THE HIMALAYA MOUNTAINS: THEIR AGE, ORIGIN AND SUB-CRUSTAL RELATIONS

By
D. N. WADIA, F.R.S., F.N.I.,
National Professor of Geology and Geological Adviser,
Department of Atomic Energy, Government of India, New Delhi

NATIONAL INSTITUTE OF SCIENCES OF INDIA
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THE RISE OF THE HIMALAYAS FROM THE OCEAN-BED

At a period in the geological history of our earth, which to compare earth-history with the known human history since its earliest dawn, would be as recent as the closing years of the Moghul dynasty, the geographical outlines of India were of the haziest description and it was not separated from Eurasia by the present formidable mountain ranges, which so effectively barricade it from the west, north and east. One of the most clearly established facts of geological science tells us of a sea, which girdled India along its north face through vast aeons of time—a true mediterranean sea, which divided the northern continent of Eurasia (known as Angaraland) from a southern continent of more or less uncertain borders, but which united within its compass the present disjointed peninsulas of Africa, Arabia, India and Australia (known to geologists as Gondwanaland). Between the Deccan and the Siberian lowlands as far as the Arctic Ocean, there was then no mountain barrier of any importance, save the stunted and broken chain of the Altaids of Eastern Turkestan, and our own

Aravallis ; and there then prevailed an oceanway which provided, in the beautiful words of the hymn, "from Greenland's icy mountains to India's coral strand", an uninterrupted intercourse and migration of marine animals, unknown in the world of today. These facts, well substantiated by full and satisfactory evidence, establishes the first principle of Geology that our earth's geography is mobile and is constantly changing.

The rise of the Himalayas from the floor of this mediterranean sea is an epic of the geological history of Asia. All the relevant facts of this event are well dated and documented in the rock-records of these mountains. But before we refer to this, let us briefly discuss the mechanics of mountain uplift in the dynamics of the earth's crust. It should be realised at the outset that, contrary to our rooted ideas of the strength and rigidity of our *terra firma*, the earth has a mobile crust, sensitive to loads and under-loads, to pressures acting from the sides, from the interior of the earth and even from above, *e.g.*, great and abrupt changes of atmospheric pressures. It responds to these forces in a manner which led many early geologists to postulate a hot liquid interior of the earth, fluid through the entire 4,000 miles radius, and only supporting a cold solid crust of 50 to 100 miles thickness.[1] There are many kinds of earth-movements recorded in every part of the globe and definitely registered at the surface—small and large, rapid and slow, local and widespread, secular and periodic. Of these various kinds of earth-pulsations, the most significant are the great periodic deformations of the crust which affect long linear belts of the circumference—the mountain-building or orogenic movements. These mountain-building disturbances succeed each other at vast time-intervals and are to some extent cyclical in their recurrence. They are the great epoch-marking events of earth-history and bring about profound readjustments of lands and seas and their relative distribution. The most generally accepted view of the origin of mountain-chains is what is known as the geo-synclinal theory of mountain-formation.

THE ORIGIN OF MOUNTAIN-CHAINS

Here I shall quote from a former paper of mine :

> "Paradoxical as it may seem, mountains denote the weaker belts of the earth's crust, belts that have been depressed below the sea for long ages and have received enormous deposits of marine sediments belonging to long cycles of geological ages. It is these overloaded, and consequently weakened, zones which respond most to the lateral and tangential earth-pressures which follow the cessation of the sinking process and become folded and elevated into mountain chains. Hence has arisen the well-known principle of

geology that where areas of the earth have sunk the deepest, they also rise the highest. These sunken and loaded belts are called geosynclines in geology, and geosynclines have played a large part in the revolutions of the earth's past geography, stamping upon it the broader features of the continents, mountains and the ocean-basins. The records preserved in its sedimentary piles reveal the history of the life, deposits and earth-movements of the various periods in different regions of the èarth. During the process of compression of these sunken, loaded zones into mountains, the geosynclines are narrowed to from a half to a quarter of their original width; the formation of the Himalaya has, for instance, brought a point in Tibet nearer to a point in Bihar by seventy to eighty miles at least.

Perhaps the largest individual geosyncline on the face of the earth is the one represented by the Himalayan system of mountains—a series of ranges 1,500 miles long and from 150 to 250 miles broad. Geological work of the last few decades in these mountains has proved that, in spite of some local differences, there is an essential unity of structure, ccmposition, and stratigraphy from Kashmir to Assam, which proves clearly that this vast tract of northern India was under the waters of a mediterranean sea—known to geologists as the *Tethys*—continuously from the end of the Carboniferous period of earth-history to the end of the Eocene.

