal. The north side of the inferred island arc is not well defined by the authors, but is represented as a steep fault passing through Yasin and mid-way between Gilgit and Hunza. This tectonic line should, therefore, be the boundary between the Island Arc and the Eurasian continent. It lies, however, 100-200 km south of the 700 km long arc of intermediate focus earthquake shocks, with focal depth down to 300 km below surface, and 400 km south of the zone of major shallow-focus shocks with magnitudes greater than 8 on the Richter scale.

In the region of Soviet Asia, where there is a true Benioff zone, dipping south at an angle which may be 30-40° from the horizontal, as inferred from the depth distribution of seismic foci, there would appear to the writer to be the more likely boundary between the Indian and Eurasian plates. At its northernmost development the zone passes close to north latitude 39°. The Wanch-Akbaytal of Stocklin (1977, p. 340) may be interpreted in that light. It lies 270 km north of Yasin, close to Ozero Karakul.

Termiers' Construction

One more reconstruction (see Fig.12) may be mentioned which is by the two Termiers, (1977, p.319). On the basis of the occurrence of signs of glaciation during the early Permian, and of contrasted cold and warm water faunas, they have placed southern India between the Mascarene Ridge, Africa and Arabia on the west, and Antarctica on the east. The northern part of India is connected with the Tethys Himalaya (suggested 46 years ago by the writer), Tibet, Iran and the Tien Shan, all in conjunction bordering a wide Fusulina Sea. As remarked earlier, these authors recognise the existence of the Chagos and Mascarene Ridges between India and Madagascar during the Permian, but they place Burma, Malaysia and Indonesia 3500 to 6000 km north of India, with Australia next to Tibet (proposed also by Crawford). This scheme accepts the presence of most of the units forming the Sunda Arc, including the Sahul craton, but disengages the northern part of the arc entirely from India. It would require a clockwise rotation of the Sunda Arc, Australia and Antarctica of at least 6000 km in order to bring Burma into its present position relative to India and the northern end of the arc.

India's Northern Odyssey

The 6000 to 6500 km journey of India from the southern hemisphere since

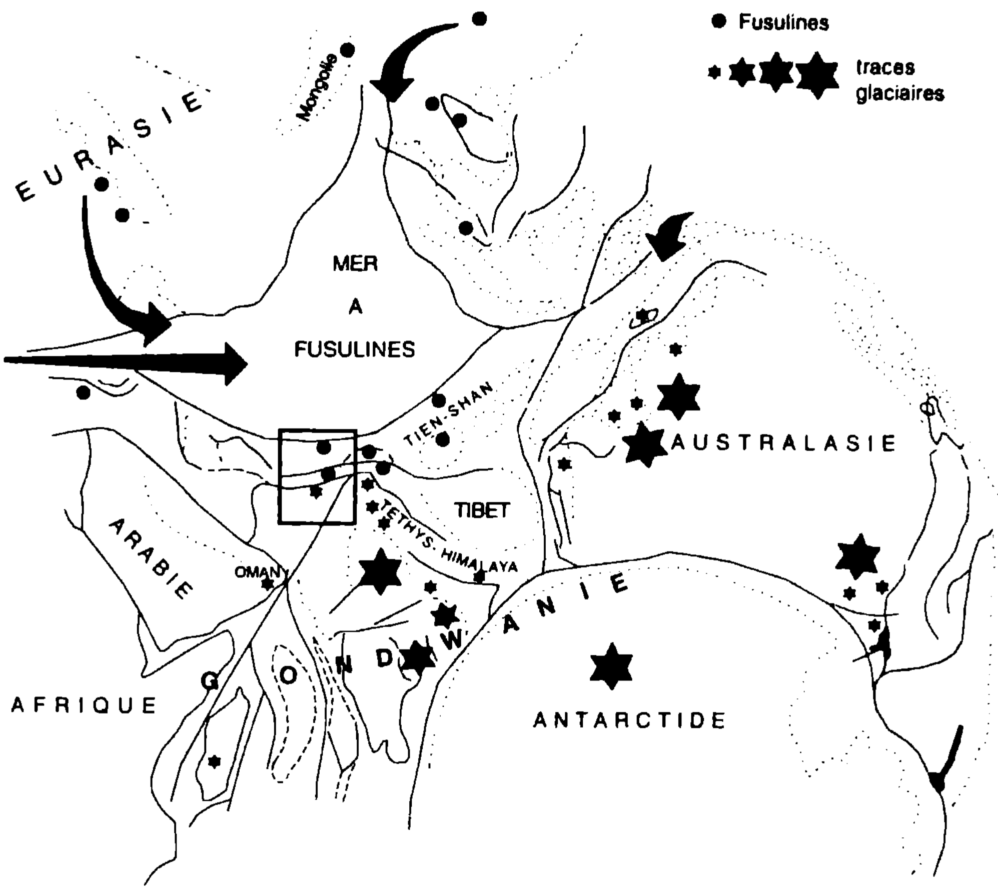


Fig.12. Reconstruction of continents around the Fusulina Sea during the Lower Permian by Henri and Genevieve Termier, 1977.

