ITALIAN EXPEDITIONS TO THE KARAKORUM (K^2) AND HINDU KUSH

Prof. A. DESIO Leader

II - GEOPHYSICS

Volume I

GEOPHYSICS OF THE KARAKORUM

by

ANTONIO MARUSSI

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SCIENTIFIC REPORTS

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ON BEHALF OF THE
ITALIAN NATIONAL COUNCIL OF RESEARCH

E. J. BRILL - LEIDEN

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ANTONIO MARUSSI

Professor of Geodesy, University of Trieste (Italy)

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1964

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PREFACE

The expedition to the Karakorum range which, during the summer of 1954 conquered K^2 (8611 m) — the second highest peak in the world — had, according to Italian traditions, a scientific as well as a mountaineering objective.

Besides the actual ascent, the programme of the expedition included research and study in the Geography, Geophysic, Geologys, Anthropology and Ethnography of the area. Also, a small collection of specimens of local flora and fauna from elevated heights was made occasionally.

The expedition was carried out in three campaings. A preliminary reconnaissance was made by Professor Desio with a guide (Mr. Riccardo Cassin), during the summer of 1953. The main stage followed in 1954 and lasted six months: it was carried out by an Italian team of five scientists (Professors Paolo Graziosi, Antonio Marussi, Bruno Zanettin, Ardito Desio and Dr. Guido Pagani, the physician of the expedition) eleven climbers and a photographer ; a medical officier (Colonel Dr. M. Ata Ullah) and an assistant surveyor (Bad Shah Jan of the Survey of Pakistan), both from Pakistan also joined the staff.

The scientific research was continued in the 1955 campaign which lasted about three months. The team this time consisted of three Italian scientists (Paolo Graziosi, Antonio Marussi and Ardito Desio) and three Pakistani assistants (Dr. N. M. Khan of the Geological Survey, Mr. M. Azizullah of the Survey of Pakistan, and Mr. Javed a student at the University of Lahore).

The territory examined during the first campaign is to be found between the upper course of the Indus river, from Skardu as far west as the Stak valley, and the principal ridge of the Karakorum to the north. However, some reconnaissance was carried out westwards as far as Hunza and Gilgit and eastwards as far as Bagicha. The territory covered in 1955 lies between the Gilgit area and Chitral.

A new scientific campaign was organized by Professor Desio during the summer of 1961 in order to explore geologically the Wakhan territory placed between the Hindu Kush and the Pamirs, and to extend westwards the geophysical observations. The leader was accompanied by Professor Marussi and two assistants (Dr. Giorgio Pasquarè and Dr. Ercole Martina) and by an Afghan geologist (Mr. Ajruddin).

While the geophysical programm was completely performed, the geological one was reduced to the survey of Central Badakhshan, for the expedition was not allowed to visit Wakhan.

In order to complete the geological researches over an area which had been omitted from the itineraries of previous expeditions and to clear up a number of unsolved problems of its stratigraphical geology, Prof. Desio, accompanied by two assistants (Dr. Ercole Martina and Dr. Roberto Galimberti) organized in 1962 a further campaign to the Western Karakorum. The territory covered this time is to be found between the Chogo Lungma and the Sosbun glaciers, and the high valley of the Hunza river.

The present volume deals with the geophysical results obtained by the 1954-1955 expeditions, mainly in the fields of gravity and magnetism. The geophysical data observed during the 1961 campaign have not yet been processed, and in order not to further delay the publication of the present volume, they appear at a later stage in another volume of these Reports.

This is not the place to draw attention to the work of Professor Marussi, who devoted himself to geophysical research, nor to summarize the results attained, but simply to point out the value of the more than 250 gravimetric measurements taken over the Western Karakorum area, in Dardistan, Swat, and as far west as the Hindu Kush, where this range joins up at a right angle with the main Himalayan and Karakorum ranges around the Hazara wedge and where the Indian plateau stretches like a spur towards the heart of the mountains of Central Asia. Previous gravimetric measurements in this region, were incomplete and this left a serious gap in the continuity of the networks of gravimetric stations covering the Indian plateau, the ridges of the Pamirs in the Soviet Republics, the Tien Shan range and the gravimetric survey carried out by the Sven Hedin Expedition in the Tarim Basin (Chinese Turkestan).

The gap has now been filled through the surveys made by Professor Marussi; these complete the picture of the gravimetric features of the main mountainous ganglion of Central Asia.

Similar conclusions apply to the magnetic survey, which closes the gap left by the existing governmental surveys on the Indian Plateau and on the Pamirs, and which borders with Dr. Filchner's surveys in Tibet.

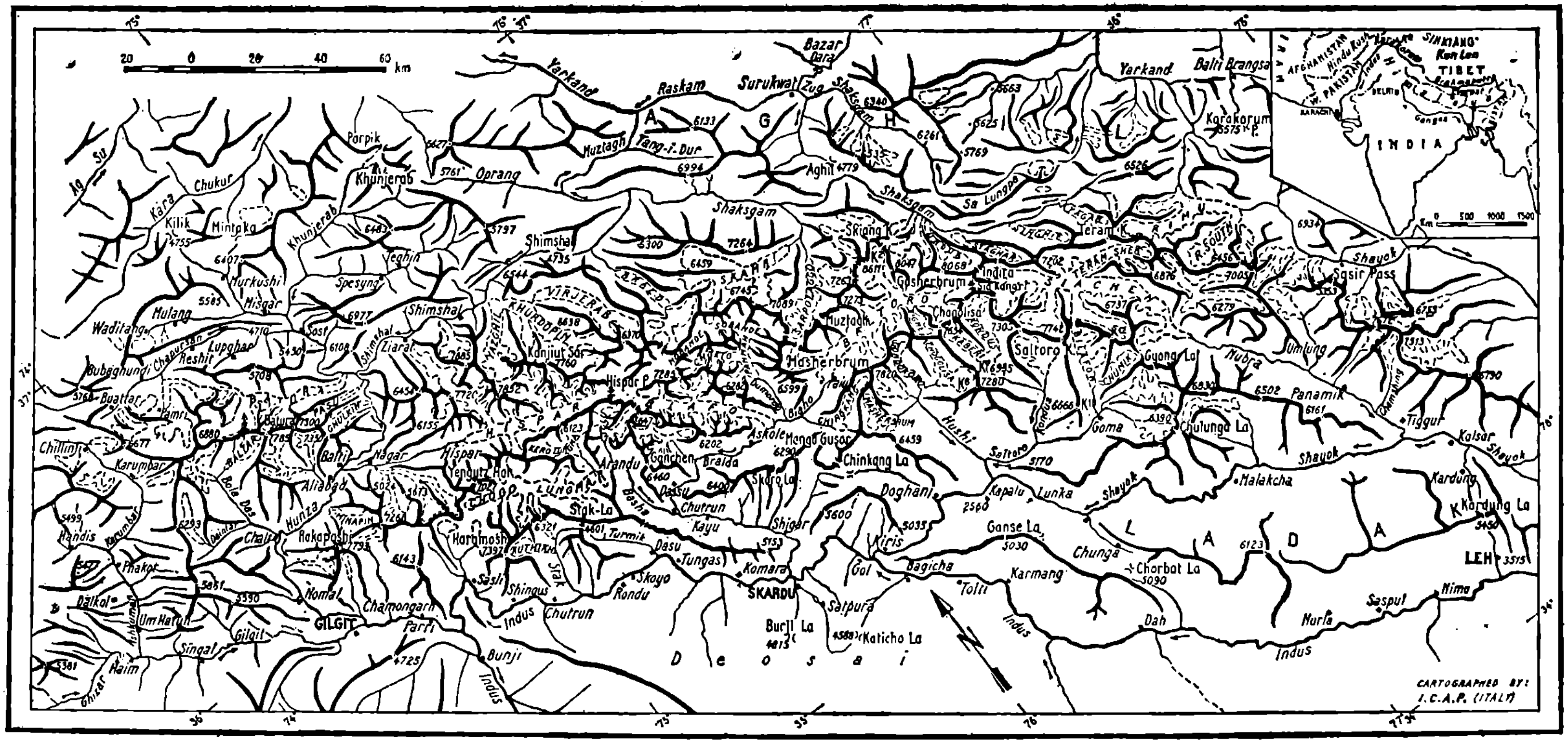
The results obtained in the gravimetric field would have been sufficient to justify our journey, and this not merely on the ground of their intrinsic geophysical value, but even more owing to the geological interpretations to which they can lead.

Before concluding this short preface, I would like to thank Professor Ma-

russi, Mr. M. Azizullah and all others in Pakistan and elsewhere, both authorities and scientists, who through their wholehearted collaboration enabled us to carry out these studies and to complete this Work.

I also wish to thank the Italian Consiglio Nazionale delle Ricerche which financed our scientific expeditions to the Karakorum and Hindu Kush, and made it possible to publish the present volume.

Prof. Ardito Desio



Orographic map of the Karakorum range.

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FOREWORD

In accordance with a long-standing tradition of major Italian exploratory expeditions, the objectives of the Italian Karakorum K2 Expedition of 1953-55 were twofold: mountaineering, in which it conquered the summit of K2, the world's second highest peak and the highest of the Karakorum Range; and scientific, in which it conducted an extensive programme of geological, topographical, anthropological, and geophysical research.

The present volume gives an account of the geophysical work of the Expedition, which the leader, Professor ARDITO DESIO, had entrusted to me.

The first geophysical campaign started in May 1954; the actual field work was begun at Skardu, where I landed on the 14th May. In the course of four months I covered, mostly on foot, the routes from Skardu to Gilgit and Haim, along the Indus and Gilgit valleys, and back along the same route to Stak; from there across the Stak-La, the valley of Turmik, the Ganto-La, to Chutrun; following the gorges of the Braldu River to the Baltoro Glacier, and on the glacier up to Windy Gap; from here back to Skardu following the Shigar Valley, and up the Indus to Bagicha, returning again to Skardu.

The second geophysical campaign started on the 8th of August, 1955 and ended on the 28th of September; during this phase I was assisted in the geophysical work by the Superintendent of the Survey of Pakistan, Mr. Mohammed Azizullah. I completed the geophysical work west of the Karakorum Range, extending it to the valleys of Dir, Chitral, Yarkhun, up to the Baroghil Pass (the northernmost point of Pakistan), and across the Darkot Pass to Gilgit; from here along the Gilgit and Indus rivers to the Babusar Pass, the valley of Kagan, the valley of Swat up to Kalam, and finally along the principal motor route from Rawalpindi to Peshawar and the Khyber Pass.

The geophysical programme can be summarized as follows:

(*a*) a new gravimetric connection between Rome, Beirut, Karachi, and Rawalpindi, performed by an air-transported gravity meter;

(*b*) a new gravimetric connection between Karachi and the Indian fundamental gravimetric station, Dehra Dun;

(*c*) gravimetric connections performed by an air-transported gravity meter between Rawalpindi and two fundamental stations in the Karakorum region, Skardu and Gilgit, in order to establish reference base stations for the ensuing detailed survey;

(*d*) a detailed gravimetric survey along routes in the Karakorum region and in the 'syntaxis' of the Himalayan and Hindu Kush ranges;

(*e*) gravimetric measurements on glaciers to determine the depth of ice;

(*f*) a detailed magnetic survey of the area indicated in (*d*) above, to determine the vertical and horizontal components of the magnetic field, using as a base the magnetic Repeat Station of the *Survey of Pakistan* at Rawalpindi;

(*g*) determination of the altitudes of the stations by means of thermobarometers and aneroids, and where possible by geodetic observation; and

(*h*) determination of deflections of the vertical, in co-operation with the Expedition's surveyor, Capt. (now Major) F. Lombardi.

The gravity instruments used by the Expedition in 1954 were Worden Gravity Meter No. 6, leased by the *Houston Technical Laboratories* of Houston, Texas, manufacturers of the instrument, and Worden Gravity Meter No. 116 on loan from the *Istituto Geografico Militare* at Florence, the latter being used for the connection between Rome, Beirut, and Karachi only. In 1955 Worden Gravity Meter No. 203 was used which was on loan from the *Istituto di Topografia e Geodesia* of the *University of Trieste.*

Gravity meters Nos. 116 and 203 are of the ordinary geodetic type with two dials, reading accuracy of 0.01 mgal, and a range of over 3,000 mgal, while Meter No. 6 is of a special type with a single dial, reading accuracy of 0.1 mgal, and a range of 800 mgal without resetting. This latter combination of sensitivity and range proved very suitable for exploratory travel.

All these gravity meters were calibrated on the Bologna-Ferrara base of 160 mgal as established by the *Commissione Geodetica Italiana*; however, gravity meters Nos. 6 and 203 were also calibrated on the Beirut-Karachi base of 730 mgal, as determined by the observations of Woollard, Bonini, and Stahl as well as by those of our Expedition.

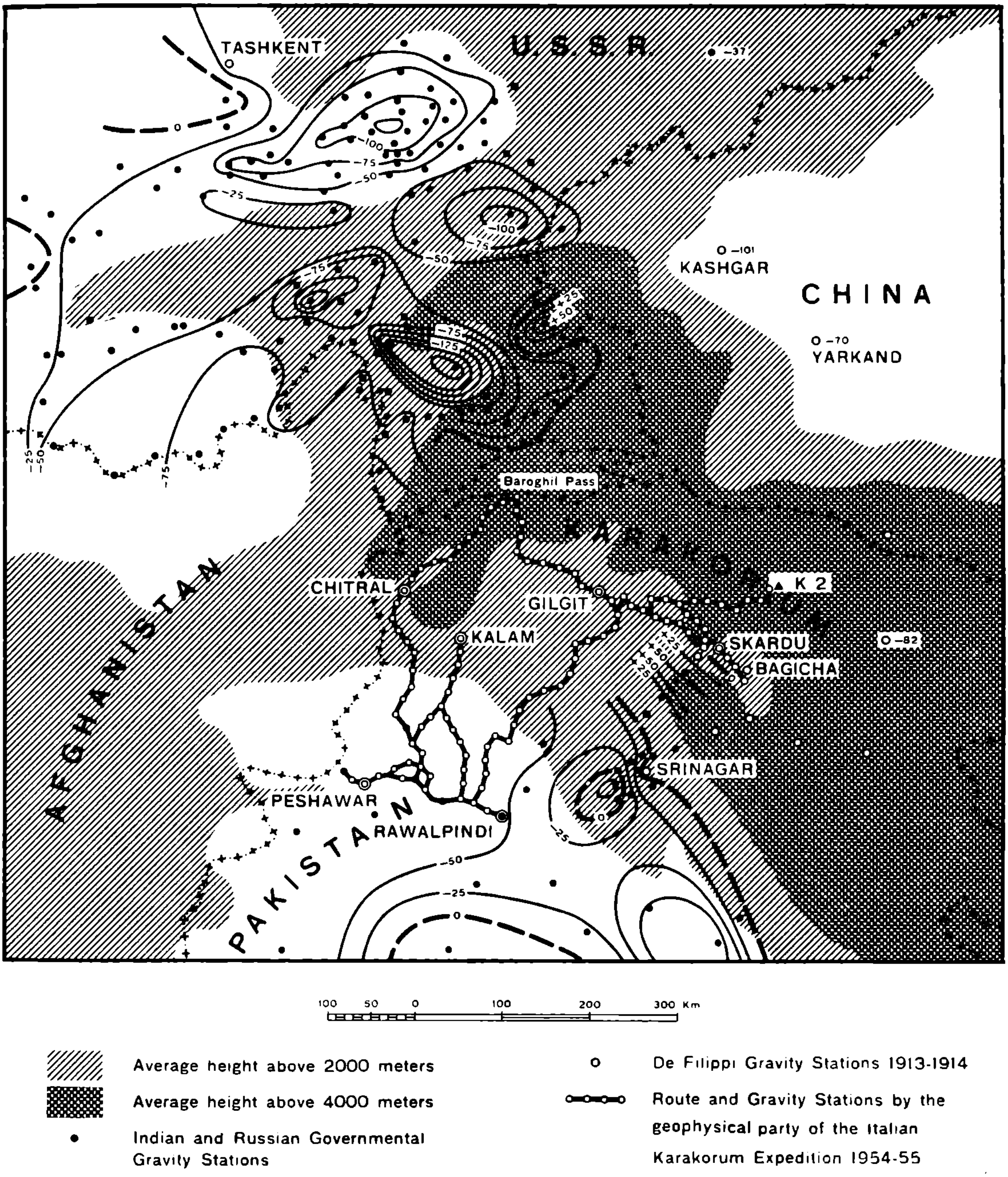


Fig. 1 - The previous gravity surveys and the routes followed by the Italian Karakorum Expedition (Contours show Hayford T = 113.7 km anomalies referred to the international formula) After Gulatee, 1956 and Erola, 1941

Furthermore, all the gravity meters employed were tested thoroughly for temperature effects by Dr. M. Cunietti at the *Istituto di Topografia, Geodesia e Fotogrammetria* of the *Politecnico di Milano*, by Dr. M. Caputo of the *Istituto di Topografia e Geodesia*, *University of Trieste*, and by Drs. I. Gabrielli and G. Poiani of the *Istituto di Fisica*, *University of Trieste*.

Also, meters Nos. 6 and 203 were tested for pressure effects equivalent to a height of 5,000 m at the *Istituto di Macchine* of the *Politecnico di Torino*.

As magnetic instruments, in 1954 the Expedition used a set of Askania-Schmidt variometers, on loan from the *Istituto di Geofisica Applicata* of the *Politecnico di Milano*.

The sensitivity of these variometers was set to 100 γ per scale division, in order to cover a wide range without resetting. In 1955 I used instead a set of Askania-Ruska variometers on loan from the *Istituto di Topografia e Geodesia* of the *University of Trieste*, set to a sensitivity of about 30 γ per scale division. Both of these sets were calibrated by the usual procedure.

Magnetic declination was observed in 1955 by using a Wild declinometer, together with a Wild T2 theodolite; the latter instrument was equipped with a Roelofs Solar Prism Attachment, kindly lent by the *Survey of Pakistan*. I wish to express my deep appreciation to the Surveyor General, Mr. M. N. A. Hashmie, for this as well as for other assistance he extended to us on several occasions.

The thermobarometers used by our Expedition were of the usual type, equipped with thermometers manufactured in Jena and by *FITBEA* (*Fabbrica Italiana Termometri Barometri ed Affini*) of Milan.

We also used two aneroids of the geodetic type, manufactured by the Swiss firm *Thommen* with a reading accuracy of 2 m, to interpolate heights between fundamental thermobarometric stations.

It had been intended to establish at Skardu a fixed recording station for daily magnetic variations, using a recording set lent by the *Istituto Nazionale di Geofisica* of Rome; but unfortunately the set was damaged in the long journey to Skardu. Consequently, it was necessary to refer to the *Pakistan Geophysical Observatory at Quetta* for the daily variations in the magnetic field. This observatory, which was established by Dr. K. A. Wienert of UNESCO, is equipped with excellent recording sets and is now operated by the *Meteorological Office of Pakistan*.

The gravimetric connection between Rome and Karachi, with an intermediate station at Beirut, was established in 1954 in two double flights with

Gravity Meter No. 116, utilizing the stations established at the airports of these three cities by Woollard and Stahl. The base between Beirut and the Lebanese locality of Dahr-el-Beidar (335 mgal) was observed twice in 1954 with Meter No. 6 in order to check its scale factor against the observations made on this base by Lejay and Stahl. Also, Gravity Meter No. 6 was flown once between Beirut and Karachi.

The connection between Karachi and New Delhi was established in 1954 by one flight made with Gravity Meter No. 6 between the airports of those cities; this work was accomplished by Captain Lombardi.

The gravity difference between Karachi, Beirut, and Rome was again observed in 1955, by one flight with Gravity Meter No. 203, made for the purpose of testing its scale factor.

Karachi and Rawalpindi were connected in 1954 by four runs performed with Gravity Meter No. 6, in part by plane and in part by train and car; and in 1955 they were connected by one flight only, using Gravity Meter No. 203. It should be noted, however, that Noorgard had previously made an extensive gravity survey of western Pakistan, connecting among other points the fundamental stations of Karachi, Lahore, Rawalpindi, and Peshawar. Nor should the many pendulum observations made by the former *Survey of India* be overlooked; of these, I repeated those made at Karachi, Rawalpindi, and Murree.

As already indicated, we chose Skardu and Gilgit as fundamental stations for the hilly region of the Karakorum. These towns are connected by an air-line with each other and with Rawalpindi; thus it was possible to establish a triangular gravimetric link between the three stations involved, by flying the meter twice for each side of the triangle.

No gravity observations had previously been made in the Karakorum area, except for the pendulum observations made in 1913-14 by the *Italian De Filippi Expedition* at fourteen stations stretched across the Himalayan Range from Kashmir to Tashkent, and five pendulum observations made in 1925 by the former *Survey of India* on the Deosai Plain south of Skardu. Two of the De Filippi observations, those at Skardu and Tolti, were within the area explored by our Expedition in 1954 and were repeated by me, thus providing an excellent basis for comparison of the results of that expedition with those found by ours.

In the area northeast of the Karakorum, in the Tarim Basin, and in Eastern Tien Shan, there are also 40 pendulum observations, made in the years 1929 to 1933 by Dr. Nils Ambolt, of the *Sino-Swedish Expedition* led by Dr. Sven Hedin. Two of these stations, Yarkand and Leh, were also occupied by the

De Filippi Expedition. There is therefore an indirect connection between Ambolt's work and ours.

The detailed gravimetric and magnetometric survey which I completed in 1954 and 1955 consisted of lines extending for approximately 2,000 kilometres from the Punjab Plains north to the Baroghil Pass and the Baltoro Glacier; to the west as far as Landi Kotal near the Khyber Pass, and to Chitral; and to the east as far as Bagicha in the upper Indus Valley. I made observations at 270 gravity stations and 70 magnetic stations spaced at close intervals along these routes. In 1955 I also made magnetic declination observations, mainly in Chitral. The net of gravimetric routes is linked, as already stated, to the fundamental stations forming the triangle of Rawalpindi-Skardu-Gilgit; while the magnetic observations are all related to the Repeat Station of the *Survey of Pakistan* at Rawalpindi.

In order to determine the drift of the gravity meters, each line either formed a closed loop or was observed in both directions.

Gravity measurements for determining the depth of ice were made across three sections of the Baltoro Glacier, at Urdukas, at Concordia, and at K2 Base Camp, and across one section of the Stak Glacier. Gravity deficiencies of as much as 20 mgal were found in several cases on the Baltoro Glacier.

Elevations were determined, as I have already indicated, by measuring atmospheric pressure and temperature at various stations, and by subsequently using Laplace's formula. All barometric measurements therefore had to be compared with those of fixed observatories maintained by the *Pakistan Meteorological Office* at Rawalpindi, Peshawar, Gilgit, Skardu, Drosh, and Chilas, all of which are located at points of previously established elevations.

As already indicated, data on daily variations of the magnetic field are available from the records of the *Geophysical Observatory of Pakistan* at Quetta. I am very much indebted to Mr. S. N. Naqvi, Director of the *Pakistan Meteorological Office*, for his kind co-operation with regard to the meteorological and magnetic work of our Expedition.

The voluminous data acquired through our observations have been processed at the *Istituto di Topografia e Geodesia* of the *University of Trieste.* My assistant Dr. M. Caputo has taken special care of the computation of the depth of ice on glaciers by Somigliana's and gravimetric methods, of the calibration of the gravity meters, the determination of their thermal drift, and finally of the computation of magnetic declination.

The *Isostatic Institute of the International Association of Geodesy* has computed, on the request of our Expedition, the isostatic reductions for zones 13 to 11, covering the entire area of our survey, and furthermore the complete reduction of 40 stations observed in Central Asia by the Sino-Swedish Expedition led by Dr. Sven Hedin between the years 1929 and 1933. I wish to express for that my deepest appreciation to Dr. W. Heiskanen, Director of the Isostatic Institute.

Furthermore, the *Geophysical Observatory of Pakistan* at Quetta has been requested to give a contribution on the distribution of earthquakes in the region covered by the survey performed by the Expedition. The Observatory has operated since 1954 an excellent set of seismographs specially designed for the study of near earthquakes, and has alreadyc ollected valuable data on the earthquakes of Baluchistan, the Hindu Kush, and the Western Himalayas. We are very glad to include in this volume a report on this subject by Mr. M. A. Choudhury, geophysicist at the Observatory.

I

GRAVITY

FORMER OBSERVATIONS

GRAVITY MEASUREMENTS AND ISOSTASY IN INDIA

The great mountain systems which lie to the north of the Indian Platform and have the Himalayan Chain as their southern border hold a key position not only in the field of modern Geodesy, Geophysics and Geodynamics, but also in the history of man's research into the static conditions of the earth's crust. It was in fact at the foot of the Himalayan Mountains that the problem of the deep structure of the great mountain systems and of their support by the earth's crust was first expressed in concrete terms, and its solution hastened under the stress of both scientific interests and practical needs.

The question of the deep structure of the earth's crust had actually been raised previously as a result of the astronomic and geodetic observations carried out by Bouguer during the memorable expedition of the French Academy to the Peruvian Andes (1735-1744) from which it was shown that there was a marked deficiency of density underneath those mountains; and it was the Jesuit Father Ruggero Boscovich, the founder of the Astronomical Observatory of Brera in Milan who first became interested in the geological interpretation of the observed facts. Although the explanation given by him would by no means hold, it is nevertheless to the credit of Father Boscovich that intensified research into the problem was made for he it was who furthered for the purpose a plan to measure an arc of triangulation in Hungary, which was begun by Liesganig in 1762, and of the "Gradus Taurinensis" which was measured in 1776 by Father G. B. Beccaria.

But it was Colonel Everest, at that time head of the Trigonometrical Survey of India, who had the privilege of carrying out along the "Great Arc" the first observations on a vast scale that provided a solid basis for the theories of isostasy which are nowadays universally accepted at least as a simple and manageable working hypothesis which comes pretty near to the truth.

In 1830 and 1847 Colonel Everest published the results obtained in the measurements of the "Great Arc" which had been established in India along the meridian of 77°30′. In this publication the computed differences between the geodetic and astronomic latitudes at the three stations of the Arc, Kaliana, Kalianpur and Damagida were given. Such differences were only to be expected; but the actual values obtained could not be explained, unless it was assumed — as Col. J. T. Walker, the previous head of the Trigonometrical Survey of India had already suggested — that there was an apparent deficiency in the density of the Himalayan Chain.

These results of Colonel Everest proved that the gravitational effect of mountains on the plumb-line could no longer be neglected; all the more because the station of Kalianpur was the origin of all geodetic co-ordinates of India, and a strong deflection in it would affect all the trigonometric net throughout the continent. The purely speculative problem, as it was until then, thus became a problem of technical importance, and had to be solved as such.

It was no doubt because of this that in 1852 Sir Andrew Waugh, Surveyor General of India, asked the Venerable Archdeacon of Calcutta, John Henry Pratt, to study the effect of the attraction of the Himalayas on the plumb-line in India, thus giving the first impulse to those studies that were to lead to the modern theories of isostasy that have today such a prominent part in Geodesy.

But the calculations presented to the Royal Society of London in 1854 and published in 1855 by Pratt, met with no more success. Taking into account the visible masses of the Himalayas, Pratt arrived at a theoretical relative deviation of 15″.885 — three times greater than the deviation actually found between Kaliana and Kalianpur.

Archdeacon Pratt's report had at any rate the merit of calling the attention of the Astronomer Royal, Sir George Airy, to the problem. Soon afterwards, in February 1855, the latter presented a report to the Royal Society which contained all the fundamental ideas on isostasy and so marked its beginnings as a study. The theory is based on the principle that the earth consists of a lighter crust supported by denser plastic materials, so that, to explain the existence of the elevated regions on the earth's surface, it must be inferred that these have "roots". Thus it is the "negative attraction" due to the defect of density of these roots which partially compensates for the "positive attraction" of the prominent masses. This theory gives a general explanation, which is both quantitatively and qualitatively acceptable, of the anomalies that have to be reconciled.

Archdeacon Pratt, in a number of later publications, took up the idea of an isostatic compensation, but in a different form from that propounded by Sir George Airy and one which proved to be much nearer to the hypothesis later developed and perfected by Maj. C. E. Dutton, J. F. Hayford and finally W. Bowie, the successive heads of the United States Coast and Geodetic Survey. This idea led to the theory which now bears Pratt's name and which forms the basis of all the main works on the shape of the earth and on isostasy later produced by Hayford and Bowie.

The isostatic theories attained new prominence and importance in research work carried out in India following the development of gravimetric measurements.

Probably the first gravimetric measurements in India date back to 1804, when, at the Observatory of Madras, Warren carried out experiments to determine the length of a pendulum beating the second. During this period Henry Kater was for a time with the Trigonometrical Survey of India and he it was who later constructed and used the first reversible pendulum, based on the theories of Huyghens. Kater worked with the Trigonometrical Survey for just three years, from 1803 to 1806, but he does not seem to have taken any particular interest in gravimetric measurements during this stay in India. Nevertheless his name is closely connected with the history of research into pendular measurements in India, inasmuch as it was on account of his practical applications of Huyghens' theories and at his instance that the Survey later decided to acquire a reversible pendulum for use at the Madras Observatory and on the island of Sumatra on the Equator. The first Kater pendulum arrived in Madras in March, 1821, but does not seem to have been put into use at that time.

Systematic pendulum operations started in India only much later, in 1865, although half a century previously Colonel Lambton, at that time Surveyor General of India, had urged a programme to be carried out according to a system of operation which is very similar to that applied later on. Colonel Everest also had contemplated undertaking such investigations; but the idea of making pendulum observations a part of the operations of the Survey was revived only in 1864 at the suggestion of Sir Edward Sabine then President of the Royal Society, who drew up a suitable programme.

It is worth quoting the letter addressed by Prof. G. G. Stokes to Sir Edward Sabine, in which the great importance of gravity measurements in India is strongly supported by the great mathematician:

"*From G. G. Stokes, Esq., Sec. R. S., Lucasian Professor of Mathematics, Cambridge to the President of the Royal Society.*

"Cambridge, June 22, 1864.

"DEAR GENERAL SABINE, — In reply to your letter of the 9th instant enclosing copy of correspondence relating to proposed pendulum observations in connexion with the Great Arc of Meridian, and stating that the Council of the Royal Society would be glad of an expression of my opinion as to the importance of the experiments, and as to the mode in which Colonel Walker proposes to carry them out, I would make the following remarks.

"The experiments may be viewed either (1) as supplementary to the survey of the arc; or (2) as affording independent information on the earth's figure, and on the cause and amount of local variations in the intensity of gravity.

"*First.* It is needless to refer to the great care and thought which have been bestowed on the Grand Indian Survey, or the cost of the operation from first to last. The result is a scientific achievement worthy of the nation, and the Great Arc takes its place in the foremost rank among those on which we depend for our knowledge of the figure of the earth. But the results of geodetic operations of this kind are, from their very nature, beset by one source of uncertainty, that arising from local variations in the directions of the force of gravity. The numerical calculations executed by Archdeacon Pratt have shown that the amount of disturbance due to the mountains and high table-land to the north of India is much more serious than might perhaps have been anticipated; but, from a comparison with the results of the Survey, it appears that some hidden source of compensation must exist, causing the effect of the mountains to be much less than would be indicated by their mere external form. These considerations referring especially to the Indian Arc, combined with the uncertainties as to local attraction which apply to any arc, render it highly desirable to apply an independent check to the amount and character of these disturbances, if we have the means of doing so at a cost which is trifling compared with the whole expense of the Survey. Now such a check is offered by pendulum observations, when the results obtained at various stations are combined. The pendulum no doubt indicates only the *vertical* component of the disturbing force, whereas it is the *horizontal component in the plane of the meridian* that affects the measures of arcs. At any one station, of course, a horizontal disturbance may exist without a vertical disturbance, and *vice versâ*; but in a *system* of stations disturbances of the one kind must necessarily be accompanied by disturbances of the other kind. Indeed it is theoretically possible from the vertical disturbances supposed known *actually to calculate* the horizontal disturbances, and that without assuming anything beyond the law of universal gravitation. Actually to carry this out would probably require observations to be made at stations more numerous than can be thought of; but the fact of its possibility shows how severe a check pendulum observations are capable of exercising on the results of geodetic operations.

"*Secondly.* The figure of the earth, as you are well aware, admits of being determined by pendulum observations independently of measures of arcs. For this purpose it is not necessary that the stations should be connected in series, in which respect, as in many others, pendulum observations have a great advantage in respect of facility over measures of arcs. At the stations of an arc of meridian we have the latitudes and elevations already determined, which saves part of the labour, especially as regards the elevation in the case of an inland station. The earth is indeed already well studded with stations at which gravity has been accurately determined, in effecting which result your own labours occupy a most prominent place. In India, however, few determinations of gravity of first-rate character have as yet been made; and besides, the stations at which gravity has hitherto been measured elsewhere are mostly situated on islands or coasts, and it would be interesting to have a good series of inland stations for comparison. Furthermore, your own observations appear to show that the observed irregular variations of gravity, which are superposed on the grand variation from the poles to the equator, are connected with the character of the formations underlying the stations; so that pendulum observations may be expected to throw light on the geology of a country.

"The last point on which you requested my opinion referred to the mode in which Colonel Walker proposes to carry out these observations. As you have such great practical experience in this matter, and I have none, my opinion is of no value compared with your own. I think Colonel Walker has done wisely in leaving a good margin for stations to be chosen according as the results obtained at the principal stations may appear to make desirable.

"If the nature of the country admits of it, I think it would be well to observe gravity at one station some way north of Kaliána, the northern extremity of the Arc. My reason is this. Any irregular excess or defect of matter north of that station would affect the direction of gravity, and consequently the astronomical latitude of the station, but might be situated too nearly in a horizontal direction from the station to have any sensible influence on the intensity of gravity *at the station itself.* Such excess or defect, however, if it existed, would make itself felt on the intensity of gravity at stations further north, and consequently more nearly over the region in which it occurred. The latitude and elevation of any such station would have to be ascertained; but an approximate determination, such as could be made with small portable instruments, would be quite sufficient. On account of the peculiar importance of Kaliána as being one of the extreme stations of the Arc, I think the additional trouble which might be involved in observing at a station not included in the Survey would be well bestowed.

"Believe me,
"Yours very truly,
"G. G. Stokes."

Captain J. P. Basevi was put in charge of the operations; three sets of instruments were used for the purpose: one Kater conversible pendulum and a set of two Russian reversible pendulums for absolute measurements, which were carried out at Kew, Ismailia, Aden, Colaba and Kaliana; and a set of two Kater invariable pendulums equipped with vacuum case and coincidence apparatus for relative measurements.

Captain Basevi's work started in India in 1865; between 1865 and 1871 he observed 30 stations, most of them along the Great Arc. In June 1871 Captain Basevi crossed the mountain passes leading to Ladakh, with the aim of measuring the intensity of gravity at high altitudes in the Himalayas; he reached the Moré Plateau, situated at an altitude of about 4,700 m, where he swung his pendulums for the last time. Wishing to have one new independent determination at high altitude, he proceeded to a point about 100 miles away from his station at Moré. He found a suitable position in lat. 34°20′, long. 79°22′ at an altitude of 5,200 m. Here he arrived on about the 15th of July and set up his instruments. But he had caught a cold a week previously, and during the whole time he suffered constantly; no medical aid was within hundreds of miles, nor any European within several days' journey. On the morning of the 17th of July he became very ill, lay down on his bed, and died almost immediately afterwards (Walker, 1879).

Captain W. J. Heaviside succeeded Captain Basevi in 1872; he collected and processed the observations of his predecessor, but did not carry out any new measurement in India; the resultant observations of Basevi were first discussed in Archdeacon Pratt's *Figure of the Earth*, published in London, 1868.

In this way the fascinating problem of the deep structure of the Himalayas and the even more intriguing one of their genesis and development were presented in new and vitally important terms, so that they have continued to absorb the interest and efforts of a large body of scientists and explorers down to the present day. In close collaboration with geologists, seismologists and geophysicists, this army of research-workers continues to operate with instruments in the field and at desk in the attempt to further our knowledge of the structure of the continent of Asia.

It would not be possible here to trace, even in broadest outline, the history of gravimetric work centred upon India, but it should be noted that the core of this work has been carried out, on a vast scale, by the Trigonometrical Survey of India and its successor the Survey of India. This work has been fully documented in a series of volumes which contain invaluable data and original research material in far-reaching aspects of geodesy, gravimetry, structural geology, geophysics and finally geodetic astronomy.

For our own purposes however we must limit ourselves to the area which forms the particular object of our studies; namely, that part of the Indian Plain, of the Himalayan, the Karakorum and Hindu Kush ranges which thrust up northwards in the direction of the Pamirs. It is in this area and beyond that, as we shall have occasion to show later, the contributions made by various scientific and combined scientific and mountaineering expeditions have played a fundamental part in completing the work of the Survey of India.

The research work which began on the Indian Plain and which, as we have seen, presented scientists with problems of such vital interest, naturally drove geodesists on to extend their research into the very heart of the Himalayan Range, with a view to finding direct confirmation of the ideas on isostasy that had in the meantime been making headway. At first however the research work of geodesists in India was strictly limited to particular problems that were met with; they little suspected the universal importance of their work and made no attempt to interpret their findings in wider and more general terms, until light was finally thrown on the matter by the work of Hayford.

In 1903 a new programme of gravimetric measurements was undertaken by the Survey of India, with the aid of the new Sterneck pendulums. The aim was to make a systematic analysis of the problem of compensation in the Himalayan Chain and to confirm the existence of the "Hidden Range" — the underlying belt of denser materials — which Burrard, some years earlier, had assumed to exist to the south of the Ganges Valley. Burrard's assumption was based on the fact that, without the existence of such a "Hidden Range", the deviations of the plumb-line, which compensation alone could not account, would be difficult to explain. Even the early pendular measurements taken by Captain Basevi seemed to confirm the existence of some belt of denser materials of this sort.

But strange as it may seem, Basevi's measurements were for a long time the only ones carried out by the Survey of India at high altitude, the nearest to these being the ones taken at 3,590 m, at a station near Darjeeling.

An equally unaccountable fact, regarding high altitude measurements, is that Major (later Colonel Sir Gerald) Lenox Conyngham should have stated, in his report on the series of measurements carried out under his direction from 1903 to 1907, that he did not consider it worthwhile, in studying conditions of isostatic equilibrium, to observe gravimetric stations at great heights, but thought it preferable to keep to the foot of the Himalayan Chain.

Not until 1925 did the Survey of India again concern itself with high altitude gravimetric measurements, when four stations were observed on the

Deosai Plateau to the south of Skardu, after Prof. G. Abetti and Commander A. Alessio, both members of the Italian De Filippi Expedition of 1913-14, had attempted to repeat the measurements of Basevi at Moré and then established a series of fourteen gravimetrical stations across the Himalayan and Karakorum chains, from Srinagar in Kashmir to Yarkand in the Tarim Basin.

The gravimetrical operations initiated by the Survey of India in 1903 with new pendular apparatus had marked the beginning of intense activity in this field, which continued uninterrupted until the outbreak of the Second World War, and then was resumed again with modern gravity meters. Finally, the fruit of this exceptional activity was embodied in a gravimetric survey, comprising more than 500 stations so well distributed over the Indian Platform that they provide a basic gravimetric outline of it which is both accurate and detailed.

In 1957 all the measurements taken were isostatically reduced, according to the various current hypotheses, by Dr. B. L. Gulatee of the Survey of India, who produced detailed contour charts of the anomalies. These charts, together with others giving the outline of the geoid, make the Indian Platform one of the areas of the world where most is known about the earth's field of gravity.

But if our knowledge can be said to be extremely satisfactory as far as concerns the general description of the Indian Platform, the same was by no means true of the mountainous area of the Karakorum and Hindu Kush ranges, and the region farther north, where research work has been much more restricted. In fact the only results in that mountainous regions are due to scientific expeditions from Sweden and Italy, as will be apparent from the following brief summary.

A large expedition in the Karakorum was organized in the year 1909 by the Duke of the Abruzzi, with the object of studying the Baltoro Glacier and the surrounding peaks, in particular K2, which was already recognized as the second highest mountain in the world. The research work carried out by this expedition does not concern us here, inasmuch as no gravimetric studies were carried out; the expedition's great merit lies however in the fact that it was the first to apply modern methods of terrestrial photogrammetry at high altitudes, and that it focused the attention of Italian scientists on the Karakorum, with the result that by 1955 no less than six Italian expeditions had successively entered the region, each one of which made a valuable contribution to the study of the area.

The first of these subsequent expeditions came in 1913, four years after the Duke of the Abruzzi's, and was organized and led by one of his team, Dr. Filippo De Filippi. This time however the expedition had a purely scientific purpose and covered the Karakorum and Chinese Turkestan. Prof. Giorgio Abetti and Comm. Alberto Alessio also took part in the roles of geophysicists, astronomers and geodesists, and measured gravity at 14 stations.

The instrument used for that purpose was a bipendular apparatus, equipped with eight pendulums, four of which were the property of the *Istituto Idrografico della Marina* of Genoa and four of the *Geodetic Institute of Potsdam.* Measurements were made with the aid of a normal coincidence apparatus and the chronometers checked by astronomical observation. The pendulums were first swung at Genoa in July, 1913 and ultimately in the same city in January, 1915. The stations observed in Asia were those of Dehra Dun (August, 1913), Srinagar (September, 1913), Dras (October, 1913), Tolti (October, 1913), Wazul Hadur (November, 1913), Skardu (November, 1913), Kargil (February, 1914), Lamayuru (March, 1914), Leh (March, 1914), Depsang (June, 1914), Suget Karaul (August, 1914), Yarkand (October, 1914), Kashgar (October, 1914) and finally Tashkent (November, 1914).

This series of observations is the only one to this day which goes across the Himalayan Chain and which directly connects the Indian stations with the Russian ones. It is of particular importance, because two stations of the gravimetrical network observed by Dr. Nils Ambolt of the Sino-Swedish Expedition led by Dr. Sven Hedin in Sin Kiang are identical with two in the Italian network. The series of observations made by the Sino-Swedish Expedition covered the southern border of the Tarim Basin, and the region of Kuruk Tagh, so that the series observed by Abetti and Alessio constitutes to this day the only material in our possession for the unification of gravity measurements in this part of Central Asia.

In the interval between the De Filippi Expedition and the next Italian one led by the Duke of Spoleto in 1929, Capt. E. A. Glennie and Capt. G. H. Osmaston of the Survey of India carried out pendular observations, in 1925, at Sonamarg and at three stations on the Deosai Plateau to the southwest of Skardu.

Owing to an accident, in which the pendular apparatus was put out of working order, the Duke of Spoleto's Expedition was unable to carry out intended gravimetrical measurements in the Karakorum. It did however gain credit for establishing a new gravimetrical connection between Genoa and the fundamental Indian station at Dehra Dun.

Also in 1929, the expedition led by Dr. Sven Hedin took place and it was on this occasion that Dr. Nils Ambolt took observations at forty pendulum stations along the south and northeast margins of the Tarim Basin, two of which, as we have already seen, were common with those of the De Filippi Expedition.

Dr. Ambolt used a unipendular von Sterneck apparatus, equipped with an auxiliary Schumann pendulum, fitted with four brass pendulums and four invar steel pendulums. The brass pendulums were swung at Potsdam in 1927 and 1928, at the outset of the expedition, and again in 1934 on its return. A maximum difference of 10.5 mgal was found. The invar pendulums on the other hand were swung in 1930 and 1934 with differences as great as 50.6 mgal.

A few words must be said about the Russian gravity measurements in the Pamirs and Southern Tien Shan. The first measurements made here are due to Zalesski and they comprise 140 stations observed in the period between 1901 and 1909. Their precision is not high, as the oscillation of the support had not been taken into account. The next stations in order of time are those observed by A. Popov in 1928 in the Ferghana Basin, at the time of the Gravimetric and Seismic Expedition in Central Asia led by D. Mushketov and P. Nikiforov. This comprised 14 stations based on Leningrad ($g = 981.936$), Pulkowo ($g = 981.897$) and Tashkent ($g = 980.081$).

Finally we know of the stations, 19 in number, observed by B. L. Oczapowski in the Pamirs, in the course of the Geophysical Mission to Central Asia by the *Seismological Institute of the Academy of Sciences* of the U.S.S.R. in 1932, which used a tripendular apparatus of the Lenox Conyngham design, constructed by the *Cambridge Instruments Co.*, and which are based on the station of Tashkent ($g = 980.080$). The mean error of these measurements was given as ± 3 mgal. One station is common with that of Zalesski; but the result of the comparison has not been given. During the mission the station of Kala-i-Wamar was reobserved, where Zalesski had found a very strong negative anomaly; but it was found that that exceptional anomaly was the fruit of a silly mistake. The heights of the stations were determined with the use of aneroids and controlled by hypsothermometers.

As we have seen, the whole of the mountainous area in the northwestern part of India accounted for only the few stations observed by the Survey of India on the Deosai Plains, and for the stations of the De Filippi Expedition; farther north in Sin Kiang we find the stations of the Sven Hedin's Expedition; and on the Pamirs the Russian gravimetric survey of which more will be said later. All the area included in these surveys, which comprises the loftiest part of the Karakorum, the region of the syntaxis between the

Himalayas and Hindu Kush, and from the latter up to the Pamirs, still awaited a surveyor willing to carry out gravity measurements and thus fill the blank on the gravimetric map of this part of Asia.

This was the task of our Expedition, which took place in the years 1953-54-55 under the leadership of Professor Desio.

Although the work was inquiring, we nevertheless had a great advantage over previous expeditions. In the latter measurements could only be taken at widely separated stations along the route followed by the expedition, owing to the fact that the instruments needed a great deal of time for their use; whereas we were equipped with modern static gravity meters which made it possible to take measurements in a very short space of time and so take readings over a closely-knit network.

Professor Desio entrusted me with the execution of the gravimetrical programme outlined for the Expedition. This programme, which was completed during the course of the two campaigns of 1954 and 1955, aimed to establish a network of a regional character in the Karakorum area and at the junction of the Himalayas and the Hindu Kush, at the point where the Indian Platform wedges the Hazara Spur into the Himalayan orogeny, to the south of the Pamirs. The network thus fills in the blank space that existed between the Indian and Russian gravimetric surveys in the area where the Himalayas pile up to form one of the most formidable mountain regions in the world.

The network consisted of 270 stations in all, of which seventy have been isostatically reduced. In addition, the programme aimed to establish a new connection, with the aid of air-borne gravity meters, between Rome, Karachi and Dehra Dun, for the purpose of obtaining a new value for the fundamental gravimetric stations of Pakistan and India. This new connection was needed in order to confirm the observations carried out by Woollard and Gulatee with the aid of air-borne Worden gravity meters in 1948.

Supplementary research work included in the programme was that of determining the thickness of some of the Karakorum glaciers by measuring gravity along sections across them.

As to the elaboration of the gravimetric results, the great contribution to these studies made by Dr. Gulatee of the Survey of India must be stressed. Dr. Gulatee reduced in 1957, in accordance with the various isostatic hypotheses, all the observations made for the Indian Platform, amounting to a total of 564 pendulum and about 2,400 gravity meter measurements. Dr. Gulatee's work thus gives us a complete picture of the gravimetric field for the whole of the platform to the south of the Himalayas and a sound support for all research work on the gravimetric outline of the Himalayan Chain itself.

With regard to the reduction of measurements carried out in the entire region, the following facts are of importance: Russian gravimetric measurements in the Pamirs amount to a total of 181. Of these 82 observed during the period from 1901 to 1908, 15 in 1930 and 71 in 1932, have been topographically reduced by Soviet geophysicists, and isostatically by the Finnish geodesist Erola.

No reduction had been carried out as yet for the 40 stations observed by Dr. Ambolt on the Sino-Swedish Expedition, but the Isostatic Institute of Helsinki has, on my request, kindly agreed to carry out this task.

Of the 270 stations observed by me during the Desio Expedition, 70 have since been reduced in the *Istituto di Topografia e Geodesia* of the University of Trieste. We have thus been able to give a complete picture of the isostatic conditions in the region which includes the fundamental orogenetic ganglia of Central Asia.

The geological interpretation of the anomalies that have thus come to light is now aided not only by the great amount of research work by geodesists of the Survey of India and by the many expeditions which have taken place in this region, but also by modern seismological observations made by the *Geophysical Observatory of Quetta* (Pakistan) and by various observatories in the U.S.S.R. We are also indebted to Soviet geophysicists for the results of several deep soundings undertaken by them in the Tien Shan and Transalai Ranges, and for studies on slow vertical movements of the ground.

INSTRUMENTS USED BY THE EXPEDITION

GRAVITY METERS

Once the programme of gravimetric exploration had been established, the choice of instruments was necessarily restricted to gravity meters rather than pendulums, as the former can be easily transported, and the taking of readings occupies no more than a few minutes.

Some types of gravity meters are thermostatically controlled, so that the sensitive part is shielded from external variations in temperature. These instruments are well suited to geodetic work, inasmuch as they make possible greater precision in those operations which involve the taking of readings widely spaced in time, the instrumental drift being unaffected by thermal variations and therefore very nearly linear. Thermostatically controlled gravity meters are for this reason also appropriate for measurements where instrumental drift cannot be constantly checked.

Other types of gravity meters dispense with thermostats and rely on a Dewar vessel to protect the sensitive cell of the instrument against abrupt variations in temperature. This type of instrument ensures a high degree of accuracy, provided the instrumental drift can be checked at frequent intervals; it is therefore particularly appropriate for local geophysical surveys in which a high accuracy and a great number of stations is required.

Obviously gravity meters belonging to the first class are much more bulky on account of the insulated case, thermostat, heaters, and power supply; on the other hand the gravity meters without thermostats are reduced to the minimum size and weight, so that the entire instrument can easily be carried by a single porter even over extremely difficult and barely accessible tracks.

Although Worden gravity meters without thermostats had already been used on a world-wide programme of gravimetric connections by aircraft (see e. g. Woollard, 1955), and the results obtained went far beyond expectation, some doubt still remained as to the possibility of satisfactorily using this type of gravity meter, which had never previously been tested by expeditions lasting for several months, in a programme that offered very little opportunity to determine the instrumental drift at short intervals. This was a matter of particular concern as it was known that when drift is determined during the transport of the instrument it differs substantially from that which could easily be determined when the instrument is at rest.

We must nevertheless state that we have never once regretted our decision to use Worden gravity meters constructed by the Houston Technical Laboratories at Houston, Texas, U.S.A. (now Texas Instruments Inc.). To take into account the residual thermal effects and the influence of non-linear drift, a special research project was planned to be carried out at the end of the expedition. The results of this research, to which I. Gabrielli, G. Poiani and M. Caputo refer in the present volume, proved very useful for correcting the values observed in the field, thus substantially improving loop closures in the traverses.

Three instruments of this type were used during the course of the operations carried out in 1954 and 1955. These were:

Worden Gravity Meter No. 6 — This instrument was used in 1954 for the gravimetric connection between Karachi and Rawalpindi, and between Karachi, Jodhpur, Jaipur and Delhi, in the triangular connection Rawalpindi-

Skardu-Gilgit, and for the regional survey carried out along the routes of the Expedition in the Karakorum. The instrument was also used together with Worden Gravity Meter No. 116 in the connection Karachi-Beirut.

The gravity meter, which was hired from the makers, is of a particular type which differs from normal ones in that it is equipped with only one dial, the small range one, which in normal instruments is used for fine readings. The sensitivity of that dial was however reduced to a tenth of the normal value, i. e. to about 1 mgal per scale division (instead of about 0.1 mgal per scale division as is usual); the range of the instrument was therefore about 800 mgal without resetting.

It can be stated this arrangement proved very satisfactory for long journeys.

The instrument was calibrated in April 1954, shortly before the departure of the Expedition, on the base Bologna-Ferrara established by the Italian Geodetic Commission; and also on the same base in December 1954, at the end of the Expedition. Further calibrations were occasionaly made between the stations previously observed by Noorgard in Pakistan, on the line Beirut-Karachi, and on the Lebanese base Beirut—Dahr-el-Beidar.

Worden Gravity Meter No. 116 — This instrument, the property of the *Istituto Geografico Militare* in Florence, was used in 1954 in the connection Rome-Beirut-Karachi. The instrument is of the normal geodetic type, with two dials, the smaller one allowing estimated readings within 0.01 mgal. It was calibrated at the beginning of the work in June-July 1954, and again at the end in December 1954 on the base Bologna-Ferrara.

Worden Gravity Meter No. 203 — This instrument, the property of the *Istituto di Topografia e Geodesia* of the University of Trieste, was used in 1955 for the regional survey in the Western Karakorum and Hindu Kush, and is of the same type as No. 116.

The instrument arrived in Pakistan directly from America, and it was therefore not possible to calibrate it at the beginning of the work. This was done at the end of the Expedition in December 1955 on the base Bologna-Ferrara; but during the course of the work it was nevertheless possible to compare measurements taken over several already known gravimetrical differences, for example on the ones between Rawalpindi and Gilgit and between Karachi and Rome.

All three instruments were tested under rapid and periodic variations of external temperature in 1955 by M. Cunietti and G. Inghilleri (1956);

moreover Gravity Meter No. 203 was further thoroughly studied during 1955-56 for the influence of thermal effects, by I. Gabrielli, G. Poiani and M. Caputo. Finally Gravity Meter No. 6 was tested by G. Busà for sudden variations in external pressure up to the equivalent of an altitude of about 5,000 m.

HEAT EXCHANGE THROUGH THE DEWAR VESSEL OF A WORDEN GRAVITY METER

(I. GABRIELLI & G. POIANI)

1. *Introduction* — During the Italian Karakorum Expedition in the years 1954-55, three different Worden gravity meters were used for the extensive gravimetric survey, and for the gravimetric connection between Rome and the fundamental Indian gravimetric station of Dehra Dun.

These gravity meters are not equipped with a thermostat; the quartz system, provided with thermal compensator, is however protected against gross external temperature variations by a Dewar vessel. Nevertheless it was noticed that the instrumental readings were affected by the variations in temperature during the day, particularly in those regions of high altitude and low latitude where the instruments were mainly used.

Professor Marussi, who carried out the gravimetric observations during the Expedition, therefore subjected one of the gravity meters used — No. 203, belonging to the *Istituto di Topografia e Geodesia* of the University of Trieste — to a series of thermal tests, to compare the variations of the ambient external temperature with that of the internal parts of the instrument and with the resulting variations of the gravimetric readings.

In making these tests, Professor Marussi requested the collaboration of the *Istituto di Fisica* of the University of Trieste, which was entrusted with the task of studying the problem both theoretically and experimentally.

For this purpose suitable devices were set up to obtain the required temperature variations in the room in which the gravity meter was kept, and to record temperature inside the instrument itself.

This paper refers both to the results obtained during the series of experiments and to their possible theoretical interpretation.

The resulting variations of the gravimetric readings were studied by Dr. M. Caputo as will be later discussed.

2. *Experimental arrangement* — The investigation involved two sets of measurements. The first refers to the temperature variations of a body of known heat capacity, insulated in a Dewar vessel, when the external temperature is kept constant, but higher or lower than the initial temperature of the body, or varies according to a sinusoidal law. The second refers to the temperature variations measured on the metallic walls of the gravity meter container, which is enclosed in its Dewar vessel, when the external temperature undergoes the above variations.

The Dewar vessel under test was kept in a thermoregulated rectangular cell, whose internal dimensions are 50 × 26 × 36 cm, with aluminium walls 0.5 mm thick. This is placed in a wooden box, whose internal walls are insulated with asbestos boards. Between the walls of the two boxes there is a space of 6 cm, where heating resistances are located.

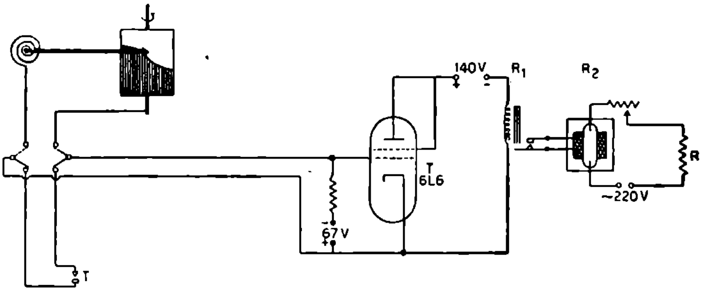


Fig. 2 - Electric circuit of the thermoregulation device

The inner compartment can be maintained at a constant temperature by a device provided with a contact thermometer as shown in the above figure. In order to avoid damaging the contact, the current flowing through it was reduced to 0.1 mA, by inserting an amplifier tube *T* and a very sensitive relay R_1 between the thermometer and the mercury relay R_2, which controls the heating resistances.

With a suitable value of the heating current, the cell temperature can be held constant within a few tenths of a degree.

Sinusoidal variations of the temperature, with a period of 24 hours, were obtained by using the following device, instead of the thermometer, as a sensitive element controlling the relay through the tube.

A platinum needle, substituted for the stylus of a bimetallic thermograph, glides with negligible friction on the cylindrical surface of a drum rotating with a period of 24 hours. The lower half of the drum is covered with a thin layer of bakelite, bounded above by a sinusoidal line; the remainder of the drum is coated with a metallic silver layer.

The drum with the thermographic needle is inserted in the electric circuit of the amplifier tube. In this way, when the temperature of the bimetallic spiral is such as to keep the gliding tip of the needle below the sinusoidal boundary between the conducting and the insulated part of the rotating drum, the electric circuit remains open and the heating is switched on. When the temperature increases, the tip goes above the boundary, the electric contact is established and the mercury relay disconnects the heating.

Because of the weakness of the operating current and of the value of the applied voltage, electric contact is ensured by only a light pressure on the platinum needle.

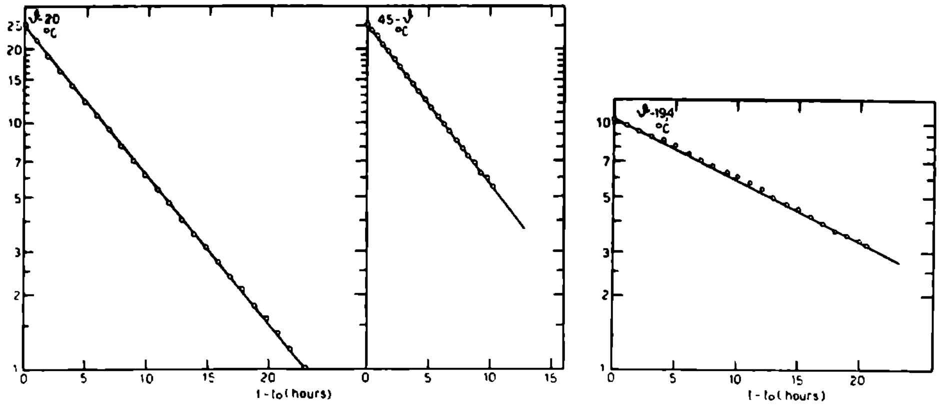
Notwithstanding the immediate operation of the electric contact, some delay is caused by the heat capacity of the bimetallic spiral. This produces fluctuations added to the value predetermined by the sinusoid.

The period of these fluctuations is found to be about 30 minutes and the amplitude about 4°C, when measured with a thin thermoelectric couple placed inside the thermometric cell. The fluctuations are evidently connected with the heat capacity of the thermocouple. If it is attached to an aluminium cylinder weighing 100 g, the fluctuations are reduced to ± 1°C.

The measurement of the temperature of the body contained inside the Dewar vessel was carried out by means of a copper-constantan thermocouple placed in contact with the body and connected in opposition to an identical couple kept at a constant temperature, both being joined in series through a galvanometer. In order to reduce to a minimum the transmission of heat, thermocouple wires of 0.25 mm in diameter were used. The galvanometer readings were automatically recorded every half hour by photography.

3. *Experimental results* — The diagrams of figures *a*), *b*) and *c*) refer to the measurements taken on an aluminium mass of 565 g (heat capacity 124 cal. degree $^{-1}$) placed in 1 litre Dewar vessel with a narrow neck (inner neck diameter = 3.8 cm), closed with a cup-shaped plastic stopper. The mass of the Dewar vessel was 264 g.

Diagram *a*) shows, on a semilogarithmic scale, the cooling curve of the body, initially at 45°C when kept in the thermostatic cell at 20°C. Diagram *b*) shows, on the same scale, the heating curve of the body, initially at 20°C, in the cell at 45°C.



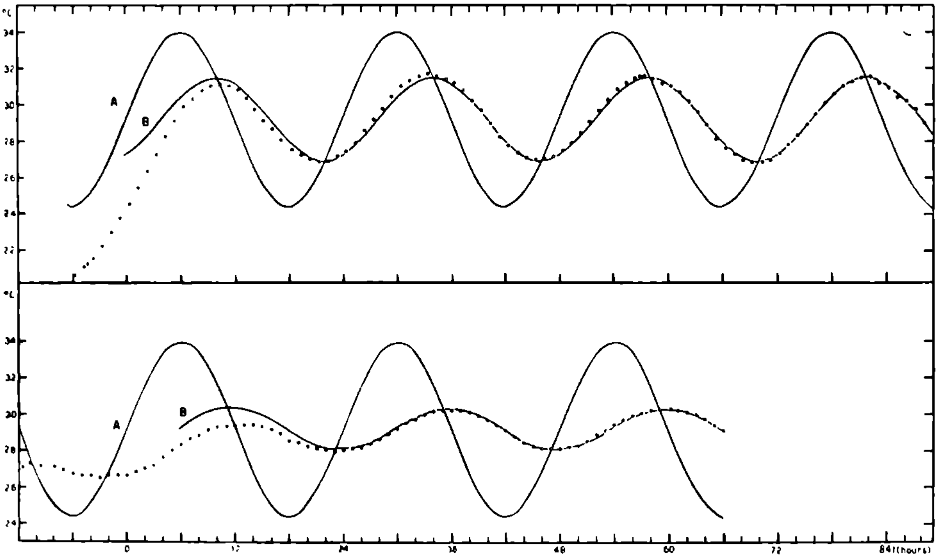
a) *b)* *c)*

Aluminium mass (565 g) placed in a Dewar vessel (1 Litre).

a) Cooling curve in 20° C external temperature. The temperature difference is reduced to 1/e of its initial value in $\mathfrak{T} = 7.0$ hours.

b) Heating curve in 45° C external temperature $\mathfrak{T} = 6.6$ hours.

c) Cooling curve of the Worden gravity meter walls inside the Dewar vessel in 19.4° C external temperature. $\mathfrak{T} = 17.2$.



d) (upper diagram) — Temperature variation of the aluminium mass in the Dewar vessel (open dots), when the external temperature varies sinusoidally (curve A). Curve B corresponds to equation 3-d.

e) (lower diagram) — Temperature variation of the Worden Gravity Meter No. 203 walls inside the Dewar vessel (open dots), when the external temperature varies sinusoidally (curve A). Curve B corresponds to equation 3-f.

Fig. 3 - Temperature response across the Dewar vessel

The open dots stand for the experimental points, the straight lines correspond respectively to the equations (*):

(a) $$\delta - 20 = (\delta_o - 20) \exp\left(-\frac{t - t_o}{7.0}\right), \ \delta_o = 45,$$

(b) $$45 - \delta = (45 - \delta_o) \exp\left(-\frac{t - t_o}{6.6}\right), \ \delta_o = 20,$$

where t represents the time in hours, δ_0 the temperature at the time $t = t_0$.

Diagram *d*) shows the temperature variation of the body placed inside the Dewar vessel, when the temperature of the thermoregulated cell varies according to the sinusoidal law represented by the full line *A*:

(c) $$\delta_e = 29.2 + 4.8 \sin \frac{2\pi}{24} t.$$

The points at the beginning of the experiment reveal a transitory phase, after which the temperature of the body begins to vary sinusoidally, within the detectable errors, as is shown by the coincidence of the experimental points with the curve *B*, derived from the equation:

(d) $$\delta = 29.2 + 2.3 \sin \frac{2\pi}{24} (t - 4).$$

Hence it is seen that the amplitudes of the thermic oscillations are reduced in the ratio 2.1 : 1 and that the phase shift amounts to 4 hours.