The thousands of feet of marine sediments laid down on the bed of this sea, from the Upper Carboniferous to the Eocene, with their characteristic entombed fossils indicative of the successive ages of deposits, were subjected to protracted compression during later Tertiary ages, as in a vice, between the two stable continental blocks of peninsular India to the south and the table-land of Tibet to the north. The uplifting of the Tethys floor resulting from this compression, its exposure to atmospheric agents, and the sculpturing of time, have produced the youngest, largest, and highest chain of mountains in the world, a chain that is probably still growing in altitude."*

The above-described process of mountain formation is preceded and accompanied by a thickening of the earth's crust along the belts which are to give rise to the future mountain-chain. Also slices and sheets of strata are thrust forward during the process of uplift from the direction of maximum pressure and pulled down to lower levels. These rocks acquire great heat by conduction of the heat of the earth's interior

*The Trend-line of the Himalayas—*Himalayan Journal*, Vol. VIII, p. 63, Oxford, 1936.

as well as from the radioactivity of the crustal and sub-crustal rocks themselves. The roots of the mountains thus must expand considerably, both in a vertical direction and to a smaller extent laterally and thus help in the elevatory effect of lateral compression from the sides.

Each typical mountain-chain, *e.g.*, the Himalayas, the Alps, the Andes, the Caucasus, etc., represents, according to present day conception, a squeezed belt of deep oceanic deposits lying in a submerged geosynclinal depression, between two inflexible rigid portions of continental blocks of the earth, of the nature distinguished in geology as "horsts". The primary motive force in this great tangential compression must be gravity, the energy of falling crust-segments in a cooling and contracting planet.

The weakening of the sunken belt of sediments, referred to above, arises through various understandable causes. The most significant is the increase of earth-temperature with depression. The strata depressed 20,000 ft below the surface in a sinking floor of the sea, as in the roots of a geosyncline, would experience a rise of the isogeotherm of over 400° C. Temperature combined with high pressure weakens rigidity. The ceaseless evolution of thermal energy by the radioactive components of some sediments in a geosynclinal belt is a contributing cause to the rise of the isogeotherms. Also certain chemical and volumetric changes taking place in the plutonic and infra-plutonic zones of the sub-crust and the convection currents prevailing there may be a further contributory cause.

It is still a question how far lateral pressures are effective in elevating a mountain-chain. According to some geophysicists, the major share in the uplift belongs to direct vertical movement caused by transfer of bodies of the liquid interior, or by changes in the density of the sub-crustal magma.

The Extreme Youth of the Himalayas

The rise of the Himalayas from the mediterranean sea-bed was not a single event, but there were three distinct and widely separated phases of uplift. The earliest phase was post-Eocene. A few patches of the Eocene Nummulitic limestone, a highly certain land-mark in geological history, are found at Kashmir, Hundes, and several parts of Eastern Tibet, capping the pile of marine sediments that had been growing on the ocean-floor since the Upper Carboniferous. This is the last record left by the Himalayan sea before it vanished. These Eocene rocks now occur at elevations from 15,000 to 20,000 ft. The next upheavals took place at the end of the Miocene epoch, which also involved and lifted the sediments laid down by rivers in estuaries along the flanks of the embryonic mountain-chain ; these today form the Middle or Lesser Himalaya ranges. The last movement did not commence till after the very end of the Tertiary and involved the foot-hills zone of Siwalik deposits, a system of strata as new as the Middle Pleistocene, and containing within its tilted beds some relics of early Man in India. There is a body of competent evidence, both physical and biological, to indicate that parts of the Himalayas have risen at least 5,000 ft since the Middle Pleistocene. Early man thus witnessed the growth of this northern barrier interfering more and more with his migrations and intercourse across the Steppes of Asia. A great ethnic watershed thus came into being early in human history.

Before we pass on to the subject of the static relations of the Himalayas and their physical adjustment with the interior of the earth, let us try to realise the geographic significance of this earth-feature that for 26 degrees of meridian presents a wall of 20,000 ft mean elevation. Standing in the path of the prevalent equatorial wind currents, one can easily imagine what dominating influence this chain must have on the water and air circulation of Asia, on its meteorology and physiography and through these on the distribution of life on the continent.

Geographical Relations

This mighty range (1600 miles long and 150-250 miles wide, with a mean elevation of the central axial range of 20,000 ft) forms by far the largest feature in the geography of Asia, if not of the world. The Himalayas are not a single continuous chain or range of mountains, but a series of more or less parallel or converging ranges intersected by enormous valleys and extensive plateaus. Connecting the Himalayas with the other ranges of High Asia, and acting like girders in the structural framework of the continent, are the Hindukush, the Karakoram, the Kuen Lun, the Tien Shan and the trans-Alai ranges, bound in the knot of the Pamir (Persian *Pa-i-Mir*, Foot of the eminences). From the Pamir ("the roof of the world") to the borders of China, Tibet and Burma, the Himalayas extend as an unbroken wall of snow-clad ranges, pierced by passes only a few of which are less than 17,000 ft in height. To the north is the block of High Asia, the biggest and most elevated land-mass on the earth's surface, of which the plateau of Tibet (15,000 ft mean altitude), the highest inhabited region of the world, is only a part. Sinkiang, the Gobi and Mongolia are the other parts.