India lies adjacent to the Oman Peninsula and is flanked on the west side by the Chagos and Mascarene ridges and on the east side by Antarctica. Australia lies east to Tibet. The Sunda Arc extends from near Mongolia to northwest Australia over 4000 km north of India. This reconstruction relates to the Lower Permian, 170 m.y. before India is considered by Powell to have been situated with Cape Comorin at 30° S.

the Cretaceous figured by Powell (1979, p.10) (*see* Fig.1) with average progress of 9 cm/year, has already been discussed. There remains to consider the series of figures prepared by Smith and Briden in their Atlas of Mesozoic and Cenozoic Paleocontinental Maps. In these maps, (1977, pp.12-24) from early Triassic to the present day, they have indicated the progressive break up of Pangaea, with the release of India, from having been wedged between Madagascar and Antarctica, across an unnamed ocean the size of Africa, virtually the same as the Panthalassa of earlier writers. India and Sri Lanka are given a north-south length of 3300 km and an east-west breadth of 2400 km and the northern limit of India has the shape of the modern land south of the Himalayan mountain system. On the northern side of this great ocean, the southern boundary of the Eurasian plate already has the shape to permit the

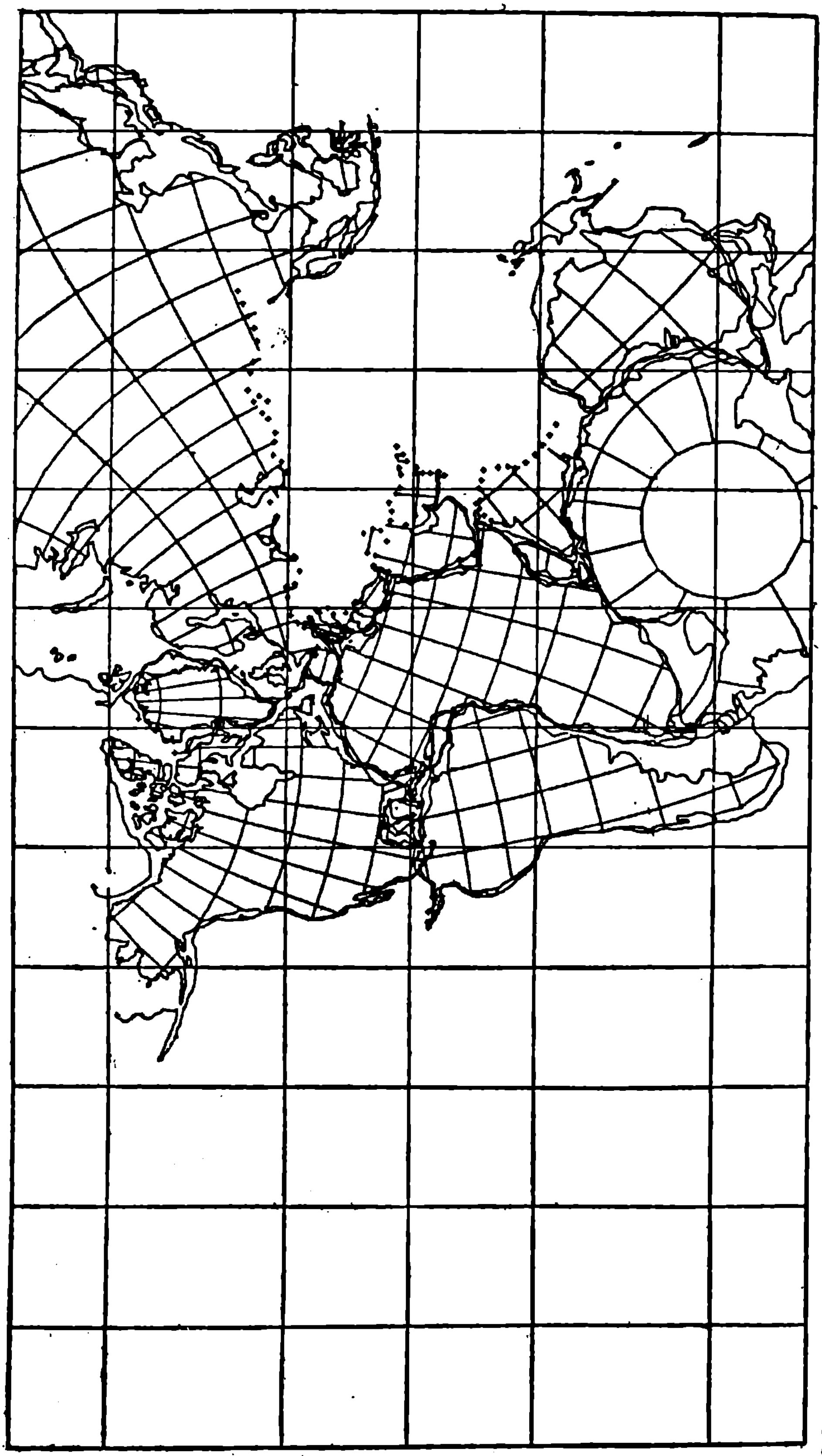


Fig.13. India's position during the latest Trias, according to A.G. Smith and J.C. Birden (1977). Madagascar is wedged between the west coast of India and Tanzania, while on the east side the Napier peninsula of Antarctica lies within the Godavari-Krishna embayment. To the northeast and north of the Indian plate occurs an ocean 6000 km wide, through which India is figured as travelling from the Triassic to the present day. See Fig.14.