In diagrams *c*) and *e*) are shown the measurements taken on the walls of Worden Gravity Meter No. 203, placed inside its Dewar bottle, contained in another cylindrical vessel, with thin chromium-plated metal walls.

In diagram *c*) is shown, on a semilogarithmic scale, the cooling curve in the cell at 19.4° C. The open dots show the experimental points and the

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(*) In these equations, as in the following, we shall represent with δ, if necessary labelled with indices, the temperature expressed in °C; the absolute temperature, expressed in °K, will be represented by T, if necessary labelled with indices. The letters Θ, ϑ, showing differences of temperature, will be used for the two scales.

straight line joining them has the equation:

$$\text{(e)} \qquad \delta - 19.4 = (\delta_0 - 19.4) \exp\left(-\frac{t - t_0}{17.2}\right) . \ \delta_0 = 30.0 .$$

In diagram *e*) are shown the oscillations of the internal temperature, when cell temperature is varied according to equation (*d*). After an initial unstable period, the internal temperature oscillates sinusoidally, and can be represented by the curve *B* corresponding to the equation:

$$\text{(f)} \qquad \delta = 29.2 + 1.1 \sin \frac{2\pi}{24} (t - 5) .$$

Compared to the sinusoidal cell temperature, the internal temperature shows a reduction in amplitude in the ratio 4.4 : 1 and a phase shift of 5 hours.

4. *Analysis of results* — Let the systems be considered as bodies of given heat capacity, at temperature T, insulated from the exterior, where the temperature is T_e, partly by the double wall of the Dewar vessel, and partly by the stopper. In the heat capacity one must include that of the internal wall of the vessel.

The heat exchange between the interior and the exterior takes place in this model by two processes:

(1) conduction through the stopper; this consists of conduction through the internal wall of the vessel neck, the edge of the opening, and, for the gravity meter, the upper part of the case which is out of the vessel;

(2) radiation through the vacuum existing between the two walls of the Dewar vessel.

We indicate with S the external surface of the internal wall of the Dewar vessel, with α its absorbing power, with σ the Stephan-Boltzmann constant, with s the section of the stopper, l its thickness and k its internal heat conductivity.

The rate of heat exchange dQ/dt from the body to the exterior will be related to the internal temperature T and the external one T_e by the equation:

$$\text{(a)} \qquad -\frac{dQ}{dt} = -C\frac{dT}{dt} = S\alpha\sigma\,(T^4 - T_e^4) + k\,\frac{s}{l}\,(T - T_e)$$

which can be written in the form:

$$(b) \qquad -\frac{dT}{dt} = \frac{S\alpha\sigma}{C}(T^3 + T^2T_e + TT_e^2 + T_e^3)(T - T_e) + \frac{ks}{Cl}(T - T_e)$$

or

$$(c) \qquad -\frac{dT}{dt} = (P + Rf)(T - T_e)$$

where:

$$S = \frac{ks}{Cl}; \qquad R = \frac{S \cdot \alpha \cdot \sigma}{C}; \qquad f = T^3 + T^2T_e + TT_e^2 + T_e^3.$$

In each experiment the difference of temperature was of the order of ten or twenty degrees, and the variation in the value of f did not exceed 10%.

If we consider the intrinsic limits of accuracy of these experiments, we can choose, as an approximate expression of equations (*a*), (*b*), (*c*), the following:

$$(d) \qquad -\frac{dT}{dt} = \frac{1}{\mathfrak{T}}(T - T_e)$$

where:

$$\frac{1}{\mathfrak{T}} = P + RF$$

and F is the mean value of f in the temperature interval considered.

We examine first of all the case where the external temperature is kept constant, $T_e = T_c$, and the initial internal temperature is $T_o \neq T_e$.

The integration of equation (*d*) is then immediate:

$$(e) \qquad T - T_c = (T_o - T_c)\exp\left(-\frac{t - t_o}{\mathfrak{T}}\right) \qquad \begin{cases} t = t_o, \text{ for} \\ T = T_o, \end{cases}$$

with $T_o > T_e$ in the cooling case and $T_o < T_e$ in the heating one.

If the external temperature varies according to a sinusoidal law:

$$(f) \qquad T_e = T_k + \Theta \sin \omega t$$

equation (*d*) becomes:

$$(g) \qquad -\frac{dT}{dt} = \frac{1}{\mathfrak{T}}(T - T_k - \Theta \sin \omega t)$$

with

$$T = T_0 \quad \text{for} \quad t = 0 .$$

After elementary substitutions the equation becomes linear and its solution is:

$$T = T_k + \left(T_0 - T_k + \frac{\Theta\mathfrak{T}\omega}{1 + \mathfrak{T}^2\omega^2}\right) e^{-t/\mathfrak{T}} + \frac{\Theta\mathfrak{T}}{1 + \mathfrak{T}^2\omega^2}\left(\frac{1}{\mathfrak{T}} \sin \omega t - \omega \cos \omega t\right).$$

If we do not consider the transitory term, which tends to zero for $t > 0$, the foregoing solution is reduced to:

$$T = T_k + \frac{\Theta\mathfrak{T}}{1 + \mathfrak{T}^2\omega^2}\left(\frac{1}{\mathfrak{T}} \sin \omega t - \omega \cos \omega t\right)$$

or, in another form:

$$\text{(i)} \qquad T = T_k + \vartheta \sin (\omega t - \varphi) \qquad \left\{ \begin{aligned} \varphi &= \operatorname{arctg} \mathfrak{T}\omega \\ \vartheta &= \frac{\Theta}{\sqrt{1 + \mathfrak{T}^2\omega^2}} . \end{aligned} \right.$$

From this solution we can obtain the behaviour of the internal temperature when the external temperature varies according to a sinusoidal law – we find that it also varies according to a sinusoidal law around the same mean value T_k, but its amplitude is reduced in the ratio $1 : \sqrt{1 + \mathfrak{T}^2 \omega^2}$ and its maximum is shifted to the amount of the quantity φ.

Both these functions depend on the product $\mathfrak{T}\omega$, whose value is:

$$\text{(h)} \qquad \mathfrak{T}\omega = \frac{C}{ks + S\alpha lF\sigma} \cdot \omega \cdot$$

In particular it is apparent that the difference in phase increases with the heat capacity of the body, the frequency of the sinusoidal variation of the external temperature and with a decrease in F, i. e., in the mean external temperature.

Accurate estimation of $\mathfrak{T}$ is limited by imperfect knowledge of the quantities on which it depends, so that the prediction of the amplitude and the phase difference of the sinusoidal curve of the internal temperature would be very difficult.

However it is possible to estimate a sufficiently accurate value of $\mathfrak{T}$ from a simple graph of the cooling and heating curves of the body when it is placed inside the Dewar vessel, kept in a room at constant temperature. The experiment can also be reduced to the measurement of the time during which the temperature difference between the body and the room is reduced to a value $1/e$ of the initial one.

The mean value of F depends on the temperature variations in the experiment, so that $\mathfrak{T}$ is different when obtained from cooling or heating or sinusoidal law experiments, even if the temperature range is the same. However, as one can easily see, these differences are very small when the temperature varies about 10°C around the mean value.

Let us suppose, first of all, that the range of temperature is the same in the cases of heating, cooling and sinusoidal variations.

In the sinusoidal case the mean value of F, calculated for a period, following equations (*f*) and (*i*) and neglecting terms of the order of the first power in the mean temperature, is:

$$F_s = 4T_k^3 \, .$$

In the cooling or heating case, in a room where the temperature is T_e and the initial temperature of the body is T_o, the mean value of F evidently depends on the final temperature reached and consequently on the duration of the experiment, and is given by:

$$\text{(m)} \qquad F = 4T_e^3 + 6T_e^2 (T_o - T_e) \frac{\mathfrak{T}}{t} (1 - e^{-t/\mathfrak{T}})$$

whith the same approximations.

This value tends to $4T_c^3$ when t tends to infinity, but even if the duration of the experiment is a low multiple of $\mathfrak{T}$, the discrepancy is very small.

The range of temperature in each of the three cases considered is bounded by $T_k + \Theta$ and $T_k - \Theta$; if we substitute these values in (*m*) and calculate the arithmetic mean between cooling and heating, we obtain:

$$F = \frac{F_c + F_h}{2} = 4T_k^3 + 12T_k\Theta^2 - 24T_k\Theta^2 \frac{\mathfrak{T}}{t} (1 - e^{-t/\mathfrak{T}}) \, .$$

It is obvious that the last two terms are very small with respect to the first one, so that we can put:

$$F_s = \bar{F} \, .$$

If we use the mean value of $\mathfrak{T}$ we obtain:

$$\frac{1}{\mathfrak{T}_c} = P + RF_c; \qquad \frac{1}{\mathfrak{T}_h} = P + RF_h; \qquad \frac{1}{2}\left(\frac{1}{\mathfrak{T}_c} + \frac{1}{\mathfrak{T}_h}\right) = P + \frac{F_c + F_h}{2} = \frac{1}{\mathfrak{T}}\,.$$

By this simple method we can calculate the value of $\mathfrak{T}$ to insert in (*i*), thus obtaining the internal thermic oscillation sought for.

Suppose now that the temperature interval, in which cooling or heating experiments are being made, does not coincide with the one related to the sinusoidal law, but differs by a certain quantity, which is of the order of the interval itself.

The same procedure would lead to the result that the difference between the two mean values of F, related to the two cases, is of the order of $T^2{}_k$. Neglecting this term with respect to the principal one $4T^3{}_k$, the error is of the order of a few percent, comparable with the experimental errors. If we apply this procedure, or limit ourselves only to measuring either the cooling or the heating, we can still obtain a value of $\mathfrak{T}$ sufficiently accurate to be inserted in (*i*).

So, for example, using in our calculations the data obtained in the cooling and heating of aluminium, where the temperature limits were 20°C and 45°C, and in the sinusoidal case with limits of 24.4°C and 34.0°C, the results obtained are the following:

cooling, experimental value: $\mathfrak{T}_c = 7.0$
heating, experimental value: $\mathfrak{T}_h = 6.6$
calculated mean value: $\mathfrak{T} = 6.8$.

Inserting this value in (*i*) we obtain:

$$\frac{\Theta}{\vartheta} = 2.02 \qquad \varphi = 4^h 1^m\,.$$

The experimental values which are obtained from diagram *d*) are:

$$\frac{\Theta}{\vartheta} = 2.07\,, \qquad \varphi = 4^h$$

and they agree with the preceding ones.

For the Worden gravity meter we have at our disposal only the cooling data, as shown in the curve of diagram *c*).

The experimental value obtained is $\mathfrak{T} = 17.2$, which inserted in (*i*), allows us to derive the values:

$$\frac{\Theta}{\vartheta} = 4.6\,, \qquad \varphi = 5^{h}10^{m}.$$

The experimental values, obtained from diagram *e*) are:

$$\frac{\Theta}{\vartheta} = 4.4\,, \qquad \varphi = 5^{h}$$

which agree very closely with the preceding ones.

5. *Conclusions* — The agreement between the calculated and the experimental data within errors of the order of fluctuations of function f or of its mean value F shows the utility of the adopted approximation.

In particular, as a practical result, and in relation to the object of this research, we emphasize the suitability of equation (4-*e*) for the calculation of the temperature of the gravity meter when it is kept for a certain time in a room at constant temperature and its initial temperature is known, and further the suitability of the relation for the prediction of the daily variations of the gravity meter temperature, when the amplitude of the daily variation is known.

ON THE BEHAVIOUR OF WORDEN GRAVITY METER No. 203 AGAINST VARIATION OF EXTERNAL TEMPERATURE AND PRESSURE

(M. Caputo)

During the Italian Karakorum Expedition in the years 1954 and 1955, Prof. Antonio Marussi, in charge of geophysical exploration in the Expedition, made an extensive gravimetric survey in the Karakorum Range, using Worden Gravity Meters Nos. 6 and 203.

In that region, there are large diurnal variations of temperature during the summer, and moreover the instrument underwent a wide range of pressure variations due to the rugged nature of the country. In order to determine how variations of temperature influence the gravity meter readings, Professor Marussi proposed some experiments which were carried out in the early months of 1955 with Gravity Meters Nos. 6 and 203, as well as with other gravity meters, by M. Cunietti and G. Inghilleri (1956) of the *Politecnico di Milano*. Other experiments to determine the influence of pressure variations on the readings were performed on Meter No. 6, with the collaboration of the *Istituto di Macchine* of the *Politecnico di Torino.* In June 1955, Gravity Meter No. 203 had to be repaired because of a severe shock, and the instrument had to be retested. On this occasion, new experiments, reported here, were performed. Reference is also made to the pressure-test to which Gravity Meter No. 6 was subjected.

As is well known, in the Worden gravity meters the quartz system is placed in a Dewar vacuum bottle in order to reduce the influence of rapid variations of temperature. Moreover, the instrument is equipped with a temperature compensating system which keeps the variations of the readings due to the temperature changes within limits which are generally satisfactory. The vacuum bottle damps out the effect of external diurnal temperature variations. The aims of the experiments were to determine the time lag and reduction of amplitude, and also to examine the resulting variation in the meter readings.

For the first objective the experiments were made in co-operation with Professor Poiani and Dr. Gabrielli of the *Istituto di Fisica* of the University of Trieste, to whom we are very much indebted.

The apparatus constructed by the *Istituto di Fisica* consisted of a temperature controlled box of 60 × 70 × 100 cm in which the gravity meter was placed, an automatically controlled heater giving a sinusoidal variation of temperature within the box, and a thermo-couple situated inside and at the bottom of the vacuum bottle of the gravity meter.

To observe the position of the beam, the microscope and cross wires were removed to the upper end of a tube 16 cm in length. A convex lens 4 cm in focal length was placed in the centre of the tube so that readings could be made while the meter was in the thermostatic box. The small dial was rotated from outside by means of a rod. Two small windows in the box permitted the reading of the small dial and of a thermometer; the levels of the instrument could be checked with the aid of two mirrors placed on the top of the gravity meter.

1. *Drift for periodic variations of temperature.* The first experiment was made by varying the temperature outside the gravity meter sinusoidally with a period of 24 hours and between 24.2°C and 33.8°C. The temperature inside the vacuum bottle was checked with the thermocouple, and a recording galvanometer. The small dial was read every hour.

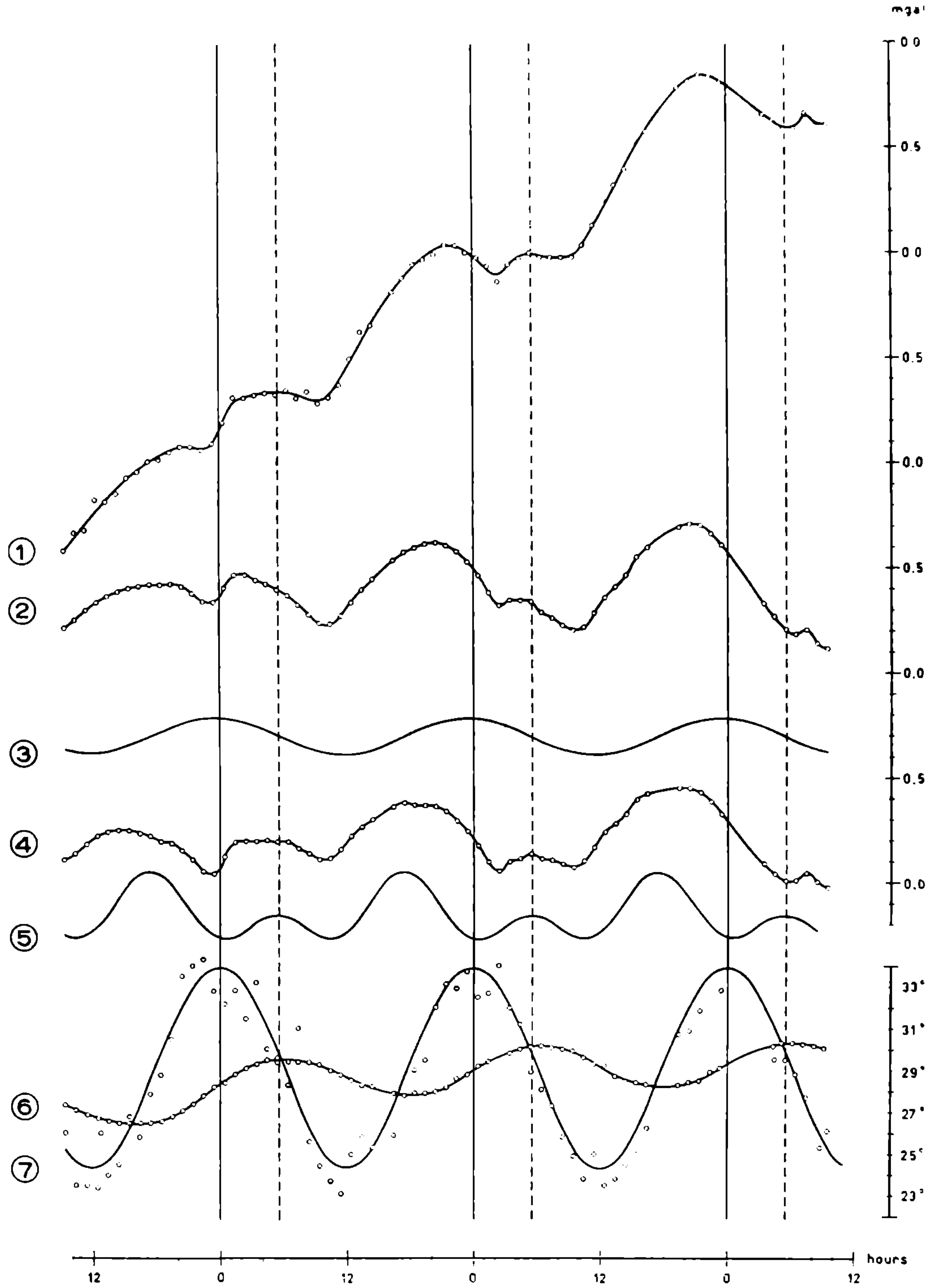

Fig. 4 - Response of Worden gravity meter to periodical changes in temperature

The results of this first experiment are given in the figure; curve (1) shows the readings corrected for tidal effects; curve (7) the temperature inside the box, and curve (6) the temperature inside the gravity meter.

From the temperature curves it can be seen that an external periodic variation of temperature of 9.6°C is transferred to the inside of the vacuum bottle with a mean delay of 5.5 hours, and that the amplitude is reduced to 2.2°C. The shape of the curve of the internal temperature is, moreover, perfectly sinusoidal.

In curve (1), showing the gravity meter readings, a constant drift is superimposed on the periodic effect. To determine the constant drift, the derivative curve of (1) was constructed, and its mean value was found to be 0.035 mgal/hour. By subtracting this hourly drift from curve (1), curve (2), which represents the periodic component, is obtained.

If we assume a linear relation between the external temperature and the effect on the gravity readings due to the parts of the gravity meter which are not protected by the vacuum bottle, a sinusoidal correction (curve (3)) in phase with the external temperature should first be applied to the readings. This correction was chosen so that the residual variation of the readings, curve (4), would represent a periodic variation in phase with the internal temperature. This residual variation is assumed to be due in part to the quartz system (and its temperature compensation) which is protected by the vacuum bottle.

Curve (4) has a peculiar shape, which is probably due to the effect of the temperature compensating system, and which may be explained as follows. Curve (4) represents two simultaneous effects: deformation of the quartz

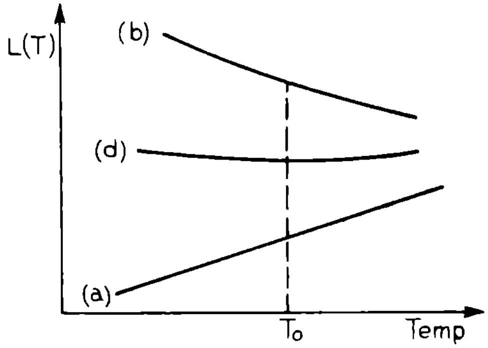

Fig. 5 - Illustrating the effect of the temperature on the quartz system and on the temperature compensating system

spring and the temperature compensating system. Assuming that the deformation of the quartz system is a nearly linear function of temperature, as indicated in the figure (curve a), and that the temperature compensating system has a non-linear effect as indicated in the same figure (curve b), then the resultant curve (d) will have a stationary value at a certain temperature, say T_0. In the neighbourhood of this point the response L of the gravity meter will therefore be proportional to the square of the difference between the actual temperature and T_0, i. e.

$$\text{(a)} \qquad L(T) = L(T_0) + \frac{L''(T_0)}{2}(T - T_0)^2 + \dots$$

by Taylor's expansion.

For periodic variations of the interior temperature in the range $T_1 < T_0 > T_2$,

$$T = T_M + T_{1.2} \sin \frac{\pi t}{12}$$

where:

$$T_M = \frac{T_1 + T_2}{2}, \quad T_{1.2} = \frac{T_2 - T_1}{2}$$

and t is the time, we have

$$\text{(b)} \qquad y = \alpha \left(T_M - T_0 + T_{1.2} \sin \frac{\pi t}{12} \right)^2 = \bar{\alpha} \left(\sin \frac{\pi t}{12} + \bar{\beta} \right)^2$$

in which

$$y = L(T) - L(T_0), \qquad \alpha = \frac{L''(T_0)}{2},$$

$$\bar{\alpha} = \alpha \, T_{1.2}^2 \qquad \bar{\beta} = \frac{T_M - T_0}{T_{1.2}}.$$

The values of the constants $\bar{\alpha}$ and $\bar{\beta}$ giving the best approximation to curve (4) are $\bar{\alpha} = 0.2013$ and $\bar{\beta} = -0.261$; the theoretical curve is represented by (5) in the figure. Taking these values for $\bar{\alpha}$ and $\bar{\beta}$, and since $T_M = 29.2$ and $T_{1,2} = 1.1$ we have:

$$T_0 = 29.5.$$

2. *Ratio of the scale constants of the two dials and sensitivity at various temperatures.* Tests were performed by keeping the instrument at a constant temperature for a long time in order to assure complete stabilization of the internal and external temperatures. Two tests were made during the period of stabilization of the interior temperature, and three further tests after stabilization was attained. For the first two tests, the time variation of the internal temperature was observed for a constant external temperature. The relation found experimentally can be represented with sufficient accuracy by the formula:

$$T = \Theta^* + (T^* - \Theta^*)\, e^{-\frac{t}{12}} \tag{a}$$

where Θ^* and T^* are the initial external and internal temperatures respectively and T the internal temperature at the time t in hours. By means of this formula the internal temperature of the instrument during the observations was estimated with adequate accuracy for the present purpose. To calculate the ratio R of the dial constants we applied the following method (Caputo, 1957).

Let L_i be the reading on the large dial, l_i the corresponding reading on the small dial, n the number of observations, R the ratio of the scale constant of the large dial to that of the small dial, and x the hypothetical reading on the small dial when the reading on the large dial is zero. The relation between l_i and L_i can be approximated by a linear function

$$l = L\,R + x \tag{b}$$

where l and L are the values of l_i and L_i adjusted to this linear relation. Introducing the notation

$$\bar{L} = (\Sigma\, L_i)\,/\,n \text{ and } L_i^* = L_i - \bar{L}$$

equation (b) may be written

$$l = L^*\,R + \bar{L}\,R + x.$$

The value of R and its standard deviation η may be obtained by the method of least squares (Caputo, 1957). This leads to

$$R = \frac{\Sigma(l_i L_i^*)}{\Sigma(L_i^{*2})} \text{ and } \eta = \frac{1}{R}\sqrt{\frac{\Sigma\,(l_i^{\,2}) - \frac{\Sigma\,(l_i^{\,2})}{n} - \frac{(\Sigma\, L_i^*\, l_i)}{\Sigma\,(L_i^{\,*2})}}{(n-2)\,\Sigma\,(L_i^{\,*2})}}\,.$$

The calculated values of *R* and the standard deviation are given below.

Date			Temperature	*R*	$\eta \times 10^3$
October	30,	1956	19°C	50.928	1.4
”	31,	56	25°C	51.004	2.4
November	5,	56	18°C	50.940	1.6
”	7,	56	25°C	51.030	1.2
”	8,	56	2°C	50.729	1.2

With these values, the graph below showing *R* as a function of temperature, has been drawn.

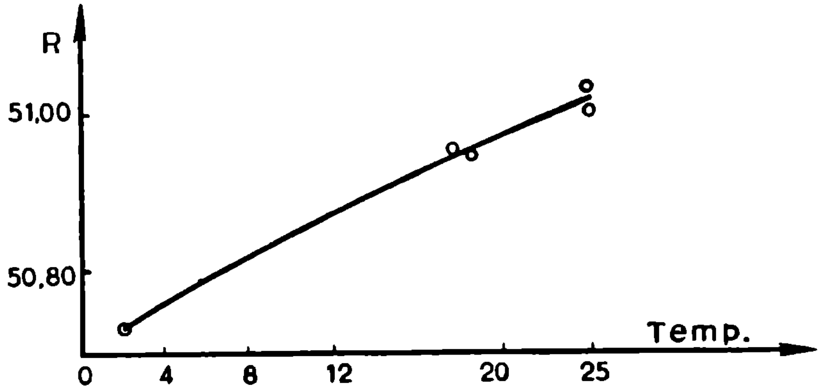

Fig. 6 - Relation between the temperature and the ratio between the dial constants

For the sensitivity, expressed in units of the small dial required to move the beam from the centre line to an outside line, the values shown in the following table were obtained.

Date			Temperature	Sensitivity
October	30,	1956	18°C	36.7
”	31,	1956	26°C	39.9
November	8,	1956	2°C	35.4

3. *Influence of pressure.* Little need be added about the pressure test to which Gravity Meter No. 6 has been subjected.

The experiment was performed in the decompression chamber of the *Istituto di Macchine* of the *Politecnico di Torino.* The pressure was varied abruptly from a value corresponding to an elevation of 200 m (height of

Turin) to that of 2,500 m and later from 2,500 m to 5,000 m and back in about four hours. During this time, the variation of temperature was 2.5°C. Obviously the variation of temperature was mainly due to the adiabatic effect of the pressure changes, and for this reason its effect on the meter was not delayed by the vacuum bottle. The effect of temperature variation cannot therefore be neglected, and the combination of the two superimposed effects, pressure and temperature variations, becomes rather difficult to interpret. We can only say that during these variations the gravity meter showed abrupt changes in the readings up to 0.5 mgal, and in some cases the changes were permanent.

This test proved that in gravity links of high accuracy made with an instrument carried by air, the instrument must be kept inside a pressurized cabin, in order to avoid such abrupt and possibly permanent changes in the readings.

CALIBRATIONS

(M. Caputo)

1. Method Used

Professor Marussi asked me to perform the calibration of the gravity meters used in the Expedition, and to complete the closing calibrations that were still missing. The fundamental calibration base was that fixed by the Italian Geodetic Commission on the line Ferrara – Malalbergo – Altedo – Argine – Bologna which forms part of the European calibration base and whose gravimetric differences determined by Professor Morelli, are as follows:

Bologna	
	50.32 mgal
Argine	
	33.24
Altedo	
	30.27
Malalbergo	
	47.23
Ferrara	
	161.06

The method used is the one illustrated in my note "*A procedure for the calibration of gravimeters*" (1956); it consists of taking into consideration the thermal drift of the gravity meter by making measurements at intermediate stations (at which the gravity is not necessarily known), and in applying a procedure used in a different case by Dr. M. Cunietti which permits the removal of drift from the observed readings.

The determination of the drift curve is made in the following way. The calibration base must have several stations and must be traversed a number of times, with readings taken at all the stations. The readings taken with the gravity meter, already corrected for lunisolar effect, are drawn on tracing paper, using a different sheet for each station, marking the times on the abscissae and the values of the readings on the ordinates, and using the same scale in all the graphs. The sheets are placed one on top of the other so that the time scales coincide. The sheets are then moved parallel to the ordinate axis until the points as a whole form approximately a curve of minimum mean curvature which represents the drift curve.

With this curve each individual reading can thus be corrected so that drift effect, whether due to thermal or elastic effects is eliminated. In order to obtain the scale factor K of the gravity meter from the readings corrected in this way, the following formula is used:

$$(a) \qquad K = \frac{[g^2]}{[gl]}$$

where l_i is the reading taken at the time t_i at the base stations and

$$\bar{g}_i = g_i - \frac{[g]}{n}$$

where g_i represents the values of gravity at the points corresponding to the readings l_i, and n the total number of observations. As can be seen from (*a*) all the readings made are taken into account symmetrically.

The standard relative error of K is given by:

$$(b) \qquad \eta = \frac{\sigma(K)}{K} = K \sqrt{\frac{[l^2] - \frac{[l]^2}{n} - \frac{[\bar{g}l]^2}{[\bar{g}^2]}}{(n-2)[\bar{g}^2]}} .$$

2. Calibration of Gravity Meter No. 6

Gravity Meter No. 6 was equipped only with the small dial, and its scale factor was about ten times greater than normally used in Worden gravity meters, i. e. one division of the dial corresponded to a difference in gravity of about one mgal, and the instrument had a range of about 800 mgal without resetting. It was calibrated twice on the Ferrara-Bologna base in April and in December 1954, immediately before and after the work done by the Expedition in 1954; a further intermediate control calibration was made, also in 1954, by Professor Marussi, on the Beirut – Dahr-el-Beidar – Ksara base in Lebanon.

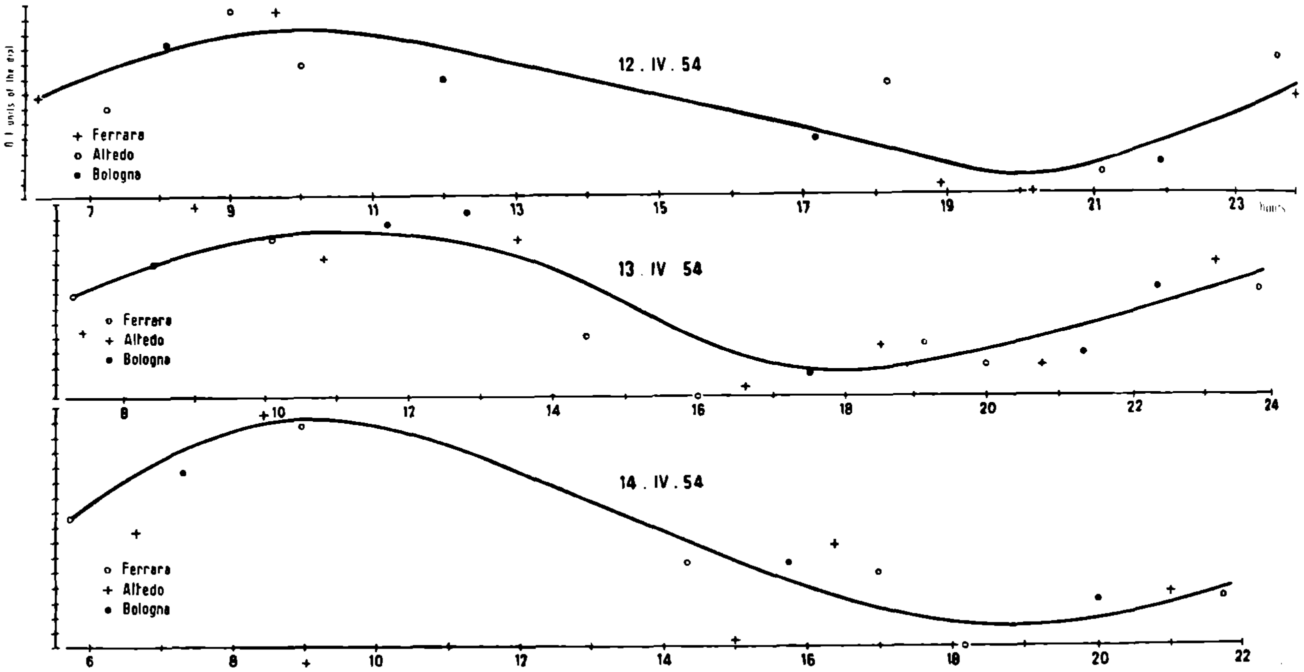

Fig. 7 - Drift curve of Gravity Meter W 6, small dial

The calibrations made in Italy have been computed by the method already mentioned; in the annexed figure the drift is shown and the table gives the readings taken at the base stations corrected for lunisolar effect (*Column A*) and the values corrected for drift effect using the preceding graphs (*Column B*).

Reproduced below is a table with the final results of the calibration; the meaning of the symbols which are to be found in the table is as follows:

Calibration of Gravity Meter No. 6 on the base Ferrara-Altedo-Bologna
(Observers Marussi, Caputo, Busà)

Date	Station	Time in hours	*A*	*B*
April 12, 1954	Ferrara	06.20	441.93	441.93
	»	09.40	442.49	442.04
	»	18.55	441.30	441.81
	»	20.10	441.24	441.77
	»	24.10	441.89	441.73
	Altedo	07.10	366.76	366.59
	»	08.55	367.39	366.96
	»	10.00	367.05	366.60
	»	18.10	366.91	367.26
	»	21.05	366.30	366.77
	»	23.40	367.06	367.06
	Bologna	08.00	286.63	286.31
	»	12.05	286.38	286.05
	»	17.10	285.99	286.24
	»	21.55	285.79	286.11
April 13, 1954	Ferrara	07.15	748.48	748.48
	»	10.10	748.87	748.45
	»	14.25	148.21	748.47
	»	19.05	748.15	748.61
	»	23.50	748.50	748.38
	Altedo	07.25	673.23	673.18
	»	09.00	674.06	673.74
	»	10.50	673.71	673.26
	»	13.30	673.82	673.58
	»	16.40	672.87	673.32
	»	18.30	673.13	673.62
	»	20.45	672.98	673.23
	»	23.10	673.68	673.62
	Bologna	08.20	592.82	592.59
	»	11.40	593.06	592.62
	»	12.50	593.13	592.78
	»	17.35	592.07	592.56
	»	21.25	592.18	592.45
April 14, 1954	Ferrara	05.45	748.99	749.00
	»	08.55	749.63	748.95

Date	Station	Time in hours	*A*	*B*
April 14, 1954	Ferrara	14.20	748.72	748.88
	»	17.00	748.64	749.22
	»	18.05	748.15	748.85
	»	21.40	748.47	748.87
	Altedo	06.35	673.87	673.61
	»	08.20	674.66	674.03
	»	15.00	673.31	673.58
	»	16.25	673.79	674.32
	»	19.10	672.82	673.55
	»	21.00	673.47	674.03
	Bologna	07.20	593.29	592.84
	»	15.45	592.70	593.10
	»	20.00	592.45	593.12
April 15, 1954	Ferrara	07.10	210.02	210.02
	»	10.10	210.45	209.97
	»	17.30	209.63	210.03
	»	19.15	209.50	209.76
	»	21.55	210.01	209.93
	Altedo	07.45	134.74	134.56
	»	09.30	135.49	135.01
	»	15.00	134.42	134.68
	»	16.45	134.69	135.05
	»	19.50	134.92	135.13
	»	21.20	135.00	135.00
	Bologna	08.20	54.31	53.99
	»	15.50	53.45	53.79
	»	20.35	53.48	53.50
December 14, 1954	Bologna	08.45	527.53	527.53
	»	11.45	527.35	527.57
	»	14.45	527.13	527.49
	»	17.25	526.99	527.51
	Ferrara	10.10	682.58	682.71
	»	13.25	682.44	682.73
	»	16.00	682.39	682.80
December 15, 1954	Bologna	08.20	528.18	528.18
	»	11.20	528.09	528.18
	»	14.10	528.09	528.17
	Ferrara	09.50	683.40	683.48
	»	12.40	683.51	683.56

A Readings on the gravity meter corrected for lunisolar effect
B Readings on the gravity meter corrected for lunisolar effect and instrumental drift

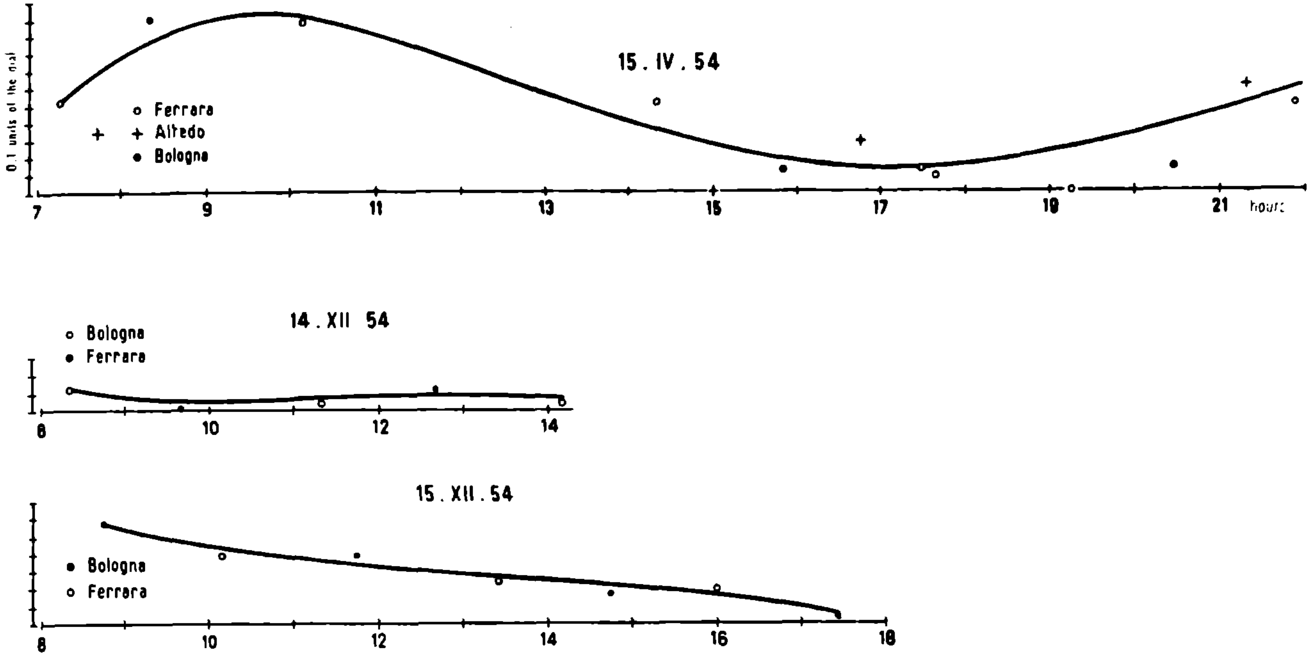

Fig. 8 - Drift curve of Gravity Meter W 6, small dial

K is the value of the scale factor, L_m is the mean reading of the dial, T_m is the mean outer temperature during the calibration.

GRAVITY METER No. 6

Date	K	$\eta\ 10^3$	L_m	T_m
April 12, 1954	1.035	4.2	364	10°C
» 13, »	1.033	2.2	670	13
» 14, »	1.033	4.0	670	13
» 15, »	1.031	2.3	132	16
December 14, »	1.038	3.2	605	16
» 15, »	1.037	3.5	605	11

Taking into account the values of K found in April and given in the table we have, for K as a function of L_m, the following graph (continuous line):

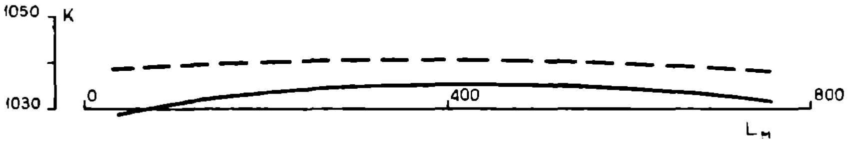

Fig. 9 - Scale factor K of the large dial (W 6)

The values of the scale factor for the various sectors of the dial given in the foregoing list and graph agree very well with the values given in the curve furnished by the makers (dotted line on the graph), even though they are all increased by a constant.

From the values found in April and December 1954 on the base Bologna-Ferrara it appears that the scale factor has undergone a change, which we shall assume to be linear with time.

We shall therefore adopt the value of K given by the following formula:

$$\text{(W No. 6)} \qquad K = 1.0337 + \frac{0.0035}{245} t = 1.0337 + 0.000014\, t$$

in which t indicated the time (in days) elapsed since April 14, 1954. This value of K naturally refers to the sector of the dial around $L_m = 605$.

In order to determine K for the other values of L_m the curve given by the makers is used, as reproduced in the preceding graph.

As already stated, in order to check the scale factor of Gravity Meter No. 6, Professor Marussi occupied, in October 1954, the gravimetric bases of the Lebanon, between Beirut R. S. J., Dahr-el-Beidar and Ksara. The portion Beirut-U. S. J.-Dahr-el-Beidar was covered by two round-trips and a mean difference of readings $\Delta\, l = 327.55$ mgal was obtained; the portion Dahr-el-Beidar - Ksara was covered in one round-trip with the result: $\Delta\, l = 70.55$ mgal.

On the basis of the values of the difference of gravity which were communicated to us by Stahl (*) as being $\Delta\, g = 339.4$ and $\Delta\, g = 73.0$ respectively, the scale factor $K = 1.0358$ for Gravity Meter No. 6 is obtained relative to the sectors of the dial about the reading 500; and this value agrees well with the value $K = 1.0356$, corresponding to October 1954, and made relative to the sector of the dial corresponding to the reading 500.

From above the accuracy of the adopted formula for the calculation of K is thus confirmed.

3. CALIBRATION OF GRAVITY METER No. 203

Gravity Meter No. 203, was used by the Expedition in 1955. Before being put into use, in June 1955, it underwent repairs at the makers which

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(*) These values were communicated by Stahl to Prof. Marussi in a letter dated February 10, 1955.

caused substantial modifications, so that the results recorded below are not comparable with those obtained before June 1955. After the repairs had been carried out the makers sent this gravity meter directly to Pakistan, so that it was not possible to carry out any calibration before the instrument was put into use. The calibration of the large dial was carried out later, in December 1955, on the Bologna-Ferrara base, after the work of the Expedition was concluded. Only the large dial was examined, on account of the fact that the instrument was used mainly for connections involving great differences of gravity.

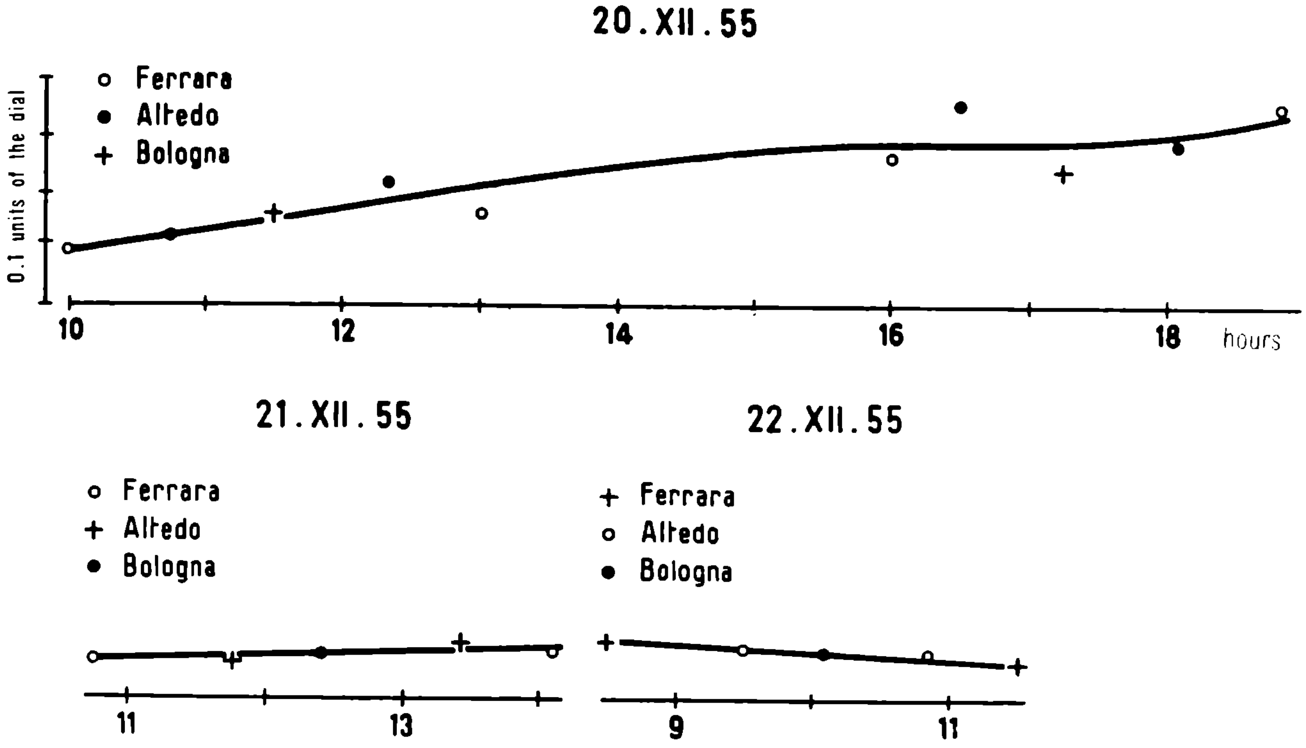

Fig. 10 - Drift curve of Gravity Meter W 203, large dial

The observations taken during this calibration were worked out by the method explained above; the preceeding graphs show the drift curves and the table gives the values observed at the base stations and corrected for lunisolar effect (*Column A*), and those further corrected for drift effect (*Column B*).

CALIBRATION OF GRAVITY METER No. 203 (LARGE DIAL) ON THE BASE FERRARA-ALTEDO-BOLOGNA

(Observers Caputo and Busà)

Date	Station	Time in hours	*A*	*B*
December 20, 1955	Ferrara	10.00	641.505	641.51
	»	13.00	641.559	641.46
	»	16.00	641.657	641.48
	»	18.50	641.745	641.52
	Altedo	10.45	625.305	625.29
	»	12.20	625.407	625.33
	»	16.30	625.547	625.34
	»	18.05	625.477	625.28
	Bologna	11.30	607.855	607.81
	»	17.15	607.927	607.74
December 21, 1955	Ferrara	10.45	647.824	647.82
	»	14.05	647.834	847.81
	Altedo	11.45	631.725	631.72
	»	13.25	631.747	631.73
	Bologna	12.35	614.106	614.29
December 22, 1955	Ferrara	08.30	634.291	634.29
	»	11.30	634.264	634.29
	Altedo	09.30	617.997	618.01
	»	10.50	617.984	618.00
	Bologna	10.10	600.686	600.70

A Reading on the gravity meter corrected for lunisolar effect

B Reading on the gravity meter corrected for lunisolar effect and instrumental drift

The table below shows the values of the scale factor of the large dial; in this table L_m is the mean reading on the dial over the interval involved in the calibration, T_m the mean ambient temperature during calibration, and η the error relative to the respective scale factor.

GRAVITY METER No. 203

Date	*K*	$\eta \times 10^3$	L_m	T_m
December 20, 1955	4.778	4.7	625	6°C
» 21, »	4.806	5.3	631	5°
» 22, »	4.790	8.8	617	5°

Professor Marussi also took readings on this gravity meter to determine the ratio between the large and small dials. The large dial was moved one division at a time and the null-point setting was recovered by turning the small dial, so that pairs of readings were obtained as shown in the following table:

GRAVITY METER No. 203

L	l	L	l	L	l	L	l
374	05.63	360	76.55	379	05.03	365	76.52
373	10.45	365	51.47	378	10.08	366	71.67
372	15.54	370	26.09	377	15.27	367	66.61
371	20.62	374	05.39	376	20.28	368	61.47
370	25.61			375	25.53	369	56.46
369	30.69			374	30.52	370	51.33
368	35.86			373	35.66	371	46.12
367	40.95			372	40.82	372	41.15
366	46.01			371	45.95	373	35.95
365	51.09			370	50.91	374	30.87
364	56.28			369	56.24	375	25.66
363	61.19			368	61.25	376	20.62
362	66.34			367	66.37	377	15.66
361	71.55			366	71.34	378	10.52
360	76.55			365	76.43	379	05.25

Indicating by L_i the readings on the large dial, by l_i the readings on the small dial, by y the ratio of the constants and by x the hypothetical reading on the small dial corresponding to zero on the large one, we have for the n pairs of readings:

$$L_i y = l_i - x \qquad (i = 1,\ 2,\ \ldots.\ \mathrm{n}).$$

With the method of the least squares, considering the l_i affected by errors, we obtain

$$x = \frac{[l]\ [L^2] - [L]\ [Ll]}{n\ [L^2] - [L]^2}\ ; \quad \sigma^2(x) = \frac{[L^2]\ \sigma^2\ [l]}{n\ [L^2] - [L]^2}$$

$$y = \frac{n\ [Ll] - [L]\ [l]}{n\ [L^2] - [L]^2}\ ; \quad \sigma^2(y) = \frac{n\ \sigma^2(l)}{n\ [L^2] - [L]^2}\,.$$

Assuming as origin of the readings their mean L_m and putting $L_i = L_i - L_m$ we have

$$y = \frac{[Ll]}{[L^2]} \qquad \sigma^2(y) = \frac{\sigma^2(l)}{n}$$

$$\bar{x} = \frac{[l]}{n} \qquad \sigma^2(x) = \frac{\sigma^2(l)}{[L^2]}$$

$\bar{x}$ now being the reading on the small dial corresponding to the reading L_m on the large one.

The readings have been divided into four groups which give the following values for y:

Gravity Meter No. 203

Date		group	y	$\eta \times 10^3$	weight	T_m
August 7,	1955	I	50.80	1	28	28°C
»	»	II	50.81	6	1	28
September 28,	»	III	51.07	2	12	27
»	»	IV	50.98	2	14	27

and therefore when the weights are taken into account, we have:

$$y = 50.91.$$

After the repairs effected in June 1955, the makers furnished the following graph on which is drawn the curve which gives the scale factor K of the large dial as a function of L_m.

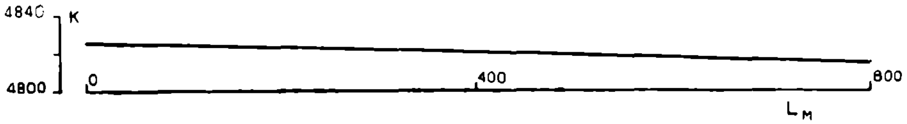

Fig. 11 - Scale factor K of the large dial (W 203)

For the scale factor of the small dial the makers gave the value $k = 0.09467$. The scale factor of the large dial corresponding to $L_m = 380$ is shown in the graph as $K = 4.8196$ and the ratio between the scale factor of the dials for that value is therefore $y = 50.91$. This value coincides exactly with that found during the Expedition. As the scale factor for the small dial the value $\frac{K_m}{y}$ is therefore assumed, where $K_m = 4.7908$ is the weighted mean of the values of the table above

(*a*) (W No. 203) $k = \frac{K_m}{y} = \frac{4.7908}{50.91} = 0.09410.$

As in December 1955 the value $K = 4.7908$ was found for $L_m = 624$ for the large dial scale factor, and the makers in July of the same year gave (also for $L_m = 624$) the value 4.8162, we will assume that K has varied linearly between July and December in the following way:

(*b*) (W No. 203) $K = 4.8162 — 0.00016\, t$ $(L_m = 624)$

t being the time (in days) elapsed since July 19, 1955; and the variation of K as a function of L_m is taken from the graph furnished by the makers.

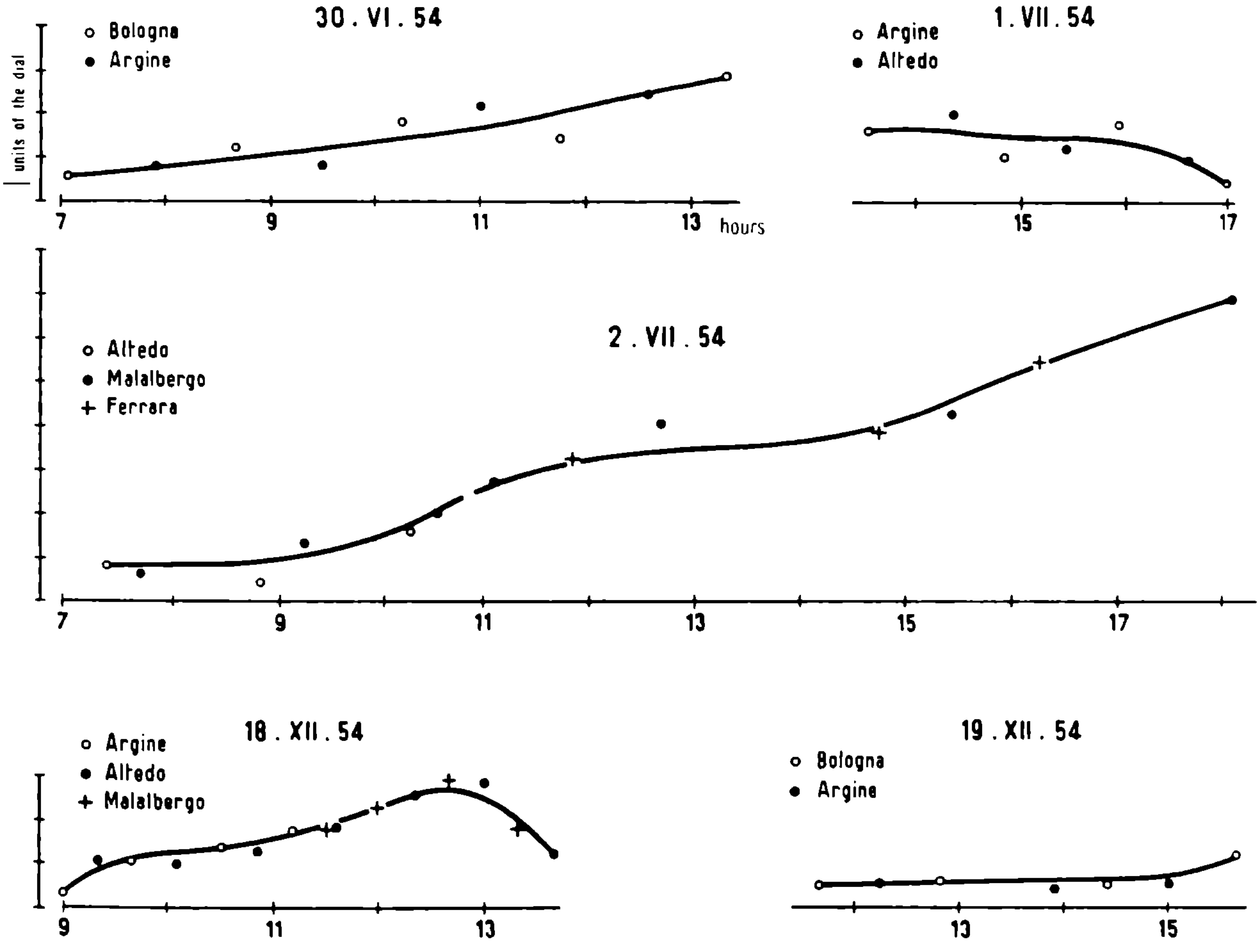

Fig. 12 - Drift curve of Gravity Meter W 116, small dial

4. CALIBRATION OF GRAVITY METER No. 116

Gravity Meter No. 116 was calibrated twice on the base Ferrara-Bologna, in June and December 1954, before and after the field observations. The values observed on the Rome-Beirut-Karachi connection by Lt. Colonel Cecioni, G. Salvioni and P. Bencini, of the *Istituto Geografico Militare*, have been reduced by the normal methods. The graphs show the drift curves and the tables show the values of the readings at the base stations, corrected for luni-solar effect (*Column A*) and the values corrected for the drift using the preceding graphs (*Column B*).

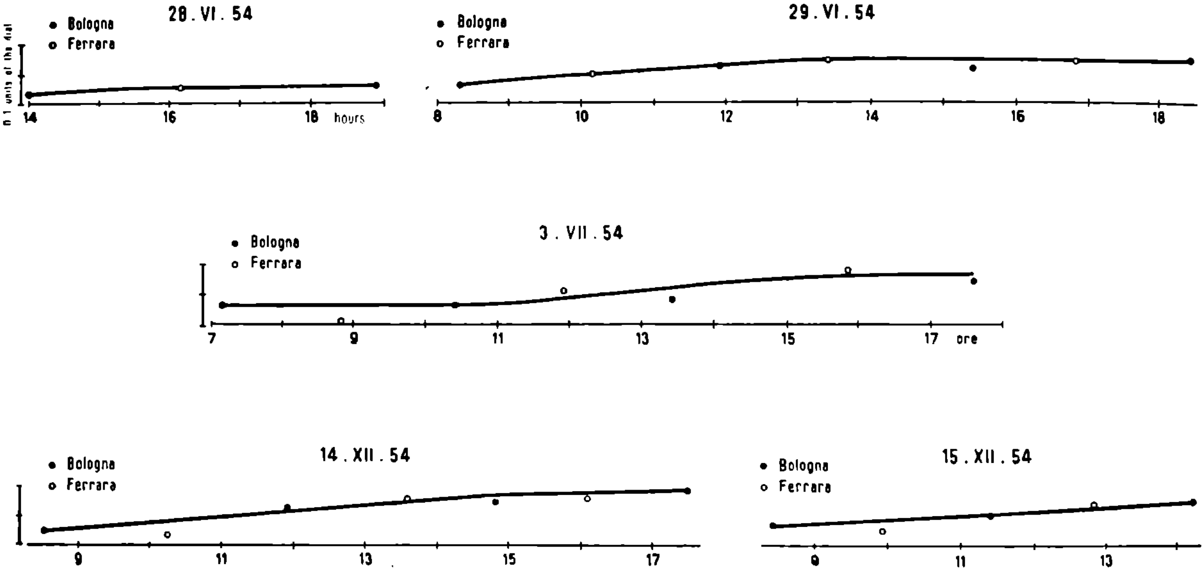

Fig. 13 - Drift curve of Gravity Meter W 116, small dial

Calibration of Gravity Meter No. 116 (small dial) on the base Bologna-Argine-Altedo-Malalbergo-Ferrara

(Observers Cecioni, Salvioni, Bencini)

Date	Station	Time in hours	*A*	*B*
June 30, 1954	Bologna	07.05	14.90	14.90
	»	08.41	14.97	14.90
	»	10.14	15.04	14.93
	»	11.44	15.10	14.94
	»	13.20	15.13	14.90
	Argine	07.58	62.45	62.42
	»	09.30	62.45	62.38
	»	10.59	62.59	62.45
	»	12.36	62.61	62.42
July 1, 1954	Argine	13.37	20.42	20.42
	»	14.49	20.35	20.38
	»	15.57	20.44	20.47
	»	17.01	20.31	20.42
	Altedo	14.17	51.85	51.86
	»	15.23	51.78	51.81
	»	16.32	51.75	51.82
July 2, 1954	Altedo	07.25	20.33	20.33
	»	08.49	20.29	20.29
	»	10.14	20.40	20.31
	Malalbergo	08.05	48.84	48.84
	»	09.32	48.92	48.88
	»	10.52	48.98	48.86
	»	11.05	7.88	7.87
	»	12.40	8.02	7.92
	»	15.26	8.03	7.88
	»	18.06	8.27	7.87
	Ferrara	11.50	52.53	52.48
	»	14.42	52.59	52.44
	»	16.16	52.75	52.47
December 18, 1954	Argine	09.00	12.28	12.28
	»	09.40	12.36	12.27
	»	10.30	12.39	12.28
	»	11.10	12.44	12.29
	Altedo	09.20	43.78	43.72

Date	Station	Time in hours	*A*	*B*
December 18, 1954	Altedo	10.05	43.78	43.69
	»	10.50	43.81	43.68
	»	11.30	43.86	43.69
	»	11.35	21.90	21.90
	»	12.20	21.98	21.90
	»	13.00	22.00	21.92
	»	13.40	21.84	21.89
	Malalbergo	12.00	50.60	50.55
	»	12.40	50.66	50.56
	»	13.20	50.55	50.57
December 19, 1954	Bologna	11.40	11.29	11.29
	»	12.50	11.30	11.29
	»	14.25	11.30	11.30
	»	15.35	11.36	11.30
	Argine	12.15	58.88	58.88
	»	13.55	58.87	58.86
	»	15.00	58.89	58.86

A Readings on the gravity meter corrected for lunisolar effect
B Readings on the gravity meter corrected for lunisolar effect and instrumental drift

CALIBRATION OF GRAVITY METER NO. 116 (LARGE DIAL) ON THE BASE BOLOGNA-FERRARA

(Observers Cecioni, Salvioni, Bencini)

Date	Station	Time in hours	*A*	*B*
June 28, 1954	Bologna	14.06	480.94	480.94
	»	18.56	480.97	480.94
	Ferrara	16.07	511.10	511.08
June 29, 1954	Bologna	08.22	480.89	480.89
	»	11.57	480.96	480.89
	»	15.24	480.96	480.89
	»	18.32	480.99	480.89
	Ferrara	10.10	511.05	511.00
	»	13.27	511.10	511.00
	»	16.52	511.09	511.00

Date	Station	Time in hours	*A*	*B*
July 3, 1954	Bologna	07.12	484.99	484.99
	»	10.23	484.98	484.98
	»	31.25	485.00	484.96
	»	17.35	485.06	484.95
	Ferrara	08.50	515.01	515.06
	»	11.55	515.11	515.09
	»	15.52	515.17	515.08
December 14, 1954	Bologna	08.28	393.85	393.85
	»	11.55	393.92	393.83
	»	14.50	393.94	393.84
	»	17.30	394.00	393.85
	Ferrara	10.17	423.90	423.89
	»	13.35	424.02	423.89
	»	16.05	424.02	423.89
December 15, 1954	Bologna	08.25	394.01	394.01
	»	11.25	394.04	393.99
	»	14.15	393.91	394.01
	Ferrara	09.55	424.06	424.01
	»	12.50	423.95	423.96

A Readings on the gravity meter corrected for lunisolar effect
B Readings on the gravity meter corrected for lunisolar effect and instrumental drift

Two tables are reproduced below showing the final results of the calibrations; the meaning of the symbols in these tables is as usual.

GRAVITY METER No. 116 (small dial)

Date	k	$\eta \times 10^3$	L_m	T_m
June 30, 1954	0.1059	3.2	388	29
July 1, »	0.1058	3.7	361	29
» 2, »	0.1060	3.5	347	23
» 2, »	0.1059	2.9	305	28
December 18, »	0.1058	3.2	292	10
» 18, »	0.1056	3.1	364	12
» 19, »	0.1058	0.7	352	12

GRAVITY METER No. 116 (large dial)

Date		K	$\eta \times 10^3$	L_m	T_m
June	28, 1954	5.344	1.3	396	31
»	29, »	5.349	1.2	396	29
July	3, »	5.350	1.5	400	25
December	14, »	5.360	1.1	409	12
»	15, »	5.360	1.6	409	11

For the scale factor of Gravity Meter No. 116 (large dial) the *Istituto Geografico Militare* furnished us with the following values of K subsequently determined:

GRAVITY METER No. 116 (large dial)

Date		K	T_m	L_m
June	1954	5.347	28.3	398
December	»	5.360	11.5	409
June	1955	5.343	26.7	412
October	»	5.344	20.0	417
June	1956	5.343	19.0	427
October	»	5.344	21.0	?

It is to be noted that the scale factor of this gravity meter can be considered constant with time, and that in the sector of the dial examined during the two years to which these calibrations refer (a sector which comprises about thirty divisions of the large dial), no noticeable variation has been found in the scale factor. It is therefore assumed that for this gravity meter the value is that determined from the arithmetic mean of the six calibrations carried out; we have therefore:

$$\text{(W No. 116)} \qquad K = 5.347$$

For the small dial scale factor we have instead

$$\text{(W No. 116)} \qquad k = 0.1058.$$

OBSERVATIONS BY THE EXPEDITION

GRAVIMETRIC CONNECTION ROME-BEIRUT-KARACHI-JODHPUR-JAIPUR-DELHI-DEHRA DUN

(M. CAPUTO)

During 1954 the Expedition, using the Worden Gravity Meter No. 116 of the *Istituto Geografico Militare*, carried out the Rome-Beirut-Karachi connection with two round-trips by air.