For geographical purposes, the long alignment of the Himalayan system has been divided into: the *Punjab Himalayas* from the Indus to the Sutlej, 350 miles long; *Kumaun Himalayas* from the Sutlej to the Kali, 200 miles; *Nepal Himalayas* from the Kali to the Tista, 500 miles and the *Assam Himalayas* from the Tista to the Brahmaputra, 450 miles long.

Longitudinally, the system is classified into three parallel zones differing from one another in well-marked orographical, hydrographical as well as vegetational features: (1) the *Great Himalaya,* composing the innermost line of high ranges of perpetual snow; their average height is 20,000 ft, carrying the peaks Everest (29,028′), Kanchanjunga (28,145′), Nanga Parbat (26,620′), Nanda Devi (25,645′), Namcha Barwa (25,445′) etc.; (2) the *Middle Himalaya*—a series of ranges closely related to or bifurcating from the former, of mean elevation of 12,000-15,000 ft: their average width is about 50 miles; (3) the *Outer Himalaya* or the *Silwalik ranges,* which intervene between the middle Himalayas and the plains of the Indus-Ganges; they are of varying width from 5-30 miles and form a system of foot-hills of average height 3,000-4,000 ft.

River Systems and Glaciers : The drainage system of the Himalayas, composed of rivers and glaciers, is of a complex nature. The most important fact to be realised regarding the drainage is that it is not, in a large measure, a *consequent* drainage, that is, its formation was not consequent upon the relief of the mountains, but there is clear evidence to show that the principal rivers of this area were of an age anterior to them. In other words, many of the great Himalayan rivers, the Indus, the Sutlej, the Bhagirathi, the Alakananda with the other tributaries of the Ganges system, and the Brahmaputra are older than the mountains they traverse. During the slow process of mountain formation by the folding and upheaval of the rock-beds, the old rivers kept very much to their own channels although working at an accelerated rate. The great momentum acquired by this upheaval was expended in eroding their channels at a faster rate. Thus the elevation of the mountains and the erosion of the valleys proceeding *pari passu,* the mountain chains emerged with a completely developed valley-system cutting it in very deep transverse gorges. These deep gorges of the Himalayas are a highly characteristic feature of these mountains. This circumstance of *antecedent* drainage of the Himalayas explains the peculiarity that the great rivers drain not only the southern slopes of these mountains, but to a large extent, the northern Tibetan slopes a swell, the watershed of the chain being not along its highest peaks but a great distance to the north of it. This drainage of the northern slopes flows for a time in longitudinal valleys through Tibet, parallel to the mountain chain, *e.g.* the Indus, the Sutlej and the Brahmaputra. But these rivers invariably take an acute bend and descend to the plains of India by cutting across the mountains in the manner described above. These transverse gorges of the Himalayas are often thousands of feet (10,000′-17,000′) in depth from the crest of the bordering precipices to the beds of the rivers.

Glaciers : The snow-line, the lowest limit of perpetual snow, on the southern slopes of the Himalayas facing the plains of India, varies from 14,000 ft in the eastern Himalayas to about 19,000 ft in the western. On the opposite Tibetan side the snow-line is about 3,000 ft higher, owing to the desiccation of that region caused by the absence of moisture-bearing winds. The Great Himalaya Range is the gathering ground of snow, nourishing a multitude of glaciers, some of which are among the largest in the world, outside the Polar Circles. Though a majority of the Himalayan glaciers are two to three miles in length, there are giant ice-streams 20 miles and upwards, such as the Milam and the Gangotri glaciers of Kumaon, the Zemu, draining the Kanchanjunga in Sikkim. The largest glaciers of the Indian region are those of the southern face of the Karakoram, discharging into the Indus—the Hispar and the Batura, 36-38 miles long, while the Biafo and the Baltoro glaciers of the Shigar tributary of the Indus are about 37 miles in length. The lowest limit of descent of the glaciers is very variable; while in the eastern part of Assam and Nepal, the glaciers move hardly below the level of 13,000 ft, those of Kumaon and Kashmir Himalayas descend to 12,000 ft in the former, and 8,000 ft in the latter.