migrant India to dovetail into the Eurasian module. It is difficult to envisage that India, moving northwards over such a great distance as an isolated continental mass, with its own structural grain, could finally fit neatly into the loose ends of structure in Eurasia, and then that these disparate units should be so welded together that recognition of the ligation has not yet been definitely established in the field. It would be expected that in the case of a far-travelled Indian plate, docking so to say within the Eurasian module, there would be not only great disturbances, but also the juxtaposition and truncation of masses totally alien in nature and divergent in structure. Instead, in many areas the proposed plane of ligation transects identical bordering formations, as if there had always been a common history of deposition of the originally far-separated units, which eventually coalesced along the collision zone, with unification of their once disparate heritage.

Sub-Crustal Penetration

Crawford regards Tibet as having been a shallow epicontinental sea on continental crust which is an extension of the Indian plate, and suggests that the real suture line between India and Eurasia is along the Tien Shan. As mentioned earlier, Veevers, Powell and Johnson (1975, p. 386) consider that the ophiolite belt along the Indus and Tasng-po headwaters of the Brahmaputra does represent the surface expression of the suture between India and Eurasia, but they suggest that the Indian plate has underthrust the Tibetan crust as far north as the Kun Lun, Astin Tagh and Nan Shan mountain belts. This would explain according to these authors the abnormally thick crust of 70 km under Tibet. Such a concept of sub-crustal penetration requires a horizontal latitudinal underthrust of some 12°, 1300 km, at modern longitude 95°E, for no inclined Benioff zone exists along the Himalayan front. This would indeed be a cosmic phenomenon. Stoneley includes the Indus line in his diagram, and like Crawford evidently accepts it as an important structural feature, but he places the edge of the Indian plate approximately along the north edge of Tibet.

Manifest Fault Zones

Two fault zones may be considered as possible lines of intercontinental union, the Indus fault, with its eastern extension of the upper Tsang-po, and the Chaman-Ornach fault system. Gansser has long considered that the Indus fault is the suture between the Indian mass and Eurasia. There is a considerable body of opinion, however, that regards the Indus fault as a deep fracture within the Indian continental crust, but not as the termination of the Indian mass.

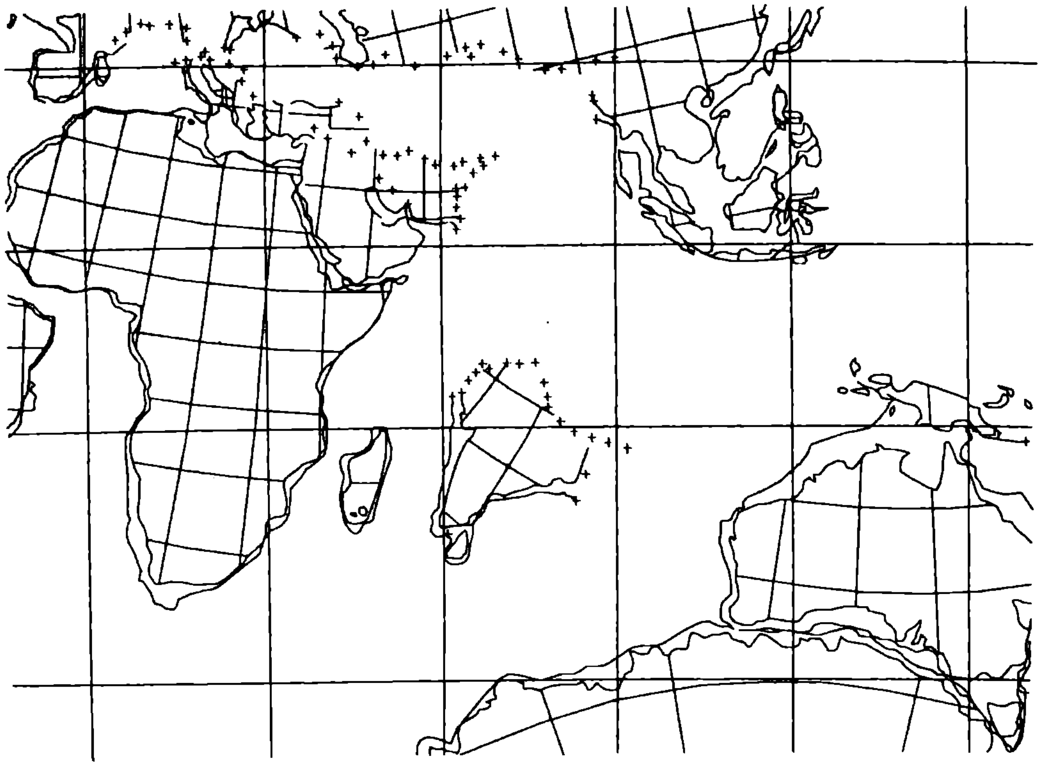


Fig.14. India's position during the late Cretaceous. Smith and Birden (1977), reproduced by A.R. Crawford (1979), who commented on the complete isolation of India. In both figures 13 and 14 the Sunda Arc is shown as belonging to Eurasia, but without links to New Guinea and India, which could have exerted no control over the arc formation. The southern limit of central Eurasia, and the eastern edge of Iran-Afghanistan, are shaped, as if in anticipation, to receive the northern limit of India as it travelled its solitary route, without neighbours, through the wide ocean over a period of about 100 m.y.