Connection	Gravity Meter No.	Date	ΔL	L_m	Δl	L_m	K	k	Δg
		October							
BEIRUT-ROME	116	19, 1954	— 123	308	+ 18.8		5.347	0.1058	— 655.68
» »	116	22, »	— 123	308	— 20.1		5.347	0.1059	— 655.75
» »	116	26, »	— 123	308	+ 12.0		5.347	0.1058	— 656.41
» »	116	29, »	— 123	308	— 15.9		5.347	0.1058	— 656.00
» »	203	7, 1955	— 136	511	+ 14.4		4.805	0.0941	— 652.10
KARACHI-BEIRUT	116	20, 1954	— 137	178	— 11.9		5.347	0.1058	— 733.80
» »	116	22, »	— 137	178	— 5.2		5.347	0.1058	— 733.09
» »	116	27, »	— 137	178	— 11.2		5.347	0.1058	— 733.72
» »	116	29, »	— 137	178	— 5.8		5.347	0.1058	— 733.15
» »	203	7, 1955	— 152	367	— 11.0		4.807	0.0941	— 731.70
» »	6	15, 1954			— 705.3	363		1.0366	— 731.11
» »	6	29, »			— 703.9	374		1.0369	— 729.88
		November							
JODHPUR-KARACHI	6	1, 1954			+ 33.8	38		1.0371	+ 35.05
» »	6	4, »			+ 35.1	41		1.0371	+ 36.40
JODHPUR-JAIPUR	6	1, »			+ 6.3	32		1.0371	+ 6.53
» »	6	4, »			+ 7.3	54		1.0371	+ 7.57
JAIPUR-DELHI W.A.	6	1, »			— 142.3	120		1.0373	— 147.61
» »	6	4, »			— 142.7	122		1.0373	— 148.02

ΔL	difference in readings on the large dial between the two stations
Δl	difference in readings on the small dial between the two stations
K	constant of the large dial
k	constant of the small dial
Δg	calculated gravity difference
L_m	mean reading on the large dial during each individual connection

Lieutenant Colonel Enrico Cecioni and Capt. Francesco Lombardi, both of the *Istituto Geografico Militare*, collaborated with Prof. Antonio Marussi in this work. Lt. Col. Cecioni took the readings of the instrument at Ciampino Airport in Rome, Captain Lombardi those at Karachi Airport, while Professor Marussi took the readings at Khaldè Airport in Beirut. The same connection was also made with Worden Gravity Meter No. 203 on a single flight from Karachi to Rome in 1955 (Professor Marussi). With Gravity Meter No. 6 only, the Beirut-Karachi strip was covered on a two-way flight in 1954 (Captain Lombardi and Professor Marussi).

The connections between Karachi, Jaipur, Jodhpur and Delhi were made in 1954 with Gravity Meter No. 6 (Captain Lombardi) during a two-way flight, as indicated in the following table which also shows how the readings of the gravimetric differences were taken in all the above-mentioned connections.

From the preceding table is derived the following summary of the weighted means Δg_m of the gravity differences, calculated for each gravity meter. In this summary the m. s. e. of Δg_m is indicated by η and the number of connections from which Δg_m was obtained by n.

Connection	Gravity Meter No.	Δg_m	n	η
Beirut-Rome S. R.	116	— 655.96	4	0.38
Beirut-Rome S. R.	203	— 652.10	1	
Karachi-Beirut	116	— 733.44	4	0.32
Karachi-Beirut	203	— 731.70	1	
Karachi-Beirut	6	— 730.50	2	0.61
Jodhpur-Jaipur	6	+ 7.05	2	0.72
Jaipur-Delhi W. A. ..	6	— 147.82	2	0.91
Jodhpur-Karachi	6	+ 35.73	2	0.95

Finally at Delhi a connection was made between the points situated at Willington Airport (Delhi W. A.), Palam Airport (Delhi P. A.), the Imperial Hotel (Delhi I. H.) and the Pendulum Station of the Survey of India (Delhi P. S. S. I.). The compensated values, taking Delhi W. A. as the origin, are as follows:

Delhi W. A. - Delhi P. A.	+ 3.86
Delhi W. A. - Delhi I. H.	— 0.68
Delhi W. A. - Delhi P. S. S. I.	+ 1.64

Taking the weighted means of the results obtained with the various gravity meters the following table of the gravity differences with respect to Rome S. R. is arrived at:

		mgal
Beirut	– Rome S. R.	655.19
Karachi	– »	1387.54
Jodhpur	– »	1351.81
Jaipur	– »	1358.86
Delhi W. A.	– »	1211.04
Delhi I. H.	– »	1210.36
Delhi P. A.	– »	1214.90
Delhi P. S. S. I.	– »	1212.68

We now reproduce the values of the gravity differences between Dehra Dun N. G. S. and Delhi given us by Dr. Gulatee of the Survey of India in a letter dated May 9, 1956 and the connection between Rome S. R. and the station Rome R. F. of the Italian Fundamental Network and Rome S. P. (cellar of the pendulum measurements) both in the Faculty of Engineering. The values of the last two connections were obtained by Stahl and Morelli.

Dehra Dun N. G. S.	– Delhi I. H.	74.8
Dehra Dun N. G. S.	– Delhi P. A.	70.3
Dehra Dun N. G. S.	– Delhi W. A.	74.2
Rome S. R.	– Rome S. P.	14.88
Rome S. R.	– Rome R. F.	15.48

From the preceding tables we have for the Rome S. R. – Dehra Dun connection the mean value of – 1285.2.

In the following table are reproduced the values of gravity at the aforementioned stations resulting from previous observations, and assuming for Rome S. P. the gravity value of 980,361.6 mgal in the Potsdam system (Column 5).

Also given are the gravity values determined by Stahl for the various stations (Column 1), and in Column 2 those found by Woollard.

In Column 3 there is the value for Dehra Dun determined by Abetti and Alessio of the Italian De Filippi Expedition (1913); the corresponding value for Rome S. P. has been calculated in order to make the necessary comparisons, by using the values obtained by Abetti and Alessio for Genoa S. G., where the departure determination was made, and also the connections Genoa S. G.–Milan S. G. = 7.66, Milan S. G.–Milan R. F. = 0.30 mgal (communicated to us by Professor Solaini), and Milan R. F.–Rome R. F. = 201.76 mgal. In Column 4 are given the gravity values obtained by Cugia during the expedition of the Duke of Spoleto, in which the same values are taken for Genoa, and for Rome, as for the De Filippi Expedition.

	(1) Stahl from Paris (1952-53)	(2) Woollard from Washington (1950)	(3) De Filippi (1913)	(4) Duke of Spoleto (1929)	(5) Italian Karakorum Expedition (1954-55)
Rome S. R.	980,347.7	980,348.1	980,348	980,348	980,346.7
Rome S. P.	980,362.6				980,361.6
Beirut	979,693.4				979,691.5
Karachi	978,962.9	978,960.1			978,959.2
Delhi W. A.		979,135.7			979,135.7
Delhi P. A.		979,146.6			979,131.8
Delhi I. H.		979,137.1			979,136.3
Delhi P. S. S. I.					979,134.0
Dehra Dun			979,079	979,069	979,061.5
Jodhpur					978,994.9
Jaipur					978,987.8

To obtain the values referred to the absolute determination of Lorenzoni at Padua add:

to the values of Columns 3 & 4	10.0 mgal,
to the values of Column 1	10.6 mgal.

To obtain the values referred to the absolute observations of Washington D. C., Commerce Building, add:

to the values of Column 5	+ 0.4 mgal.

The value of Rome S. P. referred to Washington D. C., Commerce Building, was determined by taking the value 980,119.0 mgal for Commerce Building and the value – 243.0 mgal for the connection of this station with Rome S. P.

Finally for Dehra Dun the value of 979,061.5 mgal, referred to Potsdam, has been obtained. This differs by 1.5 mgal from that adopted officially by the Survey of India, which is thus substantially confirmed.

As a consequence of this very slight difference, the official value of the Survey of India for Dehra Dun — 979,063 — has been kept in the reduction of all the gravity values observed during the course of the Expedition in order to maintain uniformity between the values adopted for continental India and for the mountainous zone of Pakistan.

NOTES ON THE STATIONS MENTIONED

Beirut	Khaldè Civil Airport: — In the underground corridor, in front of the point marked with a ' G ', 50 cm from the north wall between doors S 18 and S 13. (See Annales de l'Observatoire de Ksara (Liban); Mémoires, Tome II, Cahier 2, page 14).
Beirut U. S. J.	S. Josef University — (See Annales de l'Observatoire de Ksara (Liban), Mémoires, Tome II, Cahier 2, page 16).
Dahr el Beidar	Police station — Dormitory floor, the in SE corner of the building, in front of window E (See Annales de l'Observatoire de Ksara (Liban), Mémoires, Tome II, Cahier 2, page 16).
Delhi I .H.	Imperial Hotel — Main entrance (Survey of India station).
Delhi P. A.	Palam Airport — At ground level, near the entrance to the passengers building (Survey of India station).
Delhi W. A.	Willington Airport — At ground level, near the entrance to the passengers building (Survey of India station).
Delhi P. S. S. I.	Pendulum Station of the Survey of India.
Karachi	Civil Airport — Half-way along the corridor which leads from the rotunda to the verandah, under the control tower.
Ksara	Magnetic pavilion of the Observatory, inside; at ground level in front of window E (See Annales de

	l'Observatoire de Ksara (Liban), Mémoires, Tome II, Cahier 2, page 16).
Jaipur	Airport.
Jodhpur	Airport.
Rome S. P.	(Stazione Pendolare) Pendulum Measurement Cellar, Via Eudossiana 18, Facoltà d'Ingegneria.
Rome R. F.	Station of the Rete Fondamentale Italiana, Facoltà d'Ingegneria.
Rome S. R.	West Ciampino Civil Airport — Sala Rosa.
Milan S. G.	Pier in the gravimetric room of the Istituto di Geodesia, Politecnico (Sala gravimetrica).
Milan R. F.	Station of the Rete Fondamentale Italiana.
Genoa S. G.	Pier in the gravimetric room of the Istituto Idrografico della Marina (Sala gravimetrica).
Dehra Dun N. G. S.	National Gravity Station.

GRAVITY OBSERVATIONS IN 1954

The gravimetric work carried out in 1954 may be summarized as follows:

(*a*) Connection Rome-Beirut-Karachi-Delhi;
(*b*) Connection Karachi-Rawalpindi;
(*c*) Triangular connection Rawalpindi-Skardu-Gilgit;
(*d*) Gravimetric survey along the routes followed by the Expedition in the Karakorum;
(*e*) Gravity measurements on glaciers to determine the depth of ice.

Elsewhere in this volume M. Caputo refers to items (*a*) and (*e*) and gives details about the calibrations and tests to which the gravity meters used were submitted; therefore here we are concerned only with the remaining parts, (*b*), (*c*) and (*d*), of the programme which was brought to completion with Gravity Meter No. 6.

Before entering the matter, it should be noted that already during the course of the 1954 campaign it became evident that the difference between the instrumental drift shown by the meter during the periods of rest, and that on the actual move (which even resulted to be negative) could be accounted for by thermal effects rather than by jarring or other causes. Laboratory experiments carried out later on proved that this view was perfectly tenable.

From these experiments it appeared, in fact, that external harmonic oscillations of temperature with a daily period caused in the interior of the Dewar vessel, in which the sensitive unit of the meter is situated, a corresponding harmonic oscillation of temperature with a strongly reduced amplitude and a shift of about 6 hours in the phase (*see* the contribution by I. Gabrielli and G. Poiani in this volume). This oscillation, on its turn, affects the readings, owing to imperfect thermal compensation of the sensitive unit.

If it is now borne in mind that most of the gravimetric observations are of necessity taken during the day, when the temperature is high, whereas the instrument is at rest during lower temperatures at night, a systematic effect must result which shows a clear discrepancy between the instrumental drift at rest and the actual carrying of the instrument during the journey.

Thus having ascertained the cause, it seemed no longer appropriate to merely apply to each individual reading a correction for linear drift, even if this was computed by taking into account only the periods during which the instrument was in action. The following process was therefore devised.

As the behaviour of the temperature in the container of the meter during the whole day was not known, the readings of the thermometer having been taken only at the time of the gravimetric observations, a sinusoidal oscillation with a daily period and a maximum at 2 p. m. was assumed, the amplitude being determined for each individual day from the extreme temperature observed during that day. Curves were then drawn on the basis of the laboratory tests referred to, and corrections were consequently applied.

The procedure greatly improved the closure errors both in the loops and in the traverses, as can be seen from the following table:

Loop or traverse	time (hours)	loop closure (mgal)	
		no thermal drift correction	with thermal drift correction
Skardu-Dasu-Hurimal-Skardu	97	— 4.6	+ 0.5
Dasu-Kurchung-Hurimal-Dasu	57	— 1.6	+ 1.5
Kurchung-Gilgit-Kurchung	101	— 3.2	— 0.7
Dusso-K2 B. C.-Dusso	163	— 10.3	— 0.9
Skardu-Bagicha-Skardu	14	— 0.9	— 0.6

Before discussing the details of the subsequent adjustments, it should be noted that adjustments of local nets have previously been carried out at Karachi, Rawalpindi, Skardu and Gilgit, in order to connect several local points of interest in the neighbourhood of these localities. The rigorous method of the least squares has been used for Karachi, Rawalpindi and Gilgit, and the results are shown in the form of graphs which are self-explanatory. The local net around Skardu has been adjusted empirically owing to the small discrepancies found.

KARACHI

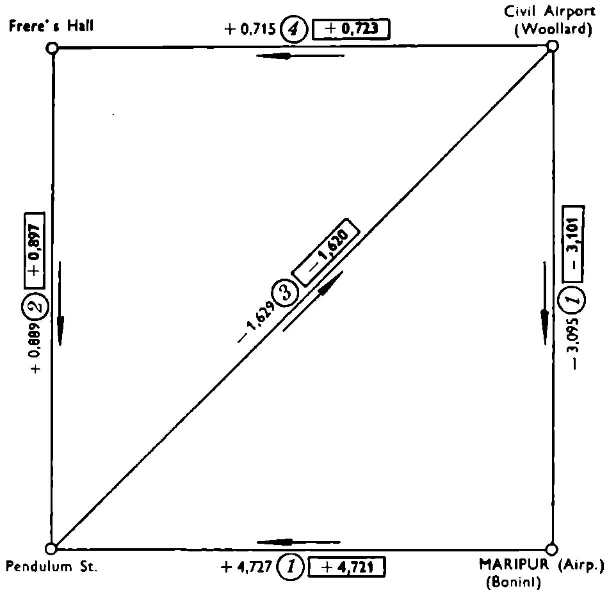

Fig. 14 - Adjustment of gravity differences observed in the surroundings of Karachi

+ 4.727	observed value (mgal)
①	number of observations
$\boxed{+ 4.721}$	adjusted value (mgal)

We shall now pass to the presentation of the main work, which can be subdivided into the following sections:

(i) Connection Karachi-Lahore,
(ii) do. Lahore-Rawalpindi,
(iii) do. Rawalpindi-Skardu-Gilgit,
(iv) Gravity survey along the routes followed in the Karakorum.

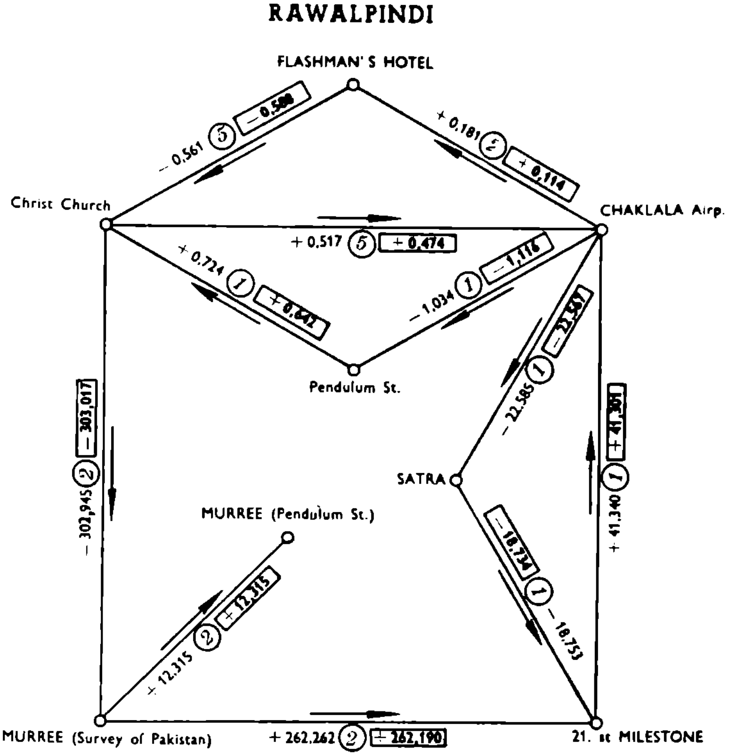

Fig. 15 - Adjustment of gravity differences observed between Rawalpindi and Murree, and in the surroundings of Rawalpindi

+ 262.262	observed value (mgal)
②	number of observations
+ 262.190	adjusted value (mgal)

Connection Karachi-Lahore — The connection has been carried out by means of three flights on a plane with non-pressurized cabin. The results obtained are summarized in the following table:

Date	Lahore Civil Airport		Karachi Airport	Gravity difference corrected for drift
	(hours)			(mgal)
October 5, 1954	17.05	⟶	21.20	427.411
» 7, »	23.00	⟵	19.20	426.660
» 13, »	9.50	⟶	13.35	427.401
	mean value			427.157

Observations at Karachi were made at the Civil Airport, at the point established by Woollard; those at Lahore in front of the Control Tower at the Civil Airport.

In the first outward journey from Karachi to Lahore and Rawalpindi the instrument was transported by train. In addition, measurements were also taken at Jacobabad and Quetta in Baluchistan. Because of the length of the journey the measurements are obviously only uncertain; the gravity differences found have therefore been adjusted on the values obtained by the above-mentioned air connections, and the results of the adjustment are shown in the attached graph. Gravity at Jacobabad was observed on the platform of the railway station, close to the water-fountain.

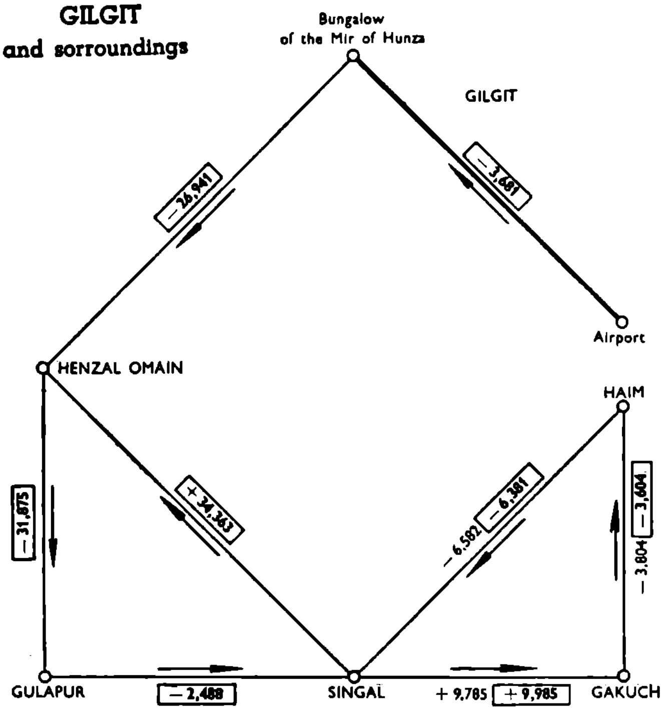

Fig. 16 - Adjustment of gravity differences observed between Gilgit and Haim, and in the surroundings of Gilgit
+ 9.785 observed value (mgal)
$\boxed{+ 9.985}$ adjusted value (mgal)

Connection Lahore-Rawalpindi — The connection was carried out by covering the distance once by plane, once by train and twice, with intermediate stops at the Jelhum and Gujranwala railway stations, by motor-car. The results of this connection are clearly shown in the annexed graph.

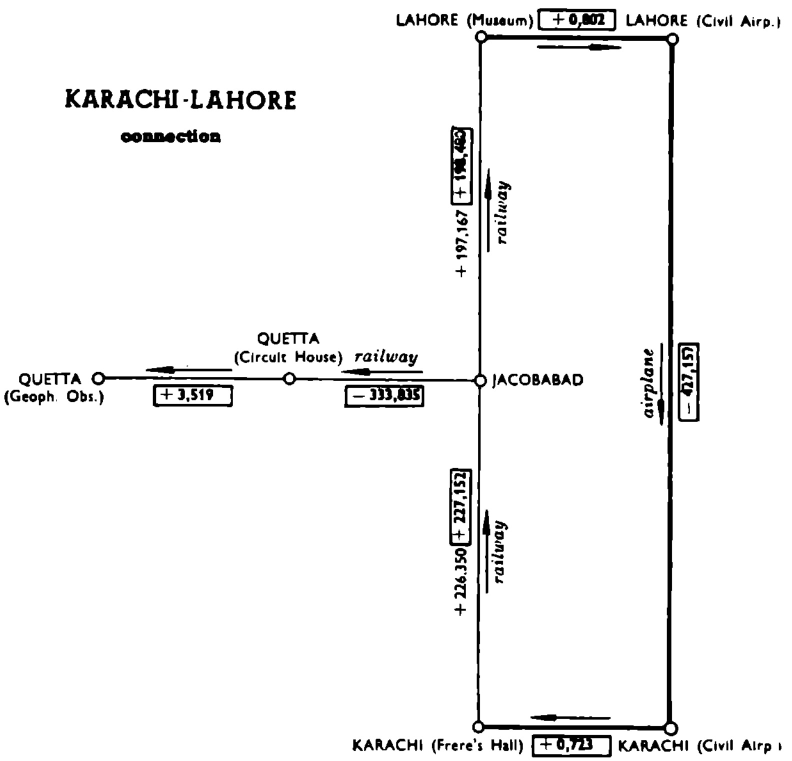

Fig. 17 - Adjustment of gravity differences observed between Karachi, Jacobabad, Quetta and Lahore
+ 226.350 observed value (mgal)
$\boxed{+\ 227.152}$ adjusted value (mgal)

Connection Rawalpindi-Skardu-Gilgit — This connection was carried out by flying the meter twice on each of the sides of the triangle, and by adjusting the observations by the method of least squares. The results are shown in the annexed table, where the last column gives the adjusted values, increased by 4 in 10,000, in order to conform formally the calibration of Gravity Meter No. 6 to the calibration of the other meters used, as results from the Beirut-Karachi connection.

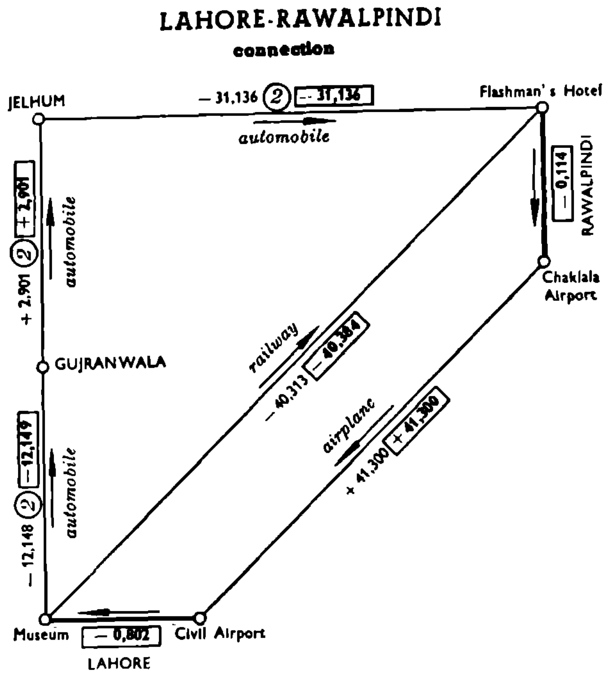

Fig. 18 - Adjustment of gravity differences observed between Lahore, Gujranwala, Jelhum and Rawalpindi

— 31.136	observed value (mgal)
②	number of observations
$\boxed{-\ 31.136}$	adjusted value (mgal)

Stations	1954 Date	Gravity difference observed (mgal)	Mean value (mgal)	Adjusted final value (mgal) × 1.000,4
Rawalpindi Skardu	May 14	— 441.983	— 442.503	— 443.070
Skardu Rawalpindi	September 30	+ 443.024		
Skardu Gilgit	September 30	+ 223.998	+ 223.998	+ 223.697
Gilgit Skardu	September 30	— 223.998		
Rawalpindi Gilgit	October 9	— 219.672	— 219.677	— 219.373
Gilgit Rawalpindi	October 10	+ 219.681		
		Loop closure	1.172	0.000

GRAVITY SURVEY ALONG THE ROUTES FOLLOWED IN THE KARAKORUM

All the lines observed were covered on foot, with the only exceptions of the Sasli-Haim and Skardu-Bagicha traverses, which were covered in both directions by jeep.

The routes followed are presented in schematic form in the annexed graph.

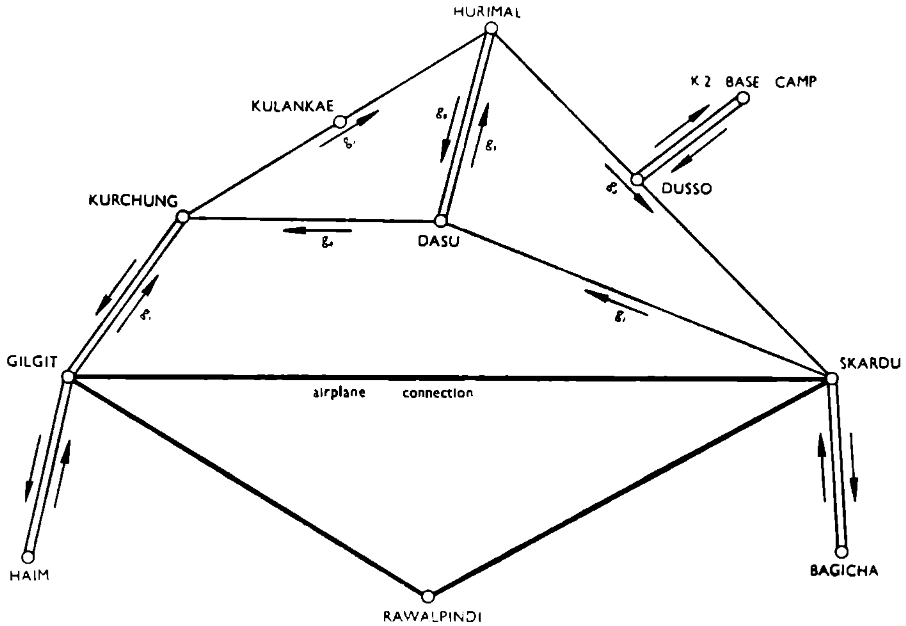

Fig. 19 - Adjustment of gravity differences observed along the routes followed by the Expedition in the Karakorum (1954) g_1-g_7 = gravity differences

As can be seen, the network is based on the fundamental difference of gravity between Skardu and Gilgit, previously determined.

After having corrected each individual observation for thermal drift, an adjustment by the method of least squares has been carried out following the scheme illustrated in the already mentioned graph. The following table, to be consulted in connection with the graph, gives the numerical values.

Needless to say that after compensation of the fundamental net, the gravity values for all the stations spread along the routes have been interpolated according to it.

CONDITION EQUATIONS, LOOP CLOSURES, WEIGHTS AND CORRECTIONS

	g_1	g_2	g_3	g_4	g_5	g_6	g_7	loop closures (mgal)
w_1	+ 1	+ 1	+ 1					— 0.538
w_2				+ 1	+ 1	+ 1		— 1.498
w_3				— 1			+ 1	— 1.482
w_4		+ 1				+ 1		+ 0.336
1/P (hours)	29	3	65	26	29	2	101	
corrections (mgal)	+ 0.132	+ 0.233	— 0.900	— 0.506	— 1.097	+ 0.106	— 1.856	

COMPARISON WITH THE PREVIOUS PENDULUM OBSERVATIONS IN THE KARAKORUM AND SURROUNDING REGIONS

The comparison is illustrated in the following table. As can be seen, the all-over link between the previous pendulum stations in the region is ensured by the pendulum observations of the Italian De Filippi Expedition 1913-14; of the 7 observations, 2 (Dehra Dun and Srinagar) are in common with the Survey of India; 2 others (Leh and Yarkand) are in common with the Sven Hedin

Station	Italian Karakorum Expedition 1954	Survey of India	Italian De Filippi Expedition 1913-14	Sven Hedin Sino-Swedish Expedition 1929-33	Russian net	Adopted values
Dehra Dun	979.063.0	979.063.0	979.079 *	—	—	979.063.0
Karachi P. S.	978.962.3	978.961 *	—	—	—	978.962.3
Rawalpindi P. S.	979.345.4	979.346 *	—	—	—	979.345.4
Murree P. S.	979.030.8	979.024 *	—	—	—	979.030.8
Srinagar P. S.	—	979.083 *	979.090 *	—	—	979.083.0
Skardu (DE FILIPPI)	978.915.3	—	978.925 *	—	—	978.915.3
Tolti (DE FILIPPI)	978.853.6	—	978.853 *	—	—	978.853.6
Leh (DE FILIPPI)	—	—	978.529 *	978.523 *	—	978.521.8
Yarkand (DE FILIPPI)	—	—	979.529 *	979.518 *	—	979.519.7
Tashkent 1902	—	—	980.078 *	—	980.073 *	980.070.0
1910	—	—	—	—	088 *	—
1911	—	—	—	—	079 *	—
1928	—	—	—	—	081 *	—

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* pendulum observations

Expedition; 1 (Tashkent) is in common with the Russian Survey; and finally 3 (Dehra Dun, Skardu and Tolti) are now in common with our Expedition.

GRAVITY OBSERVATIONS IN 1955

Gravity measurements in 1955 were all carried out with Worden Gravity Meter No. 203.

All the gravimetric traverses observed are linked to two fundamental stations, Rawalpindi and Gilgit. The gravimetric difference already determined between these two stations in 1954 was used in adjusting the current series of observations.

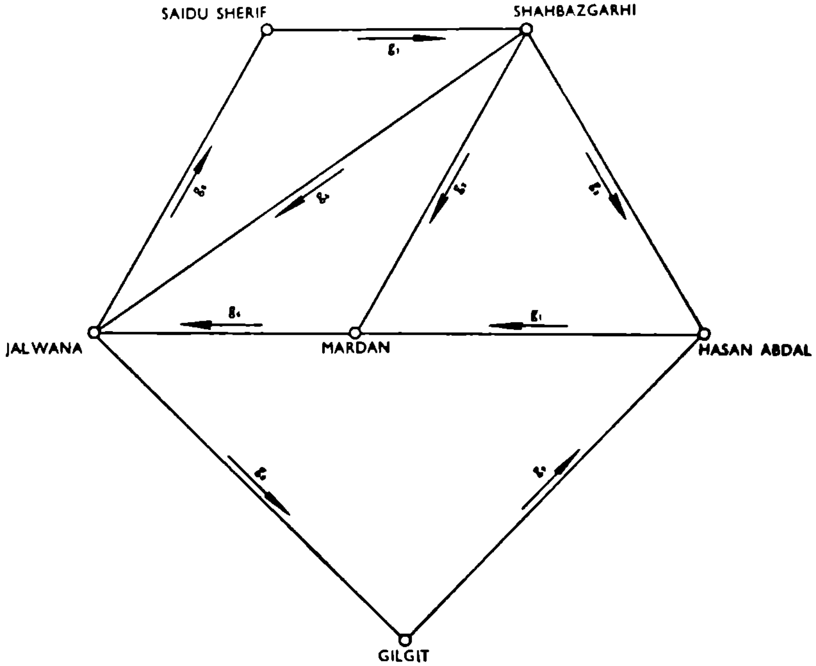


Fig. 20 - Adjustment of gravity differences between Hasan Abdal, Shahbazgarhi, Saidu Sherif, Jalwana, Mardan, and Gilgit
g_1 — g_9 = gravity differences

The principal routes followed partly by jeep and partly on foot are shown in the figure which indicates at the same time the loops which have been adjusted by the method of least squares. Some minor traverses have also been observed, such as the Rawalpindi-Hasan Abdal, the Jalwana-Landi Kotal, and Saidu Sherif-Kalam.

The average hourly drift determined during the periods on the march came to +0.011 mgal/hour, less than half the value +0.025 mgal/hour, corresponding to the periods of rest. Here too correction of the readings simply with the average drift gave no satisfactory improvement in the loop closures; accordingly the method already used for reducing the 1954 observations was applied in this case as well. The table below shows the loop closures after correction for average drift only, and also after correction for thermal drift.

Loop	Time in hours	Loop closures (mgal)	
		no thermal drift correction	with thermal drift correction
w_1	207	— 1.5	— 0.2
w_2	15	+ 0.2	+ 0.3
w_3	9	— 0.1	+ 0.1
w_4	9	— 2.0	— 1.7

After these corrections had been applied, the traverses were adjusted by allotting to each observed gravimetric difference a weight inversely proportional to the number of hours involved in its measurement. The method followed, the condition equations, and the corrections, can be seen in the following table which should be consulted together with the foregoing figure.

	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	loop closures (mgal)
w_1	+ 1			+ 1				+ 1	+ 1	—0.193
w_2					+ 1	+ 1	+ 1			+0.255
w_3		+ 1		+ 1	+ 1					+0.135
w_4	+ 1	— 1	+ 1							—1.739
1/P (hours)	3.25	1.60	4.24	3.90	4.11	4.51	6.50	162.20	38.16	
corrections (mgal)	—0.624	+0.289	—0.825	—0.044	+0.110	+0.059	+0.085	+0.385	+0.091	

These adjusted measurements, together with the gravimetric difference between Rawalpindi and Hasan Abdal also determined in 1955, made it possible to compare the gravity difference between Rawalpindi and Gilgit as determined in 1955 with that determined in 1954 by air-borne gravity meter. The result is as follows:

Gravimetric difference between the airfields of Rawalpindi and Gilgit:

— as established in 1954 by air-borne gravity meter	219.373 mgal
— as established in 1955	220.005 »
discrepancy	0.632 mgal

In order to ensure complete uniformity between the results of 1954 and 1955, and owing to the smallness of the discrepancy found, it was deemed sufficient to multiply all gravimetric differences determined in 1955 by the factor

$$0.997\ 13 = \frac{219.373}{220.005}$$

which is the ratio between the two already stated values for the gravity difference Rawalpindi-Gilgit.

No further reference is made to the computations for other stations of the principal and minor traverses, since these follow the usual procedures.

BOUGUER AND ISOSTATIC ANOMALIES

Amongst the 198 stations for which gravity and height have been observed during the 1954 and 1955 campaigns, 69 nearly equally spaced stations have been selected with the aim of computing the topographic and isostatic reductions; to these, 6 further stations observed by Prof. G. Abetti and Comm. A. Alessio of the De Filippi Expedition have been added, thus bringing the number of points for which anomalies in the various hypotheses have been computed, to a total of 75.

Furthermore, the Isostatic Institute of the International Association of Geodesy has computed, with the courtesy of Prof. W. Heiskanen, the reductions for 40 stations observed by the Sino-Swedish Expedition (Dr. N. Ambolt) led by Dr. Sven Hedin.

The values of the anomalies thus computed for the above-mentioned 115 points have allowed to fill the gap existing in the former anomaly maps of this part of Asia drawn by Dr. B. L. Gulatee for the Indian Platform, and by V. Erola for the Pamirs and Tien Shan. The plates annexed to this volume thus give the complete picture resulting from the integration of all the now available data.

The topographic and isostatic reductions have been computed in the usual way, using Cassinis's tables and the tables and maps published by the Isostatic Institute of the I. A. G.; still in some instances the number of compartments in the conventional templates has been increased, according to the suggestion of Prof. S. Ballarin.

For the isostatic reduction of the inner zones up to 13, use has been made of the *New Isostatic Tables* published in 1938, by Prof. W. Heiskanen; whereas for the outermost zones 10 to 1, the *Topographic-Isostatic World Maps* published in 1951, by E. Niskanen and L. Kivioja were used. The reductions for zones 13 to 11, that were not available, have been especially computed for the whole region covered by our survey, by the Isostatic Institute of the I. A. G.

In the computation of reductions, wide use has been made of the *Quarter Inch Map* of Pakistan and neighbouring regions, and of the *World Map* in the scale 1 to 1,000,000. Nevertheless, where possible, use has also been made of more detailed maps drawn by former expeditions or resulting from the photogrammetric and topographic surveys performed by Capt. F. Lombardi and the Pakistani Surveyor Bad-Shah-Jan of our Expedition.

In all instances the adopted height of the stations is that determined by our observations, which are reported in the attached sheets; but naturally the topographic reductions result from the differences of heights as derived from the map.

The following lists are self-explanatory, and need no further comment.

GRAVITY VALUES AND HEIGHTS OBSERVED BY THE EXPEDITION

(Approximate Latitude and Longitude of stations are derived from the Quarter Inch Map)

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
101	Skardu	a – Airport, passengers' lounge	35°17′	75°38′	2292	978 903.4
		b – Rest House near the Political Agent's Residence; on the window in SW room of the building			2270	909.1
		c – Compound of old Rest House; in the small building SW of the old bungalow; behind actual Officers' Mess; this station is identical with the pendulum station of the De Filippi's Expedition			2230	915.3
		d – Meteorological Observatory, W of Combined Hospital, on the top of a small hill; pluviometer			2237	915.0
		e – Fort, main entrance			2341	893.3
		f – Ferry-boat on Indus River; N side			2197	991.7
		g – Combined Hospital			2218	917.4
102	Hoto	– Camping ground	35°22′	75°30′	2279	907.0
103	Ayub Bridge	– N end of bridge	35°27′	75°26′	2253	915.8
104	Tsari	– Camping ground	35°28′	75°25′	2230	911.4
105	Gurbidas		35°30′	75°21′	2172	922.6
106	Byicha	a – Gali; top of the pass SE and 2 hours from Byicha	35°35′	75°20′	2431	876.1
		b – Camping ground (platane tree)			2117	922.7
107	Dasu	– Small square behind the mosque	35°36′	75°19′	2555	850.5
108	Twar	– Camping ground	35°36′	75°12′	2232	922.5
109	Rondu	– 2 ½ miles W of Twar, + 15 m above Indus River	35°36′	75°10′	1967	953.0
110	Sterika	a – Camping ground	35°35′	75°06′	2048	937.1
		b – 2 miles W of Sterika, 20 m above Indus River; « G »			1936	933.0
		c – At milestone 37 1/2, 10 m above Indus River			1936	949.1
111	Strongling	– 5 m above Indus River	35°38′	75°02′	1878	978 950.4

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
112	Stak – Indus confluence	– On the glacial saddle W of the confluence of Indus and Stak rivers, at the crossing of the footpath leading to Stak	35°43′	75°04′	2176	978 914.8
113	Malupah	– Small waterfall on the footpath, 50 m above Indus River	35°38′	74°59′	1864	927.9
114	Chutran	a – E end of village, underneath big rocks, ruins of houses	35°39′	74°57′	1974	914.9
		b – Crossing of a torrent, 20 m above Indus River			1766	917.5
115	Baroluma Gah	– Crossing of Baroluma Gah, 5 m above Indus River	35°43′	74°51′	1698	951.9
116	Shengus	a – Grave-yard			1914	929.9
		b – Gali 1; easternmost of two passes above Shengus	35°43′	74°49′	3155	723.0
		c – Gali 2; westernmost, and highest, of two passes above Shengus			3322	686.5
117	Burumdoir	a – At the crossing of Khalola Gah, 25 m above Indus River	35°46′	74°46′	1552	978 999.7
		b – 2 ½ miles NW of Burumdoir, at the foot of the spur causing the big bend of Indus River			1515	979 011.8
		c – Hot spring			1555	000.4
118	Shahbatot	– Foot-bridge on Ishkapal River, S of village, 15 m above Indus River	35°48′	74°44′	1481	020.2
119	Sasli	a – (Sassi, Haramosh) - Mosque	35°50′	74°45′	1529	015.1
		b – Camping ground S of Police Post, E of a rock facing Indus River			1515	022.9
		c – Confluence of Shirimal and Indus rivers, 1/2 mile N of Sasli; 1 m above Indus River				024.9
		d – Small cairn on the rock facing Indus River W of camping ground			1542	979 021.7

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
120	Indus – Gilgit River Confluence	a – 1 ½ miles NNE of the confluence of Indus and Gilgit rivers, at the sharp bend of jeepable road, on the alluvial terrace			1492	979 100.4
		b – Big rock E of jeepable road	35°46′	74°39′		101.0
121	Alam Bridge	– W end of the bridge	35°47′	74°34′	1388	134.1
122/360	Dak Chanki	– Milestone 8 miles from Gilgit, 10 from Parri, 77 from Chilas (1955)	35°53′	74°25′	1494	128.5
123/359	Gilgit	a – Airport, Control Tower, ground (1955)			1418	127.2
		b – Mir's of Hunza bungalow, yard of the bungalow, ground level	35°55′	74°18′	1558	123.5
124/355	Gakuch	– Rest House (1955)	36°10′	73°46′	1877	072.0
125/354	Haim	– Untraceable point; common in 1954 and 1955 expeditions	36°17′	73°43′	1905	979 068.6
126	Changmachu	– (Yowai) – Cairn on W end and below the village, facing the valley	35°40′	74°55′	2018	978 898.8
127	Stak	– Cairn on top of a small rock, facing the front of Stak Glacier	35°43′	75°04′	2737	778.3
128	Kurchung	– Big rock near the old graveyard, close to the water basin	35°42′	75°02′	2544	835.2
129	Kulankae	a – Camp 100 yards NE of a spring; « G »	35°45′	75°05′	3076	719.9
		b – Hamlet, N of the confluence of Kuthiah and Stak rivers, W of station No. 129/a			3077	722.5
		c – Kuthiah Glacier, camp at the base of the moraine, near big stones, S of Kuthiah Glacier; « G »			3305	672.7
		d – Kuthiah Hamlets – On S side of Kuthiah Valley			3291	978 691.2

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
		e – Camp IV – On S slope of Kuthiah Valley; « G »			3834	978 585.1
		f – Kuthiah Glacier – On the glacier, near the confluence of Kossomber and Kuthiah glaciers			3534	617.4
		g – Kossomber – Spur NW of the confluence of Kossomber and Kuthiah glaciers			3699	603.4
		h – Haramosh Glacier – On a spur covered with grass, 70 m above Haramosh Glacier, innermost part of Kuthiah Valley			3788	587.1
		i – Goropa – Camp in the valley of Goropa; « G »			3720	599.1
		l – Goropa – Photogrammetric Pillar A 15			4101	519.3
		m – Goropa – Camp, underneath Goropa-La			4160	506.5
130	Stak La	a – Camp W of Stak La, on a spur covered with grass between the moraine of Stak Glacier, and the slope of the mountain			4037	554.6
		b – Cairn on the Pass; « G »	35°45′	75°09′	4646	455.0
		c – Camp on E side of Stak La, on a flat ground covered with grass; « G »			4057	560.5
131	Chutrun Tormik	– Hot spring; big rock; « G »	35°43′	75°13′	3560	656.6
132	Hurimal	– Mosque	35°39′	75°17′	2898	779.3
133	Klashin	– « G » on rock	35°37′	75°19′	2724	815.0
134	Pakora	– « G » on rock 1/2 mile from the village, on the way from Hurimal to Ganto La	35°40′	75°19′	3582	641.0
135	Ganto La	– On the Pass	35°40′	75°21′	4482	476.2
136	Mantuntoro Klas	– Camping ground near hamlets; « G »	35°41′	75°22′	3610	636.9
137	Chu Tran	– Hot springs, at the entrance of the upper building; 3 m above Basha River	35°42′	75°25′	2449	978 815.7

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
138	TISSAR	a – Bontaws – Mosque	35°39′	75°26′	2441	978 833.0
		b – Gabkhor – Mosque			2441	835.0
		c – Cantilever bridge across Basha River at Tissar, W end			2401	842.2
139	MOLTO	– Ferry-boat, rock on W side of Basha River; « G »	35°39′	75°28′	2396	842.9
140	HORITSHO	– Hamlets, alluvial plain N of confluence Braldu – Basha; « G » on big rock	35°40′	72°28′	2383	840.1
141	TIGSTUN	– Mosque	35°42′	75°29′	2446	791.8
142	DUSSO	a – Mosque	35°43′	75°31′	2442	784.8
		b – Ferry-boat, N side				791.2
		c – Ferry-boat, S side, in front of Tigstun			2395	801.5
143	NIYIL	– 2 miles E of Dusso, at the level of Braldu River, underneath a steep rock with remains of wooden ladders; « G » on rock	35°43′	75°32′	2458	768.9
144	BIANO	a – Glacial saddle on the spur in front of Goyungo, 1 mile SW of Biano	35°42′	75°36′	2858	710.8
		b – Spur of rock at the sharp bend of Braldu River, above a terrace 50 m above the river; « G »			2553	748.1
		c – At the foot of the steep climb of the footpath on the moraine terrace; « G » on rock			2508	750.8
145	CHOKPIONG	a – (Gomboro) – Mosque	35°45′	75°37′	2662	739·5
		b – (Gomboro) – Wooden bridge across Hoh Lumba River, 300 yards W of Chokpiong			2609	738.9
146	TOSHA	– Braldu Gorges, foot-bridge; « G » on rock	35°44′	75°40′	2662	723·3
147	HOT SPRING	a – I – Braldu Valley	35°43′ 30″	75°41′	2704	709·3
		b – II – Braldu Valley	35°43′	75°43′	2750	978 702 5

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
148	Hoto	– (Pakoro; Braldu Valley) – Rock in a flat ground 1/2 mile W of rope-bridge; « G »	35°41′	75°44′	2804	978 695.1
149	Chaongo	– Mosque	35°41′	75°45′	2970	675.9
150	Sulphur Spring Chongo	– Lowest spring	35°41′	75°45′	3015	674.7
151	Tongnol	a – Camping ground in the highest part of the village	35°41′	75°47′	3079	664.7
		b – Mosque			3180	677.1
152	Surungo	– Mosque	35°41′	75°47′	3148	660.8
153	Askole	a – Camp above the village	35°40′	75°49′	3080	667.3
		b – Mosque			3043	672.5
154	Gortchow	– Small waterfall near the footpath, 2 miles E of Askole	35°40′	75°52′	3064	663.1
155	Ste Ste	a – Rock spur at the sharp bend of Braldu River, opposite Ste Ste; « G »	35°40′	75°53′	3001	678.6
		b – Spring 1 mile NE of Ste Ste; « G » on big rock			2992	678.1
156	Biafo	– Camp on the E moraine at the confluence of Biafo and Biaho valleys	35°41′	75°54′	3072	671.7
157	Korophon	– Hamlet underneath a big, isolated rock; « G »	35°41′	75°59′	3094	666.6
158	Laskam	– On the alluvium at the confluence of Dumordo and Biaho rivers	35°42′	75°59′	3100	660.7
159	Dumordo	a – Suspension bridge – W end; « G »	35°44′	75°59′	3182	642.0
		b – Suspension bridge – E end; « G »			3176	641.6
160	Golab	a – Isolated rock on the alluvial plain SE of the confluence of Dumordo and Biaho rivers; « G »	35°38′	76°01′	3137	659.6
		b – Camp			3147	648.7
161	Cholblak	– Roof-shaped rock on N side of Biaho River; « G »	35°39′	76°00′	3145	633.4
162	Bardumal	– Rock on N side of Biaho; « G »	35°38′	76°01′	3204	627.1
163	Bardumal Paju	– Rock on N side of Biaho; « G »	35°39′	76°05′	3270	978 613.6

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
164	PAJU	a – Camp on a small spur, 50 yards W of a small spring in a green valley; « G » on rock	35°40′	76°06′	3402	978 583.3
		b – Rock at the base of the front of Baltoro Glacier, NW of the same; « G »	35°40′	76°07′	3379	578.1
		c – Big rock 1/2 mile W of the front of Baltoro Glacier, in the middle of the alluvial plain			3410	568.9
165	BALTORO GLACIER	– On the glacier's front	35°40′	76°07′	3577	
166	LILIGO	a – Camping ground on the moraine S of Baltoro Glacier, underneath big rocks; « G »	35°42′	76°11′	3738	508.8
		b – Bottom of Liligo Valley at the confluence with Baltoro Glacier, in the small alluvial plain	35°42′	76°12′	3800	499.9
167	CHOBER ZECHEN	– (Hobertse) – Flat ground on the moraine S of Baltoro Glacier; « G »	35°44′	76°13′	3866	486.6
168	URDUKAS	a – Rock on a steep, grassy slope; « G »	35°44′	76°16′	4031	452.8
		b – On the Baltoro Glacier, 2 miles E of Urdukas	35°44′	76°18′	4136	412.6
169	BALTORO GLACIER	a – Gore	35°46′	76°18′	4315	380.9
		b – Biange	35°46′	76°22′	4269	370.4
		c – Doksam	35°45′	76°28′	4475	353.3
		d – Concordia	35°45′	76°31′	4633	319.6
170	K2 BASE CAMP	– On the Godwin Austen Glacier, 1 mile below the confluence of De Filippi's Glacier, and 1/2 mile E of the Memorial pillar (No. 171)	35°51'	76°31′	4978	267.8
171	MEMORIAL PILLAR	– Memorial pillar constructed by the American Expedition led by Houston in 1953; close to it, the grave of Mario Puchoz	35°50′	76°29′	4994	978 275.7

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
172	KASHUMAL	a – Mosque	35°35′	75°35′	2315	978 839.9
		b – Camping ground			2314	843.1
173	SILDI	– Mosque	35°34′	75°36′	2308	851.8
174	ATRORO	– Mosque	35°33′	75°38′	2295	865.4
175	HUSHUPA	– Mosque	35°31′	75°41′	2319	861.3
176	MASHINGPA	– (Marshantpa) – Mosque	35°28′	75°43′	2285	885.8
177	TUNGMO	– Mosque	35°27′	75°43′	2252	889.5
178	SENGOR	– Mosque	35°26′	75°44′	2247	888.1
179	SHIGAR	a – Small mosque at NW end of town	35°25′	75°45′	2279	890.6
		b – Big mosque			2285	889.5
		c – Polo ground			2284	890.9
180	KOTHUNG	a – On the alluvial plain of Shigar River, at the big bend of the river	35°23′	75°45′	2248	901.9
		b – Moraine at the foot of the hills on the W side of the valley; « G »			2209	915.6
181	YARBA TSO	– Willow tree at SW end of the lake	35°22′	75°44′	2208	920.2
182	SURPARAGHA	– At the foot of the steep ascent of the rocky spur, NW side	35°20′	75°40′	2204	924.5
183	BLUKRO	a – On the plain between two big rocky spurs	35°20′	75°39′	2202	922.0
		b – On the moraine covered with sand			2234	920.3
184	THURGON	– Mosque	35°18′	75°46′	2227	907.4
185	FAQIRS HUT	– At the rocky spur in front of Nurhnuchung, on the alluvial plain, 40 m above Indus River	35°20′	75°48′	2288	898.6
186	GOL	– Mosque, lowest of two	35°15′	75°52′	2319	884.1
187	SHYOK	– Wooden bridge of jeepable road S of confluence of Shyok and Indus rivers	35°13′	75°55′	2300	888.6
188	HUMAYUN BRIDGE	– W pillar of suspension bridge across Indus River	35°13′	75°55′	2306	889.2
189	SERMI	– Old mosque at S end of village; 15 m above Indus	35°11′	75°54′	2318	886.9
190	SAHLING	– SE end of polo ground	35°08′	75°57′	2340	978 889.8

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
191	MANTHOKA	– Big mosque	35°06′	75°59′	2340	978 895.2
192	TOLTI	– Rest House; station identical with De Filippi's Gravity Station	35°02′	76°06′	2423	853.6
193	MAIRDO	– Mosque	35°00′	76°09′	2431	841.9
194	KHARMANG	– Suspension bridge, W end, at the level of Indus River	34°57′	76°13′	2483	822.8
195	BAGICHA	– Mosque	34°55′	76°11′	2499	978 820.3
301	MARGALA PASS	– Memorial of Brigadier General J. Nicolson	33°43′	72°49′	534	979 349.0
302	HASAN ABDAL	a – Memorial of Gurn Nanak, main entrance	33°50′	72°42′	434	385.1
		b – Railway Station h=1,450 ft.			454	378.9
303	ATTOCK BRIDGE	– Rawalpindi, side end, at the door of Police Office	33°53′	72°15′	289	417.9
304	NOWSHERA	– Main entrance of railway station	34°01′	71°58′	299	414.3
305	MARDAN	– Main entrance of railway station (under construction)	34°11′	72°04′	314	432.2
306	SHERGARH	– Near milestone No. 33 (18 miles from Mardan and 15 miles from Malakand)	34°24′	71°54′	383	413.6
307	MALAKAND	– At the road crossing, in front of Shell petrol pump	34°33′	71°58′	826	329.5
308	JALWANA	– Bridge on the motorable road, 1 1/4 mile NE of But Khela village	34°37′	72°00′	665	353.9
309	BANDAGAI LEVY POST	– Main entrance	34°45′	71°51′	775	338.2
310	KHAL	– NW end of the mosque, towards wooden bridge	34°49′	71°50′	838	372.0
311	NIAGDARA	– N end of the W side of the iron bridge	35°03′	72°00′	952	354.0
312	PANJKORA RIVER	N end of the E parapet of iron bridge over Panjkora River	35°09′	71°54′	1133	280.3
313	DIR	Main entrance of Levy Post	35°13′	71°52′	1405	979 220.8
314	LAWARAI PASS	– Pass	35°21′	71°48′	3145	978 890.0
315	ZIARAT	– Eastern end of the small				

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
		wooden bridge just below the Levy Post	35°22′	71°47′	2239	979 038.0
316	MIRKHANI	– Near the main entrance of the Scouts' Post	35°27′	71°44′	1302	211.3
317	DROSH	– Rest House	35°33′	71°49′	1359	192.4
318	BROG	– S end of the small bridge over Brog Gol, N of the village	35°43′	71°47′	1538	114.4
319	CHITRAL	– Rest House, near the water tank, S of Mehtari Residence, Naghore	35°54′	71°47′	1508	107.9
320	RIVER CONFLUENCE	– Confluence of Chitral and Mastuj rivers, on the road from Chitral to Mastuj	35°58′	71°49′	1548	098.4
321	KARI	– Small bridge south of Kari	35°54′	71°50′	1561	087.5
322	ROGH	– Mosque	35°55′	71°53′	1607	076.2
323	KOGHOZI	a – Court-yard of the mosque	35°56′	71°56′	1674	070.1
		b – Mehtari Rest House			1694	064.9
324	TUREN MORE	– On Chitral-Mastuj Road, near the confluence of Chumuruk and Mastuj rivers, opposite Turen More	36°00′	71°59′	1750	048.0
325	MAROI	– Court-yard of the mosque	36°01′	72°00′	1854	979 034.6
326	DALUM GOL	– On Chitral-Mastuj Road, at the crossing with Dalum Gol	36°03′	72°01′		978 994.5
327	BARENIS	a – Court-yard of the mosque	36°04′	72°03′		979 025.0
		b – Grave-yard SE of Mehtari Rest House				023.9
		c – Camping ground E of village				016.9
328	RESHUN	– Verandah of Mehtari Rest House, NE corner	36°09′	72°06′	1931	020.2
329	CHARAN	– In the lawn of Gulah Shah	36°10′	72°13′	1966	979 017.5
330	BUNI	– Verandah of Middle School	36°16′	72°15′	2091	978 996.8
331	AWI	– Verandah of the little mosque	36°16′	72°20′	2098	989.5
332	SANOGHAR	– Verandah of Mehtari Rest House	36°18′	72°24′	2290	950.5
333	LASPUR RIVER	– E end of the bridge over Laspur River	36°15′	72°30′	2349	978 928.4

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
334	MASTUJ	– Rest House at the Police Station	36°17′	72°31′	2331	978 943.3
335	CHAPALLI	– At the door of the mosque	36°20′	72°36′	2403	924.9
336	BREP	– Camping ground	36°27′	72°38′	2481	904.5
337	YUGUM	– Crossing of the river	36°29′	72°43′	2546	887.5
338	MIRAGRAM	– Mehtari Rest House	36°32′	72°44′	2642	876.3
339	ZHOPU	– Verandah of house	36°35′	72°55′	2762	850.9
340	GAZIN	– Camping ground on the land of Ghulam Haider about 1/8 mile E of village Gazin	36°39′	72°56′	2958	811.2
341	DOBARGAR	a –	36°41′	72°55′	2913	808.9
		b –			2943	808.5
342	LASHT	– Mehtari Rest House	36°47′	73°01′	3239	772.7
343	KISHMANJA	– Camp	36°49′	73°12′	3261	749.0
344	ISHKAWARZ	– Police and custom-house	36°50′	73°20′	3528	729.9
345	BAROGHIL PASS	– Lowest of two cairns 100 yards apart	36°53′	73°22′	3890	675.8
346	CHIKAR	– Camping ground	36°49′	73°19′	3633	700.0
347	DARKOT PASS	– Pass	36°45′	73°25′	4614	518.7
348	RAWAT	– Spring	36°42′	73°25′	3153	782.2
349	DARKOT	– Camping ground	36°39′	73°26′	2697	857.2
350	BARKULTI	– Camp	36°29′	73°21′	2460	921.8
351	YASIN	– Rest House	36°23′	73°20′	2395	951.4
352	GIUDAI	– Camp	36°18′	73°24′	2991	978 964.4
353	GUPIS	– Rest House	36°14′	73°27′	2175	979 009.0
354/ 125	HAIM	– Same station as observed in 1954	36°17′	73°43′	1905	068.6
355/ 124	GAKUCH	– Rest House (observed also in 1954)	36°10′	73°46′	1877	072.0
356	SINGAL	– Rest House	36°06′	73°53′	1824	062.2
357	GULAPUR	– Rest House	36°04′	74°05′	1737	064.7
358	HENZAL OMAIN	– Small mosque	35°58′	74°12′	1542	096.6
359	GILGIT	a – Gilgit Scouts' Bungalow	35°55′	74°18′		114.7
359/ 123a		b – Airport Control Tower (observed also in 1954)			1418	127.2
360/ 122	DAK CHANKI	– Milestone, 8 miles from Gilgit	36°53′	74°25′	1494	128.5
361	INDUS VALLEY	– Milestone, 30 miles from Gilgit	35°42′	74°38′	1356	115.3
362	THELICHI	– Rest House	35°34′	74°38′	1408	979 104.4

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
363	RAKHIOT BRIDGE	– Suspension bridge, S side	35°30′	74°36′	1300	979 120.6
364	JALIPUR	– Government Store, S of the bridge	35°27′	74°28′	1200	156.9
365	GRASS FARM	– Spring	35°24′	74°23′	1186	168.9
366	CHILAS	a – Meteorological Observatory	35°25′	74°06′	1291	242.1
		b – Compound of the Rest House			1293	248.5
367	THAK	– Bridge in the village	35°18′	74°07′	1890	979 056.0
368	UTLA BABUSAR	– Rest House	35°12′	74°03′	2985	978 834.3
369	BABUSAR PASS	– Cairn	35°09′	74°03′	4150	606.1
370	LAKE LULU SAR	– Bridge on SE end of the lake	35°04′	73°56′	3398	748.8
371	BATTAKUNDI	– Police Station	35°56′	73°45′	2665	867.6
372	NARAN	– Rest House	34°54′	73°39′	2385	922.5
373	KAGAN	– Bridge in the village	34°47′	73°32′	2064	978 983.2
374	MAHANDRI	– Rest House	34°42′	73°35′	1545	979 074.7
375	KAVAI	– Rest House	34°38′	73°27′	1498	116.9
376	BALAKOT	– Rest House	34°32′	73°21′	1011	228.2
377	ATTERSISHA	– Bridge on the road Muzaffarabad – Mansehra, 9 ½ miles from the last locality	34°24′	73°19′	1056	237.8
378	MANSEHRA	– Hazara Deputy Commissioner's Rest House	34°20′	73°13′	1096	243.2
379	ABBOTTABAD	– Mosque in bazar	34°09′	73°13′	1238	225.3
380	HAVELIAN	– Railway Station Hall h = 2,816 ft.	34°03′	73°10′	864	299.0
381	HARIPUR	– Railway Station Hall h = 1,735 ft.	33°59′	72°56′	528	361.7
382	DEHDAR	– Mosque	33°56′	72°49′	471	372.5
383	BURHAN	– Railway Station h=1,253 ft.	33°49′	72°36′	406	396.6
384	AKORA KHATTAK	– Railway Station h = 969 ft.	34°00′	72°09′	320	415.5
385	PABBI	– Railway Station h = 976 ft.	34°00′	71°47′	321	399.4
386	PESHAWAR	a – Dean's Hotel, room No. 36	34°00′	71°34′		392.3
		b – St. John's Church			371	389.9
		c – Civil Airport, verandah of passengers' lounge				390.4
387	JAMRUD FORT	– Police Station on the road	34°00′	71°23′	487	376.4
388	LANDI KOTAL	– Railway Station, main entrance h = 3,495 ft.	34°06′	71°09′	1068	264.4
389	CHARSADDA	– Mosque in the bazar	34°09′	71°45′	329	416.1
390	SHAHBAZGARHI	– Rest House, ground level	34°14′	72°10′	325	979 438.4

No.	Name	Description	Lat.	Long.	Height metres	Observed gravity
391	TAKHT-I-BHAI	– Railway Station, h = 1,129 ft.	34°16′	71°56′	356	979 416.5
392	BARIKOT	– Mosque in the new bazar	34°40′	72°14′	799	326.7
393	SAIDU SHERIF	– Hotel Swat, room No. 15	34°45′	72°22′	940	302.1
394	CHALIAR	– Bridge on motorable road, 1 ½ miles N of Khwazakhela	34°57′	72°29′	1174	333.8
395	FATEHPUR	– Bridge on motorable road, across Miandam Khwar	35°04′	72°30′	1300	290.0
396	TIRAT	– Bridge across Swat River, E end	35°10′	72°32′		274.5
397	BARANIAL	– Police Post on motorable road	35°12′	72°33′	1442	231.6
398	RAMET	– Bridge across Swat River, W end	35°17′	72°36′	1521	186.2
399	KULALI	–	35°19′	72°37′	1630	156.6
400	KALAM	– Fort	35°32′	72°35′	2017	065.4
401	NAJIGRAM	– End of motorable road	34°39′	72°14′	856	312.2
402	PACHA	– Motorable road crossing 1 ½ miles S of Pir Baba Ziarat	34°35′	72°27′	739	340.9
403	DAGGAR	– Bridge across the deep gorge	34°30′	72°28′	701	361.3
404	RUSTAM	– Bazar	34°21′	72°17′	388	415.5
405	SWABI	– Rest House	34°08′	72°29′	349	412.2
406	LAHOR	– On the main road, milestone 10 miles from Jahangira	34°02′	72°22′	311	410.6
407	LAWRENCEPUR	– Railway Station, h = 1,310 ft.	33°50′	72°31′	407	979 395.1

Stations numbered from 101 to 195 refer to the 1954 campaign
Stations numbered from 301 to 407 refer to the 1955 campaign
« G » means that a G has been painted with red paint on the rock