Geographical Limits of the Himalayas

The exact topographical limits of the Himalayas, outside the bounds of India proper, are yet undefined and are a subject of controversy. According to general belief, the Himalayas terminate to the north-west at the great bend of the Indus near Gilgit, and at the other end in the south-east at a similar bend of the Brahmaputra, in Upper Assam. Both geographers and geologists have refused to accept this limitation of the Himalayas, because, to them, this theory ignores the essential physical and structural unity of the ranges beyond the Indus and Brahmaputra rivers.

The convex arcuate trend-line of the Himalayan chain has a great bearing on the mode of origin and formation of this mountain system. For fifteen hundred miles from Assam to Kashmir, the chain follows a south-west-east-west-north-west direction and then appears to terminate suddenly at one of the greatest eminences on its axis—Nanga Parbat (26,620 ft). Detailed geological studies of the structure and stratigraphy of this area have shown that just at this point there is a great acute bend of the axis of the whole mountain-system, which turns sharply to the south and then to the south-west, passing through Chilas and Hazara, instead of pursuing its north-west trend through Chitral towards Afghanistan. This extraordinary bend (called *syntaxis*) affects the whole breadth of the mountains from the foothills of Jammu to the Pamirs. At the eastern limit of the Himalayas beyond Assam there is a similar deep knee-bend from an easterly to an aburpt south-westerly trend, away from China. As stated above, these remarkable inflections as well as the arcuate shape of the mountains, with their convexities facing India, are significant and throw light on the mechanism of mountain building. It is interpreted as a consequence of the reaction of the weakened and overloaded Tethyan zone of sedimentation, compressed between the two stable crust-blocks of Tibet to the north, and Deccan to the south. As the mountain building pressures from the north impinged on the recently elevated pliable mass of Tethyan sediments, and thrust them over and against the triangular resistant block of Deccan, they acquired this curvilinear arcuate form. The system of earth-waves and folds as they emerged from the Tethyan sea, had to mould themselves on the capes and projections of the triangle of the Deccan shield acting like a nail or pivot in the Earth's crust.

METEOROLOGICAL INFLUENCE OF THE HIMALAYAS

The Himalayas exercise as dominating an influence on the meteorologic conditions of the Indian sub-continent as over its physical geography, vitally affecting its air and water circulation systems and, through these, the distribution of life on the sub-continent, its migrations and intercourse. The high snowy ranges have a moderating influence on the temperature and humidity of northern India. By reason of its altitude and situation directly in the path of the monsoons, it is most favourably conditioned for the precipitation of all their contained moisture either as rain or snow. Snow-fields and glaciers of enormous magnitude are nourished on the higher ranges, which, together with rainfall in the middle Himalayas, feed a number of noble perennial rivers which course down to the plains in hundreds of fertilizing tributaries. In this manner the Himalayas have been a contributing factor in the desiccation which is over-spreading Central Asia and the desertic conditions that inevitably follow continental desiccation. The most significant recent instance of this effect is the vast desert tract of Tibet and the Tarim basin to its north, the latter occupying an area as large as the Indo-Gangetic Plains ; these are some of the most desolate regions of the world today. It is a well-known fact that these deserts are all recent, in the case of the Takla Makan, in the Tarim depression, of late historic growth. These once fertile and well forested regions have been fighting against adverse climatic conditions since the end of the Glacial period,and though they succeeded in preserving the remnants of their forests and cultivation even to such a late age as the early centuries of the Christian era, they have since steadily succumbed. The increasing desiccation of this area, generally admitted to be in a material way connected with the rise and inter-position of the lofty mountains on their south, has had its full toll on the river system, which once extensive and well developed, has decayed and withered to such an extent that the few existing rivers lose themselves entirely in the growing sands and surface debris which they are wholly powerless to sweep away. The Kuen Lun glaciers are wasting away and their vast reservoirs of ice are retreating. The perennial northflowing rivers which they once supported, now disappear near the foot of the mountains, either in the piedmont gravels or in the shifting dunes of Takla Makan, the immense waterless waste of sand that has replaced the once fertile, low-land stretch of Khotan and Sinkiang. The water brought by the monsoon winds is turned back to India by the Himalayan and trans-Himalayan affluents of the Indus, Ganges and Brahmaputra systems. Thus northern India is saved from the gradual desiccation that has overspread Central Asia since early historic times.

In the geography of Central Asia, today the arid and semi-desert steppe lands occupy a preponderant share of the surface area. Starting from and connected with the great Saharan belt, the arid zone of Asia of varying width from 100-500 miles crosses Arabia, Persia-Baluchistan and the Aralo-Caspian-Balkash depression of Russian Turkistan, and then extends through Sinkiang, Tarim and the Gobi to within two hundred miles of the Pacific Coast. It is the fate of ancient continents to turn into deserts, after they have been worn down to more or less level, featureless peneplains. The Himalayas have, as we have seen above, protected the Indian sub-continent, with the exception of the Indus-Rajputana strip, from envelopment within this great arid belt girdling Asia.