The Chaman fault of Pakistan and Afghanistan is certainly a major feature, along which Eocene-Oligocene flysch has been highly sheared, and a sinistral movement of perhaps 300 km may have taken place, based on what appears to be offsetting of the flysch zone. The fault may also represent a faunal barrier, although the principal barrier, between the cold-water Eurydesma sea and the Fusulina sea, appears rather to have been oriented east-west approximately along the present Oxus or Amu Darya. On both flanks of the Chaman fault are important outcrops of ultrabasic rocks, such as at Shuidar and Hindu (now Muslim) Bagh, and between Kandahar and Spin Baldock. It should be noted that these ultrabasics are at latest Cretaceous to Palaeocene in age and, as they are clustered in proximity to the narrow zone affected by the Chaman and Ornach faults, to which they are probably related, it is reasonable to assume that the fault was in movement at that time. Consequently, the crustal blocks on either side of the fault may be inferred to have been in proximity at the end of the Cretaceous, although in my view they were then in different relative positions. In the map of Smith and Briden (1977) Pakistan and Afghanistan were still separated by about 3000 km during the Palaeocene, and the ultrabasics in Afghanistan and Pakistan, on opposite sides of the Chaman fault, would have been unrelated to the collision, considered to have occurred during the late Miocene or early Pliocene.

East-West Symmetry

There is a symmetry between the zones bordering the east and west sides of the Indian sub-continent, from the Shan plateau to the crustal blocks of the Dasht-i-Margo and Lut in Afghanistan and Iran (Auden, 1974, p.243). The zonal sequences are comparable, each side with cratonic shields, volcanic line, axial zone with melange and ophiolites, thick flysch, mud volcanoes, and occasional severe seismicity. The older flysch formations of Disang and Khojak, mainly of Eocene age, are both in certain areas partially metamorphosed.

On the east side, the linkage between the Shan Plateau and Himalayan crystallines is near the tri-junction of India, China and Burma (28°13';97°21') and Putao (27°20':97°26'), and the Himalayan crystallines form part of peninsular India. The Eurasian basement of Burma, and the Himalayan crystallines which belong to the Indian peninsula, are in juxtaposition and form the framework to the Indo-Burman zonal complex.

This disposition is not in accordance with the current concept of an Indian crustal unit migrating across a wide ocean towards Eurasia since the Cretaceous, with what must have been a totally independent development of sedimentary basins connected with far-separated and unrelated shorelines. On the supposition of far migration, these basins could only have coalesced since the Plio-Pleistocene into the Indo-Burman and Makran zonal complexes. The inference is that throughout the Mesozoic and Tertiary the Indian and Eurasian crustal units were in sufficient proximity to exert a common influence on sedimentation of the intervening zones and geanticlinal development of the axial ranges.

DISCUSSION

Five years ago, in the controversy about the position of Madagascar *vis-a- vis* Africa, P. J. Smith (1976) considered that on the basis of paleomagnetic pole positions the issue had been finally settled and that Madagascar must originally have been located in the Tanzania embayment 1700km north of its present position. He continued:

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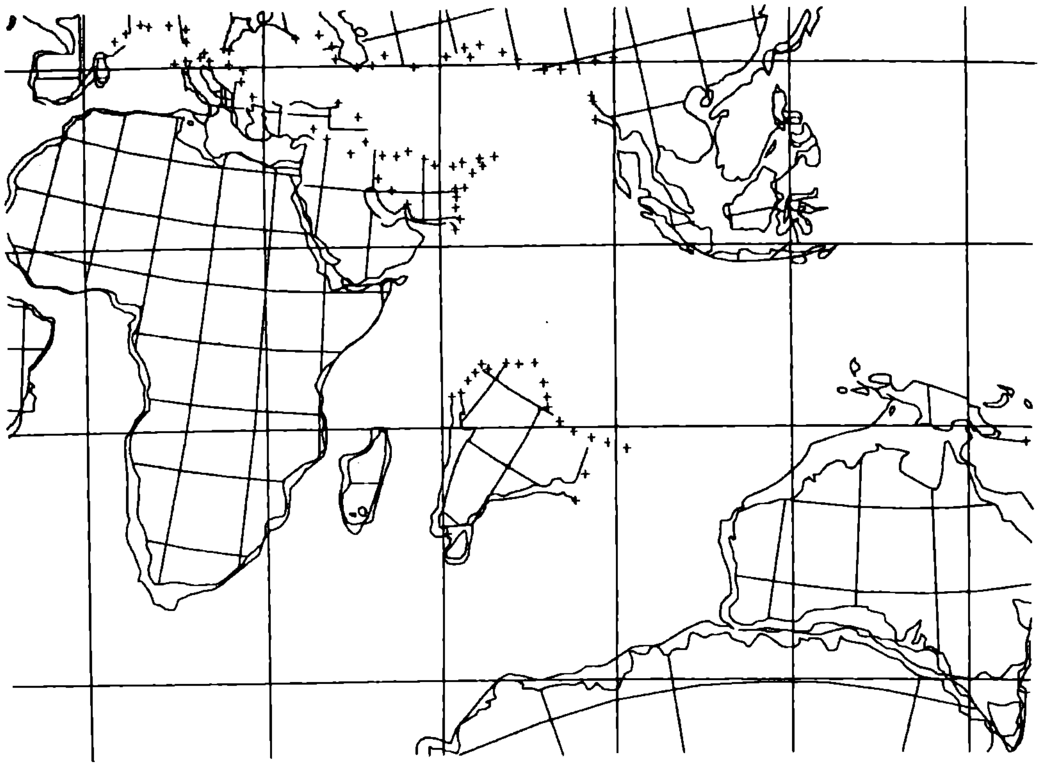