FREE AIR, BOUGUER AND AIRY ANOMALIES

for 69 stations by the Italian Karakorum K2 Expedition, 6 stations by the De Filippi Expedition, and 40 stations by the Sino-Swedish Expedition of Dr. Sven Hedin

No.	Station	Height metres		Gravity		Anomalies mgal							
								Airy			Bouguer modified		
								T					
		observed	map	observed	normal	Free Air	Bouguer	20	30	40	20	30	40
101 d	SKARDU	2237	2281	978 915.0	979 771.0	-165.7	-410.8	16.7	16.2	10.9	-356.1	-339.0	-324.0
102	HOTO	2279	2271	978 907.0	979 776.8	-166.9	-409.3	31.4	26.7	21.2	-354.4	-338.0	-321.9
103	AYUB BRIDGE	2253	2057	978 915.8	979 758.2	-174.2	-407.0	32.3	28.7	23.9	-350.4	-334.0	-317.7
106 b	BYICHA	2117	2042	978 922.7	979 795.3	-219.4	-434.0	11.8	7.7	1.3	-377.1	-360.5	-344.0
109	RONDU	1967	2027	978 953.0	979 796.7	-236.8	-436.7	4.5	- 0.8	- 6.8	-379.9	-361.7	-346.7
113	MALUPAH	1864	2042	978 927.9	979 800.8	-297.4	-461.5	-17.9	-23.5	-29.7	-405.6	-388.7	-372.1
116 c	SHENGUS	3322	2896	978 686.5	979 808.1	- 96.5	-448.4	-22.0	-26.4	-32.1	-395.9	-379.2	-363.2
121	ALAM BRIDGE	1388	1372	979 134.1	979 813.7	-251.3	-372.2	52.8	50.7	45.6	-315.0	-298.6	-283.3
128	KURCHUNG	2544	2210	978 835.2	979 806.5	-186.3	-433.1	2.2	- 3.7	-10.5	-376.8	-360.0	-343.5
131	CHU TRAN	3560	2545	978 656.6	979 806.6	- 51.5	-411.3	44.8	37.1	28.8	-357.3	-340.0	-323.2
135	GANTO LA	4482	4606	978 476.2	979 803.7	55.5	-387.8	58.3	53.3	45.9	-338.1	-320.1	-303.5
142 a	DUSSO	2442	2667	978 784.8	979 806.6	-267.7	-515.6	-60.0	-66.2	-73.1	-459.1	-442.2	-425.1
148	HOTO	2804	2926	978 695.1	979 805.1	-244.8	-529.5	-53.0	-62.3	-72.5	-475.4	-457.8	-440.4
157	KOROPHON	3094	3109	978 666.6	979 805.1	-183.8	-501.2	-14.7	-26.2	-38.1	-446.7	-429.2	-412.4
164 a	PAJU	3402	3536	978 583.3	979 802.4	-169.3	-532.7	-39.5	-52.1	-65.3	-481.0	-463.3	-446.0
168 a	URDUKAS	4031	4057	978 452.8	979 808.1	-111.4	-540.7	-34.3	-49.8	-64.3	-491.3	-473.8	-456.2
169 d	BALTORO GLACIER	4633	4630	978 319.6	979 809.4	- 57.7	-562.2	-27.6	-45.0	-61.7	-495.7	-477.2	-459.9
170	K2 BASE CAMP	4978	5000	978 267.8	979 817.9	- 14.1	-541.9	-28.5	-44.1	-60.4	-496.1	-475.9	-458.8
172 a	KASHUMAL	2315	2400	978 839.0	979 795.3	-242.3	-481.9	-25.7	-30.2	-36.6	-425.3	-408.6	-391.5
175	HUSHUPA	2319	2256	978 861.3	979 789.5	-212.6	-456.8	- 4.4	- 9.5	-15.6	-400.3	-383.8	-367.2
179 c	SHIGAR	2284	2240	978 890.9	979 782.4	-186.4	-429.8	24.0	19.0	13.3	-373.8	-357.3	-340.5
185	FAQIRS HUT	2288	2286	978 898.6	979 775.3	-170.7	-414.0	38.9	33.5	26.9	-358.8	-343.0	-326.9
187	SHYOK	2300	2339	978 888.6	979 763.9	-165.0	-408.0	41.8	35.7	27.2	-353.3	-336.7	-320.5
191	MANTHOKA	2340	2390	978 895.2	979 752.8	-135.9	-376.6	74.7	68.4	59.2	-321.8	-305.0	-288.7
192	TOLTI	2423	2576	978 853.6	979 748.4	-147.1	-401.9	55.9	48.8	37.9	-347.0	-330.0	-313.5
195	BAGICHA	2499	2316	978 820.3	979 738.5	-142.8	-383.5	58.5	55.4	48.6	-329.4	-310.1	-293.8
302 b	HASAN ABDAL	454	442	979 378.9	979 647.5	-128.4	-179.9	-52.2	-34.5	-20.4	-135.5	-122.2	-109.2
306	SHERGARH	383	396	979 413.6	979 696.3	-164.6	-207.7	-61.3	-41.9	-28.4	-164.6	-151.2	-138.7
307	MALAKAND	826	307	979 329.5	979 710.3	-126.3	-217.9	-44.9	-30.6	-20.7	-175.0	-161.9	-149.5
310	KHAL	838	762	979 372.0	979 731.6	-101.0	-191.6	17.1	27.1	32.6	-149.3	-135.9	-123.5
313	DIR	1405	1524	979 220.8	979 763.9	-109.6	-258.8	30.1	30.2	28.4	-218.6	-207.8	-191.8
314	LAWARAI PASS	3145	2713	978 890.0	979 773.8	86.6	-254.6	52.4	50.1	47.9	-218.5	-204.4	-190.8
317	DROSH	1350	1372	979 192.4	979 793.7	-182.0	-312.1	28.7	25.0	19.8	-272.7	-258.5	-245.6
319	CHITRAL	1508	1524	979 107.9	979 818.0	-245.1	-386.0	-12.7	-20.2	-30.6	-346.7	-333.5	-322.2
323 b	KOGHOZI	1694	1676	979 064.9	979 825.2	-238.2	-388.4	0.3	-10.5	-19.9	-346.3	-334.3	-321.1
328	RESHUN	1931	1981	979 020.2	979 843.8	-227.7	-410.6	- 8.9	-19.2	-30.6	-371.5	-355.7	-341.7
334	MASTUJ	2331	2438	978 943.3	979 855.2	-192.7	-428.2	- 5.8	-18.0	-29.4	-386.0	-371.0	-355.8
336	BREP	2481	2515	978 904.5	979 868.0	-198.0	-445.7	-15.2	-24.5	-34.3	-401.3	-386.1	-371.1
340	GAZIN	2958	2972	978 811.2	979 883.8	-159.9	-457.9	-16.8	-24.6	-37.4	-414.6	-388.3	-383.2
342	LASHT	3239	3200	978 772.7	979 899.7	-127.5	-469.2	-22.9	-28.3	-40.9	-424.9	-408.7	-393.4
345	BAROGHIL PASS	3890	3810	978 675.8	979 906.9	- 30.8	-460.3	0	-11.9	-23.4	-415.8	-399.8	-384.0
347	DARKOT PASS	4614	2743	978 518.7	979 895.4	47.0	-429.9	19.7	15.0	3.2	-381.6	-366.0	-350.8
351	YASIN	2395	2438	978 951.4	979 863.7	-173.3	-414.8	16.6	9.2	- 1.3	-366.6	-351.3	-336.3
354/125	HAIM	1905	1880	979 068.6	979 849.5	-193.4	-357.1	65.5	59.4	52.3	-307.8	-291.9	-276.5
356	SINGAL	1824	1890	979 062.2	979 839.5	-214.2	-386.1	31.5	26.4	18.8	-336.0	-320.1	-305.1
357	GULAPUR	1737	1722	979 064.7	979 836.5	-233.4	-383.6	30.8	26.4	20.4	-332.7	-316.1	-301.2
358	HENZAL OMAIN	1542	1524	979 096.6	979 827.9	-256.7	-382.7	25.8	23.8	19.1	-329.3	-312.5	-297.8
359/123 a	GILGIT	1418	1494	979 127.2	979 823.8	-259.7	-391.7	10.5	10.4	5.0	-337.7	-320.5	-306.7
363	RAKHIOT BRIDGE	1300	1164	979 120.6	979 788.0	-266.0	-358.0	41.4	38.4	33.9	-302.2	-285.8	-269.9
366 a	CHILAS	1291	1220	979 242.1	979 780.9	-140.4	-268.0	99.6	101.1	99.3	-215.2	-200.0	-184.9
369	BABUSAR PASS	4150	4173	978 606.1	979 757.0	-129.7	-327.9	38.9	31.3	23.7	-289.6	-272.3	-255.9
371	BATTAKUNDI	2665	2591	978 867.6	979 739.9	- 50.0	-323.6	10.4	- 2.6	-12.8	-282.8	-267.2	-252.1
373	KAGAN	2064	2134	978 983.2	979 727.2	-107.1	-314.9	- 2.7	-11.4	-18.1	-273.0	-258.3	-244.2
376	BALAKOT	1011	1067	979 228.2	979 707.5	-167.3	-269.6	-19.4	-16.4	-15.5	-226.1	-212.7	-199.4
378	MANSEHRA	1096	1067	979 243.2	979 690.7	-109.3	-232.4	-29.0	-19.1	-12.7	-188.5	-175.1	-162.2
379	ABBOTTABAD	1238	1250	979 225.3	979 674.0	- 66.7	-205.9	-10.5	- 1.7	5.3	-162.6	-149.0	-135.6
381	HARIPUR	528	533	979 361.7	979 660.0	-153.4	-195.1	-44.1	-28.7	-17.0	-150.6	-137.4	-124.6
386 b	PESHAWAR	371	351	979 389.9	979 661.4	-157.0	-199.0	-65.5	-46.2	-32.6	-156.3	-143.2	-131.1
387	JAMRUD FORT	487	457	979 376.4	979 661.4	-134.7	-189.4	-40.1	-24.0	-12.9	-147.2	-134.0	-121.9
389	CHARSADDA	329	305	979 416.1	979 674.0	-156.4	-193.6	-67.2	-45.8	-30.1	-150.7	-137.6	-125.1
390	SHAHBAZGARHI	325	320	979 438.4	979 680.9	-142.2	-179.0	-46.7	-26.3	-11.6	-135.7	-122.3	-109.7
392	BARIKOT	799	777	979 326.7	979 718.8	-145.6	-232.9	-38.4	-28.3	-21.6	-190.2	-176.8	-164.2
393	SAIDU SHERIF	940	945	979 302.1	979 724.5	-132.4	-235.7	-21.4	-14.0	- 9.3	-193.1	-179.9	-167.5
395	FATEHPUR	1300	1295	979 290.0	979 751.2	- 60.1	-196.8	90.3	90.9	90.3	-152.8	-138.9	-125.4
398	RAMET	1521	1524	979 186.2	979 769.6	-114.1	-241.4	92.1	84.8	79.3	-197.5	-182.9	-169.2
400	KALAM	2017	2012	979 065.4	979 790.9	-103.1	-315.7	43.7	37.3	29.8	-272.2	-256.6	-242.6
402	PACHA	739	762	979 340.9	979 710.5	-141.6	-221.9	-29.0	-19.3	-12.3	-178.9	-165.5	-152.7
404	RUSTAM	388	381	979 415.5	979 690.7	-155.2	-198.5	-50.0	-34.5	-21.9	-154.9	-141.7	-129.0
405	SWABI	349	366	979 412.2	979 671.3	-151.4	-190.9	-57.8	-38.1	-23.5	-146.9	-133.6	-120.9

De Filippi Expedition 1913-1914

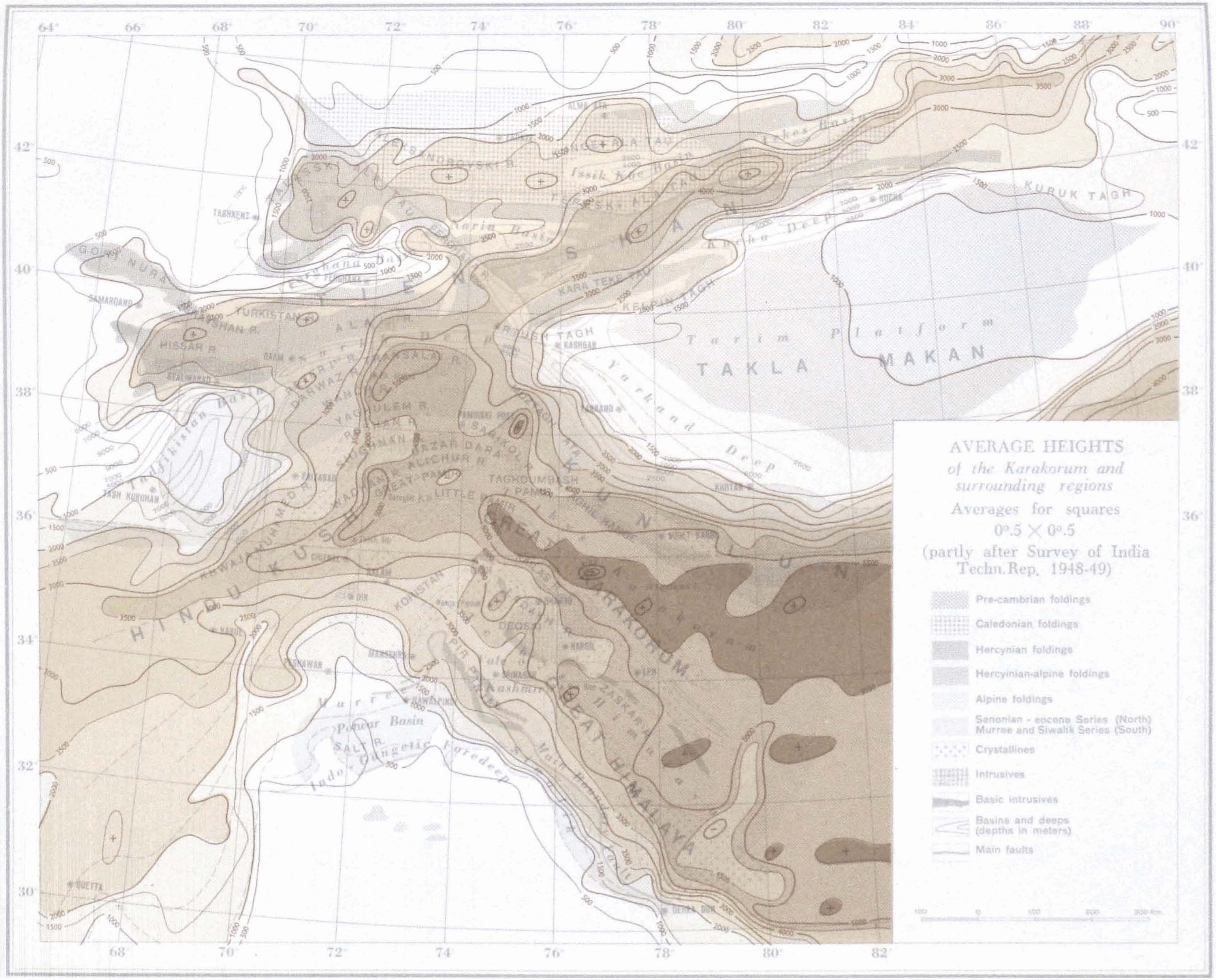
No.	Station	Height metres		Gravity		Anomalies mgal							
		observed	map	observed	normal	Free Air	Bouguer	Airy			Bouguer modified		
								T					
								20	30	40	20	30	40
	Kashgar	1343	1335	979 535.0	980 133.1	-183.7	-335.1	-87.3	-72.5	-60.4	-282.2	-266,3	-251.0
	Wazul Hadur	4243	4267	978 528.0	979 762.5	74.8	-397.4	33.6	26.0	16.3	-352.6	-335,7	-321.6
	Lamayuru	3461	3550	978 566.0	979 685.1	- 51.0	-438.2	23.8	17.3	10.3	-382.9	-365,0	-347.6
	Kargil	2713	3920	978 837.0	979 708.9	- 34.7	-339.7	99.6	93.2	86.0	-288.7	-271,1	-254.6
	Suget Karaul	3681	4500	978 733.0	979 860.8	8.0	-403.5	82.4	67.8	53.5	-357.0	-339,0	-321.6
	Depsang	5361	5363	978 165.0	979 770.1	42.3	-564.6	-42.7	-61.2	-77.8	-521.7	-504,7	-487.8

Sino-Swedish Expedition 1929-1933

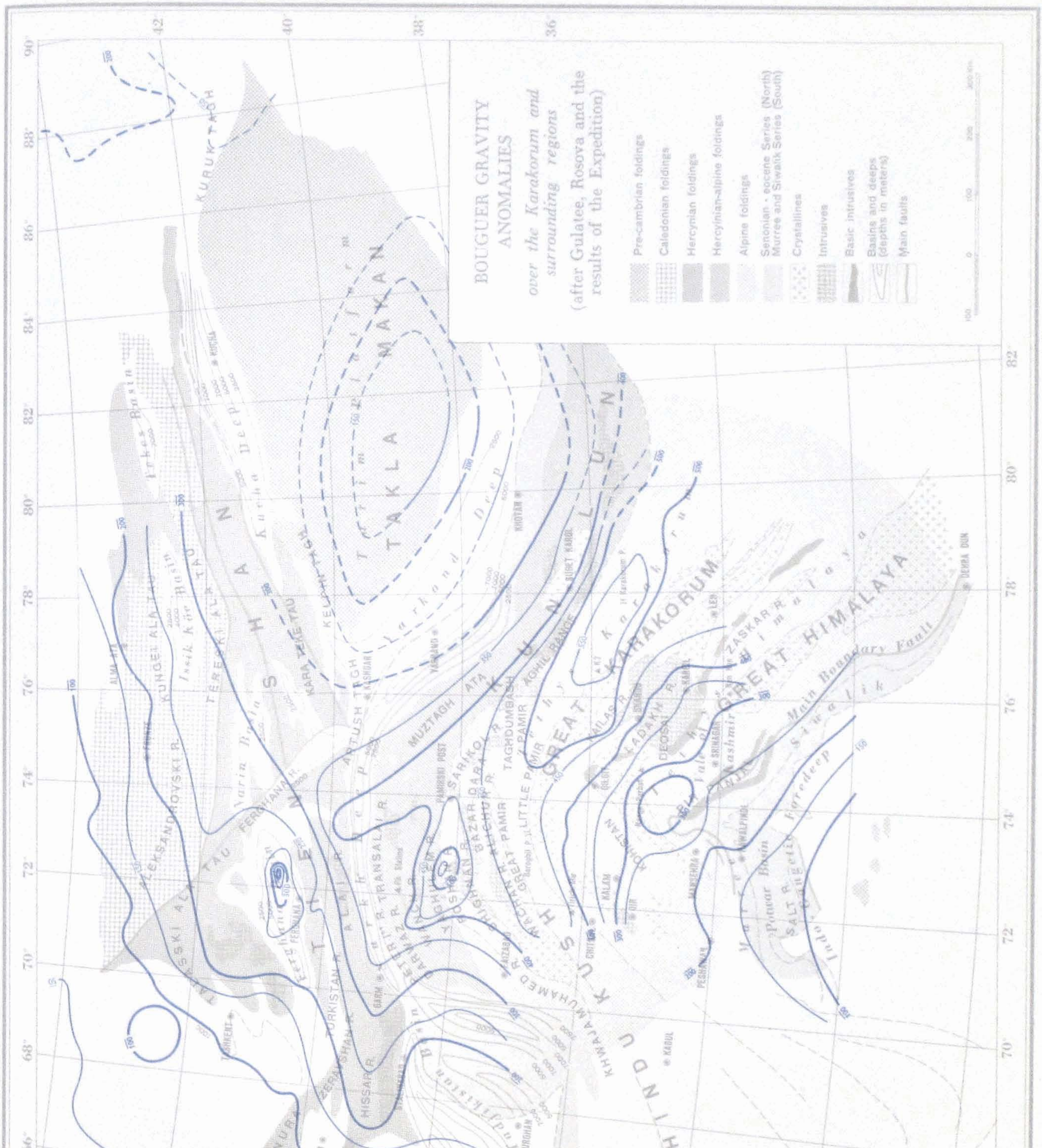
No.	Station	Height metres		Gravity		Anomalies mgal							
		observed	map	observed	normal	Free Air	Bouguer	Airy			Bouguer modified		
								T					
								20	30	40	20	30	40
1	Urumchi	924	940	980 113.3	980 519.2	-122.0	-224.9	- 63.4	- 62.2	- 62.0	-201.2	-193.8	-186.0
2	Turfan	76	50	980 218.8	980 443.9	-202.0	-210.0	-128.3	-111.3	- 99.4	-184.9	-176.8	-168.6
3	Qush-dong	-44	70	980 235.1	980 433.6	-213.0	-207.2	-137.4	-118.6	-105.8	-182.1	-174.0	-166.8
4	Su-bashi	276	250	980 187.3	980 451.3	-179.0	-210.3	-116.3	102.5	- 92.8	-185.2	-177.1	-168.9
5/17	Ch'ai-o-p'u	1115	1180	980 049.4	980 492.6	-101.0	-225.6	- 43.4	- 46.2	- 49.5	-203.0	-193.2	-188.5
6	Shor-bulaq	781	900	979 991.8	980 368.0	-137.0	-223.6	- 83.7	- 80.0	- 78.4	-198.0	-188.5	-180.4
7	Arpishme-bulaq	726	720	980 055.4	980 359.6	- 82.0	-162.4	- 40.9	- 34.5	- 31.1	-136.8	-127.3	-119.3
8	Mo-chia-khutuk	1926	2080	979 773.0	980 309.7	55.0	-156.7	10.6	4.8	1.4	-132.5	-122.6	-113.3
9	Yukken-gol	1768	1800	979 810.8	980 308.9	46.0	-150.6	11.3	7.3	5.4	-126.5	-116.2	-106.7
10	Qurbanchiq	1264	1300	979 919.0	980 291.6	16.0	-125.4	26.8	24.7	24.4	- 98.2	- 89.1	- 79.4
11	Qurghan	866	870	979 944.2	980 268.5	- 58.0	-154.9	- 25.1	- 19.3	- 17.0	-126.0	-115.6	-107.3
12	Jigde-bulaq	1189	1190	979 910.9	980 269.9	7.0	-126.2	19.3	20.4	22.8	- 96.9	- 87.3	- 76.6
13	Nan-chan-bulaq	1124	1150	979 947.4	980 291.0	2.0	-123.8	22.5	23.1	23.3	- 95.8	- 86.4	- 76.9
14	Bejan-tura	-105	- 60	980 254.1	980 420.7	-199.0	-187.4	-119.0	-101.3	- 87.9	-163.0	-155.0	-146.7
15	Bogdo-ula	2623	2050	979 831.5	980 529.2	109.0	-180.4	- 20.1	- 27.0	- 30.7	-160.7	-153.0	-145.0
16	T'u-tun-tze	620	700	980 225.5	980 557.2	-141.0	-210.5	- 88.7	- 85.8	- 83.6	-188.2	-181.6	-173.9
18	Yarkend-darya	1141	1150	979 754.5	980 220.2	-115.0	-242.6	- 89.8	- 86.4	- 79.6	-206.9	-197.0	-183.5
19	Bora-chüschkan-bashi	1199	1200	979 778.8	980 139.4	9.0	-124.2	25.9	27.5	29.2	- 90.3	- 80.9	- 71.1
20	Gilam-jajde bashi	1282	1300	979 666.3	980 050.0	10.0	-132.8	31.9	35.1	39.1	- 92.4	- 80.2	- 67.5
21	Mazar-tagh	1362	1300	979 658.6	980 046.6	31.0	-121.4	43.3	46.5	50.5	- 81.0	- 68.8	- 56.1
22	Shor-chaqma-bashi	1301	1300	979 649.1	980 038.7	10.0	-135.0	29.7	32.9	36.9	- 94.6	- 82.4	- 69.7
23	Kalu	1370	1370	979 489.8	979 988.4	- 77.0	-230.3	- 44.6	- 37.9	- 31.4	-180.5	-165.5	-150.9
24/41	Khotan	1504	1480	979 336.2	979 927.5	-129.0	-297.3	- 60.1	- 49.7	- 39.6	-240.0	-224.3	-207.5
25	Langhru	1664	1800	979 301.6	979 912.1	- 98.0	-284.8	- 6.4	- 3.0	5.8	-226.8	-213.7	-194.1
26	Lok-öghil	2882	2750	979 052.7	979 898.0	41.0	-279.7	44.5	45.3	46.6	-223.7	-206.8	-189.7
27	Ulugh-art-davan	3199	2780	978 986.6	979 898.4	72.0	-283.5	35.7	37.9	40.2	-227.3	-210.4	-193.3
28	Duwa	1878	1620	979 269.5	979 926.5	- 80.0	-289.0	- 11.4	- 5.9	- 0.3	-230.8	-215.1	-198.5
29	Tozaqchi	1567	1540	979 331.0	979 922.2	-109.0	-284.8	- 30.5	- 21.9	- 14.0	-226.5	-210.8	-194.3
30	Qaranghu-tagh	2793	3550	978 936.2	979 851.2	- 56.0	-365.7	67.0	56.0	47.4	-311.6	-294.0	-276.0
31	Yarkend	1368	1370	979 518.3	980 040.0	-101.0	-254.2	- 54.2	- 44.7	- 37.2	-201.2	-185.6	-171.3
32	Camp 425	5118	5400	978 222.4	979 772.4	22.0	-540.7	2.7	- 13.8	- 28.0	-489.5	-470.5	-450.9
33	Aqsai-chin	4918	5000	978 273.8	979 757.7	27.0	-514.4	30.2	17.9	4.3	-458.5	-437.7	-419.2
34	Keng-shewar	3950	4910	978 649.5	979 848.0	15.0	-420.9	58.7	43.3	28.8	-374.9	-356.7	-339.7
35	Camp 455	4867	5150	978 357.1	979 808.0	44.0	-492.1	28.9	10.7	- 6.2	-442.1	-423.5	-405.9
36	Camp 463	5178	5400	978 133.2	979 722.6	0	-568.3	- 11.2	- 24.2	- 37.5	-506.0	-484.5	-464.9
37	Camp 497	5785	5100	978 140.7	979 715.3	18.0	-432.6	111.5	102.8	93.3	-362.7	-338.5	-316.4
38	Könche-bulaq	2920	3210	978 980.0	979 933.0	- 55.0	-379.9	- 7.9	0.3	16.6	-324.8	-293.9	-256.6
39	Charchan	1080	1200	979 547.1	980 016.3	-137.0	-258.4	- 62.2	- 50.7	- 41.7	-205.7	-190.4	-176.2
40	Keriya	1460	1460	979 342.3	979 904.7	-114.0	-277.2	- 38.2	- 27.0	- 16.6	-216.8	-200.8	-184.5
42	Leh	3519	3660	978 522.7	979 675.2	- 66.6	-458.4	29.5	20.9	11.5	-402.8	-384.7	-367.2

Note: The number of the stations refers to the publication: Reports from the Scientific Expedition to the North-Western Provinces of China under the Leadership of Dr. Sven Hedin — The Sino-Swedish Expedition, Publication 30 — II Geodesy, 2, Relative Schwerkraftsbestimmungen mit Pendeln in Zentralasien von Nils Ambolt, Stockholm, 1948.

Station 17 is identical with station 5 and station 41 with station 24.



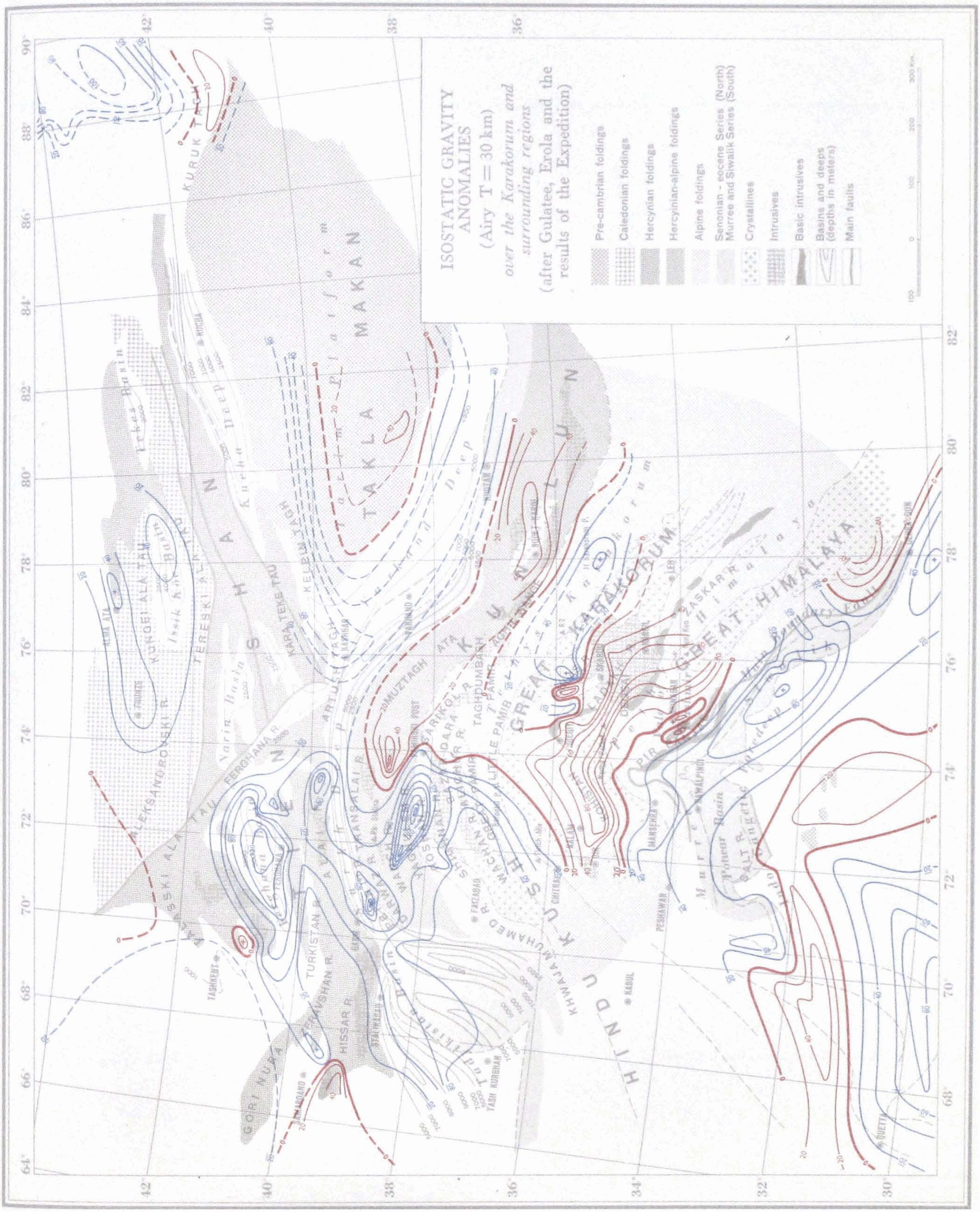
AVERAGE HEIGHTS
of the Karakorum and surrounding regions
Averages for squares
0°.5 × 0°.5
(partly after Survey of India Techn. Rep. 1948-49)



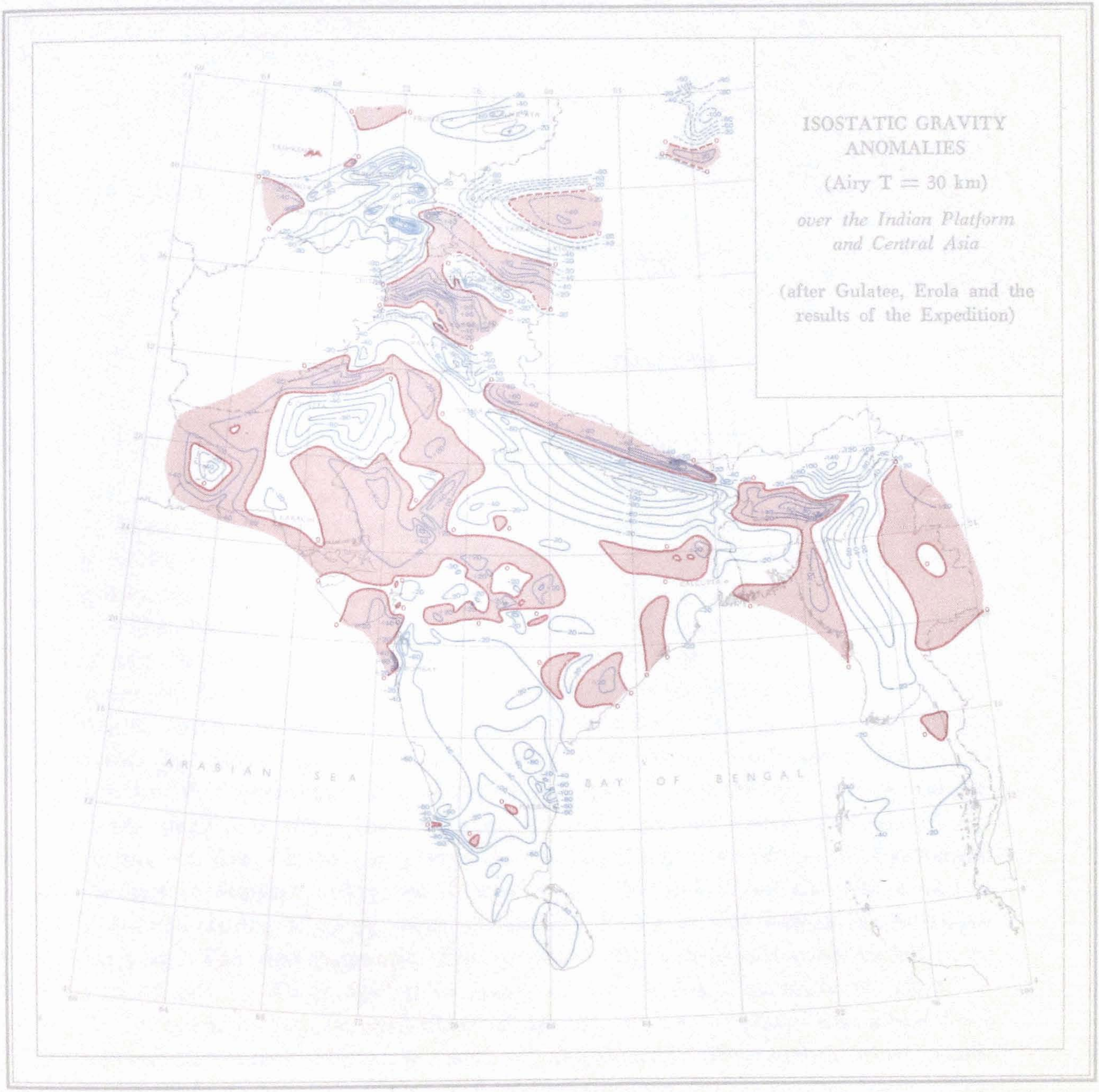
BOUGUER GRAVITY ANOMALIES

over the Karakorum and surrounding regions

(after Gulatee, Rosova and the results of the Expedition)



ISOSTATIC GRAVITY ANOMALIES
(Airy T = 30 km)
over the Karakorum and surrounding regions
(after Gulatee, Erola and the results of the Expedition)



ISOSTATIC GRAVITY
ANOMALIES

(Airy T = 30 km)

*over the Indian Platform
and Central Asia*

(after Gulatee, Erola and the
results of the Expedition)

II

MAGNETISM

FORMER OBSERVATIONS

FORMER MAGNETIC EXPEDITIONS TO INDIA, THE KARAKORUM AND CHINESE TURKESTAN

Records still exist of very early magnetic observations taken in India, mostly along coasts, and some of these are still of considerable interest for our knowledge of secular variations.

The first declination observations were carried out by traders and officers of the Royal Navy along the coasts of India from 1605; the values then observed have been collected and discussed by Hansteen (1819); for continental India the earliest data seem to be those of Hodgson, which include some dip observations, and which he published in 1833. Later, officers of the Royal Navy observed declination along the coasts during the period between 1834 and 1839; further values of declination are known from the observations of De Blosseville along the eastern coast in 1833, of Lieutenant Boileau in Rajvara, 1835, of Taylor and Caldecott along the coasts and in Southern India, 1837-39, and of Captain Elliot in the Indian Archipelago, 1845-49. The first magnetic observations in the Himalayas seem to be those carried out by Cunningham in Kashmir and Ladakh, as early as 1847.

In brief, it may be said that before 1850 magnetic observations had been carried out mostly along the coasts; in the interior, observations were available at only about 30 points, and at these mostly for declination only. This was the situation which confronted the brothers Hermann, Adolph, and Robert von Schlagintweit, as they began their famous exploration of India, the

Karakorum, Tibet and Turkestan on behalf of the Court of Directors of the Honourable East India Company.

The journey of the brothers von Schlagintweit began at Bombay in September 1854, and continued until 1857. The main result of this historic expedition, so far as geomagnetism is concerned, was the observation of the three elements of the magnetic field at 78 stations, most of which were located well within the interior of the continent, viz. 5 in Assam and Khassia Hills, 4 on the Ganges-Brahmaputra Delta, 9 in the Ganges Valley, 12 in the Punjab, Sindh and Kach, 12 in Central and Southern India, 21 in the Himalayas, 12 in Tibet, 1 on the Karakorum Pass, and 2 in Chinese Turkestan.

The measurements were carried out with English instruments made by Jones and Barrow; although the observed values, which are given by the authors in old English units with four significant digits, may contain considerable errors, and although the location of the stations is uncertain, comparison with later observations made at approximately the same places gives us valuable information on the variation of the magnetic field during the long period of time that has since elapsed.

As we shall see, the regular magnetic survey of India was begun in 1901, but it did not extend far beyond the foot-hills of the Himalayas. The whole area of those lofty mountains and of the Hindu Kush was therefore left out of the official observations, and for the knowledge of the magnetic field in this part of the continent we must rely on the results of various scientific expeditions which have explored the country.

So far as I know, the first expedition after that of the brothers von Schlagintweit to measure magnetic elements in the Karakorum and Turkestan, was that specially organized in 1905-1910 by the Department of Terrestrial Magnetism of the Carnegie Institution in Washington, which was founded in 1904 to obtain magnetic data in regions where these were lacking and where there were no organizations equipped to undertake such work.

In the course of that expedition, declination, horizontal force, and dip were observed at 308 stations in Asia, of which 32 were in Asiatic Russia, 142 in China, and 9 in Northern India. The results were published, without any reduction for daily or secular variation, by Bauer (1912).

Of special interest for our own purposes are the 55 stations observed in the region with which we are immediately concerned, and amongst these particularly those observed by D. C. Sowers in Chinese Turkestan and the Karakorum itself.

Next follows the expedition led by Dr. Filippo De Filippi in the years 1913-14 in which declination, horizontal force and dip were observed by

Prof. G. Abetti and Comm. A. Alessio at 12 stations along the route crossing the Himalayas and the Karakorum Chain, from Srinagar in Kashmir to Kashgar in Chinese Turkestan.

The work started by the De Filippi Expedition was continued in 1929 by the scientific expedition to the Baltoro and surrounding glaciers, led by the Duke of Spoleto. In this Comm. M. Cugia observed the three components of the magnetic field at 8 stations in Baltistan.

Also to be mentioned are the two expeditions in Northern Tien Shan, Tzungaria, West China, Tibet and Ladakh, led by Dr. W. Filchner in the years 1926-28 and 1935-37, during which he observed the three components of the magnetic field at 242 stations (147 on the first expedition, 95 on the second). Of these observations, 96 (56 on the first expedition, and 40 on the second) lie sufficiently close to our region to be of use in establishing the general trend of the magnetic field around the Karakorum.

In the years from 1926 to 1928 Dr. Filchner observed the magnetic field by means of a magnetic theodolite constructed by Schulze in Potsdam; the series of observations was begun at Pavlovsk (Leningrad) and Tashkent, and concluded at Dehra Dun. The observed values were published by Dr. O. Venske (1931) without any reduction for daily or secular variations.

As a general result, the magnetic field seems to be much less disturbed in Tibet than in China; this leads the author to the conclusion that all over the former region the sedimentary layers must be very thick, and the magmatic rocks very deep.

The observations of the 1935-37 expedition were processed by Dr. G. Fanselau (1943) and were published in a similar form to the previous ones, though in more detail.

The instruments used by Dr. Filchner in the course of the second expedition are same as those employed in the first, with the addition of an earth inductor to determine dip. Dr. Filchner had also with him a Schmidt magnetometer with which he carried out an extensive survey; unfortunately the field records of the determination of the constants of the instruments were lost in consequence of the war, and the vast material that he collected cannot therefore be used.

The processing of the observations of the second expedition was planned in three parts, of which only the first has been published; according to an oral communication made to me by Dr. Fanselau himself, the other two parts which were to include the magnetometer observations, the secular variations, and a geophysical discussion of the results, will never be published.

OFFICIAL GEOMAGNETIC FIELD OPERATIONS AND OBSERVATORIES IN INDIA AND PAKISTAN

The first hint of the need for systematic magnetic land observations in India was probably given by Reuben Burrow, Surveyor General of India between the years 1783-89, but concrete proposals which were acted upon were made only much later, in 1896, by Sir John Elliot, Meteorological Reporter, and by General C. Strahan, Surveyor General of India.

The field work of the magnetic survey of India was begun in November 1901, and continued until 1923; but the bulk of the survey, which comprises 1401 field stations and 80 repeat stations, was carried out between the years 1902 and 1913. At every station declination, dip and horizontal force were observed, and the data, reduced to the epochs 1909.0 and 1920.0, were published in Volume XIX, 1925, of the *Records* of the Survey of India.

The field work at repeat stations was not resumed until the outbreak of World War II, when a programme was hurriedly devised to visit repeat stations spread all over India; these observations were continued until by 1945 all the stations had been reoccupied. The sites of several stations were found to have become unsuitable due to the erection of new buildings around them, and for various other reasons. Alternative sites were prepared and observations made at them during 1946-47 and 1947-48. The data referring to this work are to be found in the *Technical Report* 1947, Part III, of the Survey of India.

Amongst the repeat stations is Rawalpindi, at which observations had been carried out in 1856, and on the following subsequent dates: 23.11.1919, 2.11.1930, 3.3.1943 and 10.12.1946. This was the base station for the observations taken by our Expedition.

The first magnetic observatory established in India dates back to 1840. It was established at Colaba, near Bombay, on the decision of the Court of Directors of the Honourable East India Company, and in compliance with the suggestion of the Royal Society that three magnetic observatories should be established in India: one near Bombay, another near Madras, and a third somewhere in the Himalaya Mountains.

Magnetic data for the Colaba station were published for the period from 1846 to 1905 by N.A.F. Moos (1910).

Further observatories were established in India at much later times by the Survey of India, in connection with the regular magnetic survey of the country begun in the year 1901. These observatories are:

Dehra Dun (Himalaya)	established	in	March	1902
Kodaikanal (Southern India)	»	»	August	1902
Barrackpore (Calcutta)	»	»	August	1903
Toungoo (Burma)	»	»	December	1904

It should also be noted that the Observatory at Colaba had to be moved to Alibag not far from the original site in 1904, because of disturbances due to the introduction of electric trams.

Unfortunately the observatories at Kodaikanal, Barrackpore and Toungoo were closed during the year 1923, and all magnetic research work was therefore confined to the task of keeping in operation the observatory at Dehra Dun which continued to function until 1943 when it was put out of action as a result of floods during the monsoon season of that year.

After the partition of India, a modern geophysical observatory was established at Quetta in Pakistan through an agreement between the Pakistan Governement and UNESCO. The Observatory of Quetta is equipped with a Ruska magnetograph, a Danish quick-running magnetograph, an Askania earth inductor, three QHMs, two BMZs, two Askania field balances with visible recorder for H and Z, and several other auxiliary instruments. It started operating during 1953, and is now under the supervision of the *Pakistan Meteorological Department.*

All observations made by our Expedition were reduced for daily and secular variations on the basis of the data kindly furnished by the *Pakistan Geophysical Observatory* at Quetta.

OPERATIONS BY THE EXPEDITION

PROGRAMME OF THE EXPEDITION

When the programme was established in 1954, the existing situation could be summarized as follows:

(*a*) In the Karakorum there existed some stations, 10 in all, at which all magnetic elements had been observed by former explorers at various periods from 1856 to 1929.

(*b*) In the Hindu Kush and Gilgit area, no observations were available.

(*c*) With regard to continental Pakistan and India a satisfactory survey existed, of which one repeat station, that of Rawalpindi, observed for the last time in 1946, gave a reliable basis for starting a new extensive survey in the Karakorum and Hindu Kush.

(*d*) Furthermore, the excellent recording station which had been established by the Pakistan Government und UNESCO at Quetta (Baluchistan) could guarantee the necessary data for daily variations and perturbations.

The programme of our work could therefore easily be established; it aimed at:

A) The extension of the former surveys to unexplored areas of the upper Indus Valley, Gilgit, Chitral and Swat.

B) The repetition of as many as possible of those stations already observed in the past, in order to determine the secular variations.

C) The production of a general map including all observations so far made in the Karakorum and surrounding regions, so as to contribute to the geophysical interpretation of the geology of the country.

The last task required an accurate preliminary study of all data available for determining the secular variation. These data were drawn firstly from the magnetic observatories for which long periods of observation existed; these are listed, in order of decreasing latitude, in the table below; and secondly from all stations in the area surrounding the Karakorum, for which observations spread out over a period of time were available.

Observatory	Latitude	Longitude	Period of activity
Tashkent (superseded by Keles)	+ 41°20′	69°18′	1882-1900; 1920-1936
Keles (successor to Tashkent)	+ 41°25′	69°12′	from 1936 onwards
Dehra Dun	+ 30°19′	78°03′	1902-1943
Quetta	+ 30°11′	66°57′	from 1954 onwards
Barrackpore	+ 22°46′	88°22′	1903-1923
Colaba (superseded by Alibag)	+ 18°54′	72°49′	1840-1905
Alibag (successor to Colaba)	+ 18°38′	72°52′	from 1904 onwards
Kodaikanal	+ 10°14′	77°28′	1902-1923 and from 1950 onwards

The results of this analysis are given in the form of graphs which require no further comment. The analysis includes of course the values observed by our Expedition at old stations.

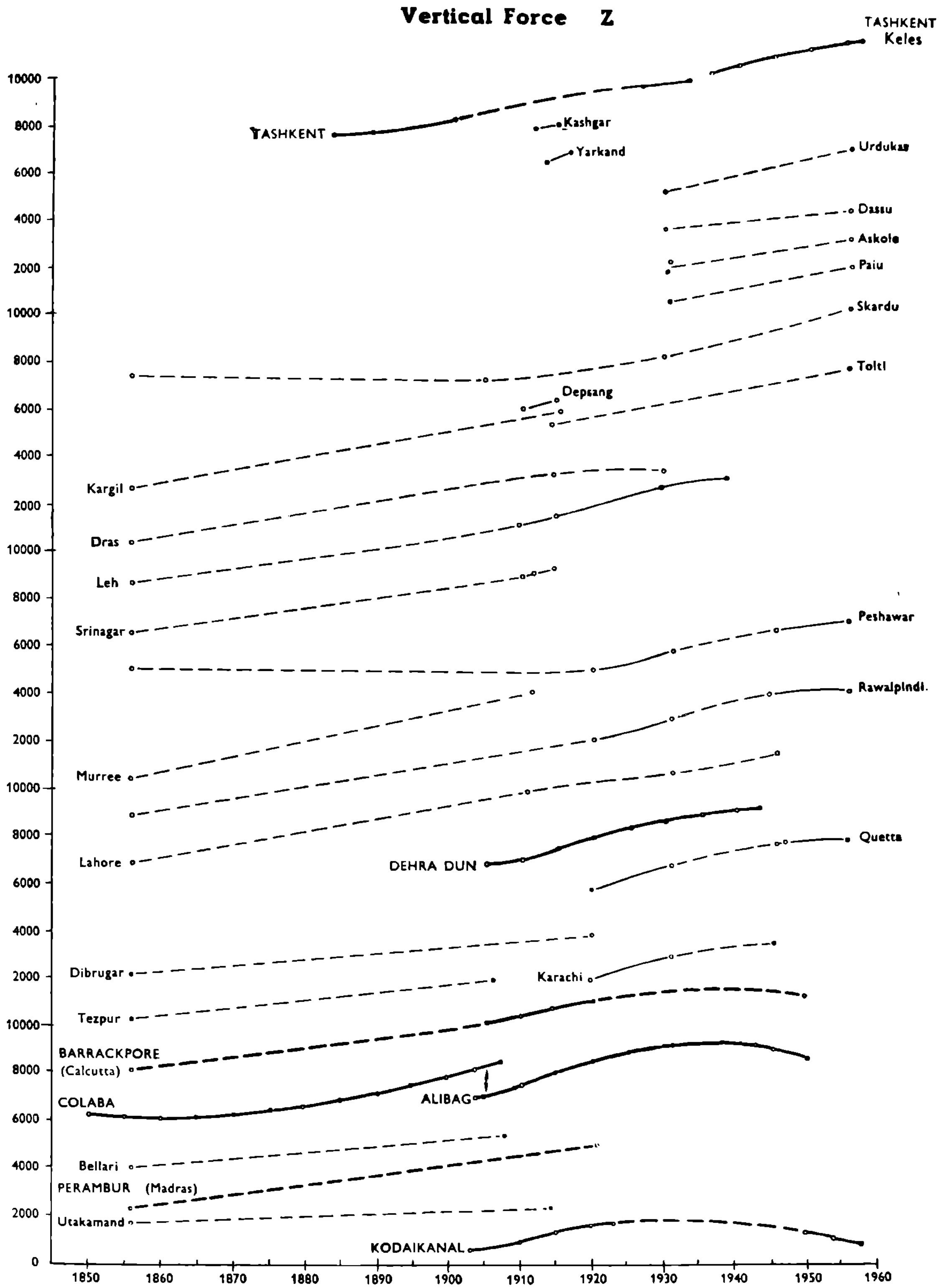


Fig. 21 - Secular variation of the Vertical Force Z at different stations (in γ)

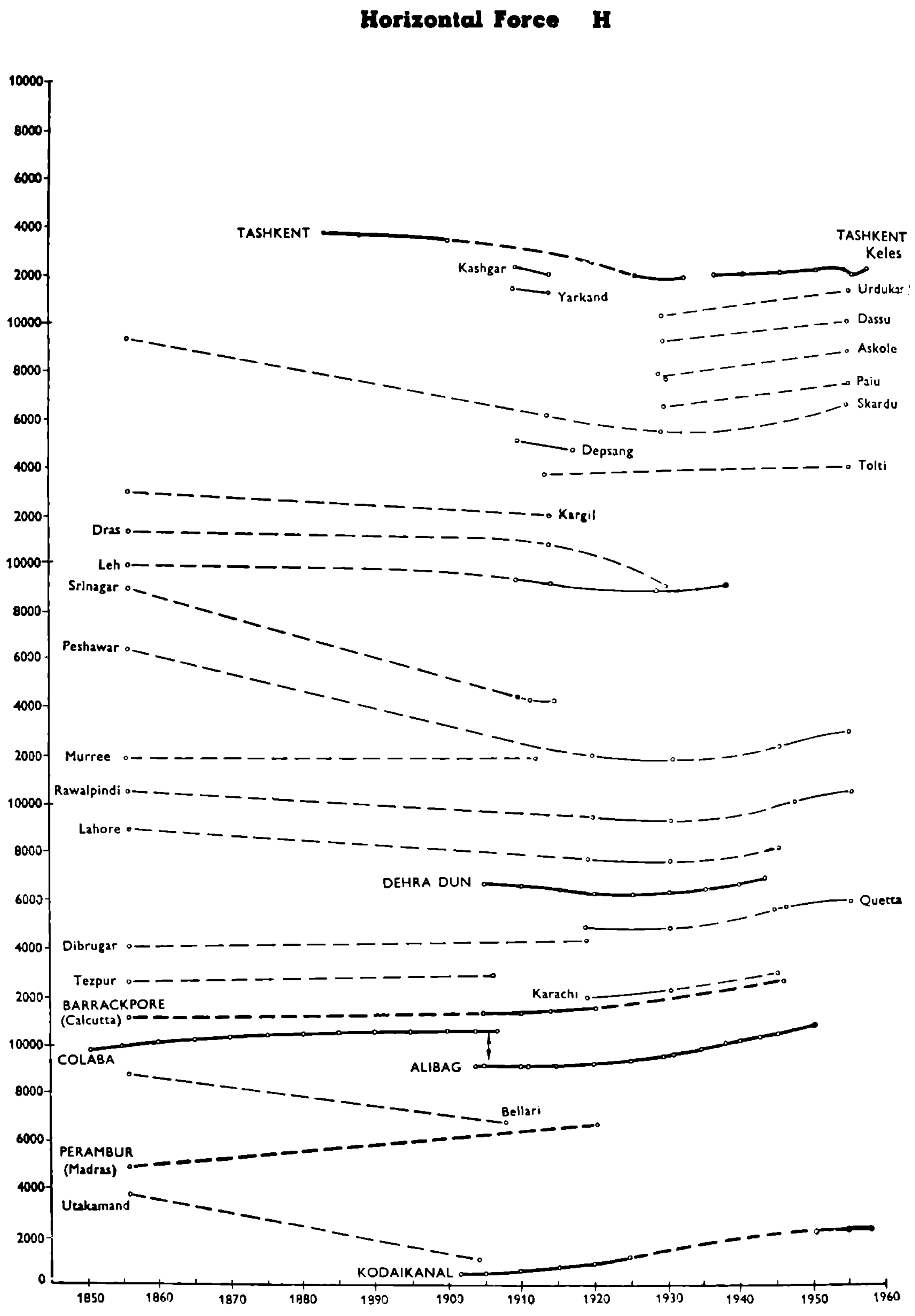


Fig. 22 - Secular variation of the Horizontal Force H at different stations (in γ)

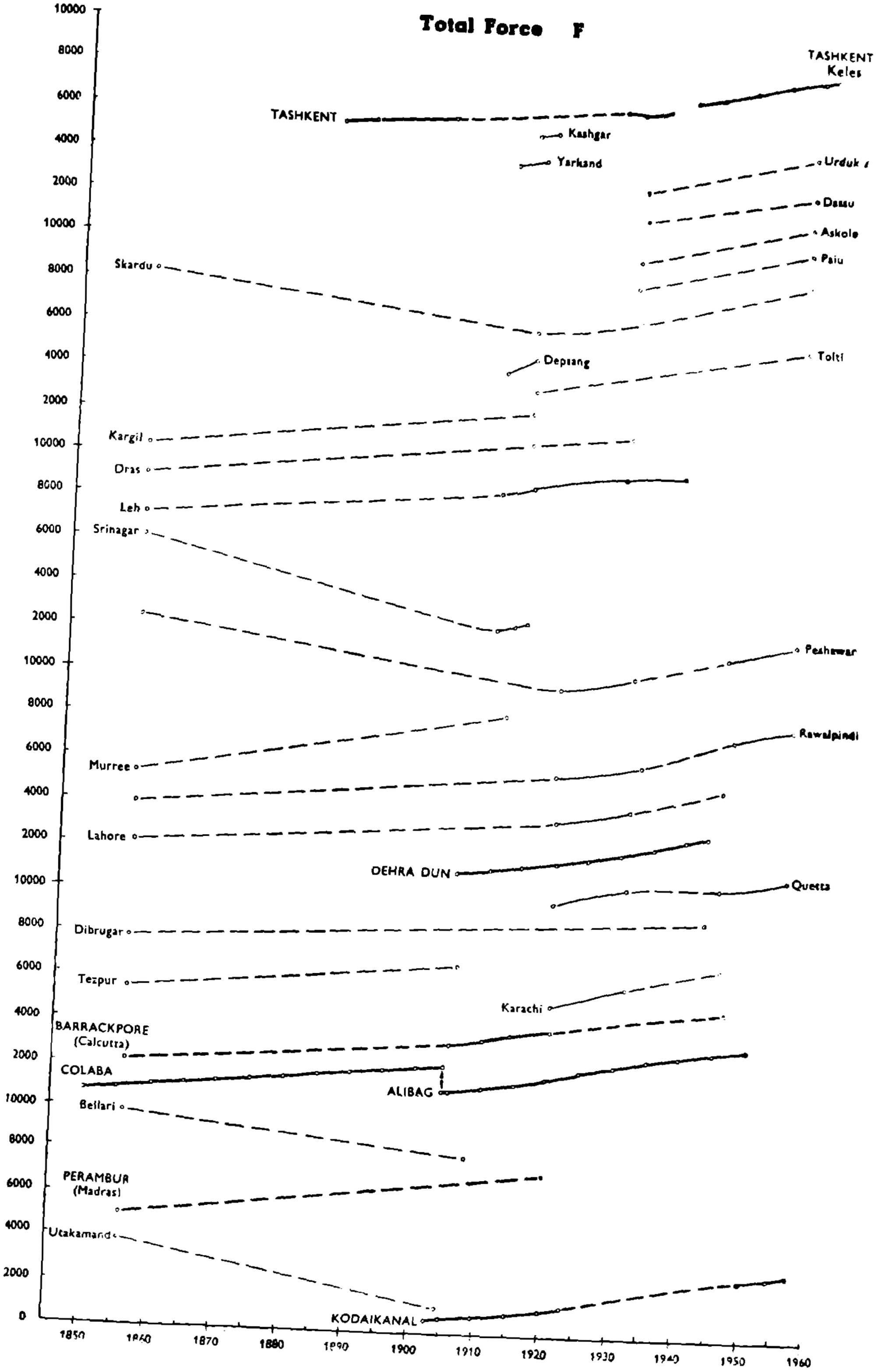


Fig. 23 - Secular variation of the Total Force F at different stations (in γ)

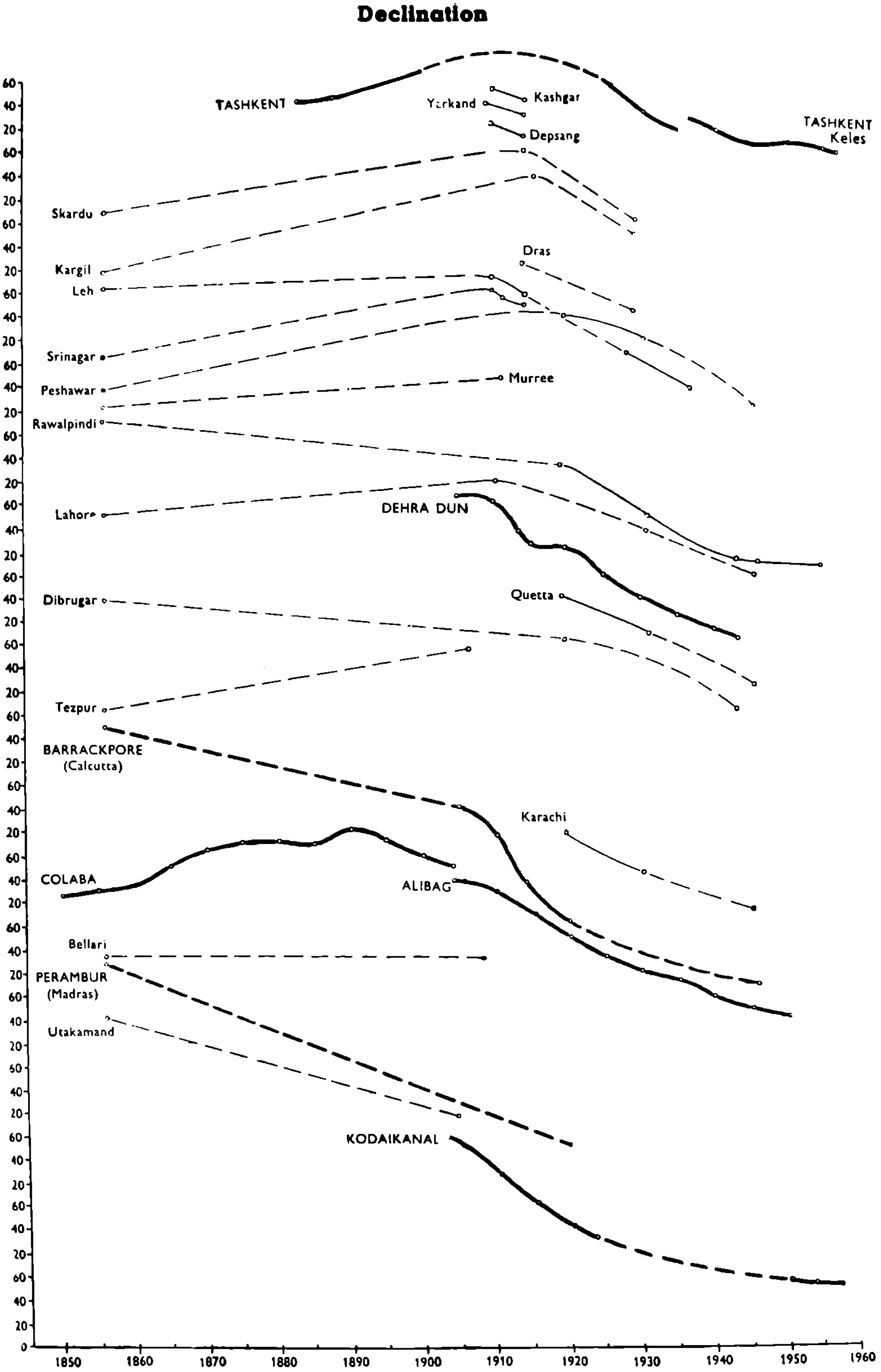


Fig. 24 - Secular variation of the Declination at different stations (in sexagesimal minutes of arc)

It can be seen from the plates that for most of the stations, the secular variation shows fairly regular trends; there are some exceptions, as for instance for Skardu, Srinagar, Peshawar, Bellari, Utakamand in H, Z and F, and Rawalpindi, Dibrugar, Barrackpore, Perambur, Utakamand in Declination, the apparently anomalous behaviour of which could possibly be explained by erroneous observations in the past.

The secular variation obtained has been used to reduce to epoch 1953.0 all available observations in the Karakorum, Chinese Turkestan, Chitral, Gilgit and Ladakh.

From the values thus obtained, anomalies have been derived by using the tables for the undisturbed field as given by B. L. Gulatee in the Survey of India *Technical Paper* No. 7, « Charts of Declination, Horizontal Force and Vertical Force for Epoch 1953.0 and Magnetic Anomalies (India, Pakistan and Burma) », Dehra Dun, 1954.

MAGNETIC OBSERVATIONS 1954

In 1954 only Z and H were observed. A set of two Askania-Schmidt magnetometers kindly lent to the Expedition by the *Istituto di Geofisica Applicata* of the *Politecnico di Milano* has been used. The sensitivity of the magnetometers had been reduced to about 100 γ per scale division, in order to avoid the use of auxiliary magnets.

The *Istituto Nazionale di Geofisica* in Rome in turn lent a set of two Askania recording magnetometers to the Expedition; but unfortunately the recording set suffered damage during the perilious journey from Rome to Skardu, and proved inefficient. The daily reductions of the observed values had therefore to be derived from the records of the excellent permanent Observatory at Quetta, which kindly put at our disposal all the data necessary for this purpose.