Forests and Vegetation

In the physiography of the Himalayas, forests form an important element. The zonal distribution of forest vegetation from the outer foothills, through the Lesser and Middle Himalayas to the central ranges is determined not wholly by the altitudinal factor, but bed-rock, soil and other edaphic factors exert quite a considerable influence. The altitude determines the sub-tropical, temperate and alpine zones of vegetation as one moves from the submontane tracts to the snowy ranges. The highest limit of forest growth in the more humid eastern Himalayas of Sikkim and Assam is 15,000 to 16,000 ft and in the drier Kumaon and Kashmir Himalayas the highest limit of tree growth is 13,000 to 14,000 ft. Beyond this altitude trees and shrubs disappear and the mountains assume rugged, wind-swept and frost-bitten character. They present an aspect of desolate snow-bound altitudes and long dreary wastes of valleys, depressed lands and plateaus, totally different from the soft soil-clad harmony of the middle ranges, green with their cover of forest and cultivation. The rainfall steadily diminishes to almost total absence of any rain in the districts lying at the back of the Kashmir and Nepal high ranges, which in their bleakness and barrenness partake of the character of Tibet.

Mineral Products of the Himalayas

Though a great extent of the inner Himalayas have yet remained unexplored and are *terra incognita* to geologists, from what has been known so far of the surveyed areas of these mountains, it is apparent that over wide stretches there are few deposits of minerals and ores of any commercial value. Productive mineral occurrences so far located occur on a moderate scale in Kashmir, Nepal and Sikkim. The best-known of these are three Tertiary coalfields, bauxite deposits and some zinc in the Jammu sub-Himalayas, lignite in the Kashmir Valley, copper-ore in Sikkim and hitherto imperfectly known cobalt and nickel-ore occurrences in Nepal. Some antimony deposits at Lahoul and fairly extensive magnesite occurrences in the Kumaon Himalayas have been mapped. Exploration for petroleum in the outer Tertiary fringe has met with some success in Western Punjab and Assam has two or three productive oil-fields. Of late radiation surveys have revealed significant patches of uranium mineralisation in the ancient crystalline rocks of Kulu and Garhwal Himalayas.

Geophysical and Geodetic Studies

To understand the underground relations of mountains and the sub-crustal support of their base, we must get an idea of recent studies on the structure of the outer layers of the earth's body, known as the lithosphere. Modern ideas about the constitution and structure of the earth's interior do not differ greatly from the old concept of a hot, virtually liquid, core of great density, nearly $^7/_8$ the diameter of the whole earth, surrounded by a relatively thin and cool rocky crust or shell. Recent geophysical, especially seismological investigations, however, on the passage of elastic earthquake-waves through different parts of the earth's body, by Gutenberg and others have thrown much light on the nature of the central earth-core as well as of the various layers which constitute the Mantle underneath the crust, their relative dimensions, strength, rigidity, elastic properties, temperature and radioactive influences.

Geophysical data deduced from study of a number of earthquakes of different parts of the world have supplied a valuable means of probing the state of interior of our earth. Beneath the stratified sedimentary layers, which are of greatly variable thickness in different regions, but which along the edges of the continents, and especially in the mountain regions, may be as much as 15 km thick and may be entirely non-existent under the ocean basins, there is a universal layer of granitic composition (the *sial*) covering the lithosphere. The thickness of this layer also, as found by gravity and seismological observations, is variable ; it is thicker in the continents and in the mountain-belts, being at a maximum of 60-70 km in mountains like the Himalayas, Alps, Caucasus and other chains ; it diminishes to about 40 km at the boundaries of the various continents, where they pass into the oceanic basins. It is of minimum thickness on the bed of the hydrosphere and, according to Gutenberg, non-existent in the great hollow of the Pacific.

The deeper layers underneath the granitic shell are of progressively more basic composition (the *sima*) and have greater rigidity and strength. The thickness and elastic properties of this intermediate layer under the sial differ notably in different regions of the earth. It is thicker underneath the oceans than under the continents in general. The lower boundary of this layer, at depth of about 70 km on the average, is known to be a surface of discontinuity from the behaviour of earthquake waves traversing it, in different continental regions—the *Mohorovicic Discontinuity*. Underneath the Mohorovicic Discontinuity, is a shell of dense basalt or dunite (an ultra-basic rock) known as the *Mantle*, of great thickness of some 2,000 km, the lower parts of which according to some geophysicists, may be of the constitution of meteorites. Several discontinuities of the second or third order separate this basic magmatic mass also into more or less concentric shells, as indicated by the speed of earthquake waves through them, their reflections and refractions. The central core, or nucleus, of the earth, of over 3,000 km in radius, is believed to be a virtually fluid mass, largely composed of iron-nickel, but behaving as a solid with high internal friction, because of the tremendous pressure of the lithosphere.