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> 'Any geological "anomalies" must now be reconciled with Madagascar's northern origin: they can no longer be regarded as convincing evidence against it.'

> Conclusions drawn from geophysical data, were taken therefore, to have precedence over those obtained from geological observations. Qualitative geological information could not contradict the conclusions drawn from palaeomagnetism.

Referring not to palaeomagnetism but to computer fits, Tarling and Tarling wrote (1979, p.32):

> "...the areas where the continental edges are clearly defined fit remarkably well; so well, in fact, that (it) is impractical to explain the fit in any other way than that they once formed a huge continent which has subsequently been fragmented."

This computer fit is reinforced in the case of South America and Africa by the polar wandering curves, and it is difficult to do other than accept the probability that these two continents may have been in juxtaposition.

When it comes, however, to the possible positions of the continents now bordering the Indian Ocean there is much less certainty, and it is with some of the very varied interpretations that we have been concerned.

Tarling and Kent (1976, p.304) pointed out that Mesozoic sediments had been found by reflection seismic survey to be present in the very place where Madagascar is supposed to have been at that time. This is an argument similar to that which I used in 1972 in regard to the postulate of P. Evans that the Shillong Plateau had migrated some 200 km eastwards, for Gondwana sediments are found at Singrimari at the west end of the plateau in an area which by hypothesis was thought to have been occupied during Permo-Carboniferous times by plateau basement.

Palaeomagnetism and Diagenesis

Hence, there are seen to be discrepancies between the conclusions drawn from palaeomagnetism and from geology, and exponents on both sides have to be careful not to issue anathemas. Tarling and Kent indicated possible sources of error in the palaeomagnetic data. They suggested that the observed remanence is complex and that thermal and alternating magnetic field de-magnetisation may not have effectively separated the different magnetic components. Detrital grains in sediments may be changed during diagenesis, particularly in the case of haematisation, which may be delayed for 100 m.y.

Turner (1979, p.289), in discussing the palaeomagnetic evolution of continental red beds, has shown that in many instances magnetisation has little or no connection with the depositional age of the rocks, much of the magnetisation being acquired over a long period of time and after considerable changes in the ambient magnetic field.

In some cases, magnetisation represents the ultimate end product of the diagenetic evolution of the red beds, a process lasting millions or years.

These conclusions refer to red beds, but it may be supposed that most rocks undergoing diagenesis and metamorphism may show the modifying effects and over-print arising from magnetisation long subsequent to the time during which they were actually deposited or intruded. It would be interesting for example to determine the palaeomagnetic properties of the Khojak Shales in Pakistan, known to be of Eocene-Oligocene age, but now presenting a fracture cleavage which is so intense that it obscures the true bedding planes.

While there can be no doubt of the great relevance of geophysical data to the understanding the geological processes, it must also be allowed that stratigraphical and palaeontological data, much of it not expressible in mathematical terms, are also of critical importance, notwithstanding the somewhat dogmatic statement of P.J. Smith.

Palaeontological Data

The palaeontological problem has been ably, discussed by Professor F. Ahmad in his *Birbal Sahni Memorial Lecture* four years ago. He concluded from the distribution of fauna and flora that the so-called Gondwanaland extended into China and Siberia at least until the Triassic, implying that land connections must periodically have existed between India and the north across the Tethyan epicontinental sea (Fig.15). Crawford, while adhering to his view that Madagascar formerly lay against the continental shelf of India, stresses the discovery of Permo-Triassic vertebrate fossils of Gondwana type in the Tien Shan and Turfan basin, and cites Colbert's conclusion that the Indian dinosaurs of early Triassic to late Cretaceous times necessitate land communications between India and the Eurasian continent (1979, p.108).

Kamen Kaye (1978) in a detailed analysis of the Permian to Tertiary faunas between Somalia, Madagascar and South Africa indicates that pelagic waters existed between Madagascar and Australia in Aptian time, rendering it unlikely that India could have existed attached to Madagascar and interrupting the faunal migration route between Madagascar and Australia. It should be noted that these pelagic waters would not be the Tethys, which has always been regarded as lying north of India in its supposed southern position. On the contrary, the pelagic waters represented the proto-Indian Ocean, south of India.