The Repeat Station of the Meteorological Survey of Pakistan situated at Rawalpindi was used as the base station for the surveys of both 1954 and 1955. At this station the three components of the magnetic field had been observed in 1919, 1930, 1943 and 1946. These observations, in addition to the knowledge of the general trend of the secular variation resulting from the abovementioned analysis, allowed us to extrapolate the values of the elements of the magnetic field to the time of the Expedition; we adopted

Rawalpindi, Repeat Station, old $Z = 38{,}220\ \gamma$
Values for 1955.0 $H = 31{,}750\ \gamma$

It should be noted however that the old observations (1919 and 1930) at Rawalpindi refer to the "old station"; in the Survey of India *Technical Report* 1947, Part III, the relation between the "old" and "new" stations is given as follows:

December 10, 1946

	lat.	long.	declin.	dip	*H*
Rawalpindi (old)	33°35′25″	73°03′06″	+ 1°56′.2	50°34′	31,270
Rawalpindi (new)	33 35 20	73 03 06	+ 1 57 .0	50 31	31,246

It must furthermore be noted that the observations in both 1954 and 1955 were made at a point, situated in the grounds of the race-course, which does not coincide with either the new nor the old station, and for which Dr. K. Wienert of the "Deutsch-Oesterreichische Himalaya-Karakorum Expedition" has determined the following relations with the former stations:

Rawalpindi (old)	$Z = 0$	$H = 0$
Rawalpindi (new)	$= + 29\ \gamma$	$= + 8\ \gamma$
Rawalpindi (race-course)	$= + 21\ \gamma$	$= -22\ \gamma$

The scale values of the *Z* and *H* magnetometers were determined at Skardu by using the Helmholz coil which is part of the instrument. Two observations were made, both at Skardu, one on 16.5.54, before the beginning of the exploration, and one on 27.9.54, on the return to Skardu.

The magnetometers were read with coil currents of 0, 3, and 6 mA, both direct and reversed.

The method of least squares, applied to the observed values, gave the following results, expressed in γ per scale division:

Date	*Z*	*H*
16.5.1954	103.16	105.16
16.5.1954	106.21	107.79
27.9.1954	104.60	107.20
mean value adopted	*104.60*	*106.70*

The observed values of *Z* and *H* have been reduced by first applying the daily variation with the use of the photographic records kindly put at our disposal by the Geophysical Observatory at Quetta, taking the components of the field at Quetta, 1955.0, as

$$Z = 33{,}660\ \gamma$$
$$H = 32{,}925\ \gamma.$$

MAGNETIC OBSERVATIONS 1955

During the 1955 campaign, declination was observed in addition to Z and H. For the observation of Z and H a set of two Ruska magnetometers of the Schmidt type, belonging to the *Istituto di Topografia e Geodesia* of the University of Trieste, was used. The sensitivity of the instruments could not be reduced to such low values as those used in 1954; the actual scale values were about 16 γ per division. The use of auxiliary magnets was therefore necessary for almost all the stations, partly on account of the wider range in latitude of the routes followed in 1955, and partly on account of the greater anomalies encountered.

The scale values for both components were determined at Rawalpindi both at the beginning and at the end of the exploration; the results obtained by the method of least squares are as follows:

	Z	H
August 8, 1955	18.35	16.66 γ per division
	18.32	16.64
September 28, 1955	20.36	17.01
	20.39	16.99

As can be seen, the scale values for both components show a remarkable increase between the beginning and the end of the journey. If we attribute such drift to the jarring to which the instrument was subjected during the last days of the trip, which took place by jeep between Gilgit and Rawalpindi, it is best to use for the scale values the figures determined at the beginning of the journey; we therefore propose to adopt the following values:

adopted scale value for Z, 18.34 γ per division
» » » » H, 16.64 γ » »

Auxiliary magnet No. 3177 was used for the vertical magnetometer, and No. 3178 for the horizontal one. The length of each magnet was 35 mm.

The effect of the auxiliary magnets was taken into account by determining their moments at the base station in Rawalpindi and at several other places, by the method to be described presently; the moments thus determined, which show a marked drift in time and a rather strong dispersion, were plotted against time, and then a smoothed curve was drawn. The latter was used for interpolating the moments at the time of each observation.

For the determination of the moment of the auxiliary magnet attached to the Z magnetometer, the following procedure was used.

We first write

$$\Phi_i = \frac{D^5_i}{D^2_i + (2L^2_a - 3L^2)}$$

where $L^2 = 17.2$ cm^2, $L_a = \frac{5}{12}\lambda$, λ being the length of the auxiliary magnet ($= 3.5$ cm, therefore $L^2_a = 2.13$ cm^2), and D_i being the distance in cm between the axis of rotation of the needle of the magnetometer, and the geometric centre of the auxiliary magnet held vertically on the vertical through the geometric centre of the needle; if we further indicate by ε_z the (known) scale value expressed in γ per division, by l_i the readings on the scale of the instrument, and by M the moment sought, from the theory of the Schmidt balance we have

$$\delta_i Z = \varepsilon_z (l_i - l_o) = \frac{2M}{\Phi_i}$$

as the effect due to the auxiliary magnet, l_o being the reading in the absence of the magnet.

If we now have n measurements taken at the same point, with the same auxiliary magnet set at different distances, we get n equations in the two unknown quantities M and l_o:

$$2M + \varepsilon_z \Phi_i l_o = \varepsilon_z \Phi_i l_i \qquad (i = 1, 2, \ldots n).$$

The use of the method of least squares leads us to the following solutions

$$M = \varepsilon_z \cdot \frac{[\Phi l][\Phi^2] - [\Phi][\Phi^2 l]}{2(n[\Phi^2] - [\Phi]^2)}$$

$$l_o = \frac{n[\Phi^2 l] - [\Phi][\Phi l]}{n[\Phi^2] - [\Phi]^2}.$$

Should there be only two observations, the solutions are

$$M = \frac{\varepsilon_z}{2} \frac{\Phi_1 \Phi_2}{\Phi_1 - \Phi_2} (l_2 - l_1)$$

$$l_o = \frac{l_1 + l_2}{2} + \frac{l_1 - l_2}{2} \cdot \frac{\Phi_1 + \Phi_2}{\Phi_1 - \Phi_2} = \frac{l_1 \Phi_1 - l_2 \Phi_2}{\Phi_1 - \Phi_2}$$

and therefore

$$\Delta Z = \varepsilon_z \frac{l_1 \Phi_1 - l_2 \Phi_2}{\Phi_1 - \Phi_2}$$

gives directly the value in γ corresponding to the reading in the absence of the auxiliary magnet.

In the case of the H balance, a slight complication arises from the effect on the readings of the vertical component.

As for the Z component, we write (by dropping the index i)

$$\Psi = \frac{D^5}{D^2 + (6L^2 - \frac{3}{2} L^2_a)}$$

where as before $L^2 = 17.2$ cm², etc.; we have further, for the effect of the auxiliary magnet of moment M:

$$\delta H = \varepsilon_H (l - l_o) + \frac{\Delta Z}{2f} (l - 30) = \frac{M}{\Psi},$$

ΔZ being the difference between the actual value of the field, and the value at the base station, (l-30) the reading referred to the vertical position of the needle, and f the focal length of the telescope.

We may also write

$$2M + \varepsilon_H \Psi l_o = \varepsilon'_H \Psi l - 30 \frac{\Psi \Delta Z}{2f} .$$

having put

$$\varepsilon'_H = \varepsilon_H + \frac{\Delta Z}{2f} .$$

We therefore get a system of equations similar to that already considered for the Z balance; in the case of two observations only the solution is

$$M = \varepsilon'_H \frac{\Psi_1 \Psi_2}{(\Psi_1 - \Psi_2)} (l_2 - l_1).$$

The value of l_0 cannot of course be used in the same simple way as for the Z balance.

REDUCTION TO EPOCH AND ANOMALIES

All values of Z and H have been reduced for the daily variation, as stated before, taken from the records of the Geophysical Observatory at Quetta, and have been referred to epoch 1955.0.

In order to obtain the anomalies, and to compare them with those given by B. L. Gulatee in *Technical Paper* No. 7, 1954, of the Survey of India, all values have been further reduced to 1953.0 by using the isopors given in that publication. The same reduction to 1953.0 was also carried out for the observations of von Schlagintweit, Sowers, De Filippi, Spoleto and Filchner, in order to obtain an overall picture of the magnetic field in this part of Central Asia, by taking into account all available material.

Anomalies were then found by comparing the actual values with those of the undisturbed field as given for 1953.0 by Gulatee in Chart I of the above-mentioned *Technical Paper.*

By means of the values of the anomalies thus determined, the annexed plates have been drawn, which give a sketch of the magnetic anomalies in the Karakorum and surrounding regions.

Magnetic Observations 1954

No.	Station	Date 1954	Observ. red. to 1953.0		Normal values		Anomalies	
			Z	H	Z	H	Δ Z	Δ H
9	Rawalpindi (Repeat Station)	May 8-9-10-11-12-13						
		Oct. 12	38183	31671	38181	31611	2	60
101/a	Skardu	May 14-26	40087	30903	40272	30910	—185	— 7
101/b	Skardu	» 16-25						
		Sept. 29	40272	30820	40272	30910	0	— 90
101/e	Skardu	May 23	40071	30895	40272	30910	—201	— 15
102	Hoto	» 27	40398	30780	40318	30850	80	— 70

No.	Station	Date 1954	Observ. red. to 1953.0		Normal values		Anomalies	
			Z	H	Z	H	Δ Z	Δ H
104	TSARI	» 27-28	40495	31209	40440	30790	55	419
105	GURBIDAS	» 28	40287	30437	40450	30764	—163	— 237
106/b	BYICHA	» 29	40179	31111	40694	30700	—515	— 411
109	RONDU	» 30	40522	29847	40545	30670	— 23	— 823
110/b	STERIKA	» 30	40180	30408	40540	30670	—360	— 262
114/a	CHUTRAN	June 3-15	40612	30612				
116/a	SHENGUS	» 4-14	40615	30338	40640	30558	— 25	— 220
116/c	SHENGUS	» 5	40633	30300	40640	30558	— 7	— 258
117/a	BURUMDOIR	» 5-13	40610	30316	40640	30540	— 30	— 224
119/b	SASLI	» 6-12	40703	30179	40700	30440	3	— 261
123/359	GILGIT (Grave-yard)	» 11-12	40670	30336	40770	30411	— 100	— 75
123/a/359	GILGIT	» 11						
		Oct. 10	40722	30125	40770	30411	— 48	— 286
125/354	HAIM	» 10	40581	30280	41000	30147	—419	133
128	KURCHUNG	May 31						
		June 2-16	40632	30399	40636	30588	— 4	— 189
129/a	KULANKAE	» 18-30						
		July 18-26	40691	30512	40680	30600	11	— 88
129/c	KULANKAE	» 10-12	40789	30347	40680	30600	109	— 253
129/i	KULANKAE	» 23	40712	30316	40680	30600	32	— 284
130/a	STAK LA	» 28	40676	30363	40680	30600	— 4	— 237
130/c	STAK LA	» 29	40608	30409	40680	30610	— 72	— 201
131	CHUTRUN TORMIK	» 30	40608	30272	40660	30630	— 52	— 358
134	PAKORA	Aug. 4	40684	30693	40630	30647	54	46
135	GANTO LA	» 4	40757	30698	40630	30650	127	48
137	CHU TRAN	» 6	40929	30806	40665	30647	264	159
138/b	TISSAR	» 7	40609	30394	40630	30676	— 21	— 282
140	HORITSHO	» 7	40624	30486	40650	30640	— 26	— 154
142/a	DUSSO	» 8						
		Sept. 20	40634	30396	40655	30610	— 21	— 214
145/a	CHOKPIONG	Aug. 9	40584	30257	40730	30610	—146	— 353
153/a	ASKOLE	» 11	40670	30571	40680	30705	— 10	— 134
158	LASKAM	Aug. 12	40651	30518	40680	30695	— 29	— 177
162	BARDUMAL	» 13	40514	30494	40630	30735	—116	— 241
164/a	PAJU	Aug. 14	40707	30492	40709	30730	— 2	— 238
168/a	URDUKAS	» 16	40852	30451	40750	30718	102	— 267
174	ATRORO	Sept. 22	40349	30435	40549	30764	—200	— 329
179/c	SHIGAR	» 22	40619	30192	40454	30800	165	— 608
186	GOL	» 27	39978	30737	40270	30950	—292	— 213
192	TOLTI	» 28	39749	30767	40100	31110	—351	— 343
195	BAGICHA	» 28	40181	31006	40100	31175	81	— 169
356	SINGAL	Oct. 9	41018	30185	40909	30260	109	— 75

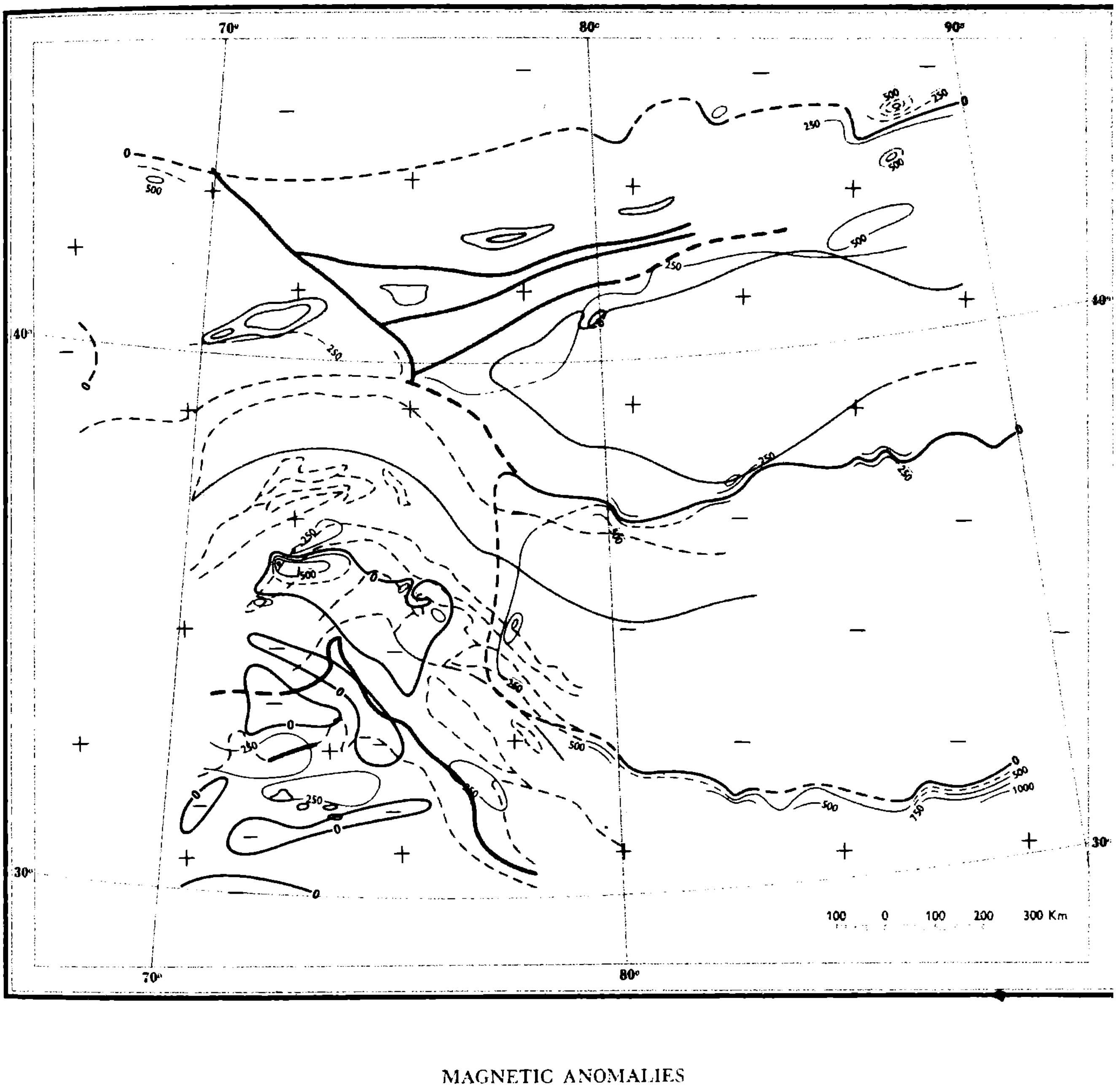
MAGNETIC OBSERVATIONS 1955

No.	Station	Date 1955	Observ. red. to 1953.0		Declination red. to 1953.0	Normal values		Anomalies	
			Z	H		Z	H	ΔZ	ΔH
9	RAWALPINDI	Aug. 8	38161	31626	01°41′24″	38181	31611	— 20	15
314	LAWARAI PASS	» 10	40519	30156		40050	30411	469	— 255
317	DROSH	» 11	40041	29843		40217	30323	—176	— 480
319	CHITRAL		40531	29679	02°31′13″	40522	30117	9	— 438
323	KOGHOZI	» 28	40638	30180		40565	30117	73	63
327	BARENIS	» 29	40723	29536	02°30′22″	40652	30058	71	— 522
329	CHARAN	» 30	39881	29474		40765	30000	—884	— 480
332	SANOGHAR	» 31	41212	30599	02°36′03”	40950	30000	262	599
334	MASTUJ	Sept. 1	40961	29342	02°21′14″	40940	30000	21	— 658
336	BREP	» 3	41236	29454		41090	29909	146	— 455
340	GAZIN	» 4	41448	29179	02°46′31″	41290	29787	158	— 608
342	LASHT	» 5	41825	29272	01°56′33″	41410	29720	415	— 448
343	KISHMANJA	» 6	41766	29187	02°38′07″	41450	29720	316	— 533
344	ISHKAWARZ	» 7	41833	29205	02°02′42″	41500	29705	333	— 500
349	DARKOT	» 9	41694	29319		41340	29853	354	— 539
351	YASIN	» 11	41125	29173		41090	30000	35	— 827
353	GUPIS	» 12	40478	29954		40950	30117	—472	— 163
355/124	GAKUCH	» 14	40420	29465		40900	30220	—480	— 755
359	GILGIT	» 16	40796	30241		40770	30411	26	— 170
366	CHILAS	» 18	40165	30689		40270	30676	—105	13
372	NARAN	» 19	39786	30811		39731	30940	55	— 129
376	BALAKOT	» 19	39355	31038		39322	31090	33	— 52
386	PESHAWAR	» 21	38526	31229		38518	31200	8	29
390	SHAHBAZGARHI	» 22	39073	31035		38950	31140	123	— 105
400	KALAM	» 25	40250	30243		40265	30400	— 15	— 157
401	NAJIGRAM	» 26	39330	31387		39340	30900	— 10	487

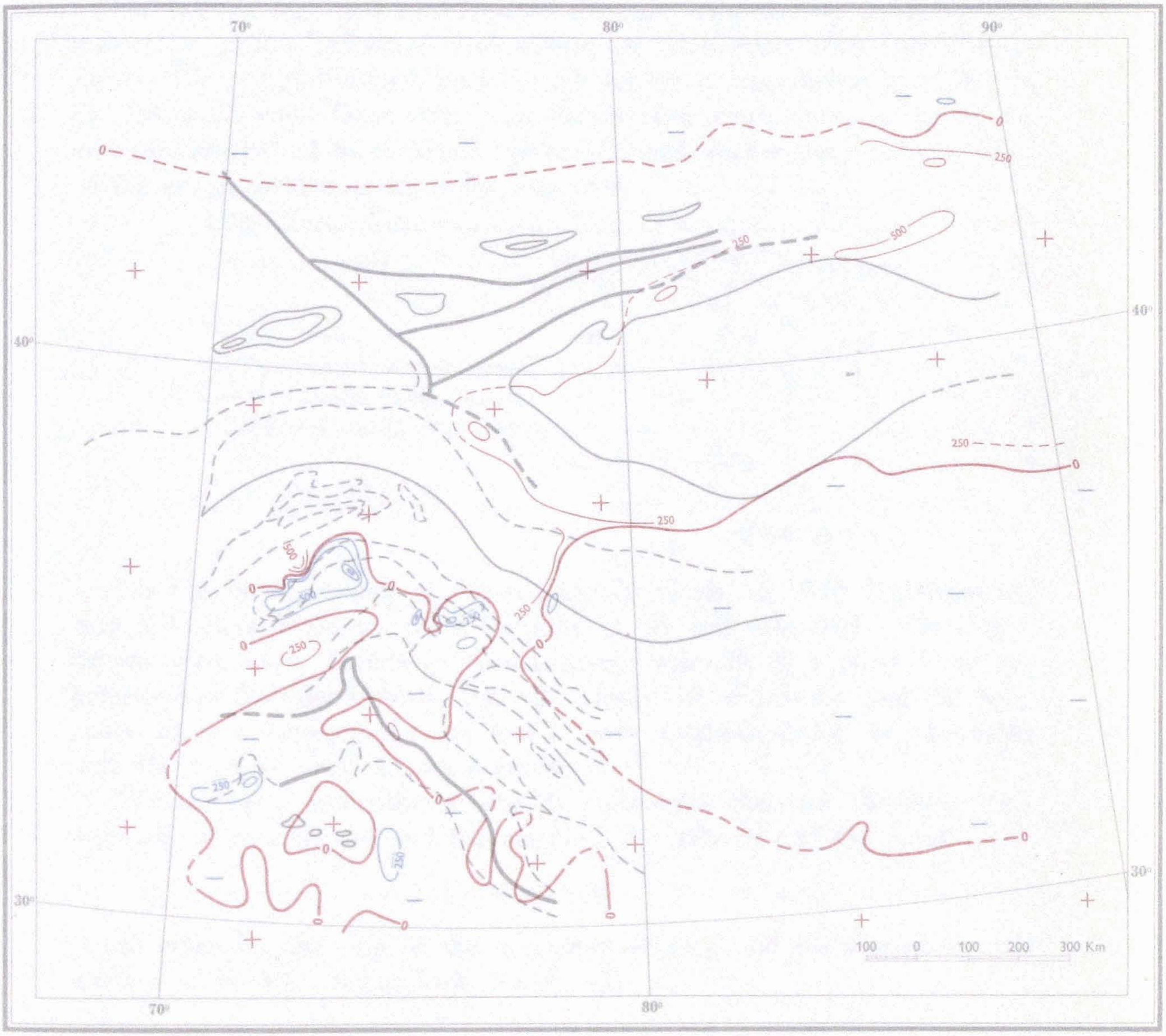
OBSERVATIONS OF DECLINATION

(M. CAPUTO)

The magnetic programme of the Italian Karakorum Expedition in 1955 also included the survey of the magnetic declination in the eastern part of the Hindu Kush. The field work was done by Prof. A. Marussi and by the Superintendent of the Survey of Pakistan Mr. Mohammed Azizullah. At the end of the expedition Professor Marussi entrusted me with the computations to reduce the observed values. The following account presents the results of these computations, including an analysis of the accuracy obtained.



MAGNETIC ANOMALIES
over the Karakorum and surrounding regions
Vertical force
(after the observations of Abetti, Alessio, Cugia, Filchner, Marussi, Schlagintweit, Sowers and the Survey of India)



MAGNETIC ANOMALIES
over the Karakorum and surrounding regions
Horizontal force
(after the observations of Abetti, Alessio, Cugia, Filchner, Marussi, Schlagintweit, Sowers and the Survey of India)

The declinometer used in the survey was the Wild No. 56620 with the azimuthal circle divided into 360 degrees, read to the nearest $0^{\circ}.1$.

On January 23, 1956 I determined the zero correction by comparing this instrument with a calibrated declinometer of the *Istituto Nazionale di Geofisica.* The comparison was made in the garden to one side of the office of the Rocca di Papa Observatory, by determining from the same point the magnetic azimuth of three distant marks with each declinometer in turn. The results are illustrated in the following table:

Point	Calibrated instrument	Wild No. 56620	Corrections
Tuscolo cross	$3^{\circ}\,35'$	$4^{\circ}.0$	$-25'$
French convent, steeple cross	$312^{\circ}\,06'$	$312^{\circ}.5$	$-24'$
South-east solid corner of the steeple of the Grottaferrata Abbey	$309^{\circ}\,08'$	$309^{\circ}.5$	$-22'$
		Mean	$-24'$

For the determination of the astronomic azimuth a Wild $T\,2$ theodolite with a Roelofs prism for the collimation of the sun was used. The observations were taken as follows: the magnetic azimuth of a point C on the horizon was first determined; then the altitude h of the sun and the horizontal angle η between the sun and C were determined by the theodolite with the vertical circle in two positions.

The magnetic declination d was then obtained from the difference between the astronomic (α) and the magnetic (Θ) azimuths of the point C:

$$(a) \qquad d = \alpha - \Theta;$$

α was given by the sum of the horizontal angle η and the astronomic azimuth a of the sun, found from the formula

$$(b) \qquad \cos a = \frac{\sin \delta - \sin h_m \sin \varphi}{\cos h_m \cos \varphi}$$

where φ is the latitude of the observation point, which was taken with the longitude λ from the 1 : 253,440 map of the region; h_m is the mean altitude of the sun S, found by averaging the two observations h_l and h_r made with the vertical circle in the two positions, and by correcting for refraction.

The declination δ of the sun was first assumed approximately; with it, and h_m, λ, and φ, the G. M. T. of the fictitious instant τ of observation was computed from a nomogram [Roelofs, 1950]. Then using the 'Connaissance des Temps' tables, the exact declination δ was computed.

To analyse the precision of the results we must first study the precision of the quantities appearing in formulae (*a*) and (*b*). Let us begin with δ. In the first approximate computation of δ its value at noon of the day of observation is assumed; δ is then affected by an error which in the months of the observations (August and September) is $8'$ at a maximum. φ is taken from the above-mentioned map with a maximum error of $2'$ and h observed with a maximum error of $5''$.

This involves an error on L. M. T. inferior to 2^m, which is the accuracy allowed by the nomogram. Since λ is taken from the map with a maximum error of $2'$, the G. M. T. τ is known with the same accuracy of L. M. T. Such an accuracy allows a second determination of δ with a maximum error of $2''$.

Let us now consider the precision of the determination of a by means of (*b*),; differentiating we have

$$(c) \quad da = \frac{-1}{\cos\varphi\cos h\sin a}\left[\cos\delta d\delta + \frac{\sin\varphi\sin\delta - \sin h}{\cos\varphi}d\varphi + \frac{\sin h\sin\delta - \sin\varphi}{\cos h}dh\right].$$

Since the quantities δ, h, φ appearing in (*c*) are subject to the limitations

$$(d) \quad \begin{array}{ccc} 33^0 < \varphi < 37^0 & & 92^0 < a < 106^0 \\ 6^0 < \delta < 17^0 & \text{or} & 265^0 < a < 285^0 \\ 5^0 < h < 32^0 & & \end{array}$$

assuming for them the maximum errors $|\varDelta\delta| = 2''$, $|\varDelta\varphi| = 2'$, $|\varDelta h| = 5''$ the maximum possible error in the determination of a is given by:

$$(e) \quad \text{Max}\,|\Delta a| < 1.53\,|\Delta\delta| + 0.935\,|\Delta\varphi| + 0.775\,|\Delta h| < 2'.$$

This is much smaller than the possible error of $0^0.1$ in the readings of Θ, and we can therefore neglect it.

We must still consider the fact that in the computations of $\alpha = a + \eta$ the two quantities a and η are not referred to the same position of S, because a is the azimuth corresponding to the altitude h_m, the average of h_l and h_r observed with the vertical circle respectively in the left and the right position, whereas η is referred to the position of S resulting from the average a_m of the readings to the horizontal circles corresponding to h_l and h_r.

We shall see that the error which arises from taking a_m instead of $a(h_m)$ is negligible with respect to the other errors. In fact

$$(f) \qquad \cos a_l = \frac{\sin\delta - \sin\varphi \sin h_l}{\cos\varphi \cos h_l}$$

$$\cos a_r = \frac{\sin\delta - \sin\varphi \sin h_r}{\cos\varphi \cos h_r} \, .$$

The error is then:

$$(g) \qquad \mathrm{a}\,(h_m) - \frac{1}{2}\,(a_l + a_r) = \frac{1}{2}\left[\arccos \frac{\sin\delta - \sin\varphi \sin h_l}{\cos\varphi \cos h_l} + \right.$$

$$\left. + \arccos \frac{\sin\delta - \sin\varphi \sin h_r}{\cos\varphi \cos h_r} - 2 \arccos \frac{\sin\delta - \sin\varphi \sin \frac{1}{2}\,(h_r + h_l)}{\cos\varphi \cos - \frac{1}{2}\,(h_r + h_l)}\right].$$

For small variations of h it is

$$(h) \qquad \mathrm{a}\,(h_m) - \frac{1}{2}(a_r + a_l) = -\frac{1}{2}\left(\frac{\partial^2 \arccos a}{\partial h^2}\right) dh^2$$

where

$$(i) \qquad dh = \frac{h_r - h_l}{2} \, .$$

Formula (h) gives the correction to be applied to the mean direction observed for the sun to obtain that corresponding to the mean altitude. For our observations it may be readily shown that this error is negligible with respect to the others.

The values obtained for the magnetic declination d referred to the G. M. T. of the fictitious instant of observation were then reduced to epoch 1955.0 by means of the graphs of the variation of d at Quetta, which were kindly given to us by the Quetta Observatory. It was assumed in making these reductions that the variation of d in the Eastern Hindu Kush was the same as at Quetta.

The following table gives the quantities observed at the various stations. The reduction to epoch 1953.0 was obtained by means of the nomogram of the annual change published in the Survey of India *Technical Paper* No. 7 by B. L. Gulatee (1954).

Station	Date			Latitude	Longitude	h_l	h_r	η_l
Rawalpindi	August	8	a. m.	33° 35′ 15″	73° 02′ 58″	07° 35′ 58″	06° 28′ 40″	352° 41′ 33″
»	»	8	» »	33° 36′ 15″	73° 02′ 58″	05° 46′ 27″	06° 11′ 38″	352° 41′ 30″
Chitral	»	12	» »	35° 53′ 40″	71° 47′ 11″	29° 44′ 17″	29° 44′ 17″	99° 54′ 50″
»	»	12	» »	35° 53′ 40″	71° 47′ 11″	31° 28′ 34″	30° 48′ 43″	81° 48′ 06″
»	»	26	» »	35° 53′ 40″	71° 47′ 11″	30° 49′ 56″	31° 10′ 19″	288° 09′ 29″
»	»	26	» »	35° 53′ 40″	71° 47′ 11″	32° 15′ 59″	31° 41′ 45″	327° 46′ 10″
Barenis	»	30	» »	36° 04′ 23″	72° 02′ 35″	32° 35′ 12″	32° 42′ 05″	146° 37′ 07″
Sanoghar	»	31	p. m.	36° 18′ 27″	72° 23′ 50″	12° 31′ 00″	11° 50′ 27″	104° 06′ 10″
»	»	31	» »	36° 18′ 27″	72° 23′ 50″	10° 26′ 25″	11° 12′ 17″	236° 09′ 13″
Mastuj	September	1	» »	36° 17′ 04″	72° 30′ 55″	13° 29′ 34″	12° 47′ 28″	00° 16′ 15″
»	»	1	» »	36° 17′ 04″	72° 30′ 55″	12° 02′ 06″	12° 06′ 39″	320° 20′ 22″
Gazin	»	4	a. m.	36° 38′ 40″	72° 55′ 37″	17° 44′ 19″	18° 33′ 43″	316° 39′ 42″
»	»	4	» »	36° 38′ 40″	72° 55′ 37″	18° 56′ 42″	18° 52′ 34″	316° 39′ 42″
Lasht	»	6	» »	36° 47′ 28″	73° 01′ 02″	23° 12′ 10″	24° 04′ 20″	23° 15′ 02″
»	»	6	» »	36° 47′ 28″	73° 01′ 02″	24° 42′ 07″	24° 37′ 02″	23° 15′ 02″
»	»	6	» »	36° 47′ 28″	73° 01′ 02″	25° 03′ 20″	25° 48′ 55″	23° 15′ 02″
Kishmanja	»	6	p. m.	36° 48′ 42″	73° 12′ 07″	13° 24′ 38″	12° 36′ 36″	272° 38′ 06″
»	»	6	» »	36° 48′ 42″	73° 12′ 07″	12° 12′ 57″	12° 14′ 22″	272° 38′ 06″
»	»	6	» »	36° 48′ 42″	73° 12′ 07″	11° 52′ 17″	10° 58′ 54″	272° 38′ 06″
»	»	6	» »	36° 48′ 42″	73° 12′ 07″	13° 24′ 38″	12° 36′ 36″	272° 11′ 18″
»	»	6	» »	36° 48′ 42″	73° 12′ 07″	12° 12′ 57″	12° 14′ 22″	272° 11′ 18″
»	»	6	» »	36° 48′ 42″	73° 12′ 07″	11° 52′ 17″	10° 58′ 54″	272° 11′ 18″
Ishkawarz	»	6	a. m.	36° 49′ 49″	73° 20′ 17″	28° 57′ 31″	29° 16′ 31″	190° 22′ 15″
»	»	6	» »	36° 49′ 49″	73° 20′ 17″	30° 13′ 26″	29° 33′ 35″	190° 22′ 15″
»	»	6	» »	36° 49′ 49″	73° 20′ 17″	30° 36′ 19″	30° 29′ 52″	190° 22′ 15″
»	»	6	» »	36° 49′ 49″	73° 20′ 17″	28° 57′ 31″	29° 16′ 31″	239° 11′ 51
»	»	6	» »	36° 49′ 49″	73° 20′ 17″	30° 36′ 49″	29° 33′ 35″	239° 11′ 51″
»	»	6	» »	36° 49′ 49″	73° 20′ 17″	30° 13′ 30″	30° 39′ 52″	239° 11′ 51″

η_r	a_l	a_r	Declination	1955.0	Mean value 1955.0	Mean value 1953.0
352° 41′ 39″	323° 40′ 26″	324° 36′ 20″	1° 49′ 11″	1° 45′ 30″	1° 47′	1° 41′
352° 41′ 30″	324° 53′ 06″	324° 17′ 40″	2° 03′ 07″	1° 49′ 19″		
99° 54′ 50″	193° 30′ 54″	193° 25′ 30″	2° 50′ 38″	2° 45′ 01″		
81° 48′ 09″	176° 18′ 58″	176° 31′ 55″	2° 50′ 42″	2° 45′ 05″	2° 40′	2° 31′
288° 09′ 36″	21° 12′ 29″	22° 07′ 55″	2° 41′ 24″	2° 36′ 48″		
327° 46′ 10″	62° 01′ 39″	62° 18′ 02″	2° 38′ 36″	2° 34′ 00″		
146° 37′ 17″	112° 08′ 13″	113° 01′ 52″	2° 44′ 23″	2° 39′ 22″	2° 39′	2° 30′
104° 06′ 13″	110° 27′ 33″	111° 05′ 43″	2° 47′ 35″	2° 45′ 02″	2° 45′	2° 36′
236° 09′ 09″	244° 09′ 58″	243° 27′ 25″	2° 47′ 37″	2° 45′ 04″		
00° 16′ 23″	46° 14′ 50″	46° 54′ 53″	2° 35′ 36″	2° 33′ 10″	2° 30′	2° 21′
320° 20′ 26″	7° 19′ 14″	07° 31′ 54″	2° 29′ 52″	2° 27′ 19″		
316° 39′ 43″	328° 23′ 06″	328° 19′ 38″	3° 00′ 26″	2° 54′ 49″	2° 56′	2° 47′
316° 39′ 43″	329° 16′ 27″	328° 37′ 54″	3° 01′ 51″	2° 56′ 14″		
23° 14′ 59″	252° 06′ 48″	258° 06′ 05″	2° 10′ 32″	2° 04′ 55″		
23° 14′ 59″	253° 22′ 38″	252° 33′ 05″	2° 12′ 00″	2° 06′ 30″	2° 06′	1° 57′
23° 14′ 59″	253° 41′ 02″	253° 34′ 26″	2° 11′ 45″	2° 05′ 53″		
272° 38′ 05″	18° 51′ 52″	19° 37′ 30″	2° 48′ 24″	2° 45′ 31″		
272° 38′ 05″	19° 46′ 01″	19° 53′ 58″	2° 47′ 06″	2° 44′ 48″		
272° 38′ 05″	20° 01′ 38″	20° 50′ 48″	2° 47′ 52″	2° 45′ 34″	2° 47′	2° 38′
336° 11′ 17″	18° 51′ 54″	19° 37′ 30″	2° 51′ 36″	2° 49′ 03″		
336° 11′ 17″	19° 46′ 00″	19° 53′ 58″	2° 51′ 18″	2° 49′ 00″		
336° 11′ 17″	20° 01′ 38″	20° 50′ 36″	2° 51′ 05″	2° 48′ 47″		
190° 22′ 13″	13° 38′ 14″	14° 43′ 06″	2° 18′ 18″	2° 13′ 12″		
190° 22′ 13″	14° 50′ 34″	14° 59′ 36″	2° 17′ 01″	2° 11′ 55″		
190° 22′ 13″	15° 12′ 25″	16° 03′ 20″	2° 12′ 20″	2° 07′ 14″	2° 12′	2° 03′
239° 11′ 43″	13° 38′ 44″	14° 43′ 06″	2° 19′ 49″	2° 14′ 41″		
239° 11′ 43″	14° 50′ 34″	14° 59′ 36″	2° 18′ 31″	2° 13′ 25″		
239° 11′ 43″	15° 12′ 25″	16° 03′ 20″	2° 14′ 50″	2° 09′ 44″		

III

GEODESY

LATITUDE AND LONGITUDE OBSERVATIONS DEFLECTIONS OF THE VERTICAL

The geodetic work carried out by the Expedition in 1954 may be summarized as comprising the observation of 5 astronomical stations for latitude and longitude, and the measurement of several bases and local geodetic networks to connect the photogrammetric surveys to one another and to the geodetic network of the Survey of Pakistan.

The astronomical observations were made in cooperation by Prof. Antonio Marussi and Capt. (now Major) Francesco Lombardi, using Wild T2 Theodolite No. 9886 and Nardin Chronometer No. 3315. The method adopted was that of observing on the almucantar of 30° zenith distance. The passages of the stars across the horizontal cross-hair were recorded by means of a stop-clock.

The results of the observations, with their m. s. e., are collected in the table which follows.

For the photogrammetric stations at Camps III and IV in Stak Valley, which are points of a geodetic network observed for photogrammetric purposes by Capt. Lombardi it was possible to deduce the deviations of the vertical, referred to the Indian Ellipsoid of Everest defined by the following:

$$a = 6{,}377{,}276 \text{ m}$$
$$\alpha = 1 : 300.8017$$

and oriented on the station at Kalianpur, assumed to have a deviation of the vertical of 0".31 to the South and 2".89 to the West.

Station	Latitude	Longitude	Number of stars observed
Skardu (Meteorol. Obs., pluviometer; gravimetric station No. 101/d) May 23, 1954	35° 18′ 22″.6 ± 1″.02	75° 38′ 10″.8 ± 1″.56	10
Sasli (pillar; gravimetric station No. 119/d June 8, 1954)	35° 50′ 26″.2 ± 1″.15	74° 44′ 13″.7 ± 1″.09	12
Gilgit (Meteorol. Obs.) June 10, 1954	35° 55′ 48″.9 ± 1″.38	74° 18′ 46″.2 ± 1″.53	12
do. June 11, 1954	35° 55′ 47″.3 ± 2″.24	74° 18′ 46″.8 ± 1″.77	8
do. *mean of the foregoing*	*35° 55′ 48″.5* *± 1″.17*	*74° 18′ 46″.5* *± 1″.16*	*20*
Photogramm. Camp III in Stak Valley June 26, 1954	35° 45′ 45″.3 ± 1″.28	75° 04′ 33″.3 ± 1″.12	16
do. June 27, 1954	35° 45′ 46″.4 ± 1″.05	75° 04′ 33″.1 ± 1″.06	17
do. June 28, 1954	35° 45′ 44″.8 ± 1″.23	75° 04′ 30″.4 ± 1″.06	20
do. *mean of the foregoing*	*35° 45′ 45″.5* *± 0″.48*	*75° 04′ 32″.3* *± 0″.92*	*53*
Photogramm. Camp IV in Stak Valley (pillar; gravimetric station No. 129/e) July 7, 1954	35° 47′ 16″.8 ± 0″.80	75° 00′ 42″.7 ± 0″.62	16

The aforementioned network was connected to the following trigonometric points of the Indus Series:

No. 121 — Pk. 57/43 I (Thanmori)
No. 122 — Pk. 58/43 I (Haramosh)
No. 123 — Pk. 59/43 I (Korang Kar)
No. 124 — Pk. 60/43 I (Shinka Mashkila)
No. 1 — Pk. 1/43 M (Paraber)

Station Height	Latitude φ Longitude λ	$\varphi_g - \varphi_a$	$\lambda_g - \lambda_a$	η
Pamir Boundary Pillar, 4,137 m	37° 26′ 73° 47′	— 6″		— 4″
Stak Valley, Camp IV	35° 47′ 75° 01′	— 8″.3	— 5″.0	— 4″.8
Stak Valley, Camp III, 3,900 m	35° 46′ 75° 05′	— 11″.5	+ 31″.0	+ 16″.2
Remu Gl. 4,912 m	35° 21′ 77° 39′	+ 9″.8		
Skardu 2,233 m	35° 18′ 75° 39′	— 28″.30	+ 10″.85	+ 6″.3
Depsang 5,361 m	35° 17′ 77° 58′	+ 2″.8	+ 6″.0	+ 2″.3
Wazul Hadur 4,243 m	35° 12′ 75° 32′	— 25″.7		
Deosai II 3,903 m	35° 02′ 75° 24′	— 7″.96		
Deosai I 4,057 m	34° 57′ 75° 15′	— 0″.44		
Deosai III 3,777 m	34° 56′ 75° 26′	— 18″.22		
Minmarg 2,850 m	34° 47′ 75° 05′	+ 7″.5		
Churawan 2,484 m	34° 39′ 74° 54′	+ 16″.1		
Kargil 2,713 m	34° 34′ 76° 07′	+ 0″.9	— 9″.9	+ 10″.7
Sonamarg 2,758 m	34° 18′ 75° 16′	+ 12″.0		
Lamayuru 3,461 m	34° 17′ 76° 48′	— 6″.3	— 9″.2	+ 10″.2
Hayan 1,855 m	34° 14′ 74° 58′	+ 20″.81		
Gandarbal 1,585 m	34° 13′ 74° 46′	+ 18″.24		

Station Height	Latitude φ Longitude λ	$\varphi_g - \varphi_a$	$\lambda_g - \lambda_a$	η
Baramula 1,585 m	34° 12′ 74° 21′	+ 1″		
Shadipur 1,589 m	34° 11′ 74° 41′	+ 15″.89		
Leh 3,519 m	34° 10′ 77° 35′	+ 14″.5	+ 10″.5	+ 6″.1
Rustamgarhi h. s. 1,631 m	34° 05′ 74° 50′			+ 28″.1
Srinagar 1,584 m	34° 5′ 74° 49′	+ 17″.19		
Ganga Choti 3,045 m	34° 05′ 73° 45′			+ 19″.1
Lalpur 1,717 m	34° 5′ 74° 32′	— 3″.26		
Zebanwan h. s. 2,682 m	34° 04′ 74° 54′	+ 25″.6		
Poshkar h. s. 2,537 m	34° 02′ 74° 30′	— 13″.8		- 9″.9
Tosh Maidan 3,144 m	33° 55′ 74° 30′	— 1″.7		
Murree Observ. S. 2,273 m	33° 55′ 73° 24′			+ 5″.5
Murree h. s. 2,196 m	33° 55′ 73° 23′	+ 20″.0		
Pingalan 1,593 m	33° 54′ 74° 56′	+ 16″.17		
Gogipatri 2,363 m	33° 52′ 74° 41′	— 3″.0		— 9″.4
Yus Maidan 2,398 m	33° 50′ 74° 40′	— 2″.5		
Korag 3,338 m	33° 49′ 74° 33′	— 2″.0		
Reban h. s. 1,660 m	33° 45′ 75° 00′	— 8″.0		
Yaoli h. s. 585 m	33° 17′ 73° 10′			+ 1″.8

The following results were obtained:

	$\varphi_g - \varphi_a$	$\lambda_g - \lambda_a$	η
III Photogrammetric Camp 3,900 m	$-11''.5$	$+31''.0$	$+16''.2$
IV Photogrammetric Camp 4,150 m	$-8''.3$	$-5''.0$	$-4''.8$

The geodetic coordinates were taken from the official publications of the Survey of India; the deviation in the prime vertical η has been calculated from the formula given on p. VIII of the "*Supplement to the Geodetic Report*, vol. VI, Indian Deflection and Gravity Stations, Dehra Dun, 1931", where the geodetic longitudes have all been corrected by a term equal to $-3''.16$.

These values of the deviations may be added to the list of others determined in the Karakorum and neighbouring regions by the Survey of India and the De Filippi Expedition, which will be found attached.

DETERMINATION OF HEIGHTS

METHOD OF OBSERVATION

One of the most arduous collateral tasks in the carrying out of the gravimetrical programme of the Expedition, was that of the establishment of the height of the stations, needed for the computation of the topographic and isostatic reductions.

As any value of the gravity measured by the Expedition presents an uncertainty which, taking into account the circumstances in which the observations were made, may be evaluated at not more than 1 or at most 2 mgal, and as the influence of height on the combined free air and Bouguer reduction is of about 2 mgal for every 10 metres, it would not have been possible to use any of the existing maps of the Karakorum in order to determine heights without prejudicing the final results.

Nor, on the other hand, it would have been possible to make systematic use of the trigonometric method for the purpose. Even though the eastern part of the Karakorum is partly covered by the Kashmir Principal Series laid down by the Survey of India in 1855-60, and the western part by the Gilgit Series of 1909-1911, it must be noted that the vertices of these fundamental chains lie without exception on the highest peaks of the mountains, whereas the greater part of the gravimetric routes covered are along the paths at the bottom of the valleys. Therefore only in very exceptional cases would the favourable conditions have been present for observation of horizontal and vertical angles.

It was therefore necessary to fall back upon the only method, which would allow the determination of heights by independent observations, i. e. the barometric one, which was in fact used during the operations both of 1954 and 1955.

The method consists, as is well known, in determining the atmospheric pressure at the field station whose height is to be determined, and in comparing this pressure with that measured simultaneously in one or more fixed observatories of known height. Together with the pressure the temperature of the air and the pressure of the water vapour are also observed both at the field station and at the observatories, in order to find the mean density of the column of air between the two.

Let P and P_0 be the pressures at the field station and at the observatory respectively, t and t_0 the temperatures, and ε and ε_0 the pressures of the vapour, by the Laplace formula the difference in height H is as follows:

$$(1) \qquad \Delta H = 18{,}400\,(1.001\,57 + 0.003\,67\,t_m)\left(1 + 0.377\,\frac{\varepsilon_m}{P_m}\right)\lg\frac{P_0}{P}\,.$$

The factor 0.003,67 is the coefficient of dilatation of the air per 1°C, t_m is the mean temperature of the column of air between the two stations, that, on account of the almost linear variation of temperature against height, is assumed to be the mean of the temperatures of the two stations; ε_m is the mean pressure of vapour between the two stations, and P_m the mean pressure. The coefficient 0.377 is equal to 1 — 0.623, where 0.623 is the density of the water vapour compared to dry air at the same pressure and temperature. The constant 18,400 (barometric constant) takes into account the density of the air at normal conditions, and of its contents of CO_2.

The absence of the factor $\frac{g_{45}}{g}$ in formula (1), the ratio between normal gravity at sea level and 45° latitude, $g_{45} = 980{,}629$ mgal, and that of the stations will also be noted. This has been purposely omitted in order to express the heights in dynamic metres. There exists between the metric heights H' and the dynamic heights the relation:

$$g_{45}\,\Delta H = g\Delta H'; \qquad \Delta H = \frac{g}{g_{45}}\,\Delta H'.$$

Nevertheless we note that the ratio between the gravity in the Karakorum and g_{45} differs from unity in quantities which vary from 1.2 to 2.7 in 10,000; in which case the difference between the dynamic and metric heights is certainly within the limits of observational errors.

As we have seen, the application of the method requires the collaboration of one or more fixed observatories to record with sufficient continuity the necessary above-mentioned data. Fortunately such co-operation was assured by the *Pakistan Meteorological Office*, which operates at some excellent meteorological stations in the zone under consideration, and whose work was most generously put at the disposal of the Expedition. I am very pleased to be able to express my gratitude to Mr. Naqvi, Director of the Service, and to his very kind assistants, who helped us in every way on every possible occasion.

The fixed observatories of the Meteorological Office utilized in 1954 are those of Skardu and Gilgit, and in 1955 those of Rawalpindi, Peshawar, Drosh, Gilgit and Chilas.

All the observatories were equipped with excellent mercury barometers with the exception of Gilgit, which in 1954 was still without any and had an aneroid barometer. The readings were taken at 0, 3, 6, 9, 12 and 15 hours G.M.T. (5, 8, 11, 14, 17 and 20 hours Pakistan Mean Time).

With reference to the instruments used by the Expedition, having abandoned the idea of using mercury barometers which prove most unpractical on long and difficult journeys, the criterion used was to employ high precision aneroids manufactured by *Thommen*, and to check them from time to time at different heights with a set of thermobarometers. Thermobarometers had already been used in the Karakorum with excellent results by Professor Abetti and Commander Alessio of the Italian De Filippi Expedition of 1913-14 on account of which we had some good previous experience available. In these instruments atmospheric pressure is of course determined by measuring the temperature of the boiling point of water.

All the instruments used were checked against each other at various times, and in the most diverse conditions of use that were encountered. Once that was done, one of the thermobarometers used was taken as fundamental and corrections were made to all other instruments, both fixed in the observatories or belonging to the Expedition, in order to make them uniform with this one.

In order to speed up and simplify the ensuing calculations, we followed the approach of first expressing every reading, whether the temperature of the boiling point of water, or pressure, in conventional heights corresponding to the standard atmosphere as established by the specifications of the *International Civil Aviation Organization* (*I.C.A.O.*), and published in the "Manual of ICAO Standard Atmosphere" of May 1954. It takes into account dry air of a density of 1.2250×10^{-3} gr/cc in normal conditions ($P = 1013.250$ mbar, $t = 15^{0}C$), a pressure of 1013.250 mbar and a temperature of 15^{0} C at sea level, the value there of gravity being 980.665 gal, and a linear decrease of temperature with the height H according to the law $t = 15^{0}C — 0.0065^{0}C\ H$.

The standard atmosphere is fixed up to a height of 12,000 m which marks the troposphere, and corresponds, roughly, to the actual dry atmosphere at 40^{0} latitude.

The *U. S. National Advisory Committee for Aeronautics* and the *Istituto per le Applicazioni del Calcolo* of the *Consiglio Nazionale delle Ricerche* in Rome, calculated together, with these elements, the tables published in the above-mentioned Manual, which gives at 50 m intervals of dynamic height the other corresponding physical quantity (Table II), and the dynamic heights in metres for the pressures measured in tenths of mbar (Table III) and in tenths of torr (Table IV).

The temperatures for the boiling point of water were first of all converted with the aid of well-known tables into pressures expressed in torr; from these the corresponding ICAO heights were obtained by use of the tables of Standard Atmosphere. In the same way the readings of the barometers were converted, where necessary, into torr, and then into ICAO heights. Only in the case of the Thommen aneroids was the conversion process unnecessary inasmuch as their dials already give the ICAO heights.

This process also facilitated the ensuing use of the Laplace formula, since the individual differences of height obtained by the ICAO tables, naturally referring to the fundamental thermobarometer, had only to be multiplied by the ratio between the actual coefficients of temperature and humidity, and those referring to the standard atmosphere.

OBSERVATIONS IN 1954

The thermometers used are part of the series of old and well-tried Fuess thermobarometers owned by the *Istituto Geografico Militare* in Florence. They were entrusted to Captain Lombardi, who accompanied the writer almost continuously during the course of the operations in 1954.

Each one of these thermometers covers an interval of about 8°, each degree being represented by a length of about 4 cm subdivided into 100 parts, so that the reading of one hundredth of a degree is easy and direct. The series used was composed of 9 thermometers marked with the serial numbers 1689, 1853, 1854, 1855, 3204, 3206, 3207, 3211 and 3217.

Captain Lombardi was also equipped with a Thommen aneroid of the geodetic type No. 26320, with an effective range going from 0 to 10,000 m, and a reading accuracy of 2 m. Such Thommen aneroids have a direct transmission from the indications of the Bourdon tube to the index; but they have proved to be excellent in every respect, and affected by very small hysteresis. The writer was in possession of an absolutely identical aneroid, No. 26064, which was mainly used simultaneously with the first one, except on a few occasions when Captain Lombardi and the writer had to operate separately.

A Salmoiraghi aneroid barograph with weekly recording was installed at Skardu, with the intention of using it to interpolate the readings of the mercury barometer at this fundamental station at the precise time of each individual field observation. With regard to the height of the Observatory at Skardu, this was determined by trigonometric observations, carried out by Captain Lombardi, based on several vertices of the Indus Series. The value adopted for the height of the observatory, which is built on the top of a small hill overlooking the polo ground, was 2,245 m. That height is in complete agreement with the one determined by geodetic observations of the De Filippi Expedition in 1913.

At Gilgit it was not possible to make a direct trigonometrical connection with any of the points of the "Gilgit Series", as no trigonometric point is visible from this locality. There the height of 1,495 m given by the *Pakistan Meteorological Office* was adopted. This height was obtained originally by trigonometrical methods, and we have to assume it with a margin of error of ± 10 metres. This height was also checked barometrically, as will be explained later.

The Meteorological Observatory at Gilgit is on the left bank of the Gilgit River on the alluvial terrace, just beyond the large bridge that leads to Hunza.

The calibration operations of the various instruments were carried out in the following way:

The thermobarometers in the care of Captain Lombardi were repeatedly checked at Skardu both with the mercury barometers at the station and with the Thommen aneroids. These operations were repeated at Gilgit. In the course of the Expedition, during the longer stops, or in the more important stations, both the thermobarometers and the Thommen aneroids were read simultaneously.

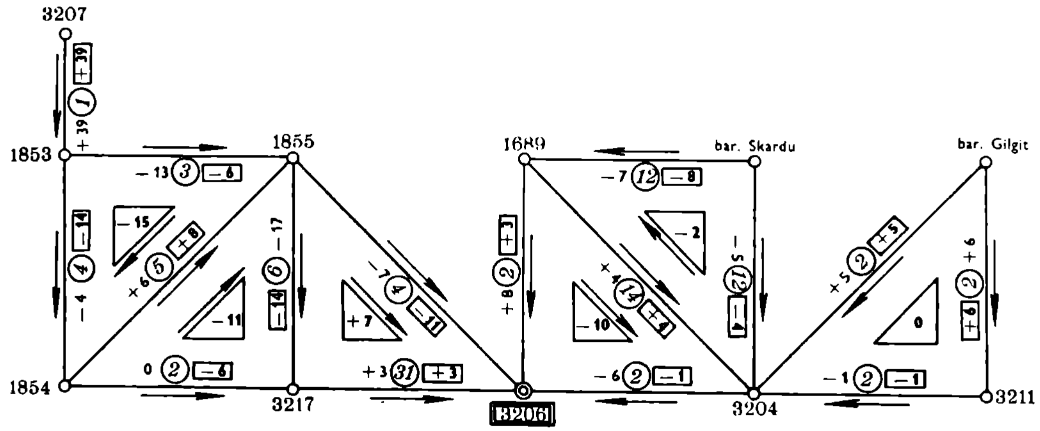


Fig. 25 - Calibration of hypsometers Nos. 1689, 1853, 1854, 1855, 3204, 3207, 3211, 3217 and of the barometers at Skardu and Gilgit, against the fundamental hypsometer No. 3206. Each side represents a calibration with the mean of observed values (in metres according to Standard Atmosphere, and in the direction of the arrow)

+ 8 observed value (metres) ② number of observations |+ 3| adjusted value (metres)

− 10 loop closure (metres)

Thermometer No. 3206 was afterwards taken as fundamental, in that its range allowed it to be used more frequently than any other. All calibrations of the other instruments against this are shown in the annexed graph, in which the readings have already been converted into ICAO standard heights.

That having been done, the ICAO corrected heights furnished by the thermobarometers, were compared with the ICAO heights given by the Thommen aneroids. It resulted that the correction to apply to the Thommen aneroids is a function of height, as is shown in the annexed graphs.

The results obtained are summarized in the table below, which clearly indicates the operations to be carried out in order to get uniform values referred to thermometer No. 3206.

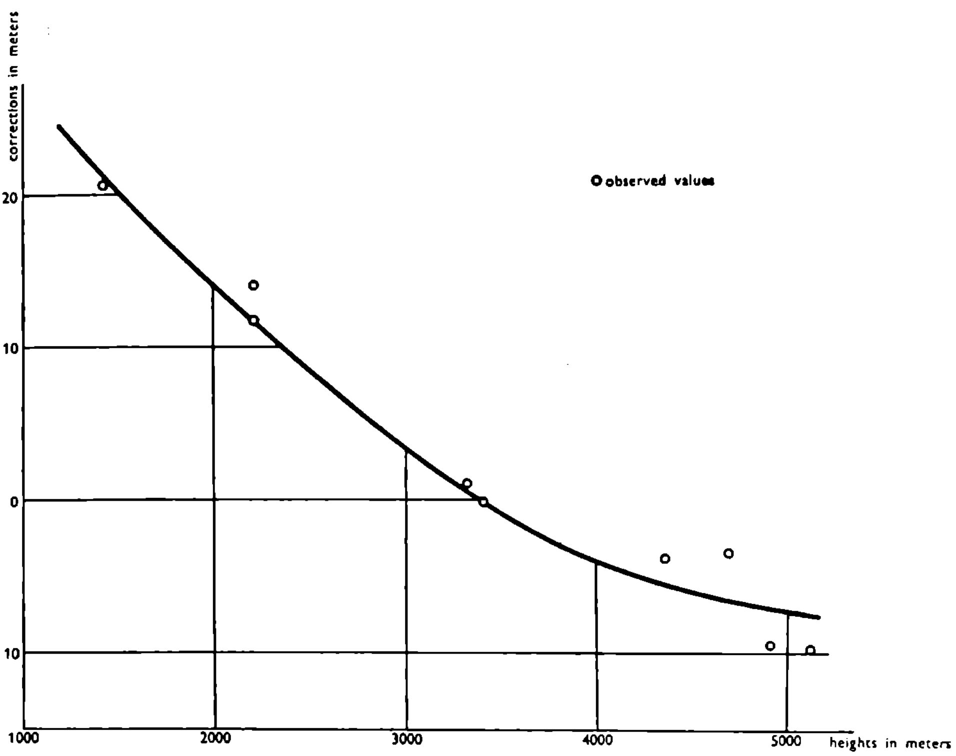


Fig. 26 - Corrections to be applied to the mean of the readings of Aneroids Nos. 26320 and 26064 to reduce them to the fundamental thermobarometer No. 3206. The corrections are expressed in metres according to the ICAO Standard Atmosphere.

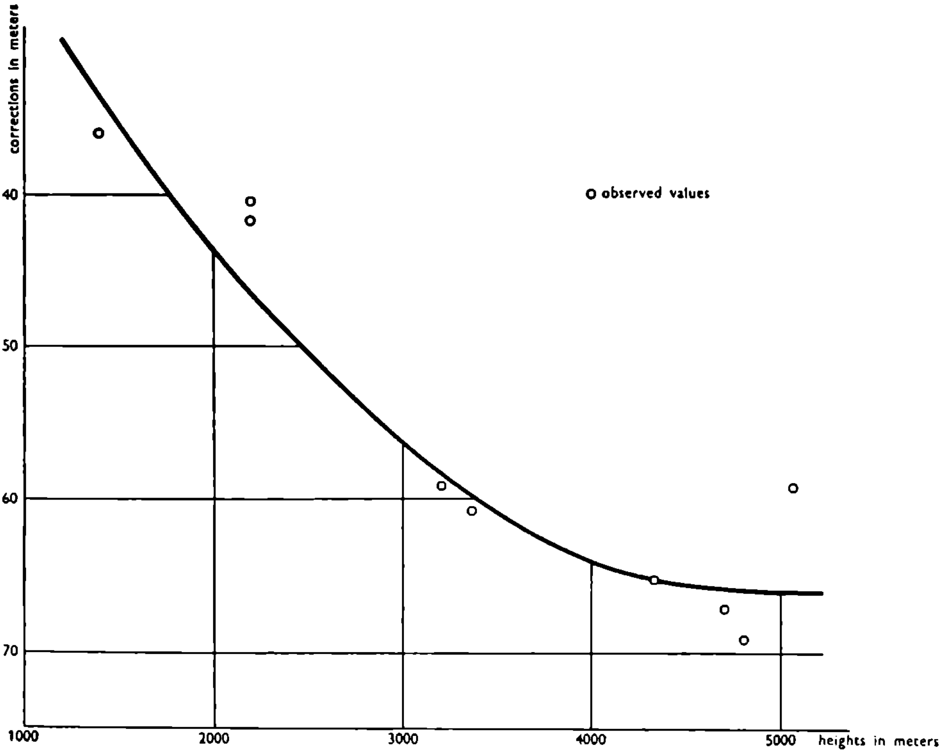


Fig. 27 - Corrections to be applied to the readings of Aneroid No. 26064 to reduce them to the fundamental thermobarometer No. 3206. The corrections are expressed in metres according to the ICAO Standard Atmosphere.

Thermobarometers		Barometers and aneroids	Correction
No.	Correction		
3206	0	Skardu	— 5
1689	+ 3	Gilgit	+ 4
1853	— 17	Thommen	
1854	— 3	average of	
1855	— 11	Nos. 26064 and 26320	Graph
3204	— 1		
3207	+ 22	Thommen	
3211	— 2	No. 26064	Graph
3211	— 2		
3217	+ 3		

Corrections to be applied to the altimetric measurements carried out with the various instruments used in 1954 by the Expedition, to reduce them to the fundamental thermobarometer No. 3206. The corrections are expressed in metres according to the ICAO Standard Atmosphere.

All that having been done, the values used for actual computation of heights were those of the Thommen aneroids, as these instruments were used much more frequently than the thermobarometers.

The difference between such values and the simultaneously recorded values at the Observatories of Skardu and Gilgit already furnish the required difference in height, on the assumption that the physical conditions are those of the Standard Atmosphere.

This not being the case, a further correction must be applied to each individual difference in order to take into account the real conditions of temperature and humidity of the air.

Using the Laplace formula it is obvious that we can pass from the differences of level determined on the hypothesis of the standard atmosphere, to the real one by multiplying the first by the ratio:

$$k = \frac{(1.001\,57 + 0.003\,67\,t_m)\left(1 + 0.378\,\frac{\varepsilon_m}{P_m}\right)}{1.001\,57 + 0.003\,67\,\Theta_m} \simeq$$

$$\simeq [1.000\,00 + 0.003\,67\,(t_m - \Theta_m)]\left(1 + 0.378\,\frac{\varepsilon_m}{P_m}\right)$$

where Θ_m is the mean temperature in the two stations in the hypothesis of the standard atmosphere.

The two factors that figure on the expansion of *k* are given in logarithmic form in the publication "Misure altimetriche in base alla pressione atmosferica" published in 1930 by the *Istituto Geografico Militare* of Florence. We thus obtained the dynamic differences of height by a very simple arithmetical operation.

With reference to the water vapour tension, this was determined both at the observatories and at the field stations by a wet and dry bulb psychrometer, and using the "Diagram for the determination of the absolute tension of vapour" constructed by A. Pericoli according to the formula of Sprüng and published in 1947 by the *Istituto Geografico Militare* of Florence.

OBSERVATIONS IN 1955

The fundamental thermometers used in connection with the hypsometers in the following year are those carrying the numbers 550701, 550702 and 550703 constructed by the *Fabbrica Italiana Termometri Barometri ed Affini FITBEA* of Milan. They are similar to the Fuess type already described, and cover, with slight overlapping, the range of heights from 200 to 4,500 m.