Intensive research on earthquake waves and gravity observations of the last 35 years in different parts of the earth have built up this concept of the structure of the earth. In the "continental layers" the velocity of propagation of seismic waves—the *longitudinal* or compressional (P) waves—is 5.5 km/sec. Below the Mohorovicic Discontinuity, the velocity increases to about 8 km/sec. The speed of the *transverse* or distortional (S) waves of earthquake motion is a little more than ½ of the P waves through these layers.

In the still deeper ultra-basic zone below the Mantle, separated by a number of secondary discontinuities, the speed of seismic waves is found to increase with depth. This is because the ratio of elasticity to density increases with depth. Below this, however, the rate of increase is observed to be much lower, as a consequence of the transition from the crystalline magma of the upper layers to the amorphous or glassy magma of the deeper layers. Underneath this comes the core of the Earth, of much higher density but of greatly reduced rigidity and elasticity. Its outer boundary is tolerably defined by the changes and deflections the earthquake waves undergo as they graze its surface, or are refracted through its mass. It transmits the P waves through it with much less velocity than the intermediate shell because of its non-elastic state. The S waves are not transmitted through the centre of the earth.

The Earth's crustal shell, taken as a whole, has considerable flexibility and has well-defined belts of mechanical weakness. Nevertheless the average strength of the crust, though greatly fractured and often yielding under long-continued stresses (*e.g.*, at the foot of mountains, under load of sediments, in deltas, or under the weight of ice-sheets), is at ordinary depth, distinctly more than the crushing strength of basalt rock at the surface. The strength of rocks of the lithosphere probably increases downwards till it becomes several times that of surface rocks. At the depth of the intermediate layer, underneath the sial, it begins to decrease and, in the deeper sima layer, it may be only $^{1}/_{10}$ of that of surface rocks, yielding under strain by plastic flow to regions of less pressure.

Early Study of Geodesy in India

India is particularly favourably circumstanced for the study of geophysics and geodesy, the science of investigating the size, shape and structure of large areas of the earth. The crust-movements implied in the formation of the Himalayas, the youngest mountains of the world, were juxtaposed against the land-mass of the Deccan, one of the most stable ancient blocks of the earth's shell, which has experienced no folding of the mountain-building type since the dawn of earth-history. Measurements of gravity in relation to earth-features have been carried out by the Survey of India since 1800 and have given some most interesting results. Early in his work (1830) Everest recognised that the Himalayas would exercise a disturbing effect in the triangulation of India, which necessitated the accurate measurement of the arc of the meridian of 78° through the length of India from Cape Comorin to near Mussoorie. A large volume of accurate data from these measurements has been collected, though some of the results are discrepant and are not capable of explanation on existing theories. This is natural, for Northern India is a region of extraordinary tectonic disturbance which has deformed the *geoid* (the shape, or figure of the earth) to such an extent that in no other part of the world has the direction of gravity been found to undergo such abnormal variations as have been detected by the Survey of India in Northern India and by the Russian surveyors north of the Pamirs in Ferghana. According to Sir Sidney Burrard, in no other country in the world does a surface of liquid at rest deviate so much from the horizontal. It was in India that it was discovered that a deficiency of matter underlies the vast pile of superficial matter, the Himalaya; that, on the other hand, a chain of dense matter runs hidden under the Indo-Gangetic plains; and that sea-ward deflections of the pendulum, rather than towards the Ghats, prevail round the coasts of the Deccan. These discoveries led to the formulation of the theory of "mountain compensation" in about 1854 by the Rev. J.H. Pratt, Archdeacon of Calcutta, a theory which was subsequently elaborated and expanded in the doctrine of *Isostasy*. This simple hypothesis, which has had a great vogue, particularly in America, implies a certain amount of hydrostatic balance between the different segments of the earth's crust and an adjustment between the surface topographic relief and the arrangement of density in the sub-crust, so that above each region of less density there will be a bulge, while over tracts of greater density there will be a hollow—the former will be the continents, plateaus and mountains, the latter the ocean-basins. The excess material over portions of the earth above the sea-level will thus be compensated for by a defect of density in the underlying material, the continents and mountains being floated because they are composed of relatively light material; similarly the floor of the ocean will be depressed because it is composed of unusually dense rocky substratum. If an extra load is imposed on any part of the surface, *e.g.*, deltas and ice-sheets during a glacial epoch, it must sink under it, while regions exposed to prolonged denudation must rise until equilibrium is established. The depth at which isostatic compensation is supposed to be complete is found in the United States of America to be about 118 km. In India it is difficult to arrive at any such definite figure, for isostatic conditions must evidently be different in the Peninsula, a region of high geological antiquity, from those of the extra-Peninsular mountain region, which have undergone very recent orographic movements of the crust. In the former area isostatic balance must obviously be more perfect than in the Himalayas.