In contrast to the palaeontological evidence, palaeomegnetism has led Smith and Briden (1977, p.24) to indicate that during the early Triassic, (220 m.y.) India was wedged between Madagascar and Antarctica, and the northern limit was separated from Eurasia by 50° to 70° of latitude occupied by the Tethyan Ocean approximately 5500 to 8000 km if the earth then had its present dimensions.

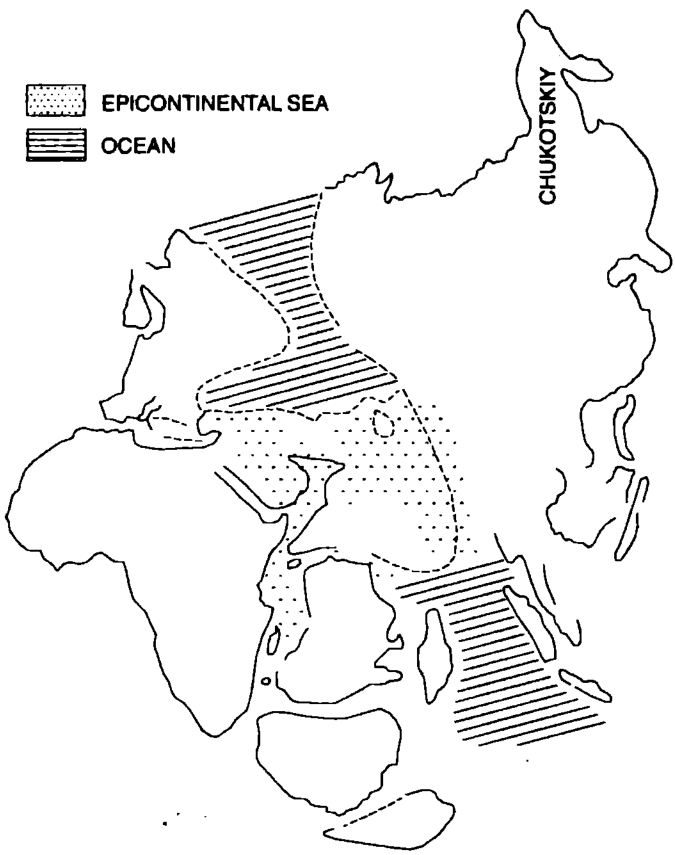

Fig.15. Permian Palaeography as deduced by F.A. Ahmad (1978). Compare with Fig.2. The southern part of India is close to Somalia, and a shallow epicontinental sea separates India from Eurasia. This disposition is comparable to that of the Termiers (Fig.13) except that Australia is not located next to Tibet but is placed by Ahmad within the Godavari-Krishna embayment, and Antarctica is separated from India by the whole width of Australia.

Conflict of Evidence

There is, thus, a manifest conflict of evidence and it is unsound to claim the certainty and finality of palaeomagnetic evidence when the physical phenomena are themselves liable to revised interpretation as more data about the size and changing internal status of this planet become available, and more is known of the effect of diagenesis and metamorphism subsequent to the magnetisation of the rocks as they were originally formed.

Pre-Cretaceous rocks are now present in areas which were, according to many authors, occupied by Antarctica and Australia during the Cretaceous. It is difficult to conceive how these older rocks could replace two large continental masses and create a totally different structural pattern inherited from their previous pre-emplacement environment.

The present coastlines and continental-shelf edges make a convenient but, it is suggested, often deceptive, termination of continental crust, along which attempts can be made to match the outlines of reciprocal coastline features. It is a different matter away from the coasts, where the locations of continental masses are by supposition replaced by other masses with no residual palimpsest or outline to mark the former configuration of the departing continents.

While Australia and Antarctica, covering 22 million square kilometres, are assumed to have left Tibet and India, Palaeozoic and early Mesozoic rocks must have moved in to take their place. Manifestly, the Bayar Kara Shan triangle 500,000 km^2 in area, centred on 32°N: 101°E, and largely comprising Triassic rocks with long narrow intrusions of granite, could not have been in their present relative position *vis-a-vis* India if Australia had actually been occupying that space.

Simultaneously, Antarctica, with a radius, of 2,000 km and part of which coastline is supposed to have been adjacent to the Madras embayment, must also during the Cretaceous have covered on this hypothesis what is now Burma, Malaysia, Thailand, Sumatra and Vietnam, each area with its own long geological history pre-dating the Cretaceous when their present positions were supposed to be occupied by Antarctica. These complex areas may, too, have moved since the Cretaceous, but from where? Antarctica would have overlapped the northern half of the Sunda arc, the development of which, however, began as a mega tectonic entity during the Laramide orogeny, involving the whole space between Burma and New Guinea, without the obstruction of a land mass 13 million square kilometres in area. It would be sounder perhaps to assume that the present configuration of geological formations between India and the China Sea is the result of indigenous processes that were operating *in situ*, and that neither Australia nor Antarctica was in the usurping position postulated for them during the Cretaceous. It is true that folding and thrusting have modified the original zonal relationships which now characterise the Sunda arc, and that strictly it is impossible to suggest that any development along an orogenic belt is *in situ*. It is reasonable however to use that term broadly for processes which occur in a well-defined group of zones in contrast to the contortions necessary to bring the Sunda arc to its present position if New Guinea were really opposite to the Tarim basin at the end of the Mesozoic.