Station	Thermobar. 550702			Thermobar. 550703			Thommen aneroids				Barometers	
							26064		26320		Pakistan Meteor. Off.	
	ob- serv.	corr.	cor- rected	ob- serv.	corr.	cor- rected	ob- serv.	corr.	ob- serv.	correc- tion	ob- serv.	corr.
Drosh	1492	- 3	1489	—	—	—	1431	+58	1436	+ 53	1497	- 8
Gilgit	1450	- 3	1447	1453	0	1453	—	—	1386	+64	1448	+ 2
Chilas	—	—	—	—	—	—			1242	(+58)	1298	(+ 2)
Rawalpindi	—	—	—	567	- 4	563			497	+66	558	+ 5
Peshawar	—	—	—	400	- 3	397			335	+62	402	- 5

Calibrations of the Thommen aneroids of the Expedition and of the mercury barometers of the Pakistan Meteorological Office against the thermobarometers Nos. 550702-3. All values are given in metres according to the Standard Atmosphere.

The technique followed in 1955 was the same as that of the preceding year; but it was not possible to compare the three barometers directly with each other. The calibrations furnished by the makers take the place of these comparisons.

The thermobarometers have also been compared with the five mercury barometers of the Pakistan Meteorological Office distributed in the zone under study in 1955; namely, those of Drosh, Gilgit, Chilas, Peshawar and Rawalpindi.

The results of all the calibrations are summarized in the annexed table from which the excellent state of correction of the mercury barometers of the Pakistan Meteorological Office is apparent. In the table can also be seen the only calibration carried out in respect of the Thommen aneroid No. 26320 which was used only in the first phase of the operations, because it was later damaged by an accidental knock.

CORRECTIONS DUE TO LAGS IN METEOROLOGICAL QUANTITIES BETWEEN GROUND AND FREE ATMOSPHERE

CONCLUSIONS

It is well known that even after having taken into account the periodic effect due to the daily variation of pressure, temperature and humidity, or after having compared, by Laplace's formula, the actual values simultaneously observed at the stations to be connected, there still remains a periodic effect in elevation differences thus determined. This is due to the lag between the meteorological quantities as measured on the ground, and those pertaining to the free atmosphere.

Already the brothers von Schlagintweit (1862) had taken into account this effect at the time of their famous expeditions, and gave an exhaustive report on their *Results of a Scientific Mission to India and High Asia*, in Volume II, Hypsometry.

In processing the abundant material collected, they recognize a yearly period, involving a correction for the month, and a daily period involving a correction for the hour.

As far as the yearly period is concerned, the curves that represent the apparent differences in height as determined from the comparison of simultaneous readings at two stations, are

(*a*) Considerably too low in February and March; i.e. the temperature of the soil is lower than that of the atmosphere.

(*b*) The curve reaches its first maximum a short time before the setting in of the rains. During the whole of this period, the surface of the earth is in excess of temperature as compared to the free atmosphere.

(*c*) The rain season is characterized by a very steep and rapid descent of the curve. The deflection results because the lower strata of the atmosphere are, in consequence of the evaporation, comparatively more cooled by rains than the upper ones.

(*d*) In autumn again, during the first approach of the cool season, there is another decided rise on the surface of the ground chiefly in connection with the uninterrupted action of the sun through a cloudless sky.

There results the following table of corrections (for India and the outer Himalayas), expressed in decimal fractions, of the differences in height:

February, June, July, August	+ 0.002
October, November, December	— 0.0015

For Tibet, Turkestan, and the northern Himalayas no monthly correction is required.

The daily effect is more important; the main results obtained in this respect by the brothers von Schlagintweit are summarized in the graphs obtained from the comparisons between Leh and Massuri (Mussoorie) (1,605 m difference in height) and between Leh and Simla (1,364 m difference in height) in the months of July, August and September 1855, which are shown in a simplified form in the annexed figures, and in the following statements:

(*a*) All the curves showing the apparent differences in height have a minimum at about one or two hours before sunrise, and a maximum from about 11 a. m. to 5 p. m. The form of this maximum, however, is irregular, and immediately dependent upon local circumstances. In several cases there is a secondary depression at about 1 or 2 p. m. followed by a corresponding rise.

(*b*) All the curves reach their mean value twice, once in the morning and once in the afternoon; at the same time it is evident that the a. m. value is by far better defined since it is included between 8 and 10 a. m. for all curves and for all seasons; whilst the p. m. value takes place between 4 and 11 p. m. and altogether in a much irregular part of the curve.

(*c*) In general the range of the daily period increases to a certain extent with the relative height.

(*d*) For practical purposes, it is advisable to take, if possible, the mean of 8, 9 and 10 a. m., or the combination of 6 a. m. with 3 or 4 p. m.

(*e*) For Himalayan and Tibetan stations, situated at great absolute height, as well as in general for those in the dry parts of Tibet and Turkestan, the corrections have to be deduced for each district respectively.

Furthermore, the corresponding stations should be preferred in a N-S direction, since winds blow mostly from W to E; and irregular variations are generally greater for stations of less elevation.

Similar results for the daily effect were found by C. Alessandri on the Alps; the graphs for the two stations at Alagna and M. Rosa (difference in elevation 3,356 m) are given by him for July and August, 1919, in Vol. III, p. 383-387, of the Reports of the Italian De Filippi Expedition (1931), and are shown in the annexed figure.

On our side, in several cases we determined the curves for the daily effect by utilizing the three hourly data of the Meteorological Observatories at the time of our Expedition. The observations from which the annexed graphs have been derived, refer to the following stations and periods:

Date			Stations	Mean difference in elevation	Days
1954,	May	23-31	Skardu-Gilgit	727	9
	June	1-30	do.	760	30
	July	1- 7	do.	727	7
	»	8-31	do.	758	24
	August	3-23			
	September	4-11	do.	759	29
	»	12-24	do.	759	13
1955,	August	11-28	Chitral-Drosh	35	18
	»	11-28	do. -Chilas	237	18
	»	11-28	do. -Gilgit	7	18
	»	11-15	do. -Peshawar	1,178	5
	»	22-28	do. -do.	1,152	7

As can be seen, the data have been grouped in periods which show average values inconsistent by as much as 30 m, without being it possible to give a simple rule to eliminate the inconsistency.

All differences in elevation determined during the course of both the campaigns of 1954 and 1955 have been corrected for the daily effect only, by choosing for each station or group of stations a suitable curve; but no attempt has been made to apply any monthly correction.

From this fact, and from other sources of error, it may be expected that even though the elevations given in the list of stations attached to this volume are derived from at least two fixed meteorological observatories, they may be in error by as much as ± 15 m and in individual cases even more. This applies especially to the stations situated at very high altitude or far away from the observatories.

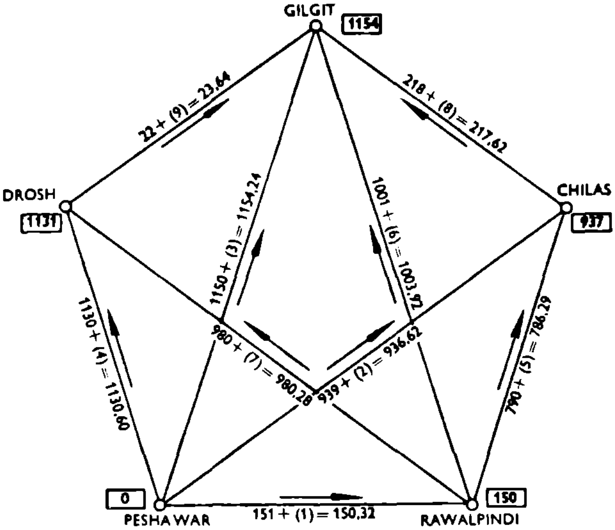


Fig. 28 - Adjustment of barometric height differences between Peshawar, Rawalpindi, Chilas, Gilgit and Drosh as determined from the observations of the Pakistan Meteorological Office, not corrected for calibration with fundamental thermobarometer No. 3206. In the frame, adjusted heights to the nearest meter are given with reference to Peshawar.

With regard to the heights to be attributed to the five barometers of the Pakistan Meteorological Office, we have already mentioned the height attributed to Gilgit; the heights of Rawalpindi and Peshawar are perfectly reliable as they are determined from the bench marks of the spirit levelling which passes through the respective localities.

Doubts could arise only about the heights attributed to the barometers of Drosh and Chilas, and it was therefore considered necessary to carry out a check by comparing the barometric differences obtained using the formula of Laplace based on the values of the pressure, temperature and humidity determined by the meteorological observatories themselves.

As we had at our disposal the measurements of pressure, temperature and humidity determined at 5, 8, 11, 14, 17 and 20 hours during all the days the Expedition remained in the region, we were able to determine for 25 consecutive days the differences in level between the observatories taken in pairs, nevertheless limiting the calculation, for reasons of economy, to the hours 8 and 20 and excluding only the connection between Drosh and Chilas. In this way we obtained 9 differences, each one of which results from the average of 50 comparisons.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	metres
weight	82	20	16	62	33	20	28	444	28	
$1/p$	3.5	7.0	8.0	4.0	5.5	7.0	6.0	1.5	6.0	
$1/p^2$	12.25	49	64	16	30.25	49	36	2.25	36	
Tr. 1.2.5.	+ 1			— 1			+ 1			+ 1
» 1.3.4.		+ 1	— 1					+ 1		+ 7
» 1.4.5.			+ 1	— 1					— 1	— 2
» 2.3.4.					+ 1	— 1		+ 1		+ 7
» 2.4.5.						+ 1	— 1		— 1	— 1
Corrections in metres	— 0.68	— 2.38	+ 4.23	+ 0.60	— 3.71	+ 2.92	+ 0.28	— 0.38	+ 1.63	

Condition equations, weights and corrections in the adjustement of the barometric differences in height between the Meteorological Observatories of Peshawar, Rawalpindi, Chilas, Gilgit and Drosh. Barometer readings used have not been corrected for calibration against the thermobarometers. Compare with the preceding graph.

	Peshawar	Rawalpindi	Chilas	Gilgit	Drosh
Conventional heights from the adjustment	0	150	937	1154	1131
Calibration corrections	0	+ 10	+ 14	+ 7	— 3
Conventional corrected heights	0	160	951	1161	1128
Spirit levelling heights	352	510			
Differences	352	350			
Mean of the differences	351				
Adjusted barometric heights	351	511	1302	1512	1479
Heights given by the Pakistan Meteorological Office	352	510	1268	1495	1465
Differences	— 1	+ 1	+ 34	+ 17	+ 14
Adopted heights	352	510	1285	1495	1465

Comparison between the barometric heights determined by the Expedition, and those given by the Pakistan Meteorological Office; and finally adopted values.

The results of the measurements are shown in the preceding graph.

We then proceeded to the adjustement of the network thus established. The first table gives the condition equations, 5 in number, the weights attributed to the various connections, which have been taken in inverse proportion to the distances, and the corrections. The symbols adopted are immediately recognizable if the table is compared with the graph.

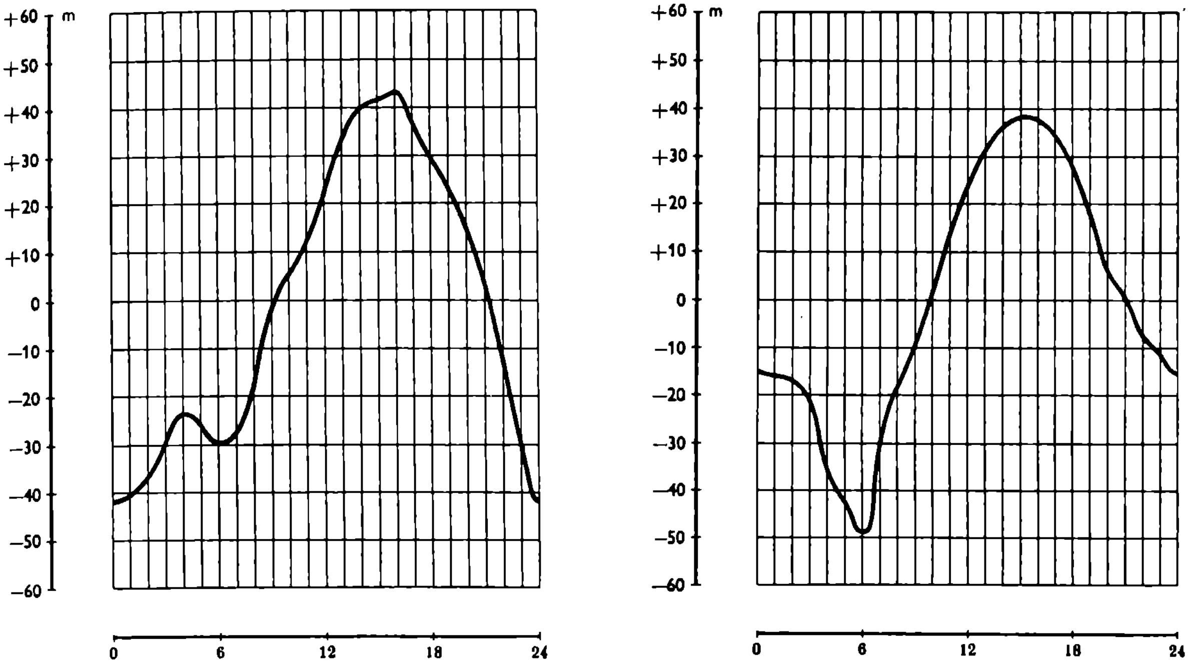
Having applied the corrections of the station, and taken the results to the nearest meter, we arrived at the second table, in which the results obtained by barometer have been compared with those given by the Pakistan Meteorological Office.

The agreement between Rawalpindi and Peshawar is excellent, that of Gilgit, whose height was checked barometrically in 1954, is also good and is thus confirmed. Also the agreement with Drosh is good, whilst we find a greater difference at Chilas.

On the last line we have given the heights finally adopted; these are all the same as those of the Pakistan Meteorological Office with the exception of that of Chilas for which we empirically adopted the value of 1,285 m.

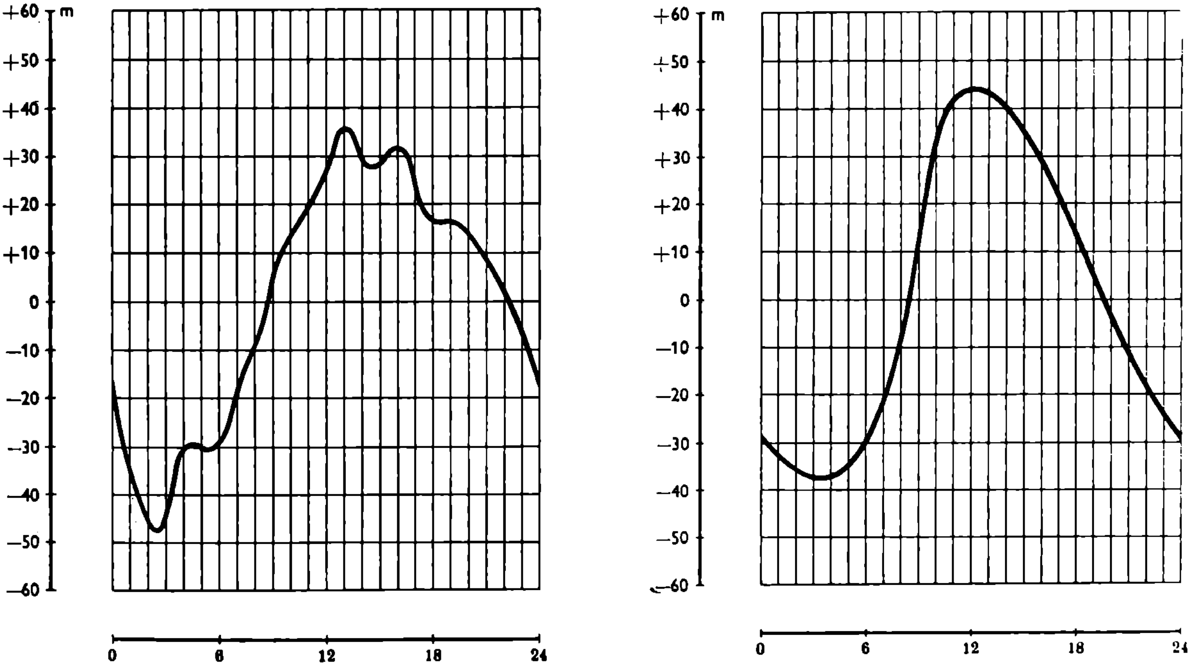
DIURNAL VARIATIONS DUE TO METEOROLOGICAL LAGS

after the observations of the brothers von Schlagintweit, C. Alessandri and of our Expedition



Mean for *July*, 1855
Leh—Massuri, 1506 m
Leh—Simla, 1364 m
(von Schlagintweit)

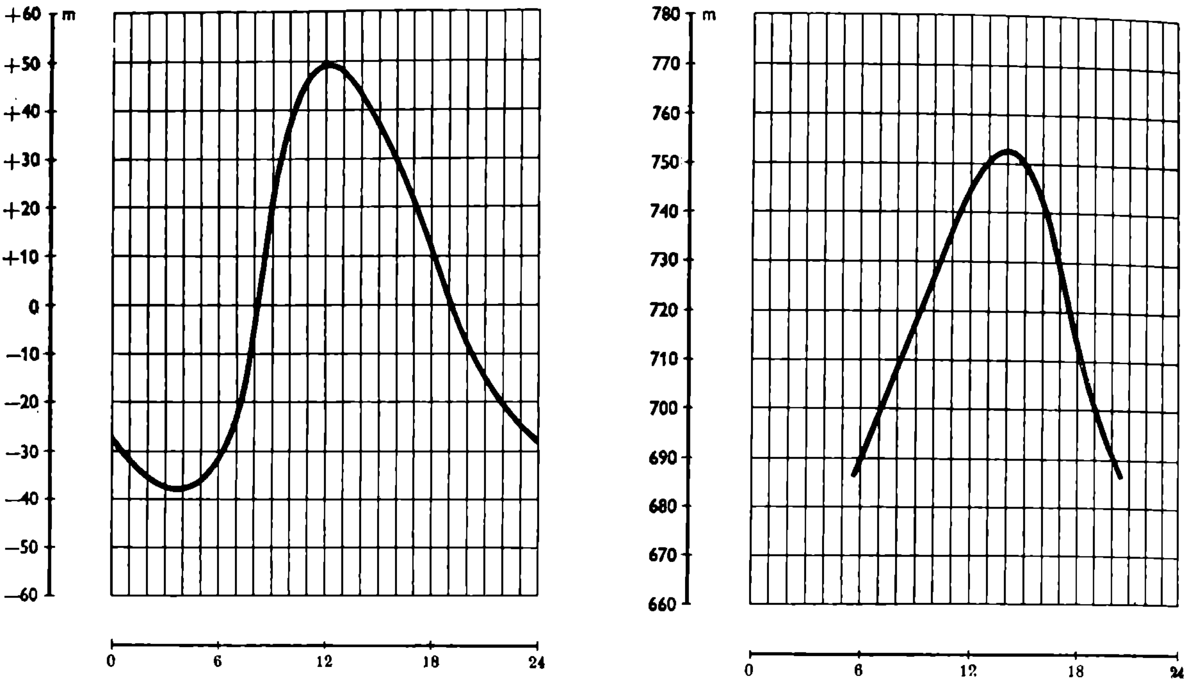
Mean for *August*, 1855
Leh—Massuri, 1506 m
Leh—Simla, 1364 m
(von Schlagintweit)



Mean for *September*, 1855
Leh—Massuri, 1506 m
Leh—Simla, 1364 m
(von Schlagintweit)

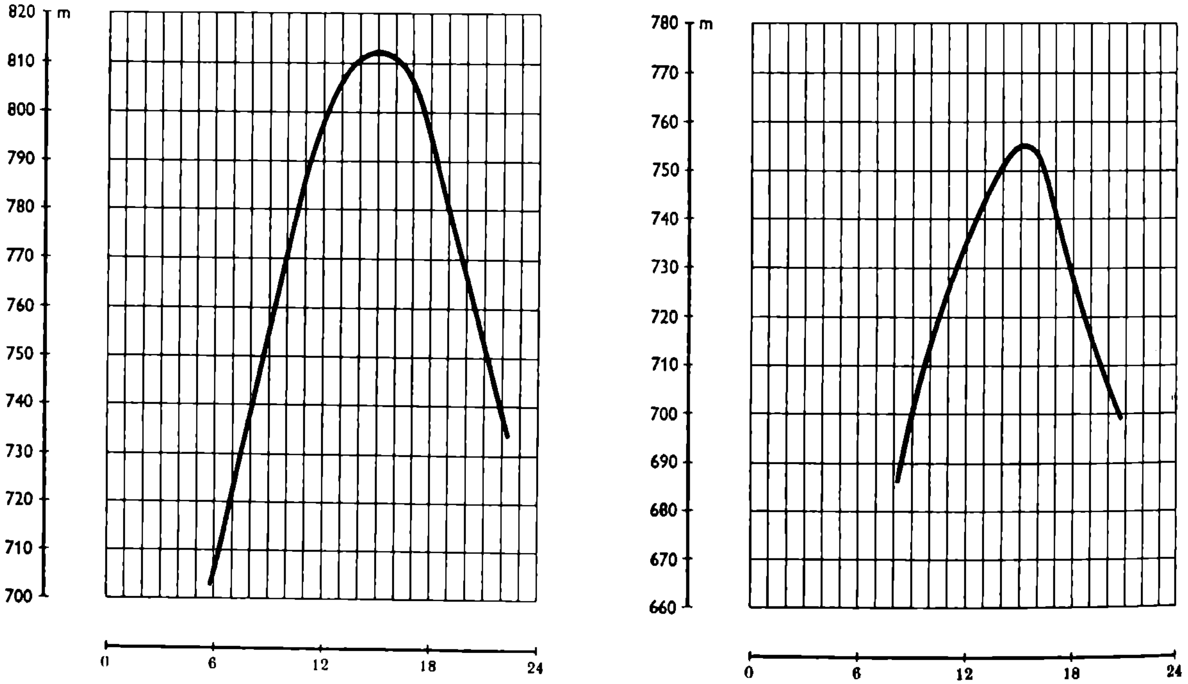
July, 1919
Monte Rosa — Alagna, 3356 m
(C. Alessandri)

Fig. 29 - Diurnal variations of altitude differences due to meteorological lags



August, 1919
Monte Rosa — Alagna, 3356 m
(C. Alessandri)

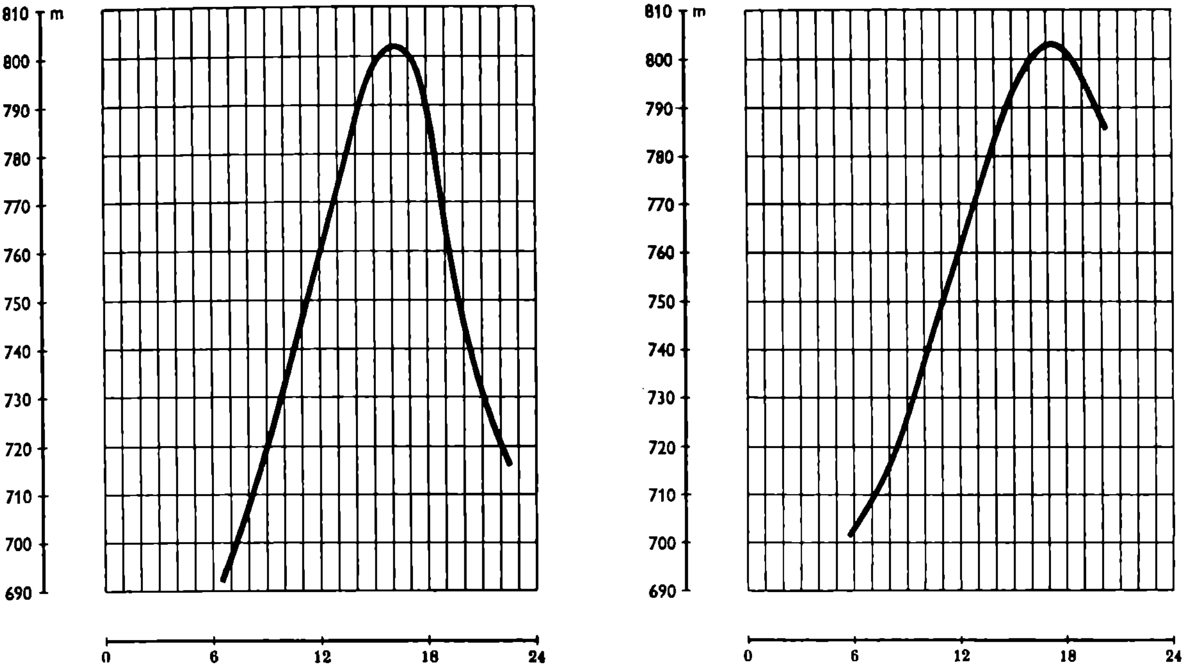
May 23-31, 1954
Skardu — Gilgit, mean value 727 m



June 1-30, 1954
Skardu — Gilgit, mean value 760 m

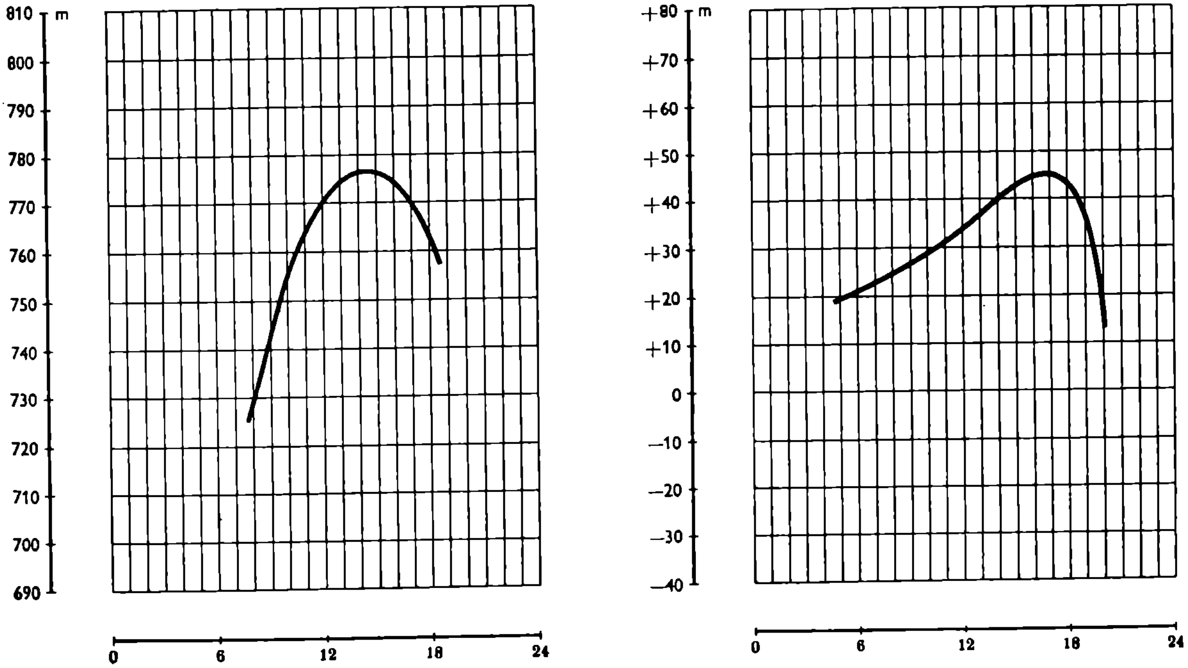
July 1-7, 1954
Skardu — Gilgit, mean value 727 m

Fig. 30 - Diurnal variations of altitude differences due to meteorological lags



July 8-31, 1954
Skardu — Gilgit, mean value 758 m

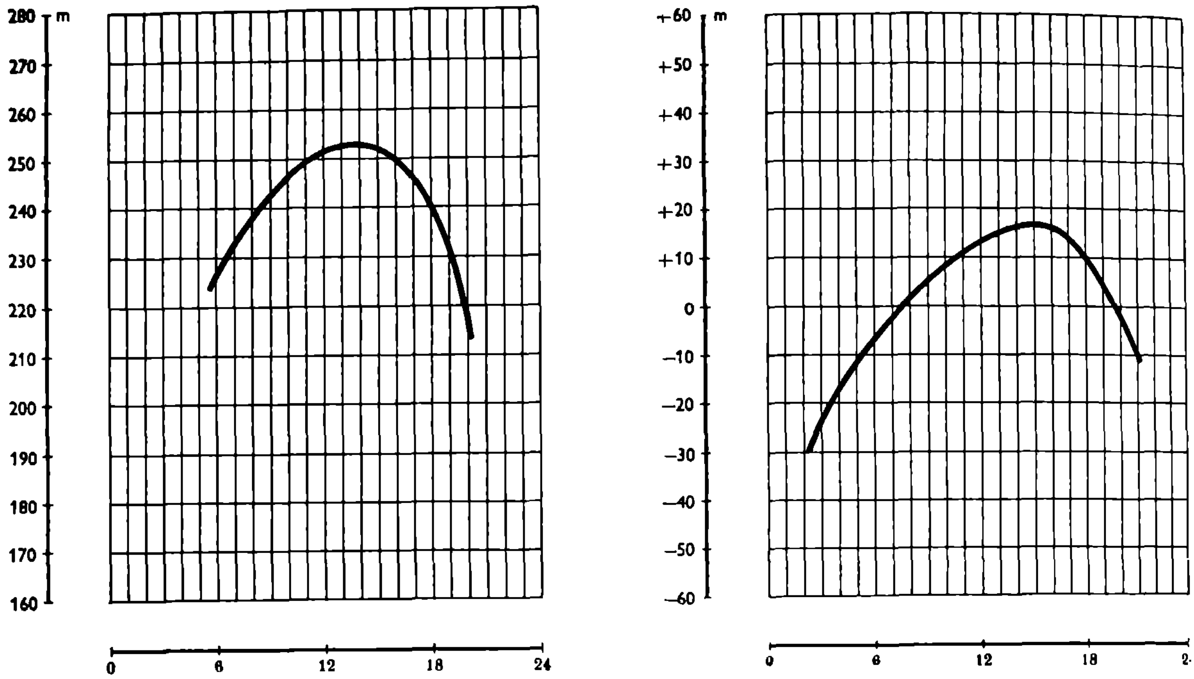
August 3-23 *and September* 4-11, 1954
Skardu — Gilgit, mean value 759 m



September 12-24, 1954
Skardu — Gilgit, mean value 759 m

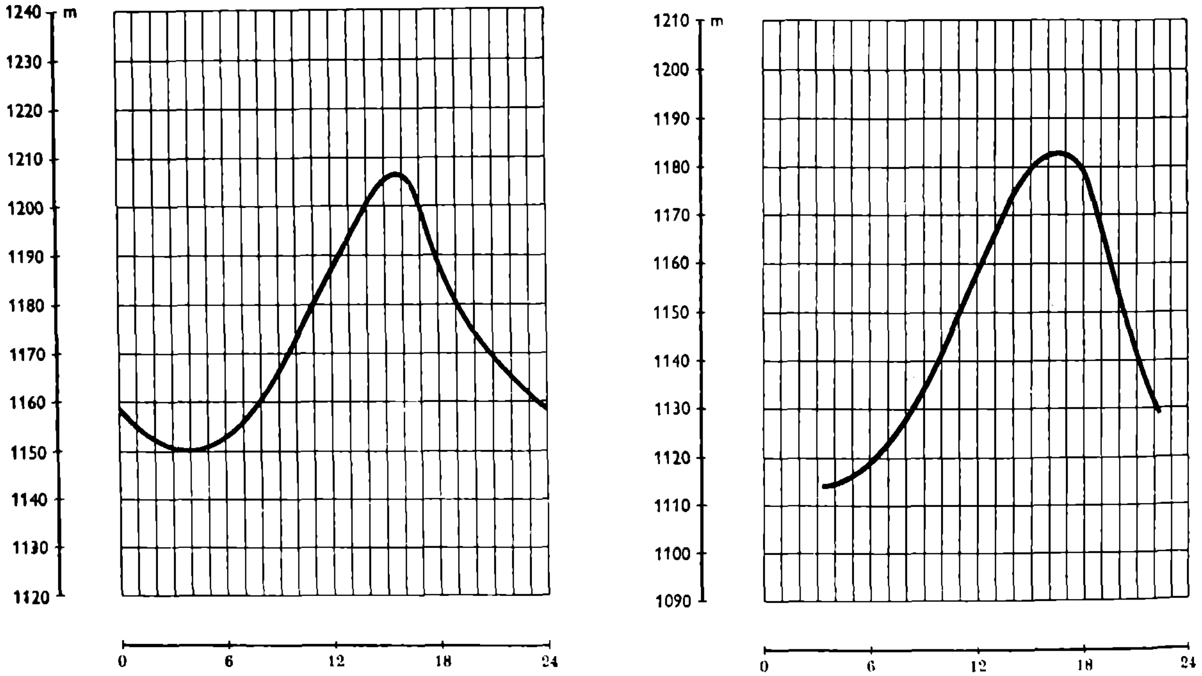
August 11-28, 1955
Chitral — Drosh, mean value 35 m

Fig. 31 - Diurnal variations of altitude differences due to meteorological lags



August 11-28, 1955
Chitral — Chilas, mean value 237 m

August 11-28, 1955
Chitral — Gilgit, mean value 7 m



August 11-15, 1955
Chitral — Peshawar, mean value 1178 m

August 22-28, 1955
Chitral — Peshawar, mean value 1152 m

Fig. 32 - Diurnal variations of altitude differences due to meteorological lags

IV

GLACIOLOGY

(M. Caputo)

DETERMINATION OF THE SECTIONS OF THE GLACIERS GODWIN AUSTEN, BALTORO AND KUTHIAH BY MEANS OF A GRAVIMETRIC METHOD

The glaciological programme of the Italian Karakorum Expedition for 1954 also included the determination of the thickness of some glaciers and if possible the survey of their cross-section.

For this programme Professor Marussi planned to use the Somigliana formula, which gives the thickness of a glacier by means of its superficial velocity, slope and viscosity, assuming that the glacier section is semielliptical; and also to introduce a new method, later used independently by others, which depends on determining the gravity anomalies over the surface of the glacier. Professor Marussi observed therefore gravity sections of the Kuthiah Glacier in the Stak Valley, of the Godwin Austen Glacier between *K2* and Broad Peak, and of the Baltoro Glacier at the Concordia Circle and at Urdukas.

At the latter site Captain Lombardi also made a photogrammetric survey of the surface of the ice on August 17 and September 12, 1954, to determine the superficial distribution of the velocity of the glacier. In the Kuthiah Glacier, however, the superficial velocity of the ice was found by measuring the angular displacements over an interval of time of some points on the ice from a point of known distance.

The photogrammetric results were evaluated at the *Istituto Geografico Militare* in Florence by F. Barducci, who measured the photogrammetric co-ordinates and parallaxes. Professor Marussi then asked me to obtain the super-

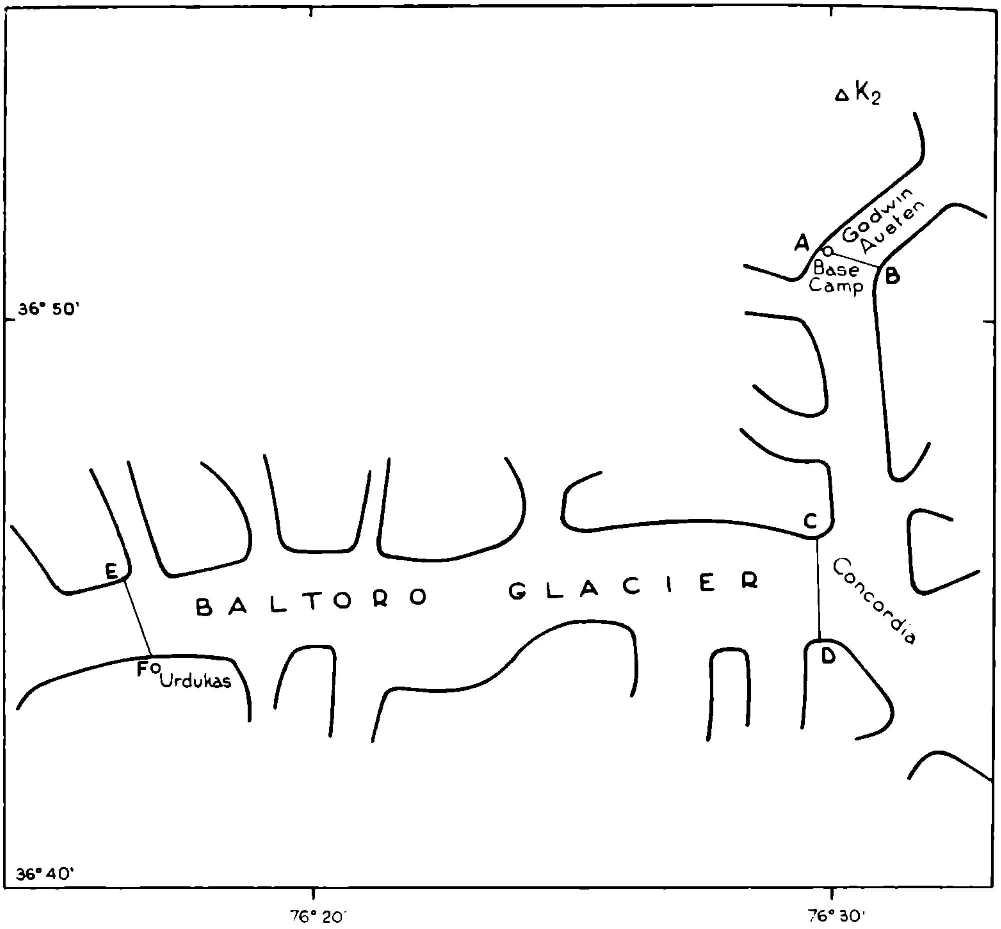


Fig. 33 - Baltoro glacier
Sections at which the depth of ice has been determined

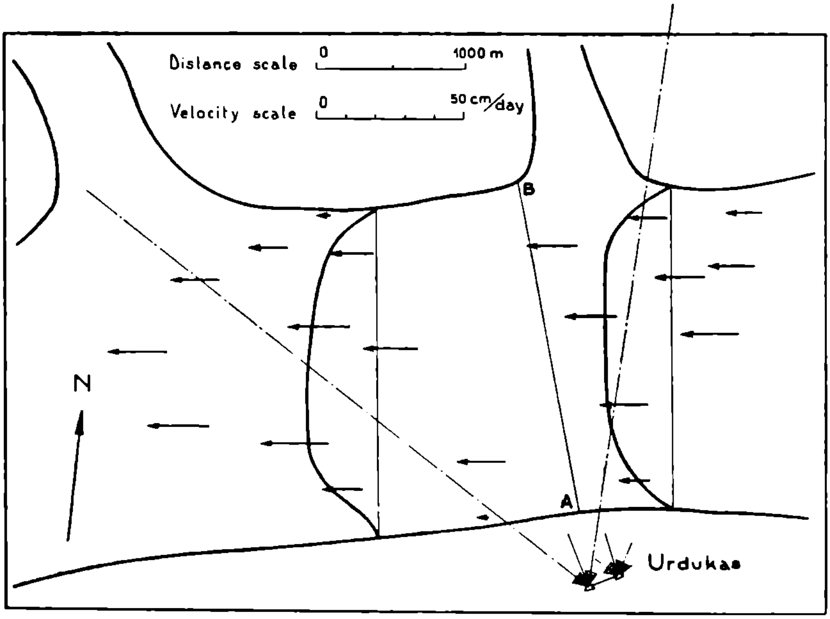


Fig. 34 - Baltoro glacier at Urdukas
Photogrammetric station and velocity of the glacier

ficial velocities for the Baltoro and Kuthiah glaciers and thus to determine their depths by the Somigliana method, and also to investigate a method of finding the depth of a glacier from the gravity anomalies across a section.

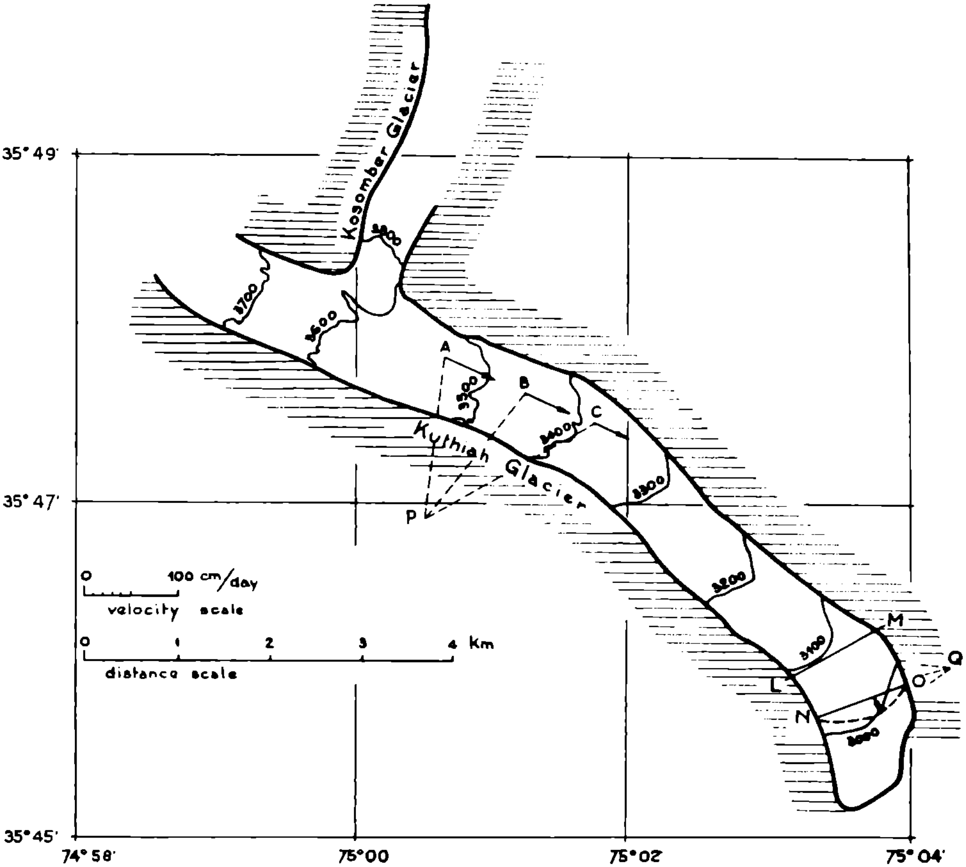


Fig. 35 - Kuthiah glacier
P, Q — theodolite observation points
LM — gravimetric section
ON — section showing distribution of surface velocity

The following gives an account of the methods developed for the solution of these problems. It is divided into three sections:

(1) development of two methods (numerical and graphical) for the determination of the gravity anomaly caused by an almost horizontal cylindrical body. Application of this method to the inverse problem, and analysis of the associated errors;

(2) application of method (1) to the case of the observed anomalies on the surface of the Kuthiah, Godwin Austen and Baltoro glaciers;

(3) application of the Somigliana method to the case of the Baltoro Glacier at Urdukas and of the Kuthiah Glacier; analysis of the errors and comparison of the results obtained with the two methods at the same place.

Let us consider an infinite cylindrical body Q of constant density d, with cross section Γ, bounded by a regular close curve C, and a system of orthogonal cartesian co-ordinates, x, y, z, with the z axis parallel to the axis of the cylinder, and the x axis vertical. The gravitational attraction of Q on a unit mass at a point P_0 $(x_0\ y_0\ z_0)$ does not depend on z_0. Assuming then $z_0 = O$, the y component of the force of attraction of Q on the unit mass in P_0 will be

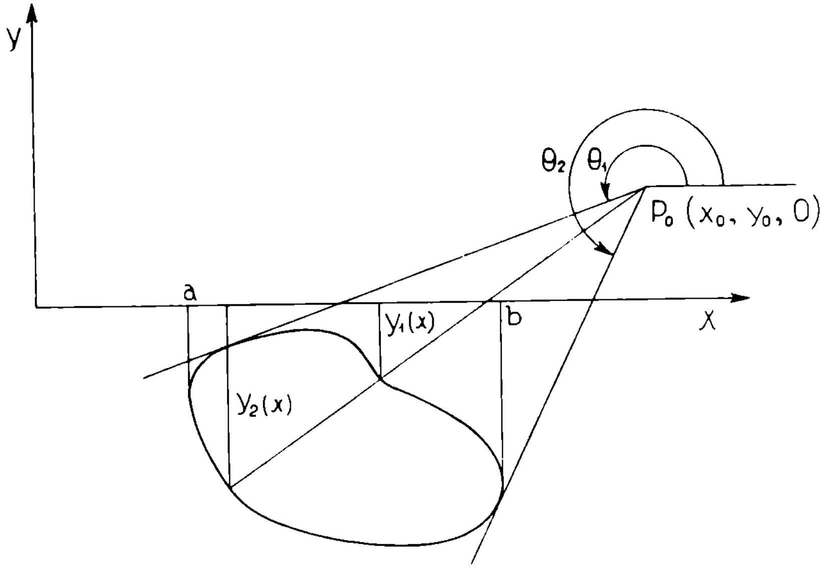


Fig. 36 - Graphical method for the computation of the vertical component of the attraction of an horizontal infinite cylinder mass

$$f_v = 2\gamma\, d \iint\limits_{\Gamma} \frac{y - y_0}{(x - x_0)^2 + (y - y_0)^2}\, dxdy. \tag{a}$$

Since any cylinder can be decomposed into one or more of the types to be discussed here, it is no restriction to assume for the present that the cylinder is bounded by a simple closed curve composed of two arcs C_1 and C_2 which are defined by single-valued functions:

$$y_1 = y_1(x) \quad , \quad y_2 = y_2(x).$$

Let p and q be the abscissae of the extreme points of the curves. Integrating (a) we have

$$(b) \qquad f_v = \gamma d \int_p^q ln \frac{(x - x_0)^2 + (y_2(x) - y_0)^2}{(x - x_0)^2 + (y_1(x) - y_0)^2} \, dx.$$

When a system of polar coordinates P_0, ϱ, ϑ with the polar axis parallel to x, is introduced, formula (*b*) becomes:

$$(c) \qquad f_v = \gamma d \int_{\vartheta_1}^{\vartheta_2} [\bar{y}_2(\theta) - \bar{y}_1(\theta)] \, d\theta$$

where $\bar{y}_1 = y_1 + y_0$, $\bar{y}_2 = y_2 + y_0$ and ϑ_1, ϑ_2 are illustrated in the figure above.

The integral (*c*) can be computed graphically in the following way. We draw on a transparent sheet a full circle divided into m equal parts, and apply the sheet to the graph of Γ, placing the centre of the circle on P_0.

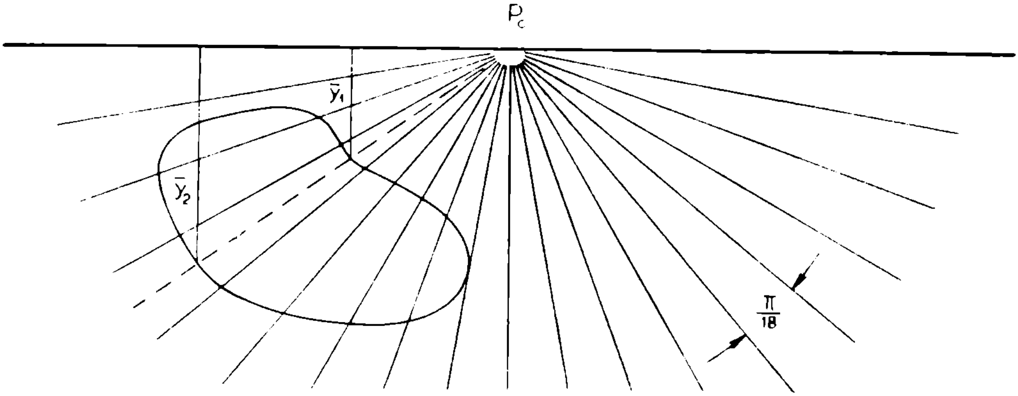


Fig. 37 - Graphical method for the computation of the vertical component of the attraction of an horizontal infinite cylinder mass

In each sector containing a part of Γ we can measure $\bar{y}_2(\vartheta) - \bar{y}_1(\vartheta)$. Summing then with respect to the n sectors which intersect Γ we have:

$$(d) \qquad f_v = 2\gamma d \frac{2\pi}{m} \Sigma \, [\bar{y}_2(\vartheta) - \bar{y}_1(\vartheta)].$$

The inverse problem to that studied above is to find the curve C when f_v is given on a segment a, b of the x axis. In the case of the glaciers the upper arc of Γ is supposed to be a segment which we put on the x axis. Formulae (*b*) and (*d*) are then much simplified since

$$(e) \qquad y_2(p) = y_2(q_1) = y_1(x) = 0.$$

The measurements were corrected for topography and reduced to the same elevation. For each glacier there resulted a curve of anomalies due to the difference between the density 2.67 of the surrounding rocks and the density 0.91 of the ice.

As a first approximation, the section of the glacier was assumed to be elliptical. The integral (*b*) was computed assuming Γ to be a semi-ellipse, with its semimajor axis *a* equal to the halfwidth of the glacier, and with five different values of the semiminor axis *b* as indicated in the table below which gives the results of these computations.

$b \backslash x_0$	0	$\frac{3a}{10}$	$\frac{a}{2}$	$\frac{7a}{10}$	a
$\frac{a}{5}$	1.1178	1.0720	0.9850	0.8365	0.2682
$\frac{a}{4}$	1.3616	1.3068	1.2035	1.0275	0.3697
$\frac{3a}{10}$	1.5927	1.5305	1.4125	1.2121	0.4763
$\frac{7a}{20}$	1.8133	1.7440	1.6128	1.3903	0.5863
$\frac{2a}{5}$	2.0239	1.9484	1.8049	1.5628	0.6981

By comparison of these values with the gravity anomalies *S* over the glacier, a first approximation of the depth of the glacier was obtained from the ellipse whose anomaly fitted *S* most closely.

To obtain a more accurate result for the Baltoro Glacier at Urdukas and for the Godwin Austen Glacier the ellipse was then modified in such a way that the corresponding new anomalies computed by means of (*d*) more closely approximated *S*.

The following graphs give the reductions, the anomalies, and the successive approximations of the sections of the Baltoro Glacier at Urdukas and at Concordia, the Godwin Austen and the Kuthiah glaciers. The symbols in the figures are:

H = elevations on the cross-section
P = topographic reduction (ice)

T = topographic reduction (surrounding rocks)
O = observed gravity
$O' = O + P$
$S = O + P + T$

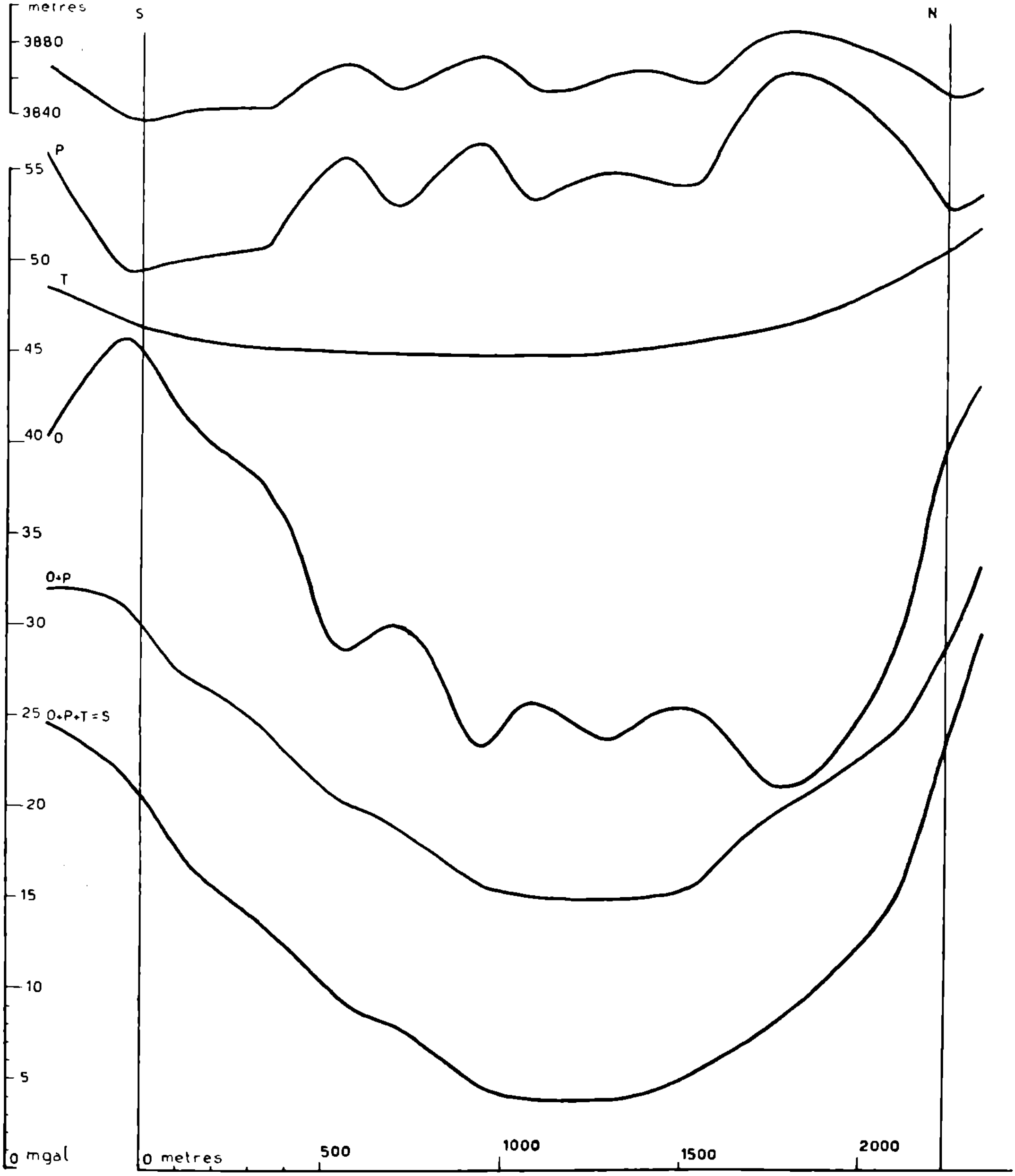


Fig. 38 - BALTORO GLACIER AT URDUKAS
Gravity reductions and anomalies

The precision of the determination of the maximum depth of the glacier by the described method is given by the following considerations. The major sources of error lie in the determination of the observed anomalies and in the computation of the theoretical anomalies.

Errors arise in the former from: (I) instrumental errors, (II) topographic reductions; and in the latter from: (III) departures from the hypothesis that the glacier is an infinite horizontal cylinder, and (IV) uncertainties in the difference between the densities of the rocks and of ice.

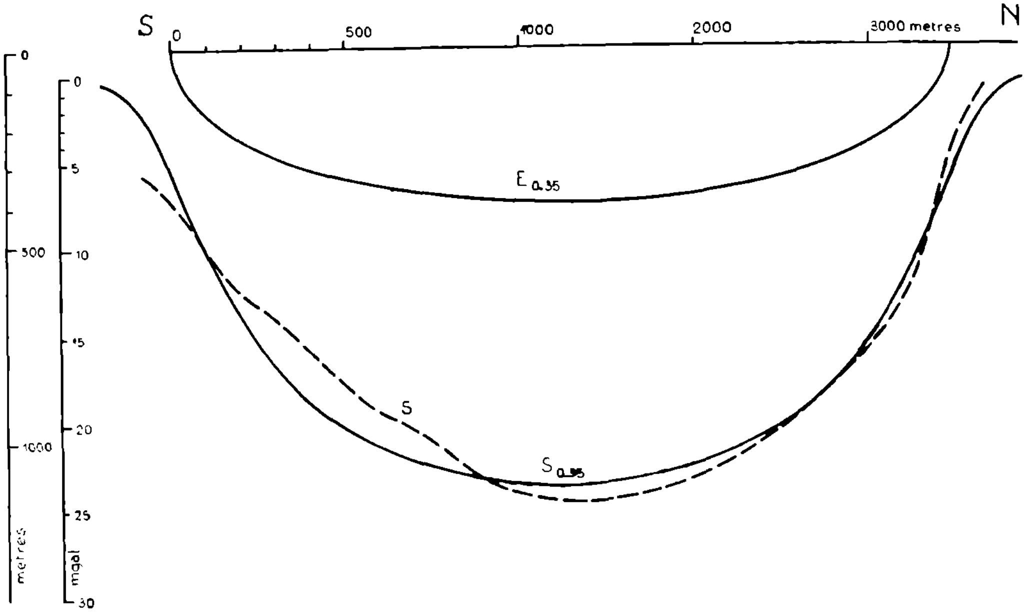


Fig. 39 - Baltoro glacier at Urdukas

— — — — observed gravity anomaly

$E_{0.35}$ elliptic section $b = 0.35\ a$

$S_{0.35}$ gravity anomaly of the elliptic section $b = 0.35\ a$

Since the errors (I) in the precision of the gravity meter used are negligible with respect to the others, and those of (III) may be taken as very small, we will not consider them further.

In the case of the elliptic sections the errors (II) and (IV) are respectively

$$(f) \qquad \delta b^* = - \frac{bc^2 \operatorname{arctg} \frac{c}{b}}{d \left[bc - a^2 \operatorname{artg} \frac{c}{b} \right]} \delta d$$

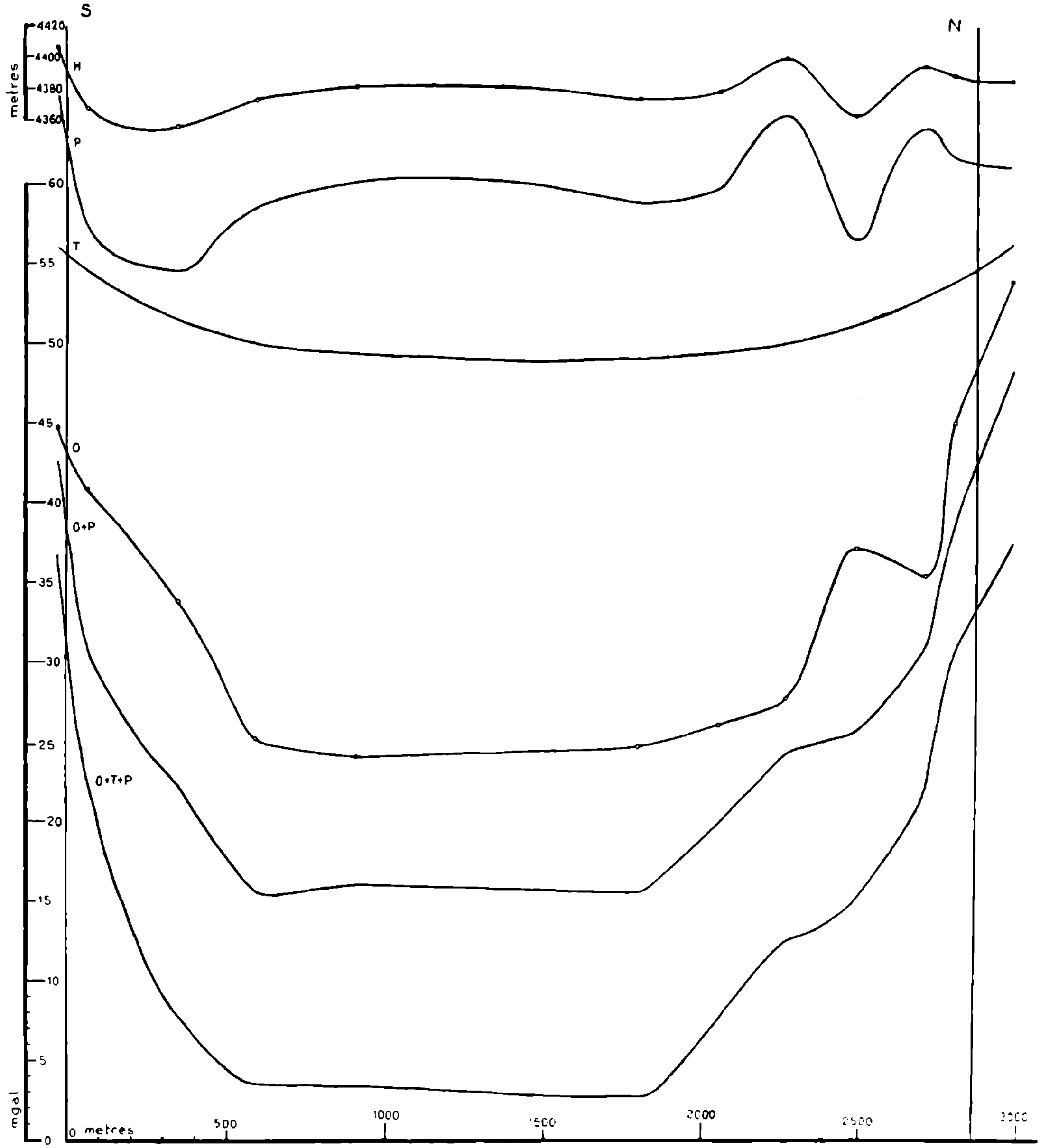


Fig. 40 - Baltoro glacier at Concordia
Gravity reductions and anomalies

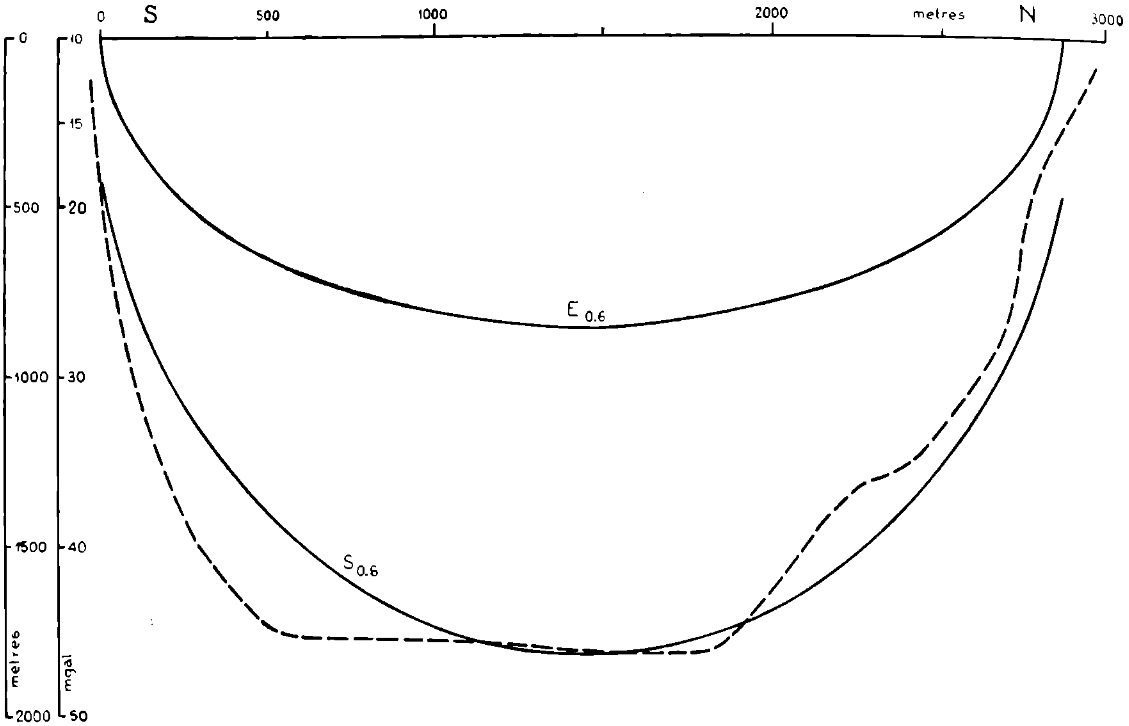


Fig. 41 - Baltoro glacier at Concordia
— — — observed gravity anomaly
$E_{0.6}$ elliptic section b = 0.6 a
$S_{0.6}$ gravity anomaly of the elliptic section b = 0.6 a

(*g*)
$$\delta b^{**} = \frac{c^3}{4\gamma d a\left[a^2 \operatorname{arctg}\frac{c}{b} - bc\right]}\,\delta\Delta g$$

where $\delta \Delta g$ are the errors in the reduction, δd are the errors in the density. For the computation of the errors (II) and (IV) we assumed $\delta \Delta g = \pm 1$ mgal, $\delta d = 0.05$ gr cm^{-3} gr.