Plumb-line and pendulum observations at Dehra Dun have shown that the "topographic deflection", *i.e.*, that due to the calculated visible mass of the Himalaya to the north is 86″, but the true observed deflection is only 31″. For Murree the figures are 45″ and 12″ respectively; while for Kaliana, north of Meerut, which is only 50 miles from the foot of the Himalayas, the observed deflection is only 1″, whereas it ought to be 58″. These observations prove that the Himalayas are largely compensated, though not fully, for the differences between the observed deflections and the theoretical, even under the assumption of isostatic compensation, are too great.

On the Indo-Gangetic plains the deflections are invariably to the south and not towards the Himalaya. This southerly deflection increases till the Lat. 23° N to the south of which the plumb-line deflects again to the north. These discrepant data have been explained by Burrard by assuming that there exists underneath the plains a chain of dense rock from Orissa north-westwards through Jubbelpore to Karachi—an assumption which is fully borne out by the large number of gravity measurements of recent years.

MOUNTAINS AND THE DOCTRINE OF ISOSTATIC COMPENSATION

Mountains, particularly the cores of mountains, laid bare after their dissection by the agents of atmospheric denudation, rain, rivers and frost, throw light on the physics of the earth's crust. Their uplift brings to the surface the deeper fundamental rock-complexes and structures lying under stratified sedimentary layers, which would otherwise be buried under thousands of metres of rock. Their uprise again, being an important event in geodynamics, requiring redistribution of density and of mass in the interior, present interesting questions of gravity and plumb-line deflection in relation to the surface-relief. It should be mentioned at the outset that geodesy does not regard mountains as mere unadjusted excrescences on the continental layer, as so much extra matter on the earth's surface. If Central Asia, with the high-standing Tibetan plateau supporting the Himalayan elevation, were extra masses of rock piled on the circumference of a homogenous earth uniform to the core, the waters of the Indian Ocean would be pulled up a considerable way towards the foot of the Himalayas, extending much above the present heads of the Bay of Bengal or the Arabian Sea. The fact that the sea-level is not appreciably affected, warped, or distorted out of the spheroid form, shows that the continents and mountainous portions of the earth's body, in relation to the hollows of the great oceans, are in some sort of adjustment with their bases and are commonly believed to be supported on a dense plastic substratum by a process of flotation, much as ice-caps are supported on the surface of the polar seas. This theory of support of mountains by flotation on a dense medium (the *sima* layer) gives a rational explanation of the existence of what is commonly termed "mountain compensation", and also accounts for the stability of some abnormally abrupt features of earth relief, *e.g.*, the great chain of the Andes on the west coast of South America, rising 20,000 ft in altitude, right in front of one of the profoundest deeps of the Pacific. Her the Andeian highlands plunge down to a depth of 26,000 ft below the ocean level, a total fall of 9 miles. This view attributes mountain-chains to a lateral compression of the geosynclinal troughs, filled with comparatively lighter sediments, causing a bulge in the crust, both upwards and downwards. The downward protuberance will cause a displacement of the denser substratum, thus providing buoyancy.

That the earth is not homogenous and uniformly rigid to the core is borne out by the phenomena of earthquakes, volcanicity, tides, etc. To small periodic forces applied for short durations of time, *e.g.*, earthquake waves, the average rigidity of our earth's crust as a whole is twice that of steel. Down to a depth of about 300 km the average rigidity of the crust is considerably more than that of steel. But to prolonged extensive pressures, such as those exerted at the roots of mountains, or by continental ice-sheets of the magnitude of that covering Greenland (a mass of over a million square miles having a thickness of 3,000 ft), the earth behaves as a plastic body and the surface sinks under the load by a viscous flow of the semi-fluid or plastic rocks underneath the solid crust. The weight of ice-sheets that covered Scandinavia in the Pleistocene Ice Age depressed that land area by several meters. This sinking of the coastline of Norway and Sweden under load of glacial ice and its re-emergence after melting of the ice at the end of the Glacial epoch, has produced a number of well-marked strand-lines along the Baltic. These well-marked beach-lines, or strand-lines were at first a puzzle but are now without much doubt ascribed to the oscillations of level due to sinking or rising of land under the load of Pleistocene ice or its melting.

Below the cold, rigid crust, the earth seems to have but little strength, to judge from these proofs of its mobility; modern geophysics regards all crust-deformities, both on a large scale and on a small scale, as essentially the result of the failure of the earth's sub-crust under sufficiently powerful stresses.