Coming to the Indian Ocean, a related argument may apply to the Mesozoic and Cenozoic rocks proved by deep-sea drilling and indicated by magnetic reversal profiles, to exist in the Indian Ocean. The UNESCO Geological Atlas of the World shows four major development of Cretaceous rocks, in aggregate about 22 million km^2 in area, separated by activity along the Carlsberg Ridge, and its off-shoot, and by evident transcurrent faulting along the 90 degree East ridge. In addition, there is an important occurrence of Jurassic rocks between the northwest cape of Australia and Java. On the assumption that Antarctica and India were closely adjacent during the Cretaceous, the immense spread of Cretaceous rocks in the Indian Ocean could only have developed after the crustal masses had become progressively separated. Alternatively, the sub-marine Cretaceous formations may have been deposited, without the postulated presence of Antarctica and Australia in immediate proximity with India and Tibet, and in continuity with the visible Cretaceous outcrops of Trichinopoly, Assam, Arakan Yoma, and the Andamans. The Jurassic found in deep sea drill hole 261 between Australia and Java is important because, being in the path between Australia and Tibet, it would not have survived the later Mesozoic migration of Australia from eastern Tibet to its present position. Deeper holes are required to penetrate below the so-called basalt basement, located in many of the existing borings, and determine what lies underneath the basalt.

Vertical Movements

The long-continued emphasis on horizontal movements of crustal masses has tended to obscure the importance of vertical movements. The classic case of an area of the crust which has been subject to vertical uplift is that of the Himalaya and Tibet.

Tibet has been the subject of detailed investigation by Chinese scientists, various papers having been read at a recent symposium in Beijing (Peking). A brief summary by Liu Tung-Sheng and Sun Hung-Lieh has just appeared in the *Geographical Journal,* v.147, p.23, 1981, after the author's Wadia lecture had been given. The Hipparion fauna found in Xizang (Tibet) implies that even in the late Tertiary the plateau may not have exceeded 1,000 m in elevation, and that three successive periods of uplift at the end of the Pliocene, during the last 100,000 years, have raised the plateau to its present level at the rate of 10 mm/yr. That uplift is also manifest in the Himalaya, south of the watershed, for river terraces which are clearly part of the present river system are found as high as 500m above present valley bottom (Wadia and Auden in Dunn et al. 1939, p.139). The Tibet plateau has an area of approximately 2,400,000 km^2, but if the Himalayan zone and neighbouring ranges are included, the total area subject to recent uplift may be not less than 3,000,000 km^2, with radius of almost 1,000 km had the area been circular. This is a megatectonic phenomenon, however it is to be explained. The immense upraised plateau is too vast to be considered as a mere peripheral bulge adjacent to the narrow Gangetic sedimentary depression.

In contrast, there is abundant evidence throughout most continents of deep sedimentary basins, with the basement crust sunk thousands of metres. The Basement, and Rajmahal volcanics of Lower Cretaceous age crop out in Bihar but are some 8 to 9 km below sea level near Dacca 300 km to the east of the outcrops. On the edge of the continental shelf west of Bombay, there are 6 km of Cenozoic sediments overlying Deccan volcanics and pre-Cambrian basement. This basement in fact extends further off-shore to a distance of 400 km from the coastline. The narrow Cambay graben, only 50 to 80 km wide, involved rift faulting which has brought down the top of the Deccan lavas to a depth of 6 km below Broach. These are just two examples of crustal depression, involving the east and west sides of the present coastal configuration of India. It should be stressed that the Deccan lavas are associated with coal-bearing Ranikot (Cretaceous-Palaeocene) sandstones in Sind, and were subject to contemporaneous lateritisation in Maharashtra, Kutch and Sind. They were, therefore, for the most part terrestrial in origin and not the products of deep-oceanic eruptions. Hence their depth below sea level is due to subsidence by tilting and faulting.

Within the continental areas as at present exposed above sea level, there is evidence for regional sinking of the basement. The question also arises whether or not certain areas of the ocean floor may represent cratonic crust that once existed at the surface and has since sunk below sea level. These would represent concealed extensions of the continental crust developed beyond the areas of the present continental shelves, and the shelf edges as now developed would not be the limits of the continental crust against which now distant crustal masses could formerly have been in juxtaposition. If such sunken continental crust exists over some areas of the Indian Ocean, it would negate attempts to bring existing shelf edges of now distant surface geographical units into juxtaposition during the Mesozoic by horizontal migration. Quite regardless of the problem of the Mascarene and Chagos Ridges intervening between Madagascar and India, it has been suggested above that Madagascar could not have been closer than to the west coast of India than 400 km because of sunken continental crust.