The results obtained with the methods above are given in the following table, together with the results given by the application of the Somigliana method which will be illustrated now.

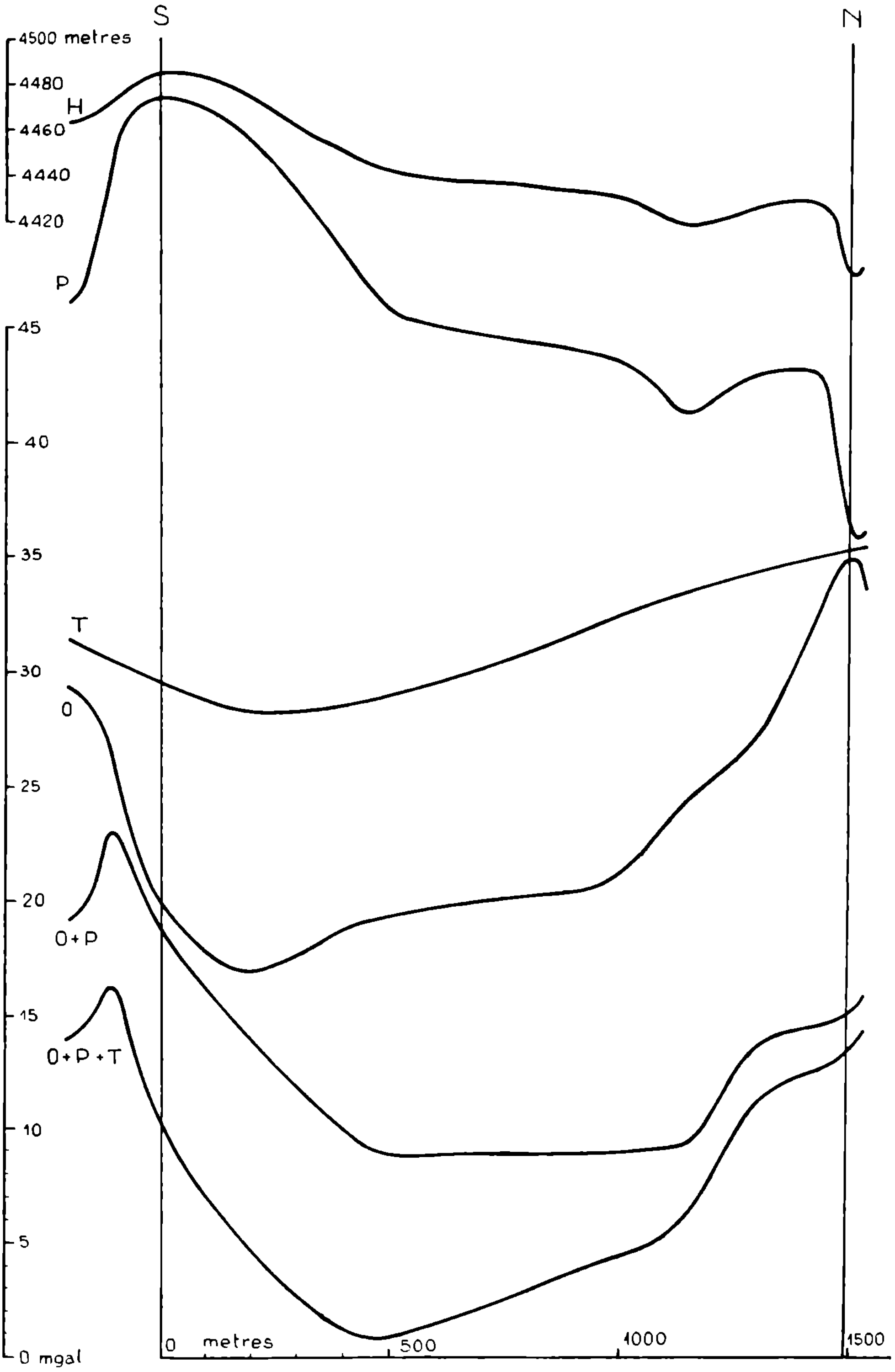


Fig. 42 - GODWIN AUSTEN GLACIER
Gravity reductions and anomalies

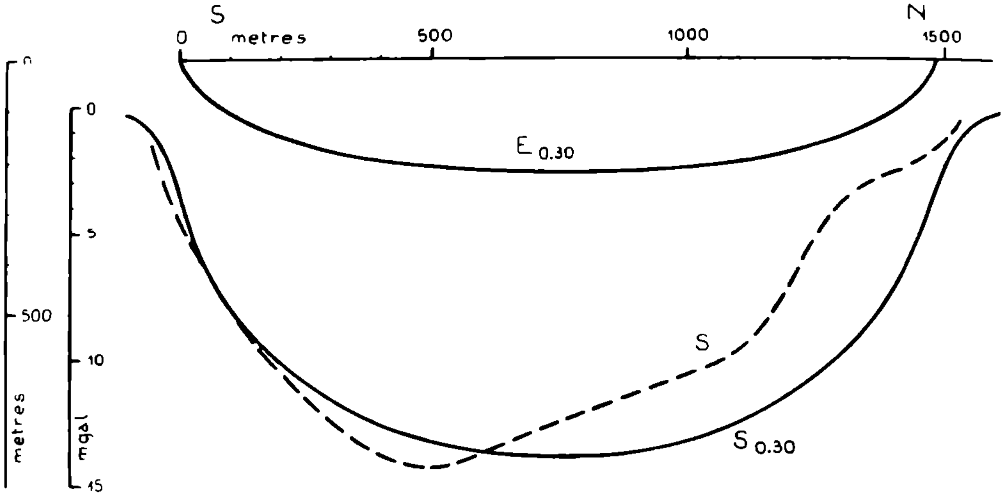


Fig. 43 - Godwin Austen glacier
— — — observed gravity anomaly
$E_{0.30}$ elliptic section b = 0.30 a
$S_{0.30}$ gravity anomaly of the elliptic section b = 0.30 a

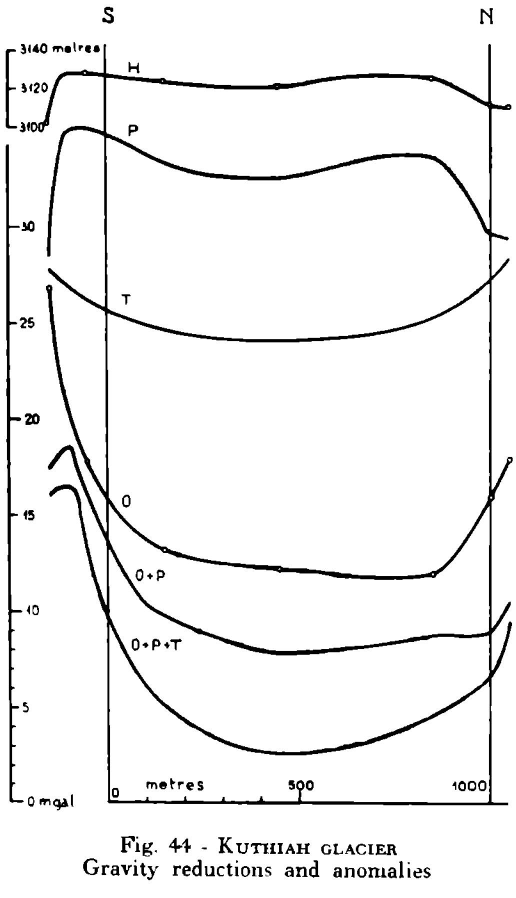


Fig. 44 - Kuthiah glacier
Gravity reductions and anomalies

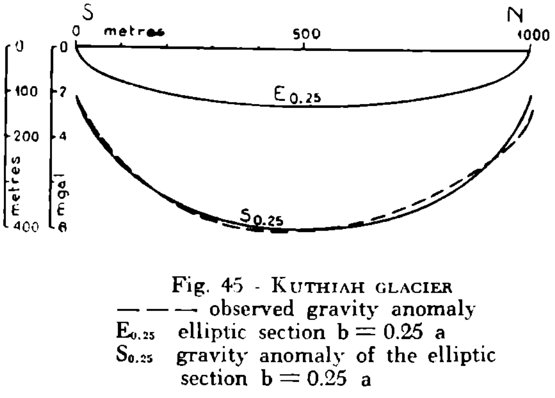


Fig. 45 - Kuthiah glacier
— — — observed gravity anomaly
$E_{0.25}$ elliptic section b = 0.25 a
$S_{0.25}$ gravity anomaly of the elliptic section b = 0.25 a

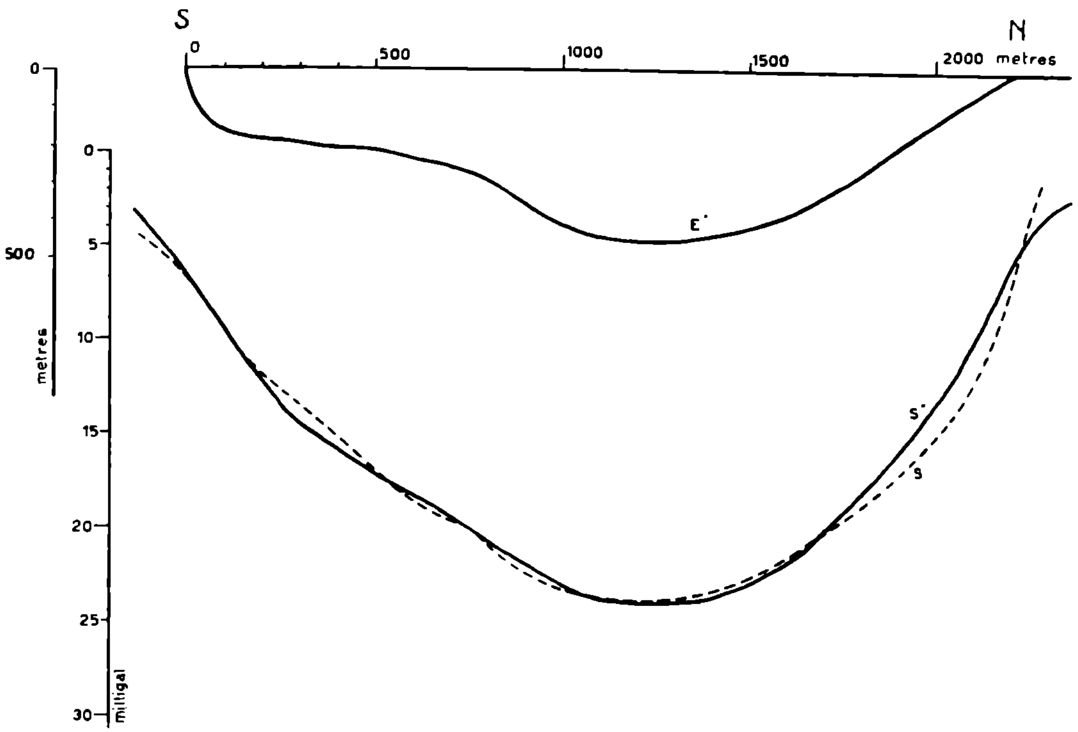


Fig. 46 - Baltoro glacier at Urdukas
—·—— observed gravity anomaly
E* bottom profile from gravity anomalies
S* gravity anomaly corresponding to E*

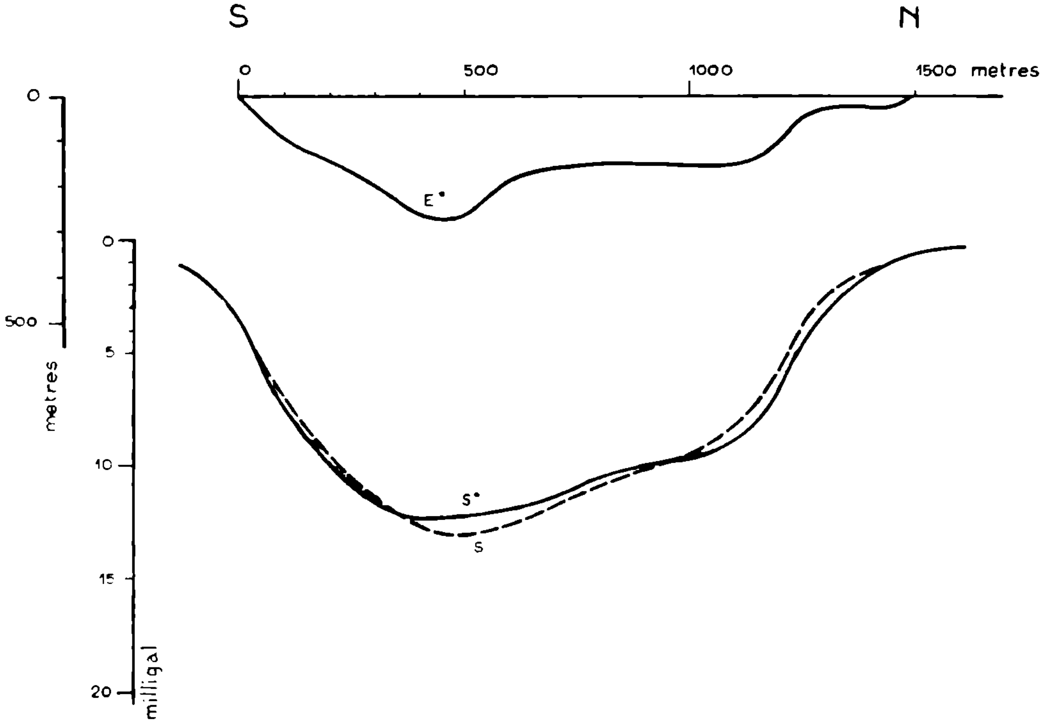


Fig. 47 - Godwin Austen glacier at K2 base camp
—·—— observed gravity anomaly
E* bottom profile from gravity anomalies
S* gravity anomaly corresponding to E*

	Godwin Austen	Baltoro at Urdukas	Baltoro at Concordia	Kuthiah A	Kuthiah B	Kuthiah C	Kuthiah L M	Kuthiah N Q
L (metres)	1490	2230	2586	800	960	900	995	1000
sin α		.006		.08	.08	.08		.10
$v_0 \left(\frac{\text{cm}}{\text{day}}\right)$		25		59	54	38		22
Maximum anomalies (mgal)	12.5	17.0	30.0				5·5	
Maximum depth, elliptical approximation	222	390	858				110	
Maximum depth, further approximation	274	465						
Maximum depth from velocity		377		180	165	153		88
δb^*	7·4	13·4	32.4				4.8	
δb^{**}	19·9	18.9	24·7				18	
$\delta b'$		14		6·7	6.1	5·7		3·3
$\delta b''$		31		11.3	10.3	9.6		8.8

DETERMINATION OF THE SECTIONS OF THE GLACIERS BALTORO AND KUTHIAH BY THE SOMIGLIANA METHOD

The Somigliana formula gives the maximum depth b of the glaciers by means of their superficial velocity assuming that the section of the glacier is semielliptical. The formula is

$$(a) \qquad b = \sqrt{\frac{2\mu L^2 (v_0 - U)}{dL^2 g \sin\alpha - 2\mu (v_0 - U)}}$$

where:

d density of the ice

μ coefficient of internal friction of the glacier

$L = 2a$ width of the glacier

g gravity

v_0 maximum superficial velocity of the glacier
U velocity at the bottom of the glacier assumed to be zero here
α inclination of the bottom of the glacier.

Since in our case $2\mu(v_0 - U)$ is very small with respect to $d\,L^2 g \sin\alpha$ formula (*a*) can be written

$$(b) \qquad h = \sqrt{\frac{2\mu v_0}{dg \sin\alpha}}.$$

The errors in the determination of the depth of the glacier with the above formula are mainly given by the uncertainty of μ and $\sin\alpha$. Differentiating formula (*b*) with respect to μ and $\sin\alpha$ we have

$$(c) \qquad \delta b' = \frac{b}{2\mu}\,\delta\mu$$

$$(d) \qquad \delta b'' = \frac{-b}{2\sin\alpha}\,\delta\sin\alpha.$$

For the computation of $\delta\, b'$ and $\delta\, b''$ the values $\delta\,\mu = 10^{12}$ and $\delta \sin\alpha = 0.001$ were assumed.

The superficial velocity was surveyed only on the Baltoro Glacier at Urdukas and on the Kuthiah Glacier. On the Baltoro the survey was done photogrammetrically.

A Zeiss phototheodolite with a focal length of 193.57 mm and plates of 12 × 17 cm was used. On August 17, 1954, three pairs of photographs were taken from each end of a base of 213.02 m parallel to the glacier and close to Urdukas. One of the pairs was normal, the other two had obliquity of 30° to the right and to the left. A length of 6,000 m of glacier was surveyed. On September 12, three further pairs were taken from the same base and in the same directions. All were taken at noon.

Unfortunately one of the pictures of the normal set was lost, so only the pictures with the obliquity of 30° were used.

The co-ordinates and parallaxes of 48 points on the glacier and of 5 on the rocks in the two pairs taken at 30° to the right were computed by F. Barducci at the *Istituto Geografico Militare.* The same was done for 48 points on the ice and 3 on the rocks in the two pairs taken at 30° to the left. The points on the rocks were used for the correct orientation of the pictures taken 26 days later.

From the co-ordinates and the parallaxes, the surveyed points were plotted.

From the variation of the abscissae measured on the pictures taken 26 days apart, it was possible to obtain the velocity in the direction of the motion of the glacier.

The figure shows the Baltoro Glacier at Urdukas and the surveyed part. In it the photogrammetric base is shown in the bottom right of the graph. The velocity of some of the points is shown and also the curves which give the superficial velocity distribution on the sections *M L* and *S R*. It is evident that the velocities tend to zero close to the edge of the glacier and are a maximum in the middle. The gravimetric determination of the section of the glacier was done in the section *A B*.

The depths were computed using formula (*b*) and the results are shown in the already discussed table. For the computations the following values were adopted: $g = 978.5$ gal, $d = 0.91$ gr cm^{-3} and $\mu = 135 \times 10^{11}$ gr cm^{-1} sec^{-1} according to the limitation $125 \times 10^{11} < \mu < 145 \times 10^{11}$ given by Somigliana.

Comparing the "maximum depth" obtained with the two methods on the hypothesis that the section of the glacier is semielliptical, it is seen that there is good agreement between the value obtained gravimetrically (390 m) and that given by the Somigliana formula (377 m). On the other hand the value (465 m) obtained by the gravimetric method, by successively modifying the ellipse of the semiminor axis of 390 m, differs considerably.

The Somigliana formula was also applied to the determination of the depth of the Kuthiah Glacier at various places. The superficial velocity was surveyed by means of the angular displacements of several points on the surface of the glacier. Three of these points, *A*, *B*, *C*, were in the central part of the glacier half way up its course; nine others were distributed over its lower reaches.

The angular displacements of these points were found by measurements taken with a Wild *T* 2 theodolite. This was done on August 10 and 16, 1954, from a point *P* for the points *A*, *B*, *C*; and at various times during June and July from a point *Q* for the other nine, as shown. In the figure the velocity distribution on the section *L M* derived from these nine points is shown together with that of section *N Q* where the gravimetric survey was done. As mentioned above the results are given in the table together with those found for the other glaciers.

V

INTERPRETATION

STRUCTURAL COMPONENTS OF CENTRAL ASIA

Working from north to south we first propose to examine the most important aspects of the structural components which constitute the region considered in the present work. These are:

(1) The Southern Siberian Plateau and the Caledonian-Hercynian chain of the Tien Shan.

(2) The pre-Cambrian Shield of the Tarim.

(3) The mountain chains of the Hindu Kush, the Pamirs, the Karakorum and the Himalayas, in which is included the Hercynian chain of the Kun Lun-Transalai.

(4) The Indo-Gangetic Plain.

In this necessarily brief summary, which is limited to the consideration of matters which can influence the interpretation of geophysical observations, we have made extensive use of the works cited in the bibliography. As must inevitably happen in any summary, where one view has to be offset against another, it may well be that certain ideas of individual authors, on whom we have drawn, have not been exactly reported in our exposition, for which we alone take full responsibility.

THE SIBERIAN PLATEAU AND THE TIEN SHAN

The Siberian Plateau takes the form of a shield, which became rigid during the orogenic movements which preceded the Alpine phase. It rises gradually towards the south until it merges into the Caledonian-Hercynian chain of the Tien Shan.

This is not to say that the Tien Shan was not affected by the Alpine mountain-building movements, and indeed it must be stated at once that the structure of this chain shows a decidedly hereditary character, in the sense that it was reactivated during the earlier orogenies and shows traces of the movements which took place both at the time of the formation of the great geosyncline of the Himalayas (using the name in its widest sense) and later at the time when the great upfolds of these mountains were formed. It has further been possible to recognize two distinct phases in these last movements: one which took place between the Palaeozoic and Mesozoic Eras, and the other between the Tertiary and Quaternary Eras.

For example, in the chain of the Hissar Mountains in the Western Tien Shan, a great upheaval which developed rapidly during the course of the Tertiary Era may be recognized; in the Northern Tien Shan there are also vertical movements which developed during the Tertiary and continued into the Quaternary. In the same way, the great synclinal basins of Tadjikistan, Ferghana and Tzungaria, to mention only the major ones, show clear traces of movements that started after the Jurassic Period and have continued up to the present time. In fact the frequent and violent earthquakes in this area are to be attributed to this reactivation of ancient structures.

The exact relationship between these movements in Tien Shan and the uprising of the Himalayas is not clear, however, when one considers that between these two great structural complexes, belonging to such different eras, there lies the Tarim Basin, which has been rigid since the pre-Cambrian. Nevertheless it seems safe to affirm that there is a complete difference of genesis between, on the one hand, the great tectonic Kucha Trough, interposed between the Tien Shan and the Tarim Plateau, and on the other, the synclinal basins mentioned above, in that the Trough seems to be related only to the Alpine orogenetic phase, even if it is possibly connected in some way with a great fracture, of much earlier date, which encircles the whole of the southern border of the Tien Shan.

The Tien Shan chain which runs in a general direction from west-southwest to east-northeast shows a marked asymmetry in transverse section. Towards the north it imperceptibly merges into the Ala Tau and the Tarbagatai chains, so to form part of the Uralo-Siberian Plateau, as we have already seen. To the south, on the other hand, the Tien Shan is distinctly bounded by the Tadjikistan Trough, which continues towards the east along the Surkh (Kyzyl-Su) Valley and divides the chain of the Hissar, Ferghana and Alai Mountains to the north from the Transalai chain to the south. This trough then continues along the Tumen (Kizil Dara) Valley to Kashgar and thence proceeds along the Kucha Trough to the northern edge of the Tarim Basin, and finally along the course of the Tarim River to its end.

The folds of the chain show a progressive development which reflects the asymmetrical form of the whole structure. In the southern part the folds follow the trend of the chain and run parallel to it, as do the fractures and troughs which limit it to the south. Further north however they become gradually more complicated and seem rather to be related to the trend of the Ural folds.

In the study of these folds and of the wide synclinal basins ('sinekliza' according to the nomenclature adopted by Russian geologists) another factor of fundamental importance must be kept in mind: the great deep 'Talass-Ferghana' fracture (following again the Russian nomenclature), which runs in a southeasterly direction for a distance of at least 1,200 km along the northeastern border of the Kara Tau, passing to the west of Talass, and reaching at least as far as Kashgar in the Tarim Basin. This fracture possibly continues across Yarkand and Khotan, and even farther along the southwestern edge of the Tarim Basin, thus conditioning the general outlines of this fundamental orogenic node of Central Asia.

In the Kara Tau this fracture separates the fundamental Hercynian-folded complex to the southwest from the mainly Caledonian folds to the northeast. In the same way, it divides the purely Hercynian (partly Alpine) folds to the west from the rest of the Tien Shan chain, which is composed mainly of Caledonian and Hercynian folds. The same fracture also divides the southern front of the Tien Shan into two distinct parts: one in the west facing the massive Hercynian-Alpine anticline of the Northern Pamirs (Transalai) and the other in the east, facing the pre-Cambrian plateau of the Tarim Basin.

The angle formed between this fracture and the trough which separates the Alai and Transalai chains, is almost entirely occupied by the enclosed Ferghana Basin, with a depth of over 5,000 m, containing deposits extending from Jurassic to recent in age.

The northern slopes of the eastern section of the Tien Shan are also marked by many synclinal basins. As also happens in the case of the folds in the southernmost part of the chain, the axes of these basins lie more or less along a geographic parallel, as in the case of those of Narin, Issyk-Kul, Tekes and Ili.

Although the tectonic features of the Tien Shan are attributable, as we have already seen, to Caledonian and Hercynian folding, the chain nevertheless was also involved in Alpine movements, which gave rise to extensive warping of the Mesozoic sediments in the loftier parts of the chain, and further deepened the interjacent synclinal basins developed from the pre-existing Palaeozoic synclinoria. The troughs along southern margins were affected by those movements to an even greater degree (as we shall see more clearly when we come to consider the Pamirs and the Tarim Basin) along with the Tertiary sediments which filled them.

The Tien Shan has recently been the object of studies by various Russian geologists, among whom are Petrushevskii, whose work on the Uralo-Siberian epi-Hercynian plateau and the Tien Shan (Moscow, 1955) is of fundamental importance, and S. S. Schultz, who has provided an analysis of the most recent movements and of the topography of the Tien Shan (Moscow, 1948).

THE TARIM BASIN

The general structure of the Tarim Basin is extremely simple — its nucleus consists of an almost completely levelled pre-Cambrian shield, with a scarcely disturbed Palaeozoic covering; encircling this nucleus, and facing the margins of the Tien Shan and the Kun Lun to the southwest and southeast is a series of deep troughs filled with material ranging from Mesozoic to recent.

The Yarkand Trough, which forms the southwestern margin of the basin, lies on the continuation of the deep Talass-Ferghana fracture, which is presumed to run on here at great depth. The trough, perhaps together with the fracture, continues further east along the northern margin of the Kun Lun. The depth of the Yarkand Trough has been given by Russian geologists as 7,000 m. The material filling it ranges from Mesozoic to recent, but, according to Petrushevskii (1955), its greatest deepening probably began in the Palaeocene, at the time of the late Alpine mountain building, when its depth was about 2,000 m.

The Kucha Trough, already mentioned in connection with the Tien Shan, does not show the continuity which is clearly seen in the case of the Yarkand Trough. It is in fact interrupted by a number of 'isthmuses' such as the one to the west of Aksu, facing the Mazar Tagh. In its eastern section, in the region of Kucha, it reaches a depth of over 7,000 m, and the history of its development is similar to that of the Yarkand Trough.

Just as the latter is marked by the continuation of the Talass-Ferghana fault, the trough of Kucha is bordered to the north, along its entire length, by another deep fault, which we shall refer to as the Chonmuzdusk fault. The troughs of Yarkand and Kucha meet in the neighbourhood of Kashgar, continuing together in a northwesterly direction along the Talass-Ferghana fault, and thus being linked with the Narin and Ferghana troughs.

The trough in the southern part of the Tarim Basin is bordered to the south by a large platform, which surrounds the Hercynian-Alpine chain of the Kun Lun, and is of the same age.

All these troughs became active, as we have seen, in the Palaeocene and were invaded by the sea until the beginning of the Oligocene, when the Alpine movements raised the region and thus caused the waters to recede.

The nucleus of the Tarim shield, on the other hand, has remained unaffected by Caledonian, Hercynian and Alpine movements, with the exception of some marginal block dislocations. However, these dislocations rapidly disappear towards the interior of the platform, so that some 30 to 40 km from the edge of the trough the strata are already found to be undisturbed.

A GENERAL SURVEY OF THE WESTERN HIMALAYAN MOUNTAIN SYSTEM

From a physiographic point of view, the most western part of the Himalayan mountain system, including all the group of folds that form the true backbone of the Himalayas, of the Karakorum, of the Kun Lun and of the Pamirs together with the chain of the Transalai, and of the Hindu Kush, is characterized by some salient features which are apparent from a simple inspection of a physical map of the region. These are:

(1) The gathering together of the folds towards the west into a narrow belt which in its smaller transverse section reaches a width of not more than 600 km (around the 75° meridian); whereas further east these folds fan out broadly to take in the vast plateau of Tibet, which at its widest section, about the 90° meridian, reaches a width of over 1,300 km.

(2) The gradual increase of the mean height of the ranges, up to a maximum which is found approximately in the region of the section of least width (*see* the attached map of average heights).

(3) The maximum heights, which in the most eastern parts (in the Great Himalaya) are invariably found on the southern border of the mountain complex, gradually shift northwards as one approaches the Karakorum in the west.

(4) Finally, the abrupt change of direction of the folding at the 72° meridian, where the ranges, which in the eastern part have a well defined NW-SE

axis (Axis of the Himalayas), turn abruptly to a NE-SW direction (Axis of the Hindu Kush), around the Hazara salient which projects northwards from the Indian Platform into the heart of the mountain complex in the direction of the Pamirs. The curvature of the ranges which to the south is at its maximum in the vicinity of the Hazara salient, diminishes gradually as one proceeds northwards.

This sudden change of direction, or syntaxis, is an unusual feature; and it is appropriate to mention here that analogous structures are found in the region of the Strait of Oman, in Baluchistan where the Suleiman Range has a very similar appearance to that of the syntaxis between the Himalayas and the Hindu Kush, and also perhaps in Assam.

From the tectonic point of view, the northern edge of the Alpine folding, which we shall call the external border, rests upon the older Hercynian chain of the Kun Lun, which further westward continues into that of the Transalai; the Kun Lun was however affected by all the Alpine movements and changed form in accordance with them. The front of the Alpine orogen towards the Hercynian chain of the Alai and towards the Tarim Platform, which constitute the more or less rigid masses that have resisted the Alpine thrusts, is thus composed of the aforementioned chains of the Kun Lun and Transalai.

The internal border is, however, of an entirely different nature; the folds of the Himalayan Tethys are here cut off by a recognizable fault along the whole length of the edge, where they seem to overlie, according to the most reliable opinions of the Himalayan geologists, the formations of Murree and Siwalik.

Both the external border, and the internal one, are accompanied along their whole length by foredeeps full of sedimentary materials, formed or reactivated during the course of the Alpine orogeny — a fact which has been known for a long time in the case of the internal border (Indo-Gangetic Foredeep) and which has recently been revealed by Russian geologists and geophysicists in the case of the external border.

Proceeding from the external border towards the internal border, the following structural units stand out clearly in the belt of chains which concentrate on the Karakorum:

(1) The Kun Lun chain, which, as we have already said, is of Hercynian origin, and which has been violently affected by the Alpine upheaval. This chain is flanked along its external border by a belt of younger formations, from Senonian to Eocene; in the region of the Tarim Basin these formations have been reduced in part to a peneplain which has been welded into

a unit by the thick alluvium which fills the great foredeep bordering the Tarim Platform.

Here, in the region of the Karakorum, the Kun Lun chain follows the trend of the Himalayan axis, but in the region of the 74° meridian, it curves, making a wide arc with its centre a little to the north of the Hazara spur, in conformity with the general outline of the syntaxis. Here the chain takes the name of Transalai. Further west still, in the region of the 72° meridian, the axis is already that of the Hindu Kush.

It is, as we have seen, the opinion of the geologists that the birth of the Himalayan geosyncline dates from the Hercynian orogenic period, when the Kun Lun chain finally separated the Himalayan Tethys from that of Central Asia.

(2) The Himalayan Tethys can be divided into two distinct units, the Karakorum Tethys, and the true Himalayan Tethys. The separation of the two synclines is marked by the geo-anticline of the Karakorum, and by a belt of formations which run from the Senonian to the Eocene, with abundant intrusions of ophiolitic rocks.

The more external part of the syncline of the Karakorum Tethys is formed by the Aghil Range, which borders closely on the internal margin of the Kun Lun; proceeding in a SW direction, this range follows the great Palaeozoic geo-anticline with granite and granodioritic intrusions of the true Karakorum. It is not certain that the geo-anticline is of very great age, but according to Norin it separated the Karakorum Tethys from that of the Himalaya at least in the Tertiary. Here are found the major peaks of the Karakorum chain, including that of K2. According to De Terra, the syncline of the Karakorum Tethys was the first to be involved in the orogenetic upheaval, and for this reason he calls this first phase « The Karakorum Phase ».

Still according to Norin, the Tethys of the Karakorum continues in a NW direction following the arc resulting from the syntaxis of the folds of the Murgat and Pohart ranges in the southern Pamirs.

The continuation of the Karakorum Tethys further west, around the syntaxis, is beyond doubt even though the relations between the various units of the true Karakorum and those of the Hindu Kush have not been completely explained.

(3) There follows the already mentioned belt of Senonian to Eocene formations which contain markedly ophiolitic intrusions attributed to the overlying Cretaceous strata which contain deep-sea sediments. We are thus led to the conclusion that these ultrabasic intrusions were formed, in accordance

with the theoretical reconstructions, at the moment of maximum deepening, or downward thrust of the geosyncline, before the beginning of the true orogenetic movements, which had their most violent development in the mid-Miocene.

Flanking this belt the formations of the Himalayan Tethys have been violently heaped one above the other and pushed towards the south. The middle part of the great syncline of the Himalayan Tethys is marked by strong Mesozoic and Cenozoic intrusions of Himalayan granite, corresponding to the Great Himalayan chain with its major peaks, among which is Nanga Parbat.

Further south we find the group of chains called the Lesser Himalayas, which correspond to a syncline filled with mainly Palaeozoic material, which is essentially different from that of the true Himalayan Tethys.

The internal border of the great Himalayan syncline is marked by extensive basic intrusions, the traps of the Panjal, whose origin is believed to go back to the formation of the geosyncline itself (Lower Permian) and to continue until the beginning of the upheaval (Triassic).

The Himalayan geosyncline is abruptly interrupted towards the foreland by a series of longitudinal faults, of which one, the Main Boundary Fault, can be followed continuously along the whole of the boundary; along this system of faults the border of the geosyncline rests upon the Murree and Siwalik formations, which in part fill the foredeep, which flanks the Indian Platform along its northern margin.

This is the so-called ‘ Nappe Zone ’. In certain regions, as in Kashmir, we can distinguish two principal faults; the Murree thrust, which represents the gliding surface of the autochthonous base zone of the Himalayan syncline (Salkala series, pre-Cambrian) over the Murree series; and the Panjal thrust, which on the other hand constitutes the gliding surface of the true Nappe Zone on the above-mentioned autochthon.

(4) Along the internal margin of the Himalayas we find, below the Main Boundary Fault, the series of marine formations of the Lower Miocene, called the Murree series, which probably comes from the erosion of the Aravalli system. This formation is autochthonous on the platform and is found only in the syntaxial bend, to the west of the 75° meridian.

(5) Superimposed on the Murree series is the Siwalik series, of mid-Miocene to Pliocene age, derived from formations of Himalayan origin.

This series borders the whole of the Himalayan chain, and rests above the Murree series along the Main Boundary Fault. The Siwalik series grades imperceptibly into the more recent alluvial deposits of the Indo-Gangetic Plain, with only one exception, in the region of the Potwar Basin to the west of the syntaxial bend. Here it gives place to a wide syncline the southern lip of which is abruptly cut off in the region of the Salt Range.

Both the Murree and the Siwalik formations occupy the marginal part of the great foredeep which flanks the Indian Platform along the whole of the margin of the Himalayan chain.

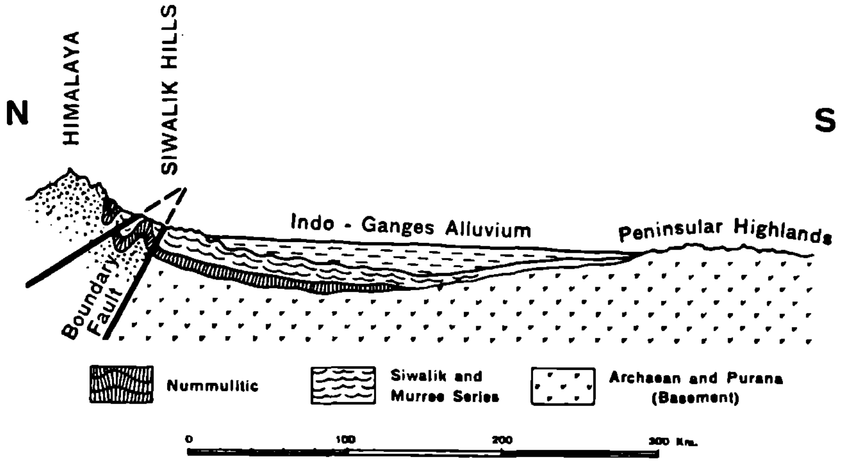


Fig. 48 - Diagrammatic section across the Indo-Gangetic synclinorium (after Wadia, 1953)

Three structures are clearly present in the region of the northwest spur of the Indian Platform; they are:

(*a*) The syntaxis between the Himalayas and the Hindu Kush.
(*b*) The syncline of Kashmir.
(*c*) The syncline of Potwar (or Soan).

These three remarkable structures will be examined separately, to the extent that they may influence the geophysical considerations which follow.

(*a*) *The syntaxis between the Himalayas and the Hindu Kush*

A simple glance at a physical map of Asia shows how the mountains of the Alpine orogen, in the southern central part of the continent, take the form of festoons, the greatest being that of the Himalayas. Without exception these festoons, which have their convexity towards the south, are joined to one another at acute angles, almost as if the rigid platform which they face presented rigid wedges around which the festoons have been fitted.

We have already mentioned that one of these wedges is clearly observable in the region of the Omar Gulf; two others are apparent in the Suleiman Range in Baluchistan, and yet another, the most pronounced, is that found to the south of the Pamirs, around which are formed the Himalayan and Hindu Kush chains; in all probability another is to be found in Assam, and forms the structural pattern around which the Himalayan chain to the west, and the chains of Burma and Indochina to the south are modelled. A common characteristic of all these spurs is that they do not break the structural continuity of the chains which are plastically moulded about them.

Of these spurs the one which concerns us is that known in writings on the geography of India as the Hazara wedge. This wedge has a considerable effect on the syntaxial bend of the Himalayan and Hindu Kush chains, and its effect is felt as far as the Pamirs; according to Kossmat the Hazara wedge had already come into play in the course of the Hercynian folding.

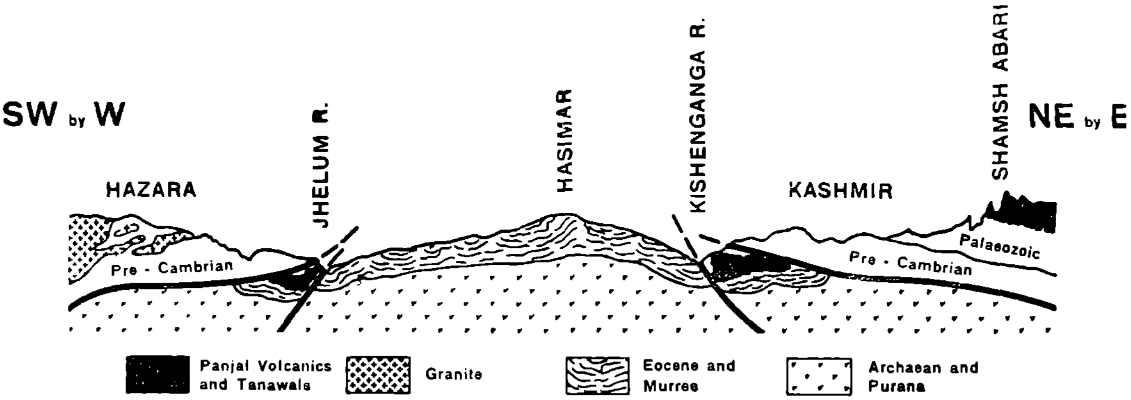


Fig. 49 - Section across the Hazara - Kashmir Syntaxis; relation of the foreland with autochthonous and Nappe Zone (after Wadia, 1939)

Above all, from the research work carried out by D. N. Wadia, little doubt remains that the syntaxis between the Himalayas, taken as a whole, and the Hindu Kush should not be interpreted as a virgation but rather as the moulding of the Himalayan mountain system in the course of its development about a sharp spur of the platform. Assuming that the thrusts came from the north, it would seem that, on encountering the spur or wedge, they developed into normal thrusts along the present axes of the Hindu Kush and of the Himalayas respectively, finally giving rise to the superimposing of the Nappe Zone on the wedge of the foreland. Some writers (Wilsdon, Glennie) even maintain that the Hazara wedge is based upon an archaic chain, perhaps connected with that of the Aravalli, going roughly in a N-S direction; or that this same axis represents an upwarping of the crust; either of these would explain the rigidity of the Indian Platform in the region of the Hazara, and in the above-mentioned direction.

Direct observation of the platform is still precluded by the autochthonous covering of the Murree series belonging, as we have already seen, to Oligocene-Miocene age. The sediments of this series are not of Himalayan origin, but come from the plateaus of the platform to the south, which sometimes exceed the height of 2,000 m. The deposits were laid down in a syncline; actually their base shows a slight dip towards the south. Only in a few points does the base appear above the surface. It is analogous to the Indian Platform and particularly to the Aravalli chain.

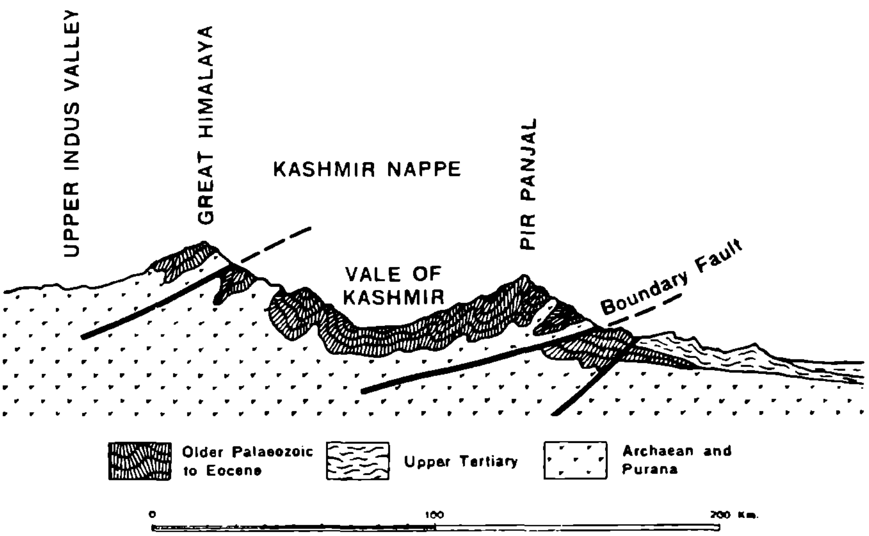


Fig. 50 - Diagrammatic section across the Kashmir Himalaya, showing the broad tectonic features (after Wadia, 1953)

The Murree series is characterized by complicated « plis de couverture » due to the thrust of the Nappe Zone of the Himalayas, which was overthrust at its internal border along the Main Boundary Fault. From detailed geological explorations, the continuity of the formations and of the structures which develop around the vertex of the Hazara wedge has been ascertained. We have already noted how this continuity exists not only for the folds near the wedge, but also for the chains which develop further north, as far as the Transalai-Kun Lun.

(*b*) *The Kashmir Valley*

This is a tectonic valley which corresponds to a syncline enclosed by the Pir Panjal to the southwest and the Zanskar Range of the Great Himalayas to the northeast. The Pir Panjal represents that part of the Himalayan Nappe Zone which was raised when it overran the formations of the foreland; towards the northeast the valley is dominated by the scarp of the Great Himalayas, which is also marked by a fault, the Zanskar thrust, dipping towards the axial zone of the Himalayan syncline, and along which have been overthrust the formations of the Himalayan Tethys.

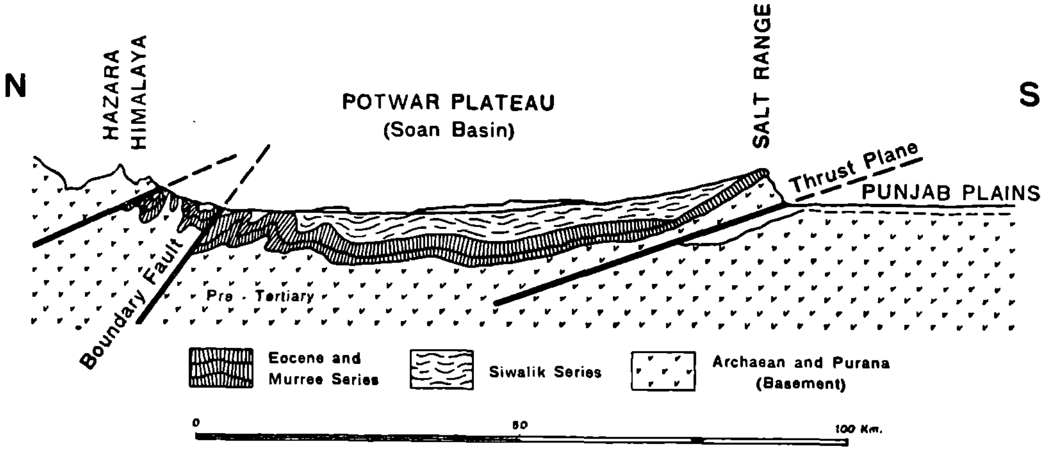


Fig. 51 - Section across the Potwar Geosyncline (after Wadia, 1953)

(*c*) *The Potwar Basin*

Whilst the synclinal valley of Kashmir lies to the east of the Hazara wedge, to the west another synclinal basin can be observed. This corresponds to the Potwar Plateau, and through it runs the Soan River. The formations affected by this structure are in part the pre-Tertiary basement, the Murree series and the Siwalik series, to a thickness of 7,500 m.

The orogenetic thrusts coming from the Hindu Kush have caused here the superposition of the Nappe Zone on the autochthonous formations of the platform along two thrust planes in which the Kala Chitta and Margala Hills originated; but these thrusts are also propagated further south, affecting part of the higher formations of the platform, which have been thrust towards the south along a sub-horizontal plane. The external part of the Nappe has thus been raised, creating the Salt Range, which meets the Punjab Plain in a steep scarp.

The monoclinal structure of the Potwar Plateau thus shows a strange structural similarity to that of Kashmir just described, of which it appears almost a reproduction on a small scale, though with a completely different geological history. The similarity is however explicable by the very similar mechanical conditions which have brought about the two structures. It is even more remarkable if we take into account the symmetry of the structures with respect to the Hazara wedge.

THE INDIAN PLATFORM

The Indian Platform is part of a rigid group which was reduced to a peneplain in a very remote geological epoch. This peneplain is known as Gondwanaland and is formed of Archaic and pre-Cambrian rocks, and is in part covered by sediments, the Gondwana series, which extend from the upper Carboniferous to the Jurassic, and of the Lower Eocene trap series of the Deccan.

The orogenic activity of the Indian Platform had already concluded in the pre-Cambrian age, when it assumed the character of a stable shield; nevertheless the general outlines of the folds of these extremely ancient mountains are still recognizable. Amongst these, the most obvious is the Aravalli chain, going in a SW-NE direction, just about perpendicular to the general axis of the Himalayas. There is no need to mention others which lie outside our field of interest, except that the existence of a very ancient chain with a direction which parallels that of the Aravalli Range has been assumed, following the Hazara spur. It should also be noted that no correlation has been found between the course of the ancient chains and the gravimetrical anomalies, which would tend to prove that perfect isostatic compensation exists here; on the other hand, isostatic compensation does not exist for the platform considered as a whole, as is fully discussed in the section concerning gravity anomalies in India.

As for the various hypotheses put forward regarding the upwarpings and downwarpings of the Indian Platform, which seem to be related to the Himalayan orogeny, these also have been dealt with in the chapter on gravity anomalies in India. Here it suffices to mention the great trough which borders the internal margin of the Himalayan chain, and which must be attributed, either to a syncline within the platform itself produced by the Alpine thrusts, or to an underthrusting of the platform under the Nappe Zone of the Himalayas.

PREVIOUS GEOLOGICAL INTERPRETATIONS OF GRAVITY ANOMALIES AND PLUMB-LINE DEFLECTIONS ON THE INDIAN PLATEAU AND IN CENTRAL ASIA

Already when we briefly traced the history of gravity measurements and isostasy in India, we had occasion to mention the deviations from perfect isostasy which had soon been discovered in India, both from astro-geodetic and from gravimetric evidence.

As happened in the case of the theory of isostasy, here too the interest of both scientists and officers of the Survey of India was soon attracted towards the problem: the scientists wished to know more about the deep geological structure of the earth's crust, and the officers of the Survey were interested in avoiding a wrong orientation of the geodetic network of the Indian continent.

The first to take into consideration the effect on geodetic measurements of anomalous distribution of density in the earth's interior, was probably General J. T. Walker, Surveyor General of India, who in 1895 presented a report to the Royal Society entitled « India's Contribution to Geodesy » (*Phil. Trans*, Vol. 186). This dealt with the deviation of the plumb-line in latitude at Kalianpur, which had at that time been adopted as the reference station for the whole of the triangulation of India. General Walker believed that the above-mentioned station was affected by a deviation of the plumb-line towards the south. For this reason he suggested that a group of astronomical stations should be set up around Kalianpur in order to eliminate strictly local geological effects and to obtain, as we should say nowadays, a regional value of the anomaly. A similar suggestion was made in 1870 by Col. John Herschel, and again in 1896 by Sir David Gill, who had first observed the arc of the 30° meridian in Africa.

Finally, in 1898 and 1899, Capt. Lenox Conyngham observed a group of nine stations of which one was at Kalianpur, four were at a distance of about 15 km from this locality, and another four at a distance of about 50 km. The mean of the latitudes thus observed gave a deviation of the plumb-line towards the north of about $0''.6$, contrary to the suppositions of General Walker, who, from a consideration of the deviations over the whole of India, had assumed a deviation of $2''$ towards the south.

That isostatic theory is not alone sufficient to explain completely the observed deviation of the plumb-line seems to be proved by the above circumstance, and another; namely, that two thirds of the deviations of the plumb-line towards the south observed up to then in India along the meridian of the Great Arc ($77^\circ 30'$), are grouped around a narrow zone between the latitudes 24° and 26°, while a new zone of deviations towards the south is found in the most southern part of the Indian Peninsula. Nevertheless the theory of isostasy must be used to consider the effect due to the Himalayas and the Indian Ocean; further interpretation of the residual deviations must take account not only of the visible topography, but also of the buried geological structures.

These arguments were given serious and detailed consideration in 1901 by Maj. S. G. Burrard in his memoir « The Attraction of the Himalayas upon the Plumb-Line in India », published in the *Professional Paper* No. 5 of the Survey of India. In this memoir the change of sign of the deviation of the plumb-line around the 24° parallel was attributed to a buried chain of a density higher than normal which presumably extends across India in an almost parallel line for over 1,600 km, and the effect of which is noticed between the 16° and 30° latitudes; the existence of this chain would explain the deviations towards the south which occur to the north of the 24° parallel and those towards the north which occur to the south of this parallel, thus partly obscuring the effect of the Himalayas.

The calculation of the deviations due to the visible structures and their isostatic compensation was developed according to the formula of Clarke, taking into account the lesser density of the alluvium of the Ganges Trough, which is reckoned to be only 600 m deep, and of the greater densities of the Deccan traps.

Thus was born the idea of the « Hidden Range » or « Hidden Cause », which for a long time was to dominate all controversy on the subject, and which has undoubtedly the merit of having opened the discussion on the structure of the Indian Platform in particular, and the geological interpretation of the gravimetric anomalies in general.

The Hidden Cause was criticised for the first time on the basis of gravimetric measurements, by Reverend V. Fisher, in his paper « On Deflections of the Plumb-Line in India ». Gravity measurements definitely show an increase in the force of gravity in the proximity of the supposed Hidden Range, but not only there. However, without excluding the possibility of abnormal distribution of density in the crust, Fisher tried to explain the deflections found on the Kalianpur meridian by assuming complete isostatic compensation of the Himalayan chain, and by considering the presence of light sediments in the great Indo-Gangetic Trough. As the normal thickness of the crust of density 2.68, he assumed the value T = 40 km, and as the density of the underlying basalt the value 2.96. He observed that the axial part of the Himalayas undoubtedly tends to rise, thus justifying the presence of roots even deeper than those required for perfect isostatic compensation, whilst the marginal part towards the plain tends to sink; and he assumed a depth of 4,500 m for the Indo-Gangetic Trough, partly filled with sediments of the Siwalik formation, and partly by more recent alluvium. He further supposed that the depth of the trough reaches maximum at the foot of the Himalayas, gradually diminishing towards the south.

In his memoir « On the Intensity and Direction of the Force of Gravity in India » published in the *Phil. Trans.* of the Royal Society, Vol. 205, 1906, S. G. Burrard gave a general survey of the material collected up to that date, but seemed to abandon the old idea of the Hidden Range.

Now comes the period in which, thanks mainly to J. Hayford, calculation of isostatic reductions both of deflections of the plumb-line and of gravity were to become routine. In 1910 Captain Cowie completed the isostatic reduction of the force of gravity for 42 stations, whilst in 1912 Maj. H. L. Crosthwait published the results of the calculation of the deflection in latitude on the hypothesis of Hayford for 102 stations.

In the same year, 1912, S. G. Burrard returned to the subject and published a memoir with the title « On the Origin of the Himalayan Mountains » presented in the *Professional Paper* No. 12 of the Survey of India. Guided by the evidence offered by the great fractures which border the Arabian Peninsula, he suggested that the Indo-Gangetic Trough could be explained as a great fracture itself; and he found confirmation of this hypothesis in the study of the deflection of the plumb-line at the stations close to the foot of the Himalayan chain. It is interesting to note that, for the first time, isostatic compensation according to Pratt-Hayford is taken into consideration, whereas previous research had been dominated by Airy's theory. In this memoir Burrard introduced the concept of the buckling of the crust or, as we should now say, the theory of « regionality » as evolved later by Vening Meinesz; and also the hypothesis of the displacement towards the south of the compensation, which seemed to be confirmed by the gravity deficiency along the foot of the Himalayan chain, where there were negative isostatic anomalies as large as those in the heart of the mountain chain.

At this point intervened in the discussion H. H. Hayden, a geologist well versed in Indian geology, with a report entitled « Relations of the Himalayas to the Indo-Gangetic Plain and the Indian Peninsula », published in the *Records* of the Geological Survey of India, Vol. XLIII, 1913. Hayden rejected the idea expressed by Burrard that the Indo-Gangetic Trough may be a fracture; and instead, basing his affirmations on geological and geophysical data, held that that trough may be likened to a wide basin with a very gentle slope (about 2°) towards the south, but with a very steep wall along the southern border of the Himalayas. This steep face is only a consequence of the reverse faults which characterize the Himalayan front and upon which this is upthrust. Hayden also gave the depth of this basin, on the assumption that the density of the alluvium which fills it is equal to 2.2, and without taking into consideration the isostatic reductions of gravity; the depth thus computed reaches a maximum of 5,600 m at Siliguri; if the isostatic correction were taken into account this depth would be reduced by between 10°/₀ and 20°/₀.

Hayden's paper was criticised, but on points which do not affect its real substance, by G. P. Lenox Conyngham, in a note entitled « In Reply to Mr. Hayden's Paper etc. » published in Vol. V of the *Records* of the Survey of India, 1914; Hayden replied to this in a polemical tone in his « Note on the Application of Isostatic Compensation » published in 1914 in Vol. X of the *Journal of the Asiatic Society of Bengal.*

It was at this point that the gravity measurements of the De Filippi Expedition took their place in the history of gravimetry of India; as we have already observed, only 14 stations were occupied, two of which, Dehra Dun and Srinagar, coincided with stations already observed by the Survey of India; but the great interest of these measurements lies in the fact that they are distributed along a traverse which cuts across the Himalayan system, and some are therefore located in the very heart of the Himalayan chain, in the Karakorum, in the Kun Lun, while two stations were located in the Tarim Basin, on the opposite side of the Himalayan chain.

It seems strange therefore that these measurements of exceptional value did not excite much interest at the time; the reason is perhaps that during the course of the expedition, the First World War broke out, and the definitive results were not published until 1925. By coincidence, the Survey of India had started a series of measurements at high altitudes that same year, on the Deosai Plains to the south of Skardu, thus recommencing the programme started in 1871 by Basevi and tragically interrupted by his death.

The interests of the geodesists and geologists of the Survey of India were still being concentrated on the problem of the Himalayan foredeep. A note was published by R. D. Oldham in 1914 in Vol. XC of the *Proceedings* of the Royal Society entitled: « On the Effect of the Gangetic Alluvium on the Plumb-Line in Northern India ». In this note the ideas of Hayden were taken up again, according to which the Gangetic Trough shows a very steep drop in the region of the marginal Gangetic faults fronting the Himalayan chain whilst towards the south it gradually vanishes. Following Oldham, it is possible to get very near the truth by assuming a maximum depth of 5,600 m at the foot of the Himalayas (even though at certain points a depth of 9,000 m is also admissible), and a width of 160 km. As to the density of the material filling the deep, one can assume a value of 2.1, which is the mean of 2.2 for the Siwalik formations, and 1.8 for the density of the superficial alluvium of the Ganges.

All computations carried out by Oldham adopted Hayford's method of the sectors and took into account isostasy.

In 1915 Capt. H. J. Couchman published in the Survey of India *Professional Paper* No. 15 a memoir entitled: « Pendulum Operations in India and Burma 1908-1913 ». In this memoir the isostatic reductions for 72 stations were given; from these calculations it became evident that the isostatic anomalies of the Himalayan stations were positive (but these stations were all on the external front of the chain), whilst the anomalies in the foot-hills were negative. Couchman therefore expressed the doubt that the compensation extended over the border of the mountain range, towards the plain, and that a zone of density deficiency existed to the north of Burrard's Hidden Range.

Colonel S. G. Burrard returned to the argument of the Himalayan foredeep in his note « On the Origin of the Indo-Gangetic Trough Commonly Called the Himalayan Foredeep » published in the *Proceedings* of the Royal Society, Vol. XCI, 1915. In contrast to Oldham, Burrard still supported, with rather polemical arguments, his thesis of the origin from fracture of the Himalayan foredeep — a thesis which had already met with little acceptance.

R. D. Oldham returned to the subject in *Memoir* XLII of the Geol. Survey of India, 1917, entitled « The Structure of the Himalayas and of the Gangetic Plain, as Elucidated by Geodetic Observations in India», where he reaffirmed, with his usual wealth of documentation, the ideas he had already advanced. Oldham admitted a maximum depth of the alluvia of between 4,500 and 6,000 m, but now he argued that the deepest part of the Gangetic Trough would not be found in the region of the boundary fault but further south, not far from the external margin of the Siwalik. Under the Siwalik the Trough would be less deep, 2,000-3,000 m, and would show a very steep escarpment in the region of the boundary fault, at least in the transverse section through Dehra Dun. It is also necessary following Oldham to distinguish clearly between the Gangetic Trough and the Indus Trough. The boundary between the two is roughly marked by the River Jumma: to the east of this there are the regular and deep deposits of the Gangetic Trough; to the west, in the Punjab, the deposits are very much thinner and irregular, and at times outcrops of underlying rocks appear.

Oldham examined the equilibrium conditions of the Himalayan chain and of the Tibetan Plateau behind it for the first time, and even with the scanty data at his disposal he drew attention to an overcompensation in the axial part of the Himalayan chain, which would be responsible for the continuous rising of the chain, and an undercompensation in the external border, towards the Gangetic Plain, responsible for its gradual subsidence. These two facts, together with that of erosion in the higher internal parts of the chain, and of deposition on its external margin, caused in their turn — as Fisher had already noted — a movement of the centre of gravity with respect to the centre of buoyancy, which would tend to accentuate the movements already in progress due to the above-mentioned defects of isostasy.

In reply to Oldham's memoir, H. McCowie struck a somewhat polemical note in his memoir entitled « A Criticism of Mr. R. D. Oldham's Memoir » published in *Professional Paper* No. 18 of the Survey of India (1921), noting some errors in the computations, and that the form claimed by Oldham for the foredeep, even supposing this to be completely compensated, does not substantially improve the observed deflections of the plumb-line and gravity anomalies. Oldham had in fact admitted complete isostatic compensation for the whole region surrounding the foredeeep, but had ignored it for the foredeep itself.

We must not forget however that all the controversies are completely invalidated by the fact that they assume a complete isostatic compensation of the Himalayan chain and of the Tibetan Plateau; whereas we know now that this ideal compensation is not fulfilled.

In 1918 S. G. Burrard published a new memoir in *Professional Paper* No. 17 of the Survey of India entitled « Investigation of Isostasy in Himalayan and

Neighbouring Regions ». In this memoir he examined the meaning of the positive anomalies of gravity found in certain stations of the Himalayas, and again tried to find the form of the bottom of the Gangetic Trough, tracing six cross-sections on the basis of both pendulum measurements and deflections.

R. D. Oldham did not reply to McCowie's criticism until 1924, when he published a note entitled « On the Geological Interpretation of Some Recent Geodetic Investigations etc. » in the *Records* of the Geological Survey. There is no need to enter into a discussion of the matter but only to note that this is the first time that the problem of the isostatic compensation of the Himalayan chain was discussed in the light of the new gravimetrical measurements made by Prof. G. Abetti and Comm. A. Alessio during the course of the De Filippi Expedition.

The most inland station which was available up to then was that at Moré observed by Basevi; it showed a Bouguer anomaly of – 119 mgal, and a Hayford anomaly of + 18 mgal, from which it was deduced that the external border of the Himalayas was undercompensated, although it was suspected without any proof that the more internal part of the chain was overcompensated.

In the following year, 1925, the Survey of India undertook a series of astro-geodetic and gravity measurements in Kashmir and on the Deosai Plateau, to the south of Skardu, thus greatly adding to the data collected by the De Filippi Expedition, which had been published in that year in a final form.

The discussion of these new important contributions was undertaken by Capt. G. Bomford (Survey of India, *Geodetic Report*, Vol. III, 1929, p. 80) who underlined the following essential facts — from the comparison between the section of the compensated geoid obtained from deflections of the plumb-line, which shows a gradual lowering of the geoid upon nearing the axial region of the Himalayas (and towards the Karakorum), and the isostatic anomalies of gravity on Hayford's hypothesis, it becomes clear that:

there is an excess of density in the region corresponding to the Pir Panjal and to the Vale of Kashmir, accompanied by a deficiency of density to the north;

the excess of gravity that is found on the Deosai Plateau is not adequately shown in the section of the geoid, from which it is assumed that its origin is local, and due to rocks of higher density near the surface. This seems to be confirmed by the rapid change of the deflections in this zone;

to the north of Skardu a strong deficiency of density is noted.

We shall see how these first conclusions were fully confirmed by the further knowledge which subsequently came to light.

In 1932 E. A. Glennie published the first of a series of papers concerned above all with a detailed study of the « Hidden Range », with its meaning in the history of Himalayan orogeny, and with the structure of the Himalayan foredeep. This first memoir appeared under the title « Gravity Anomalies and the Structure of the Earth's Crust » in *Professional Paper* No. 27 of the Survey of India. Glennie first stated that Airy's theory is much more readily, though not perfectly, adaptable to the isostatic conditions prevalent in India than Pratt's. He then passed to a detailed study of the Hidden Range of Burrard, underlining the fact that the actual geoid in that region rises by about 8 m, and the compensated one by about 6 m. Glennie assumed the crust to be formed by an upper granitic layer (density 2.67) of a normal thickness of about 10 km, and an intermediate layer (tachylyte, density 2.85) of a thickness of about 20 km, separated below by the Mohorovičić discontinuity from the underlying ultrabasic rocks (dunite) with a density of 3.3. In addition he closely linked the development of the Hidden Range with that of the Himalayan Tethys. The process of formation of the two structures thus started in at least pre-Devonian times and proceeded up to the Miocene. The tangential forces which caused the sinking of the Tethys, acted at the same time on the more rigid Indian Platform, causing an upwarping in the region of the Hidden Range; the slowness of the movement allowed the peneplaining of the upper granitic layer, but at the same time the denser underlying rocks came nearer to the surface, thus bringing into existence the Hidden Range. The effusion of the Deccan traps (Cretaceous) is also related, according to Glennie, to the approach to the surface of the heavier layers underneath. Thus the Himalayan Tethys acquired the character of a geosyncline.