The Origin of Indo-Gangetic Trough—A Complementary Event to the Rise of the Himalayas

At the foot of the Himalayas and parallel with their extension from Hazara to Assam runs the great plain tract of Northern India. These level plains of the Punjab, Uttar Pradesh, Bihar and Bengal mark the site of a deep basin or depression that is filled up with sands, clay and silt brought down from the mountains by the rivers of the Indus-Ganges systems. This hollow or trough, variously estimated as from 3,500 to 20,000 ft deep, is now regarded by Indian geologists as a "fore deep" in front of the Himalayas, a complementary sagging produced in the edge of the Peninsular foreland as it resisted the advancing crustal waves from the north. These two features, therefore, having a common origin, must be considered together. Though filled with lighter rock (the alluvium is about 18 per cent less dense than normal rock)—to such great depth, the gravitative attraction of the Indo-Gangetic plains show no corresponding defect of density, on the contrary, as mentioned above, the plumb-line in the Gangetic basin is deflected towards the plains and away from the Himalaya. This fact is of the highest significance and although its exact implications are not thoroughly understood, it suggests some kind of correlation between underground distribution of density and surface geological features; at the same time it goes a great way in accounting for the fundamental structural unity of the Himalayas and the Gangetic trough.

To what extent are the Himalayas compensated? Observations at a large number of gravity stations in the midst of the Himalayas enable us to say that there is a defect of compensation in the outer foot-hills, known as the sub-Himalayan zone, in other words, this area is under-compensated and one of overload. This defect increases in amount until, according to Oldham "at some 50 miles from the edge of the hills it reaches an equivalent to an overload of about 2,000 ft of rock. In the interior of the Himalayas, in the central ranges, observations show that at about 140 miles from the edge of the mountains this overload has disappeared and compensation is in excess." These variations in the balance between the topographical and underground compensation, according to the same authority, lend some corroboration to the theory of support of the range by flotation and seems to suggest a rather Gilbertian conclusion that the growth of the support has been more rapid than that of the range above it: "The primary problem then becomes not as to how the Himalayas are supported at their actual height, but why they are not even loftier, in other words, the problem is carried one stage further back, from the origin of the range to the origin of its root."*

The question of the origin of mountain-ranges thus acquires a new significance—the primary factor in the production of the range on the surface of the earth is not the formation and elevation of a tract carrying a deep pile of sediments, but the provision of a belt of excess of buoyancy under the range, which provides the motive force; the range itself thus becomes but a secondary phenomenon to the processes at work in the sub-crust below.

The question "Are the Himalayas compensated?" is thus in a way

*R.D. Oldham: *Q.J.G.S.*, Vol. LXXII, p. ix, London, 1916; *Mem. G.S.I.*, Vol. XLII, Pt. 2, Calcutta, 1917.

answered, for compensation is proved to exist. There are, however, differences of opinion as to the why and wherefore of the case; why compensation exists and what circumstances bring it about? Measurements of gravity and deviations from the vertical as carried out by the Geodetic Survey of India during the last two decades give some support to the main facts of isostasy, though there are doubts regarding the degree of its completeness and the depth at which it is effective; the theoretical explanation of isostasy is also found to be inadequate in explaining the large anomalies of gravity which prevail in India. These anomalies, both positive and negative, occur even when there are no surface features present to account for them. The "Hidden Chain" of Burrard, a well-marked belt of excess of density traversing the Plains from Orissa to Baluchistan is still a mystery. For the main relief features of India, although a considerable degree of compensation does exist, there are serious anomalies between the theoretical (*i.e.*, calculated from existing topography) and observed values of the direction and force of gravity which remain to be accounted for. For example, gravimetric surveys have definitely proved belts of underground excess of density and of defects of density in Northern India, which are not represented by any surface deeps or heights. This is fundamentally at variance with the hypothesis of isostasy.

To account for these anomalies, an alternative hypothesis has been propounded by Col. Glennie of the Survey of India. It aims to explain the gravity anomalies by assuming a series of bulges or upwarps and troughs or downwarps in the dense layers of rocks lining the sub-crust, at a depth of some 20 miles below the surface. These crustal warps elevate and depress the dense basaltic sub-stratum of the granitic crust, above or below its equilibrium plane and thus create conditions favourable for prolonged erosion in one area and of accumulation of sediment in another area. The subject, however, is still in the stage of examination and discussion.

It appears that on the whole India is an area of defective density. Gravity in India is in deficit in spite of all the height, bulk and weight the Himalayas have given to it, and it needs a thick stratum of rock somewhere about 600 ft, spread over the entire surface of the country to counterbalance the defect of mass in the interior.

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