The basalt encountered at the base of many of the DSDP holes is likely in many instances to be a lava, or a sill, connected with neighbouring continental volcanic environments, and not the topmost layer of the mantle. A beautiful example of a thick sill intruded in the Beacon Series is figured by Holmes and Holmes (1978, p.36) from the Taylor Glacier, Antarctica (160°E :78°S).

The recent seismic reflection profiles in the Indian Ocean, SSE of Cape Comorin and just south of the equator, are considered by Weissel and co-workers to represent basement deformation, which they regard as oceanic crust (1980, p.286). The faulted folds which are figured on pp.287-88 are identical in form to those profiled by R.S. White along off-shore Makran (1979, pp. 297, 298 and 300). These Makran profiles represent with fair certainty tectonically disturbed Cenozoic sediments. The Cenozoic inland, and just north of the Makran coast, is some 8 km in thickness. It is possible, therefore, that the structures figured by Weissel may be in continental crust rather than in oceanic crust, and that they may be a sunken cratonic crust in the Indian Ocean 1200 to 1600 km SSE of Cape Comorin.

The location by Harbison and Bassinger (1973) of a Basement ridge 400 km offshore from the west coast of India and regarded as part of the Indian peninsular crust, has already been noted. This ridge, and the basement between it and the Indian coast, has sunk, carrying with it zones of sediments. Taken in conjunction with the possibility that continental crust has also sunk in the region SSE of Cape Comorin, the presence of these areas of down-faulted crust is relevant to the problem of continental migration. The present edges of the continental shelf in parts of the Indian Ocean may not in fact represent planes of separation between continental masses that had formerly been united, for they were not the original limits of the Indian peninsular crust.

CONCLUSIONS

An attempt has been made to demonstrate the numerous conflicting continental assemblages around the Indian Ocean during the Mesozoic. However perfect the fit may be between South America and Africa, there is little agreement regarding the former distribution of continental masses which now form the perimeter of the Indian Ocean. Some of the Mesozoic jigsaw puzzle groupings would appear to have been based on the wilder shores of improbability. A cardinal factor, which is often omitted during attempts to reconstruct Pangaea, is the existence of vertical movements. Such movements, taken in isolation as a single vector, do not solve the problem of mountain ranges but they surely need to be considered in attempts to play-back the present-day configuration of continental shelves to fit Mesozoic and older cratonic masses.

It is seen that the suggestions regarding configuration based on palaeomagnetism, faunal and floral distribution, tectonics, and other geological considerations are extremely varied and tentative. It would seem, however, from the above discussion that there is considerable support for the view that India may have been throughout the Phanerozoic close to Eurasia, whatever immediate crustal neighbours it may then have had.

The idea of an immense ocean between India and Eurasia is probably untenable. In contrast, there may have been an epicontinental sea, as advocated by Ahmad. Crawford in his latest paper (1979, p.7) has come out strongly against the myth of a vast Tethys Ocean. He has also, following Carey, suggested the importance of the idea of an expanding earth, pointing out that what on a non-expanding earth is a movement of a crustal block, becomes on an expanding earth a change of parallel of latitude. Since crustal tectonics demand relative movements of crustal blocks, an expanding earth adds another vector as distances between latitude increase[1].

The existence of the formidable mountain systems bordering the Indian sub-continent necessitates movements, but the problem is to determine the scale of the movements. If the migration of India over a distance of 6500 km during the last 70 million years is excessive, and contrary to much geological knowledge, what would be accepted as a likely magnitude of movement of crustal plates, bearing in mind the manifest fore-shortening within the Himalayan and related chains? Expansion along active oceanic ridges, such as the Carlsberg and mid-Atlantic, is regarded as established. The Benioff zones next to the Tonga and Mariana trenches, Indonesia, Pamirs, Greece and the eastern border of the Pacific Ocean, are considered to represent the subduction of lithosphere that is being forced down and under other crustal plates. The convolutions of the island zones in the Banda Sea imply rotational movements between coupled forces. All this indicates mobility and extensive movements, even though not on the scale required by some exponents of telemigrations.

It has been suggested above that some of the combinations of continental masses which have been proposed appear to be improbable. This does not mean that the continents around the Indian Ocean were distributed during the Mesozoic in their present geographical locations, but solely that the right agglomeration of continental units, which does no offence to the geological histories of the different components, some of which have been almost ignored, does not yet appear to have been deciphered. It would seem to the author that India has had a relatively close association with Eurasia throughout the Phanerozoic, notwithstanding the allowance which must be made for crustal shortening during the formation of the Himalaya.

[1] It may be wondered how significant expansion is in the matter of interpreting migration of crustal blocks. Holmes (1971, p.704), basing his figures on Strahov's maps, adopts a radius of the earth 600 m.y. ago of 6130 km, the present mean value being 6371 km. A radius of 6130 km implies a circumference during the Eo-Cambrian of 38516 km, as compared with 40030 km at present. One degree of latitude 600 m.y. ago would then have been 107 km, only 4 km less than the present value.

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Note: Figures numbered 3, 5, 6, 8 and 9 in this paper include both the original comments of their authors as well as those underneath which are by the writer.