The second stage was, characterized by a rapid deepening of the Tethys, accompanied by an upwarping of the crust along a line which passes roughly through Benares, Delhi, Lahore and Peshawar. The third stage, which followed immediately, saw the upheaval of the southern margin of the Tethys, at the outer Himalayas and the Siwalik.

In a second note published in the *Geodetic Report* of the Survey of India, Vol. VII, 1932, p. 79, Glennie discussed a point that was to occupy his interest in several later notes, some of which are very recent. This concerns the thickness of the Indus alluvium; the maximum value indicated for its depth is only 1,350 m near Gorhelawala.

In a third note published in the *Geodetic Report* 1936, Survey of India, 1937, p. 47, Glennie expressed the opinion that the Gangetic Plain is very much overcompensated, while the sides of the mountains which surround it are undercompensated. From this it would appear that the processes of erosion and deposition tend to maintain isostatic equilibrium. This would explain the fact that the foci of earthquakes in this region are rather deep, below the granitic layer, and sometimes below the intermediate layer.

In a further note entitled « Gravity Data and Crustal Warping in NW Pakistan etc. » published in the *Monthly Notices* of the Royal Astronomical Society, 1956, Glennie re-examined the structure of the crust in the light of certain results obtained by the Punjab Irrigation Research Institute and the Burma Oil Co. A survey with the Eötvös torsion balance carried out by the Punjab Irrigation Research Institute seemed to have established the existence of a ridge buried beneath the alluvium of the Indus Basin, to the SW of Lahore, which is also revealed by some outcrops of pre-Cambrian rock. To the north of the ridge the depth of the alluvium is about 1,200 metres. This feature is called « The Shahpur Ridge »; it runs in a NW-SE direction and then curves towards the south, thus separating the Lahore Basin from the Indus Basin. The upwarp of the Aravalli forms the southeastern border of both basins. Near Shahpur the torsion balance showed a depth of 600 metres for the alluvium in the region of the Shahpur Ridge; but seismic research by the Burma Oil Co. has revealed depths in the alluvium of as much as 6,700 metres. The depth tends to increase in the direction of the Suleiman Range, which closes the basin. It is evident from the same research that there is a similarity between the constitution of the platform and the Shahpur Ridge. The density of the alluvium is 2.35 up to a depth of 2,100 metres, and 2.55 lower down, whilst that of the basement is 2.74.

By applying a method of his own which involves a series of approximations, and by dealing with appropriately modified Bouguer anomalies, Glennie attempted to draw a contour plan of the warpings of the crust. In a recent note entitled « Plastic Buckling in the Indian Peninsula and Ceylon » published in the volume dedicated to Prof. F. A. Vening Meinesz (Deel, 1957), Glennie again took up the study of the buckling of the crust in the region of the Indian Platform in the light of Prof. Vening Meinesz's hypothesis. In order to do this, he first limited the region under study, and then computed Bouguer reductions for topography in the internal part of the delimited region; while the topography outside this region was assumed to be isostatically compensated on Hayford's system. In computing Bouguer anomalies for internal topography, the normal value of 2.67 was assumed for density; but account is taken of the lower values of the density of the Indo-Gangetic alluvium, which was assumed to be 2.2, and of the Potwar Plateau, assumed to be 2.25. The anomalies thus derived were called « Modified Topographical Anomalies. »

Having done this, Glennie tried to explain the residual anomalies as due to irregularities of the Mohorovičić discontinuity, reckoned to have a normal depth of 30 km. In the case of upwarping, and when this is not accompanied by corresponding topographical irregularities, he assumed that a corresponding part of the upper granitic layer had been obliterated; conversely, in the case of downwarping, the empty space thus created on the surface is taken to be filled with material of normal density. The contours of the Mohorovičić discontinuity were then found by successive approximations with laborious application of the standard methods based on compartments and Cassinis' tables.

The most noticeable downwarps are to be found in the southern part of the Indian Peninsula (deviations of up to 6 km) and the maximum upwarps in the region of the Punjab. The Hidden Range loses its marked individuality, and simply becomes the separation between the downwarping zone of the peninsular part of India and the Gangetic Trough; instead there appears a particularly notable upwarp between the 70° and 75° meridians, with a clear N-S direction. In its most accentuated part to the far north this upwarp impinges upon the Punjab and the Hazara region, like a great wedge inserted into the Alpine folds and separating the Himalayan chain from the Hindu Kush. It could have an important part in the fundamental structural unity of the so-called Himalayan-Hindu Kush Syntaxis.

Although there is no denying the great interest of these results, it should not be forgotten that many of the assumptions on which they are based are quite arbitrary.

As regards the geoid, it is necessary to mention only two notes: « The Indian Geoid and Gravity Anomalies » and « Construction of the Geoid » by J. de Graaff-Hunter and G. Bomford, published in the *Bulletin Géodésique*, No. 29, 1931. There are also many other articles about the Indian Geoid in the *Geodetic Reports* of the Survey of India.

Having thus briefly outlined the history of the geological interpretation of the geodetic results for the Indian Platform and the Himalayan region, we must now briefly outline a similar history for the Central Asian region. We do not claim that this history is complete and up to date, especially on account of the difficulty of finding sources.

In the absence of gravimetric measurements in the heart of the Himalayas, the attention of the geologists of the Indian services had been concentrated on the measurements carried out on the Pamirs by Zalesski in the years 1901 to 1909. This geodesist had at that time observed 140 stations, and although their precision was not very high, the values obtained could serve as indications.

R. D. Oldham dealt with the matter in a note entitled « Support of Mountains in Central Asia » published in the *Records* of the Survey of India, Vol. XLIX, 1918-19. It is not worthwhile discussing this research further, as it was developed on incomplete data; it nevertheless confirmed the close relation between orogen and deficiency of density.

A new contribution to the geophysical studies of this part of Asia was made by the Gravimetric and Seismic Expedition to Central Asia led by D. Mushketov in 1928, the geophysical side being directed by P. Nikiforov. The two above-mentioned investigators reported on the expedition in a note entitled « Gravimetric and Seismic Expedition to Central Asia » published in the *Reports of the Academy of Sciences of the USSR* in 1919. A. Popov, who had charge of the gravimetric measurements, made 14 pendulum observations distributed within the Ferghana Basin; and the conclusion of the investigation, briefly summarized at the end of the above-mentioned note, was that all the region of the Ferghana is characterized by strong negative gravity anomalies, and therefore by a tendency towards upheaval, which would justify the frequency of the earthquakes. As to the tectonic origin of the Ferghana depression, it was presumed to be due to compression by the surrounding mountain chains. Analysing the same material, in an article published in *Gerlands Beiträge zur Geophysik*, Vol. 30, No. 3-4, 1931, P. Savitsky reached the conclusion that positive anomalies of gravity are mostly associated with oldest geological formations, massive crystallines, and intrusive rocks; whereas negative anomalies are associated with the more recent formations; and that the extensive negative anomalies in the Ferghana Basin are due to a downwarping of the Sial into the denser mantle.

Also of some interest are the remarks made by the geologist F. Kossmat, published in the *Zeitschr. der Deutsch. Geol. Gesellsch.*, Leipzig, 1932, and based on the same observational material. Kossmat observed that, in contrast to what is found in the European mountain systems, there is no foredeep between the recent Alpine folds of the Transalai-Pamir system, and the Hercynian folds of the Alai-Tien Shan system. The Alai system has reacted only with germanotype folds under the Alpine stresses of the Himalayas. There is a similar correlation between the Alpine folds of the Karakorum and the Hercynian chain of the Kun Lun, whilst the southern part of the system, bordering directly on the platform, shows the foredeep.

These views of Kossmat's are not wholly confirmed in the light of the most recent geological and geophysical observations.

With regard to the Ferghana Basin, Kossmat recalled the hypothesis formulated by Stille; namely, that it represents an element of the Uralian Vorland, und does not belong to the mountain system. However Kossmat agreed with Mushketov that the basin is not a rigid platform contained within the surrounding folded zones, as is the platform of the Tarim Basin; but that it is rather a particular development assumed here by the folds which brought the basin into existence as seems to be proved by the fact that there are in the region undoubted traces of upheaval in very recent geological times. Kossmat even went so far as to say that the Tarim Basin may also be explained in a similar manner, whereas we know nowadays that it is certainly not so, and that the nucleus of the latter basin is formed by a rigid platform.

Kossmat, noting how the virgations which appear in the Alpine formations of Central Asia are closely related to the Hazara spur by which the Indian Platform is wedged into the mountain system, observed that these virgations repeat those already in existence in the Hercynian chains; which makes him believe that the spur already existed at the time of the Hercynian orogeny.

Four years after the first geophysical mission to Central Asia, a second one was organized by the Seismological Institute of the Academy of Sciences of the USSR, with the task, among others, of observing gravity in the Pamirs. B. L. Oczapowski and D. Mushketov refer to the work done in a paper entitled « Schweremessungen mittel Pendeln, ausgeführt auf dem Pamir und in Karelien in den Jahren 1932 und 1933; Geologische Erwägungen zu den neuen Schweremessungen auf dem Pamir und in Karelien ». The paper is accompanied by a chart showing only the free air anomalies; the Bouguer anomalies were not calculated, as it was held that errors in the density of 0.4 would contribute as much as 70 mgal to the anomalies, thus invalidating all the conclusions.

The conclusion is that the Pamirs are divided into two zones, of which the western one is characterized by negative anomalies, and the eastern one by positive anomalies; and that the two zones do not correspond to any evident geological or tectonic boundaries; the anomalies are therefore attributed to very deep geological structures. It also appears that the negative anomalies are not limited to the Ferghana Basin, but extend far to the south, reaching the highest mountainous zone of the Pamirs; Mushketov concludes from this that there is a common deep structure rather than a local origin of the anomalies.

All the western zone of the Pamirs would therefore have been subjected to epeirogenetic movements; and it is noteworthy that already fifty years before, D. Ivanov had recognized the peculiar morphological character presented by the western Pamirs, modified by young features of deep and rapid erosion.

Mushketov further notes a relation between the line of zero anomaly and the great fracture which runs along the northern edge of the Tarim Plateau (Kucha Trough). From this he deduces that the whole of the Tarim Basin should have been subjected to a negative epeirogenetic movement. He also admits the possibility of warping, such as elucidated by Glennie in India.

V. Erola took up the study of gravity anomalies in the Ferghana Basin and in the Pamirs, computing topographic and isostatic anomalies on the usual hypotheses for all existing stations (Bouguer, Pratt-Hayford, Airy-Heiskanen, Vening Meinesz). He published the results of these studies in two notes, of which the second, entitled « On the Structure of the Earth's Crust in the Neighbourhood of the Ferghana Basin », is to be found in *Publication* No. 10, 1941 of the Isostatic Institute of Helsinki. The author gives a summary of his results, which can be briefly stated as follows:

(1) No isostatic hypothesis completely explains the anomalies in the Ferghana Basin and in the Pamirs.

(2) The great anomaly of the Ferghana Basin indicates notable mass deficiencies; with Airy's hypothesis one must suppose the existence of additional roots of a depth of 2-10 km. The Basin must therefore be subjected to upthrust.

(3) The compensation has a regional character; the regional anomalies are smaller and more regular than the local ones.

(4) The thickness of the crust $T = 30$ km is the most probable according to the Airy hypothesis.

(5) The positive anomalies which are found in the eastern part of the Pamirs are due to deep-seated anomalies of density, inasmuch as they are not to be found in the surface geology.

(6) The negative anomalies which are dominant in the centre of the Pamirs are related to the negative anomalies of the Himalayas.

This concludes the discussion of the observational material available up to the Second World War; more will be said in the following chapter, relating to the evidence due to modern exploration.

A REVIEW OF SEISMIC STUDIES IN THE HINDU KUSH - PAMIR REGION

(M. A. CHOUDHURY)

When Professor A. Marussi first suggested to Dr. H. I. S. Thirlaway of Unesco that a review of the seismicity of the Hindu Kush would form a valuable contribution to the account of the Italian scientific work in that area, I was engaged in the study of particular aspects of the seismicity of that area at the Sorbonne under the direction of Professor J. Coulomb and Mme Y. H. Labrouste. This work was made possible by French Government and Unesco Fellowships awarded in connection with the seismological work of the Geophysical Institute, Quetta, which Dr. Thirlaway had initiated with the Pakistan Meteorological Service under a Unesco technical assistance project.

On my return to Quetta Dr. Thirlaway gave me the opportunity of executing Professor Marussi's concept, and I am grateful to the Director of the Meteorological Service, S. N. Naqvi, and the Seismologist at Quetta, A. Q. Khan for allowing me the time to complete this review.

The work on the depth of the Mohorovičić discontinuity and anomalous S phases is published in full detail in Annales de Géophysique. In this review I have linked summaries of these two topics with a general picture of the unusual seismicity in this little visited and rather inaccessible area. I have also given preliminary indications of results of further research, as yet unpublished, in the Hindu Kush and Quetta areas.

In constructing the epicentral map much time was saved through the assistance of Mr. A. Rehman Khan of the seismological observatory, Quetta.

M. A. CHOUDHURY

The Geophysical Institute, Quetta. June 1958.

INTRODUCTION

The entire Himalayan arc lies in the well known earthquake belt from the Mediterranean through Greece, Turkey and Iran. The western and the eastern extremity of the Himalayan ranges show a very different seismicity pattern than the main central arcs. The seismic patterns have a positive correlation with the structural strikes at these extremities. The Himalayas form an arc with its convex side towards the peninsular India. At the western extremity the Himalayas strike southeast while at the eastern side the strike is east. At both ends northerly striking ranges meet the main range forming re-entrant structures, and the "Cap ranges" [1] of the Pamirs and of the mountains of Burma-China border. The major seismic activity is associated with these cap ranges. In the Eastern Himalayas — the seismicity of Assam and Burma is well known, and many of the most severe earthquakes in history have occured there, as well as a very large number of smaller shocks. A brief account of the major seismicity of the eastern Himalayan region, can be found in the work of Gutenberg and Richter [2].

In the Western Himalayas, the major seismic activity is located in the regions around the Pamirs where re-entrants are formed by the Muztagh Ata, Alai, Karakorum, and the Hindu Kush ranges.

This paper describes the seismicity of the Pamirs and the surrounding regions, and the correlation of the seismicity and gravity anomalies. Results on the deep structure under the Hindu Kush, derived from a new study of deep earthquakes, are also described.

SEISMICITY OF THE PAMIRS AND ADJOINING AREAS

The Pamirs form the connecting link between the Himalayas and other high ranges of Central Asia — the Hindu Kush, the Karakorum, the Kun Lun, the Tien Shan and the Transalai ranges. To the north and south of the Pamirs some of these mountain ranges strike at almost right angles to each other. For example the Muztagh Ata Range and the Alai Range meet nearly at right angles on the north of the Pamirs forming an inflexion zone. So is the case with the Karakorum and the Hindu Kush ranges. A detailed study of the seismicity of this region shows that a correlation exists between structural trends and seismicity.

In the figure the epicentres from 1905 up to date are plotted. The data have been collected from the following sources:

(1) Seismicity of the Earth — Gutenberg & Richter — 1905-1912
(2) I. S. S. — 1913-1948
(3) B.C.I.S. & USCGS — 1949-date

Of BCIS & USCGS the data from the former were preferred when the information was available from both. In Figure 1 the data obtained from the Observatory at Quetta (since September 1952) have not been plotted because those obtained from the three sources mentioned above do not include earthquakes of magnitude less than 5 while the network of Pakistan Observatories has permitted the location of shocks of much smaller magnitude, particularly those originating in the Sind-Baluchistan ranges. Misrepresentation of the relative seismicity of different regions included in the map has been avoided by including shocks upwards of magnitude 5 (Richter Scale) only.

The shocks are divided into those of shallow focus and deep focus. Black dots represent epicentres of shallow focus shocks ($<$ 60 km) while the triangles represent the deep focus shocks ($>$ 60 km). The map also illustrates the trends of the important mountain ranges around the Pamirs, and the gravity contours of Hayford anomalies. These contours have been reproduced from the map given by Marussi [3].

Except for the Hindu Kush region shallow focus earthquakes are prevalent, all of them probably originating in the crustal layers. In the Hindu Kush the main foci are between 200 and 250 km deep. There are, however, a few foci situated up to a depth of 60 km in this region also.

As is evident from the figure, the most active region is the small area in the Pamir "knot" bounded by the Alai and Muztagh Ata ranges on the north and the Hindu Kush on the south. While most of this area is the seat of shallow focus earthquakes, a very small area in the Hindu Kush produces all the deep focus earthquakes. In fact the Hindu Kush is the only region between the Mediterranean and the Assam-Burma ranges where large scale tectonic forces are continuously active at depths of the order of 200 km. A study which the author has recently begun shows that the region of deep focus shocks in the Hindu Kush is surprisingly small — about 2000 square miles.

The seismicity pattern of the main Himalayan arc, the Central Asian ranges and the Sind-Baluchistan ranges is approximately of the same order except for the zones of inflexion, where seismicity and gravity anomalies significantly increase. In the Hindu Kush, Pamir and Assam regions however, the seismicity is an order of magnitude greater than elsewhere. In the Pamirs, there exist two zones where the epicentres are concentrated — one just north of the Hindu Kush ranges and the other around the Pamirs in the re-entrant angle formed by the Alai Range and the Muztagh Ata Range. Of these two zones the Hindu Kush is by far the more active showing 12 earthquakes of magnitude 7 or over as against 4 in the Pamirs [2].

Gravity data are incomplete in the Hindu Kush, but the position of the maximum negative anomalies with respect to the deep shocks is suggestive of island arc structures. However, in unpublished work, the author taking a NE-SW cross section passing through the Hindu Kush epicentres and the maximum negative anomaly found random scattering of foci. The Hindu Kush does not present a recognizable island arc pattern. Moreover, it seems that there exists no coupling between the deep Hindu Kush earthquakes, and the shallow Pamir ones.

All three re-entrants, (Pamir, Assam and Quetta) show the same seismic and gravity characteristics.

(*a*) Maximum seismicity occurs at the inflexions.

(*b*) Maximum seismicity occurs on the concave side of the inflexions.

(*c*) Large isostatic anomaly gradients lead to negative anomalies on the concave side of the inflexions.

(*d*) The lines of equal isostatic anomaly follow the geological strike.

There is therefore an association of maximum seismicity with maximum surface deformation, and mass deficiency. Following Evans & Crompton [4] it is believed that the large isostatic gravity (negative) anomalies in these three areas are due to thick sedimentary material with a mean density less than 2.67 gr/cc. Detailed study in the more accessible Quetta area (under publication) points to a direct relationship between the location, depth, and direction of first motion of earthquakes, and the thick sedimentary material, through large scale thrusting of the basement (crust) over the thick sediments. The direction of thrusting must be southerly to conform with the geophysical evidence, and this receives strong support from the surface geological evidence.

Detailed study of the shallow focus Pamir–Hindu Kush seismicity on these lines has not yet been possible; the surface geology is not well known, and locally determined epicentres and depth of foci are not readily available. Careful analysis of data from the seismological observatories of Andjan, Stalinabad, Khorog, Samarkand, Tashkent, Kulyab, Murgab (USSR) and Warsak (Pakistan) will be required before the seismicity of the area can be explained in terms of tectonophysics. In the meantime it is suggested that the shallow focus seismicity of the Pamir-Hindu Kush area is related to the large negative isostatic anomalies by thrust planes (overthrust from the north) sliding over thick sedimentary rocks. This major thrusting may also account for the unusual depth of the Mohorovičić discontinuity, evidence for which is presented in the next section.

This proposed mechanism however does not account for the remarkable deep focus area under the Hindu Kush. No coupling of any kind has been detected, and the next sections treat the Hindu Kush deep focus earthquakes as separate phenomena.

THICKNESS OF THE CRUST UNDER THE HINDU KUSH-PAMIR REGION

The classical method for determining crustal thickness is the use of travel time curves of earthquake waves refracted through the sub-crustal layer. Deep focus reflections have also been utilised by Jeffreys.

The author [5] has recently made use of a deep focus reflection not from the surface of the earth, but from a discontinuity between the surface and the focus. For full details reference should be made to the original publication.

On the vertical component record of the Hindu Kush earthquakes most of the European Stations (epicentral distances between 40° and 50°) show a clear phase between *P* and *pP*. This is particularly prominent in big shocks. The delay with respect to *P* of this phase as calculated from observations of the Hindu Kush earthquake of March 4, 1949 (Magnitude 7½ Pasadena) is 32.3 sec for epicentral distance of 50°. This phase is designated *pmP.*

To explain this phase three hypotheses are possible:

I. Longitudinal wave reflected near the epicentre at a certain discontinuity.

II. Transversal wave reflected under the same condition but transformed to longitudinal wave on reflection.

III. Longitudinal wave having multiple reflection under the station.

According to Slichter's [6] calculations, the amplitudes of derived phases become negligible when the order of reflection exceeds two. For a phase reflected twice under the station and reaching the surface as longitudinal wave the maximum delay with respect to *P* is 19.2 sec which is too small to explain the phase *pmP*. Hypothesis III is therefore discarded.

The depth of the reflecting surface (Hypotheses I and II) has been calculated from observation to be as follows:

Hypothesis I:

$$h = 76.1 \pm 12.8 \text{ km}$$

Hypothesis II:

$$h = 130.5 \pm 10.4 \text{ km.}$$

According to our present knowledge about the interior of the earth the Mohorovičić discontinuity is the most significant between the surface and 250 km. It is unlikely that the Mohorovičić discontinuity can be as deep as 130 km, and discontinuities other than the Mohorovičić at these depths are improbable. Hypothesis II is therefore discarded. Analysis of the records between *S* and *sS* shows a clear phase which is designated *smS*. The delay *smS* – *S* also indicates that the depth of the reflecting surface is about 75 km, confirming Hypothesis I.

It is concluded that the Monorovičić discontinuity under the Hindu Kush region is about 75 km deep.

Tvaltvadse [7] has found from explosions that the Mohorovičić discontinuity in Georgia is about 48 km. Gamburzev [8] found 40-55 km in Tien-Shan. Tandon [9] records 46 km in Assam. It therefore appears that the Mohorovičić discontinuity is significantly deeper in the Hindu Kush area. This fact may have some, as yet unknown, connection with the unusual seismicity of the Hindu Kush, some aspects of which are discussed in the next section.

SPECIAL SEISMIC PHENOMENA IN THE HINDU KUSH

The Hindu Kush has the unique seismological feature of being the source of a large number of earthquakes from a very small and deep focal zone.

Although the depth of all the Hindu Kush earthquakes recorded at Quetta has not been precisely estimated, a comparison of the records with those of larger earthquakes of known depth is very similar. From this fact as well as from the depth calculated in many other cases it is considered that the main focal region in Hindu Kush lies between 180 and 250 km. There is indirect evidence which supports this supposition [10].

This peculiarity of the Hindu Kush focal region suggests some particular elastic properties of the material. It has been observed on the records of Hindu Kush earthquakes at moderate distances by Gutenberg & Richter [11], Mukherjee & Pillai [12], and Choudhury [10] that the depth calculated from *sS* – *S* is considerably less than that calculated from *pP* – *P*. By studying four Hindu Kush earthquakes of different depth (between 195 and 240 km) the author has found that not only *sS* but all the other waves leaving the focus as *S* and reflected on the surface, arrive earlier than predicted in the tables. Such a phenomenon can be explained by two hypotheses.

I. The value of Poisson's ratio in the focal region is smaller than that accepted in the calculation of travel timetables. This means that the ratio V_P/V_S is also small. Thus *sP*, *sS* etc. arrive earlier than predicted.

II. *sP*, *sS* etc. originate at a point different from the point of origin of *pP*. This can happen if the rupture along the fault plane propagates with a velocity greater than that of *S* waves so that an *S* wave originating at the initial point of rupture arrives later than an *S* wave starting from any other point in the fault plane.

If Hypothesis I is true we should get a low value of Poisson's ratio. Table 1 gives the data of four earthquakes studied by the author.

TABLE 1.

Values of the ratio t_S/t_P (t_S and t_P are the times of propagation of S and P waves respectively from the focus to the point of reflexion) observed and calculated from JB (1948) tables; the difference (calculated-observed) and the depth of focus H. The ratios correspond to $\Delta = 45^0$

Date	t_S/t_P observed	t_S/t_P JB	JB-obs.	H in km
1. March 4, 1949	1.655	1.801	0.146	238
2. July 9, 1950	1.683	1.794	0.111	226
3. January 6, 1951	1.682	1.792	0.110	224
4. July 5, 1952	1.725	1.782	0.057	204

The difference of JB — obs. plotted against focal depth gives a straight line.

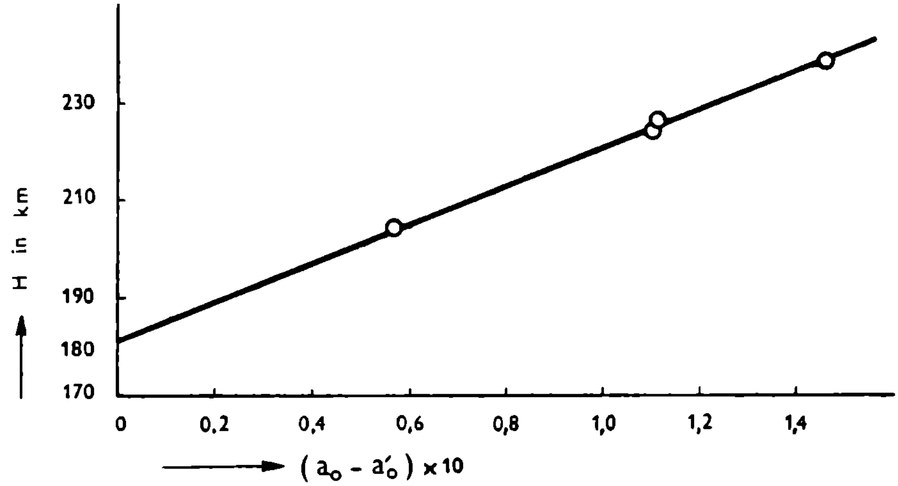


Fig. 52 - Difference of JB - obs. plotted against focal depth

Extrapolation of the straight line intersects the depth axis at about 180 km. This means that the abnormality in the ratio t_S/t_P will disappear if the focus is above 180 km depth. The abnormal ratio of t_S/t_P in the region below 180 km can now be calculated.

Let H_i be the focal depth of the earthquake considered

h_1 the depth where the abnormal ratio disappears

$h_i = H_i - h_1$

a_0 the ratio t_S/t_P calculated from JB (1948)
a'_0 the ratio t_S/t_P observed
a_i the abnormal ratio t_S/t_P in the layer of thickness h_i.

Supposing that Poisson's ratio is constant in the different layers considered,

$$a_0 (h_1 + a_i h_i) = a_0 H_i.$$

Therefore

$$h_i (a_0 - a_i) = H_i (a_0 - a'_0)$$

or

$$a_i = a_0 - H_i/h_i (a_0 - a'_0).$$

In this equation a_o, a'_o, H_i and h_i are known, so a_i can be calculated. Table 2 gives the values of a_i for the four earthquakes.

TABLE 2.

Values of a_i for the four earthquakes studied

Date	a_i	mean
1. March 4, 1949	1.202	1.229
2. July 9, 1950	1.245	
3. January 6, 1951	1.232	
4. July 5, 1952	1.238	

Thus knowing a_i which is the ratio t_S/t_P or in other words the ratio V_P/V_S in the abnormal layer, Poisson's ratio in that layer is calculated from:

$$\sigma = \frac{\frac{1}{2} a_i^2 - 1}{a_i^2 - 1} = \frac{-0.2448}{0.5104}.$$

A negative value of σ is impossible. On the other hand even for $\sigma = 0$, $a_i = 1.4$ and $h_1 = 130$ km. Observations will not support this value for h_1.

It is, therefore, evident that the phenomenon of early arrival of *sP*, *sS* etc. is not explained by the hypothesis that the material in the focal region of the Hindu Kush has a higher velocity of *S* waves than that assumed in the tables, and Hypothesis I must be discarded. Hypothesis II is now examined.

Reid [13] has indicated that the velocity of propagation of rupture (V_f) in a fault can never exceed the velocity of longitudinal waves (V_P). Benioff [14] has remarked that as V_f is not very different from V_P the effect of the waves emitted at every point will be cumulative. Thus the fracture will continue until the strain becomes too weak to effect a deformation.

As $V_P > V_f$ the recorded *P* waves will always correspond to the initial

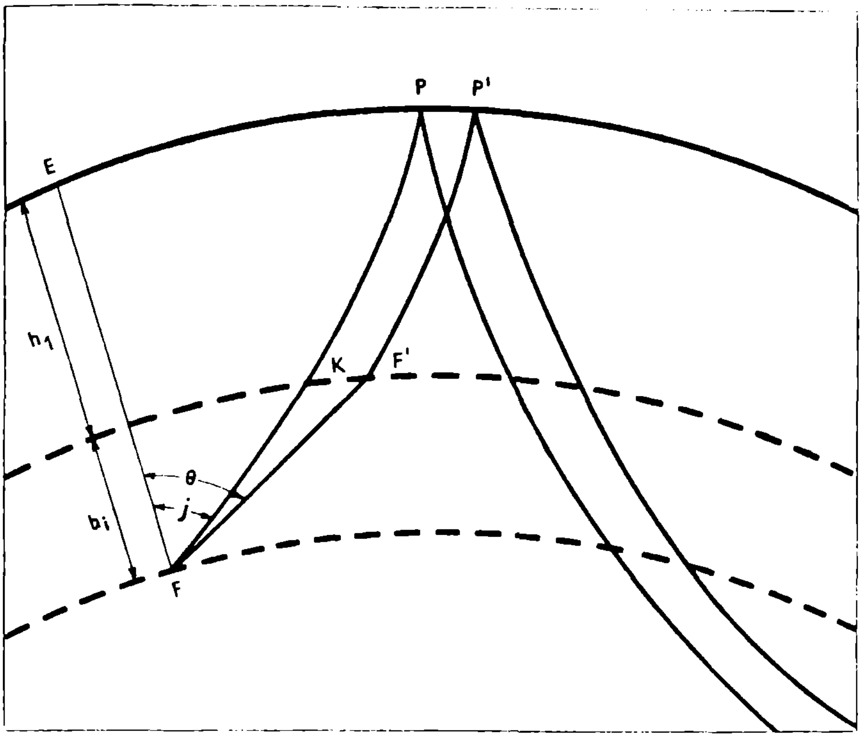


Fig. 53 - Illustrating the method of determining the velocity of propagation of rupture

point of rupture, while with a favourable orientation of the direction of propagation of the rupture, *S* waves emitted from a point other than the initial point of rupture can arrive first. Thus, sufficiently precise instrumental observations can give information on the velocity of propagation of rupture and the extent of rupture. Necessary precision seems to have been obtained by Benioff [14], who found $V_f = 0.75\ V_P$. Although this result is disputable it is the only study of this nature that has been done. In the four Hindu Kush earthquakes studied, a similar phenomenon to that found by Benioff seems to have occurred.

Without new assumptions, V_f in terms of V_P is calculated only by utilizing the value of $a_i = 1.229$ found under Hypothesis II.

The figure explains the method of calculation.

We have

$$a_i = \frac{FF'/V_f}{FK/V_P} = \frac{h_t/V_f \operatorname{Cos} \Theta}{h_i/V_P \operatorname{Cos} j}$$

or

$$V_f = \frac{V_P \operatorname{Cos} j}{a_i \operatorname{Cos} \Theta}\ .$$

If

$$\Theta \quad = j \text{ the maximum value of } V_f \text{ is obtained:}$$

$$V_f\text{max} = \frac{V_P}{a_i} = \frac{1}{1.229} = 0{,}81\ V_P.$$

This value of V_f is not significantly different from that obtained by Benioff ($V_f = 0.75\ V_P$).

Hypothesis II therefore explains the observations, and it follows that fractures in the Hindu Kush start at a deeper point and propagate upwards, from a maximum depth of 250 km ending at 180 km. That is, the maximum length of a single fracture may be 70 km.

Secondly, the material in the focal region of the Hindu Kush possesses special elastic properties which permit the fracture to originate and propagate easily in this region; the upper limit is at a depth of about 180 km and the lower limit probably does not extend below 250 km as no earthquakes are known to occur below this depth.

SUMMARY AND CONCLUSIONS

This seismic study of the Pamir-Hindu Kush demonstrates that the area has several features which are not found together in any other part of the region illustrated in Figure 1. These are:

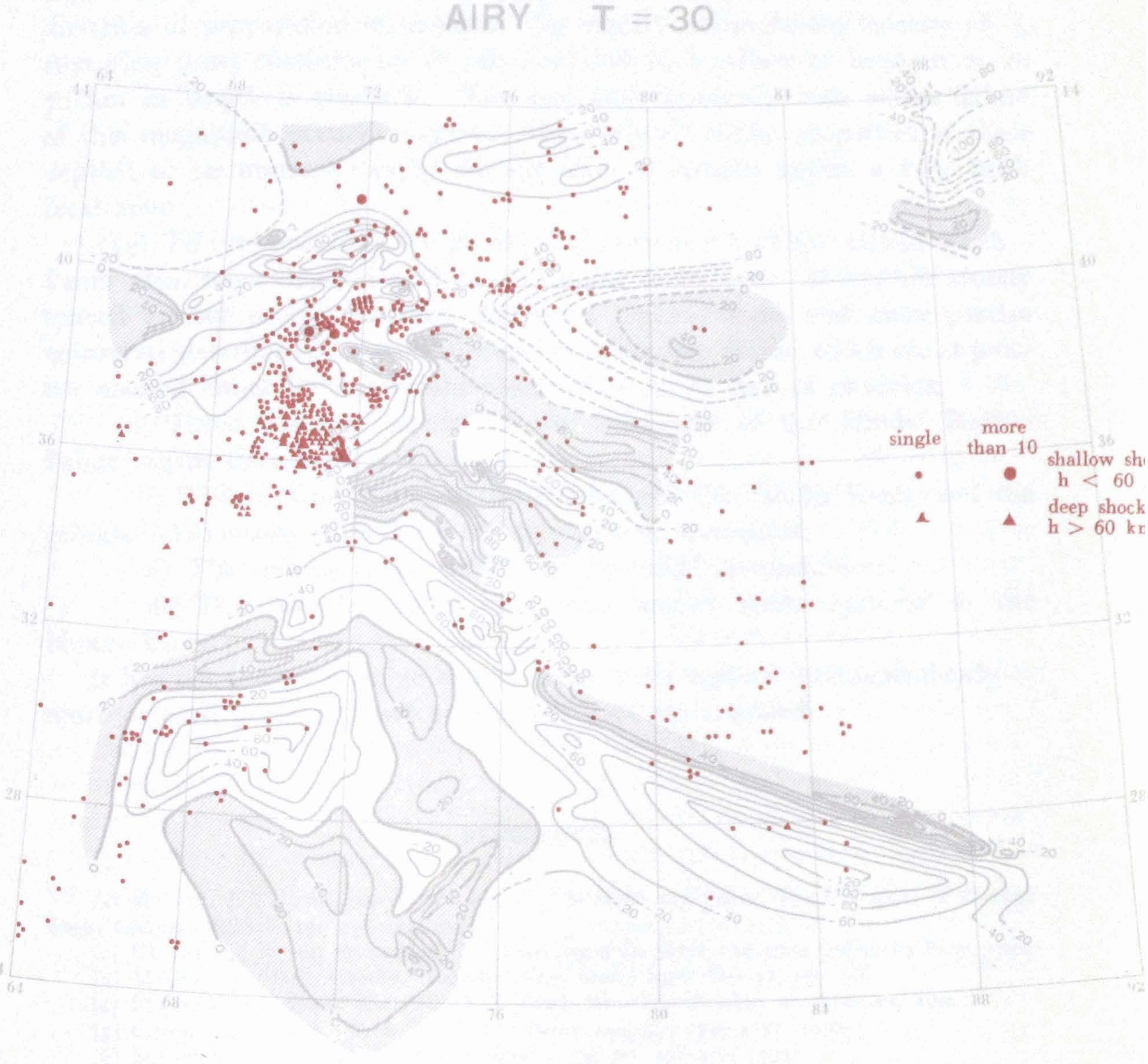
(*a*) The seismic energy release is several orders of magnitude greater.

(*b*) The region of maximum activity is extremely localized, and occurs on the concave side of a major structural inflexion.

(*c*) Two apparently uncoupled tectonic forces are operating within 300 km of each other; one at a depth of 200 km, the other in the crust. Of these two, by far the greatest energy release occurs at the deep focus zone.

(*d*) Isostatically uncompensated areas are closely associated with the shallow focus seismicity. By analogy with the better known Quetta area, it is proposed that a coupling exists between the shallow focus seismicity and negative gravity anomalies by means of basement (crustal) thrusting over very thick sediments.

(*e*) From seismic evidence the depth of the Mohorovičić discontinuity under the Hindu Kush is 75 km. This is the greatest depth of the Mohorovičić discontinuity so far observed; the Hindu Kush is the highest mountain region in which the depth of the Mohorovičić discontinuity has been measured.



ISOSTATIC GRAVITY ANOMALIES AND SEISMICITY
of the Karakorum-Hindu Kush-Pamir Region
(seismicity after M. A. Choudhury)

(*f*) All S phases leaving the focus in an upward direction from the deep focus (200-250 km) Hindu Kush zone propagate with an abnormally high velocity. This is attributed to a part of the S path coinciding with the direction of propagation of rupture. To explain the increased velocity of S, rupturing must continue up to 180 km, that is, a failure of between 20 to 70 km in length is required. The ease and frequency with which failure of this magnitude occurs, suggests either unusual elastic properties at these depths; or an unusually rapid accumulation of stresses within a very small focal zone.

(*g*) To interpret fully the geophysical phenomena of the Hindu Kush – Pamir area, more detailed geological mapping is awaited. Meanwhile closely spaced gravity profiles through the highly seismic zone, and more precise epicentral determination will do much to bring out details which are at present masked either by insufficient observations or by lack of precision.

(*h*) Three different aspects of the seismicity of the Hindu Kush – Pamir region have been reviewed:

i) The contrast between the Pamirs and the Hindu Kush, and the general relationship with large negative gravity anomalies;

ii) The unusual depth of the Mohorovičić discontinuity;

iii) The unusual elastic properties and/or stress systems in the Hindu Kush.

It has not proved possible to link these three aspects interdependently — more detailed geological and geophysical data are required.

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CONCLUSIONS

We are now in a position to draw some conclusions as to the general tectonic trends of the Karakorum and surrounding areas, taking advantage (*a*) of the information supplied by the new gravimetric measurements carried out by our Expedition. This, in connection with the other pre-existing gravity surveys in the region, gives us an overall picture of the gravity field in this part of Asia. (*b*) By availing ourselves of the evidence furnished by gravimetric observations on the Canadian and Russian Platforms and (*c*) by the results of the deep sounding exploration performed in recent years by Soviet geophysicists both in the Tien Shan Mountains and in the Pamirs.

The conclusions that will be discussed are based on the maps attached to this volume; these in their turn are drawn from the 270 gravity stations of our Expedition, the Indian stations in continental India (1903-1925), the Russian stations in the Pamirs and Tien Shan (1904-1909; 1928-1932), the stations of the Italian De Filippi Expedition (1913-1914) and those of the Sino-Swedish Expedition of Dr. Sven Hedin (1927-1934).

A large amount of the gravity measurements just mentioned has been reduced in accordance with various hypotheses, but in the discussion which follows, we conform only to the reductions arrived at according to the isostatic hypothesis of Airy, for a normal thickness of the earth's crust of 30 km and a density contrast of 0.6 gr/cc between the materials of the crust itself and the denser ultrabasic ones below.

The resultant anomalies are shown in the annexed plates. In order to interpret them, it is of course necessary to keep in mind the hypothesis which led to their delineation.

Above all we note a considerable degree of symmetry in the general outline of the anomalies around the axial part of the Karakorum Range; a central zone of negative anomalies (up to -50 mgal) is surrounded by two strips of positive anomalies, of which the southwestern one is more marked than the other, both with regard to breadth and intensity.

These two strips are in turn accompanied on the outer side by two further belts of negative anomalies, of which, yet again, the one situated to the southwest is much more marked, both in development and intensity, than that which borders the orogen towards the northeast.

The negative anomaly found in the southern margin of the Himalayas dwindles away towards the Indian Platform. The one to the north, on the other hand, passes to positive values corresponding to the pre-Cambrian shield which occupies the central part of the Tarim Basin.

Proceeding towards the NW, the northern band of positive anomalies culminates in very marked values and then is at once replaced by a zone of even more marked negative anomalies, strictly limited to the high mountains of the Transalai. The southern belt of positive anomalies, on the other hand, shows signs of following the pattern of the syntaxis between the Himalayas and the Hindu Kush.

What conclusions can be reached from an overall examination of the anomalies of the present map?

First of all it should be noted that the isostatic hypothesis adopted leads to anomalies which, taken as a whole, are far smaller than those which would occur in the absence of isostatic equilibrium. Thus the first conclusion to be drawn is that isostasy certainly exists, in some form or other, in this part of the continent of Asia. However, the adopted hypothesis does more than just reduce the absolute value of the anomalies, which would otherwise occur — what is even more important, it also helps to create positive and negative anomalies, which, by and large, balance each other.

But, when the effect of the deep discontinuity, corresponding to the Mohorovičić surface separating the crust from the ultrabasic materials, has been eliminated by the conventional, and necessarily schematic isostatic procedure, then the reduction still allows those marked anomalies, both positive and negative, which the map shows and which are the sign of more superficial geological occurrences.

It is precisely to these that we want to turn our attention.

There is no doubt that at least a few of the negative anomalies shown on our map are to be attributed to alluvial material of low density which fills the tectonic troughs bordering the orogen. Thus, to the south, the marked negative anomaly corresponds to the trough of Yarkand — which Russian geologists estimate to have a depth of 7 km — interposed between the Kun

Lun and the Takla Makan Platform which makes up the nucleus of the Tarim Basin. Likewise, to the west, there is the Tadjikistan Trough, up to 9 km deep, and the system of troughs of Surkh and Ferghana, with a depth of around 5 km. But other negative anomalies occur, in the axial part, and indeed in the very heart of the orogen, which cannot be explained away so easily.

The positive anomalies occur, on the other hand, along the margin of the Himalayan orogen and are more marked and more extensive towards the southwest, where the orogen faces the Indian Platform, and where the most noticeable tectonic occurrences are to be found. It is less marked towards the northeast, where the Alpine-Himalayan geosyncline leans on the previously existing Hercynian folds of the Kun Lun.

The most marked values in the positive anomalies occur in the relation to basic outcrops, on the southern margin of the granodioritic massif of the Deosai. Furthermore, positive anomalies which are clearly delineated, even though far less considerable in size, occur in the Pir Panjal, along the Main Boundary Fault, where the basic rocks lying at the bottom of the geosyncline of the Himalayas crop out.

More difficult to explain are the marked negative anomalies along the axis of the Karakorum and Hindu Kush. But in order to facilitate interpretation, two extremely important facts, which recent research has brought to light, are of great help. *One of these* concerns the study of gravimetric anomalies on the big continental shields, which have been in dynamic equilibrium for a very long time, and where nature has flattened out the previously existing mountain chains and laid bare the deep roots of the mountains. Thanks to this process we have been provided with a gigantic experiment in isostatic reduction, which we do well to take as a guide when we come to make deductions in those other cases where the orogenic phenomenon is very much more recent, or still in process.

In fact, evidence has been found to show the strict correlation between gravity anomalies and plutonism. This is largely the result of work by Canadian and Soviet geologists and geophysicists and is based on observations on both the Canadian Shield, the Southern Canadian Cordillera and the Russian Platform.

The observations relating to the Canadian Shield are of special interest, owing to the fact that the region is of pre-Cambrian orogeny. The stability reached by the Shield in the course of subsequent ages entails complete isostatic equilibrium — also proved by the total absence of seismic activity. On the other hand, the almost complete obliteration of the mountains has here created, as it were, a natural isostatic reduction, so that we can eliminate any of those arbitrary assumptions usually involved in the various kinds of isostatic computation.

Furthermore, if isostasy is a true condition in nature, we must also assume that the actual peneplained surface of the stable shield is a section, at variable depths, of the old now obliterated orogen. There is, therefore, every reason to assert that gravimetric observations on the Canadian Shield are of the greatest interest for the light they throw on the structure of the core of an orogenic belt.

One of the most impressive facts to which the attention of the investigators has been drawn is the close correlation between negative gravity anomalies (any distinction between Bouguer and isostatic anomalies is immaterial here) and granitic outcrops. This correlation leads to one, and possibly to both, of the following conclusions:

(1) Granite plutons are less dense than the surrounding rocks.

(2) Granite outcrops are associated with deeper, uncompensated roots.

Analyses made on rock samples from the pre-Cambrian shield in Canada have, as a matter of fact, shown that the mean density of the upper portion of the crust (excluding granites) is closer to the value 2.78 gr/cc than to 2.67, as is usually assumed; whereas, for granitic gneisses and syenites, densities of 2.75 and still lower values are found, down to 2.70, for anorthosite. Granite batholiths therefore represent emplacements less dense than the crust itself taken as a whole (Thompson and Garland, 1957).

These results do not apply solely to the rocks of the Shield—slightly modified densities and density contrasts have also been found in the Southern Canadian Cordillera by Garland and Tanner (1957). The average density of the crust, exclusive of the granitic rocks, is here found to be 2.74; whereas, for granite, a density of 2.63 has been assumed. There is here, of course, a variation in density between the various types of granitic rocks, the coarser grained phases having lower densities.

Thus a density contrast of 0.10 gr/cc between granite and the surrounding rocks, and of 0.05, as a density excess of basic extrusives and intrusives seem to offer a reasonable working hypothesis.

Once these views are accepted, two further problems arise:

(*a*) the determination of the vertical extent of the granitic batholiths and, closely connected with the former,

(*b*) the process of differentiation from an intermediate magma in a less dense acid and in denser basic components.

Thompson and Garland (1957) conclude that, in the Canadian Shield (Quebec, south of latitude 52° N), an average negative anomaly of 16 mgal is to be explained as an effect of incomplete isostatic adjustment, following the erosion of pre-Cambrian mountains. On this assumption, the depth to which the granitic batholiths extend is taken to be about 13 km.

At similar conclusions have arrived Garland and Tanner (1957) in considering the gravity anomalies in the Southern Canadian Cordillera. Here complete Airy compensation is assumed to prevail, and density contrasts are taken into account solely to explain local isostatic anomalies. The depth beneath the surface outcrops of the granite is here found to be about 7 km.

The problem of the vertical extent of granitic batholiths raises the second question, (*b*); that is, the process leading to the differentiation and separation of lighter and heavier magma, and the location of the latter. The heavier magmas may be located just underneath the granites, or laterally; or even it may be assumed that, owing to their deeper location, they have been removed during or after the mountain-building process.

In the first case, the vertical extension of the batholiths would turn out to be far greater than in the other cases; but if the other views are accepted, then the mechanism is capable of explaining very large negative anomalies, such as are sometimes found over big mountain chains. And it should be added that positive gravity anomalies of a local character are to be explained similarly by the presence of heavier basic intrusives or extrusives.

Correlation between negative gravity anomalies and granites has been noted by several other researchers; for example, Miller (1946) in Western Canada; Woollard (1948) in New England; Bott (1953), Marshall and Narain (1954) in Australia; Coron (1954) in France; Oldham (1954) near Parry Sound, Ontario, Canada; Innes (1957) in Central Quebec, Canada, and Nevolin (1957) on the Russian Platform.

Among the papers quoted, Oldham (1954) reports density variations in pre-Cambrian gneisses ranging from 3.0 gr/cc for the most basic gneisses, to 2.6 gr/cc for the more granitic ones; and Innes (1957) states that more and more evidence is becoming available to show that massive granites are, on the whole, less dense than the average crustal rocks, including those of some sedimentary basins. He further says that, if similar conditions exist deep down within young mountains, much of the gravity disturbance associated with them and usually attributed to compensation in the form of a bulge at the lower boundary of the crust, may in reality be due to large masses of intrusive granites within the crust itself.

Similar conclusions have been reached on the basis of observations carried out on the Russian Platform. N. V. Nevolin (1957) has analysed the Bouguer anomalies of the Baltic Shield, of the Voronezh Massif and of the Tokmovo anticline, and has tried to find a relation between these anomalies and the densities of the underlying rocks.

In a section along the line Siverskii-Kama Estuary two facts come to light. Firstly, the correlation between averaged Bouguer anomaly and depression of the pre-Cambrian basement, in the sense that positive anomalies there correspond to a larger depression of the basement. Secondly, there appears a striking correlation between negative anomalies and granites underneath the sedimentary complex, as revealed by 9 bore-holes, inasmuch as without exception, negative anomalies correspond to granites (densities from 2.65 to 2.67), and vice-versa; gneisses and magnetites (densities 2.70 to 2.72, in Povers up to 3.07) are on the other hand connected with marked positive anomalies.

Also, regional positive anomalies are connected with descending movements, and negative anomalies with ascending ones.

It is noteworthy that a similar correlation between granites and negative anomalies of gravity has been found not only on the pre-Cambrian shields, but also in younger structures, as for instance in the Hercynian foldings of the Erzgebirge. Watznauer reports that granite outcrops in the zone southeast of Freiberg are related to a marked and widespread negative anomaly; and he suggests the existence of a large granitic batholith of even more recent formation than the surrounding foldings. Watznauer thinks that at the end of the main orogenetic phase, mobile masses of a dioritic nature may have been intruded from below, in connection with the rise of the axial part of the geosyncline.

It is also noteworthy that E.N. Lyustikh (1955 and 1957) arrives at the same conclusions in his research on gravity anomalies and deep tectonics in Indonesia. He finds that the only satisfactory interpretation of the distribution of gravity anomalies in that region must be based on the hypothesis that a sialic material on being separated by differentiation in the earth's mantle, rises to the surface through deep ruptures.

The other fact concerns the determination, by deep seismic sounding, of the shape and depth of the discontinuity surfaces which separate the principal materials that go to make up the earth's crust and the ultrabasic materials beneath.

This method has been employed with great success by the Russian geophysicists in the Tien Shan Mountains and in the Pamirs, by relating it to the gravimetric method. This makes it possible for us to extrapolate the results obtained by deep seismic sounding also in cases, such as ours, where we have the results of the second, but not of the first method.

We have already discussed in the preceding pages the strict correlation between granitic batholiths and negative anomalies of gravity that has been found on pre-Cambrian shields and in younger tectonic regions; if the conclusions drawn there may be extended to our case also, it would be necessary to conclude that the negative anomalies in the axial zone of the orogen of the Karakorum are due to the presence of a granite batholith which follows the whole or the middle part of the orogen itself. And this fact is confirmed by geological observations which have discovered granitic outcrops with a marked axial development.

The negative anomaly of the Karakorum extends far beyond the visible granitic outcrops and invades a large part of the area between the granodioritic intrusions of the Deosai to the southwest and the Hercynian chain, reactivated in the Alpine phase, of the Kun Lun to the northeast. This might lead one to conclude that in effect the granitic zone which appears on the ground represents nothing more than the roof of the batholith, which, in its deeper part, should be very much broader in extent.

A marked negative anomaly also accompanies the granitic outcrops of the Baroghil Chain in the Hindu Kush and repeats the same pattern already seen in the Karakorum. Of considerable interest is the marked and very localized negative anomaly discovered by Russian geophysicists in the Roshan Chain in the Pamirs. This seems to be connected with the granitic intrusions in the chain in question and in the Shighan Chain.

This strong negative anomaly should be related to the exceptional thickening of the granitic layer which has come to light as a result of deep seismic sounding. This sounding has added new and decisive proofs to the isostatic theories and to those regarding the roots of mountains, and has perfected our previous views with regard to several points. It makes it possible to trace, on the one hand, the limiting surface between the upper layer of the earth's crust, conventionally known as the granite layer, and the subsequent layer, called the basalt layer, and on the other, the limiting surface between the basalt layer and the ultrabasic materials beneath, which cannot be further differentiated by taking into account their mechanical properties. The first surface takes the name of the Conrad, the second of the Mohorovičić discontinuity.

Soviet geophysicists have applied the method of deep seismic sounding to the Northern Tien Shan, between Lakes Balkash and Issik-Koe in the Alexander Chain and, what concerns us more directly, in the Transalai (Pamirs).

The results of a general character obtained from this research work — the first in an area of Hercynian folding, the second in one of Alpine folding — are reported in a work by Kosminskaya, Mihota, Tulina, Demeniskaya, Gamburzev and Weizman. Here are the principal results.

(1) The thickness of the continental crust varies from 25 to 35 km on the old platforms and reaches figures between 40-50 km in the mountainous areas. These thicknesses depend on the geological history of the region.

(2) There is no exact correspondence between the mountain chains and the roots. Often the deep structures mark systems of mountain chains and not single chains.

(3) In the Hercynian folding, the thickening of the crust is due to a thickening of the basalt layer, which is of greater thickness than the granite one.

(4) In the Alpine folds, on the other hand, the thickening of the earth's crust is due to a thickening of the granite layer which is shown to be of greater thickness than the basalt one.

(5) Furthermore, the zone which is actively seismic — that is, the one which contains most of the active foci — is the thicker of the two. In the Hercynian folds it is the basalt layer, and the granite one in the Alpine folds.

These then are the layers which transmit mechanical stresses.

In the particular case of the region which concerns us, the thickness of the crust in the Tien Shan varies from about 45 km in the area close to the platform, near Lake Balkash, to about 55 km in the mountainous area near the Issik-Koe. Here the thickness is made up of 80% basalt and only 20% granite.

In the Pamirs, on the other hand, the thickness of the crust reaches 70 km and this thickness is made up of 60% granite, and 40% basalts lying beneath. The layer of granite has the greatest thickness ever found up to the present, reaching the figure of 40 km. The annexed plates show these results diagrammatically.

In the paper "On the structure of the earth's crust in the Alai-Pamir zone as revealed by deep sounding" Kosminskaya, Mihota and Tulina also give a contour map of the Conrad and Mohorovičić surfaces, with contours from 5 to 5 km (from m.s.l.) for the former, and from 10 to 10 km for the latter. The spacing of the lines is chosen in accordance with the accuracy that affects the observed values on the basis of which the map has been constructed.

A general concordance in the trend of both surfaces becomes evident; both surfaces are inclined towards the south in the Alai zone, which is still part of the Hercynian folding, and reach the greatest depth underneath the Academy of Sciences Range in the Transalai Alpine zone. The thinning of both the granite and basalt layers to the east, in the region located some 60 km to the north-northwest of the Kara Kul (Lake) is also noteworthy.

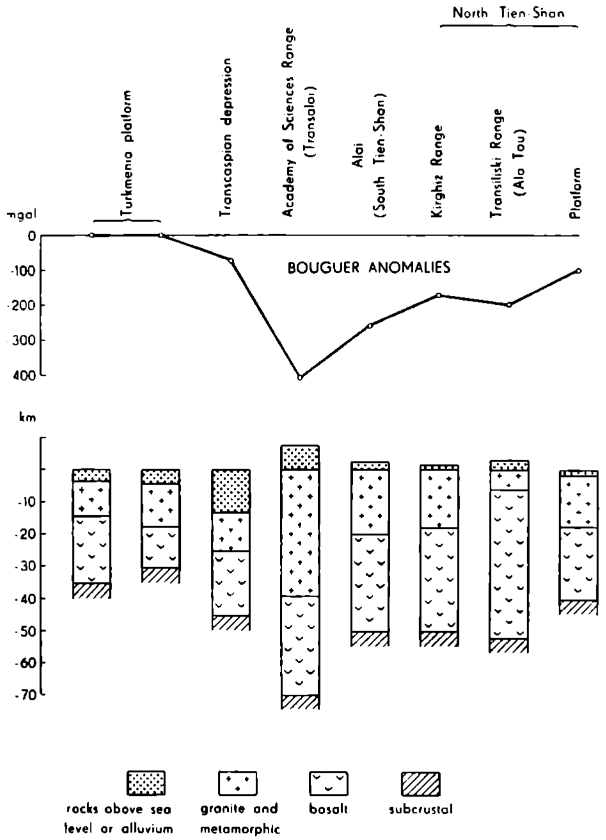
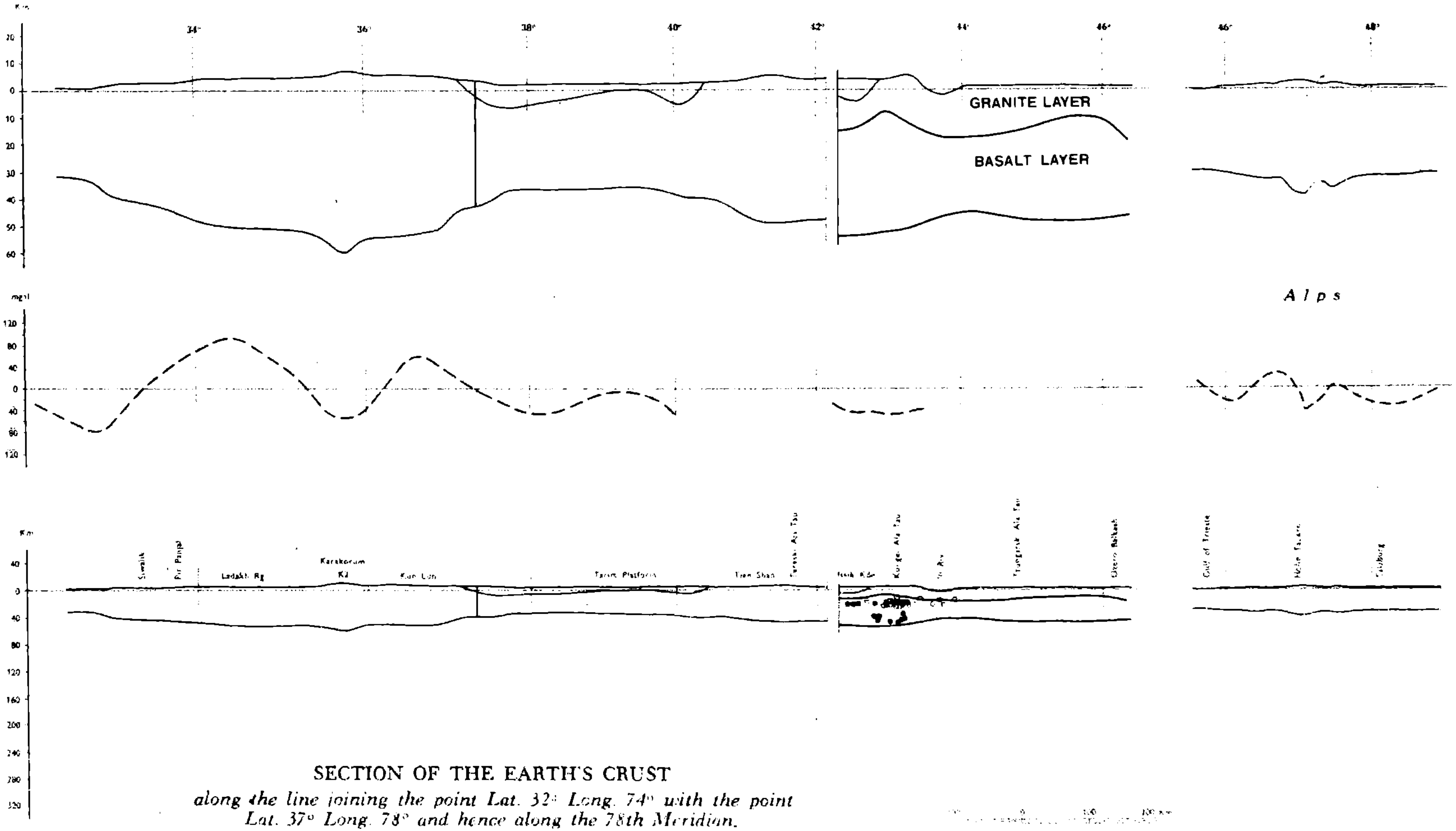


Fig. 54 - Diagrammatic sections of the earth's crust in Asia according to deep sounding and gravity exploration (after Kosminskaya, Mihota and Tulina, 1958)

There is no further marked correlation between the shape of the Mohorovičić and Conrad surfaces, and the tectonic structure of the region — we may simply point out, in accordance with the writers mentioned, that the assumed boundary between the Hercynian and the Alpine structures corresponds to the separation between the zones in which the basalt layer is thicker than the granite layer (Hercynian zone, to the north) and the zone for which



SECTION OF THE EARTH'S CRUST

along the line joining the point Lat. 32° Long. 74° with the point Lat. 37° Long. 78° and hence along the 78th Meridian.

showing the Airy T = 30 km gravity anomalies and isostatic surface (in two different scales for elevations), the results of deep seismics (in red colour) and the distribution of foci of earthquakes

(after Gamburzev, Kosminskaya, Mihota, Rosova, Tulina, Weizman and the results of the Expedition)

the opposite is true (Alpine zone, to the south). This agrees perfectly with the statements made above.

The writers have also pointed out the high degree of agreement between deep sounding results and gravimetric data; the gravity anomalies may be indeed explained fairly well by taking a density contrast of 0.2 gr/cc between granite and basalt, and of 0.4 gr/cc between basalt and the ultrabasic material below. The considerable agreement found has made it possible to extrapolate, by this method, the deep sounding results for the neighbouring zones.

Furthermore, the Conrad and Mohorovičić surfaces show a more complicated structure, with slopes of up to 10° to 12°, and oscillations of even more than 15 km in the Alpine zone; and this is not the case for the older Hercynian zones.

In summing up, we may reach the following final conclusions.

The general gravimetric outlines of a determined area are conditioned by the shape and depth of the Mohorovičić discontinuity. The regional outlines are, on the other hand, conditioned by the shape and depth of the Conrad discontinuity or, in other words, by the thickness of the granite layer. Finally, local anomalies are connected with far more superficial variations in the distribution of the density.

If we now take into account the fact that deep seismic sounding not only confirms the existence of mountain roots, but also shows that there is accord — at least in general outline — between the Mohorovičić surface and that which marks the limit of the theoretical roots of mountains after the isostatic theory — and which might be called the Airy surface — this seems to justify the procedure of using, in the interpretation of gravimetric results where more certain data from seismic sounding are not available, the isostatic anomalies according to Airy. And the normal thickness $T = 30$ km seems to be the one which best suits the case.

From all these considerations it now seems clear that the area of negative anomalies along the axial part of the Karakorum and Hindu Kush is to be attributed to a thickening of the granitic layer, without it being possible, however, to fix definitely the thickness and extent of this layer.

This anomalous zone continues from the Karakorum to the Hindu Kush, following the general pattern of the syntaxis and thus confirms the continuity between the axial granitic masses of these two chains. It also inclines one to think that these masses have played a leading role in the history of the development of the Himalayan geosyncline and orogen.

As far as the two strips of marginal positive anomalies are concerned, the one corresponding to the Hercynian folding of the Kun Lun could be related to the thinning of the granite layer which, as we have seen, occurs in the Hercynian zone; while the strip of marginal positive anomalies could be related to the granodioritic and basic manifestations in the Deosai and the Pir Panjal.

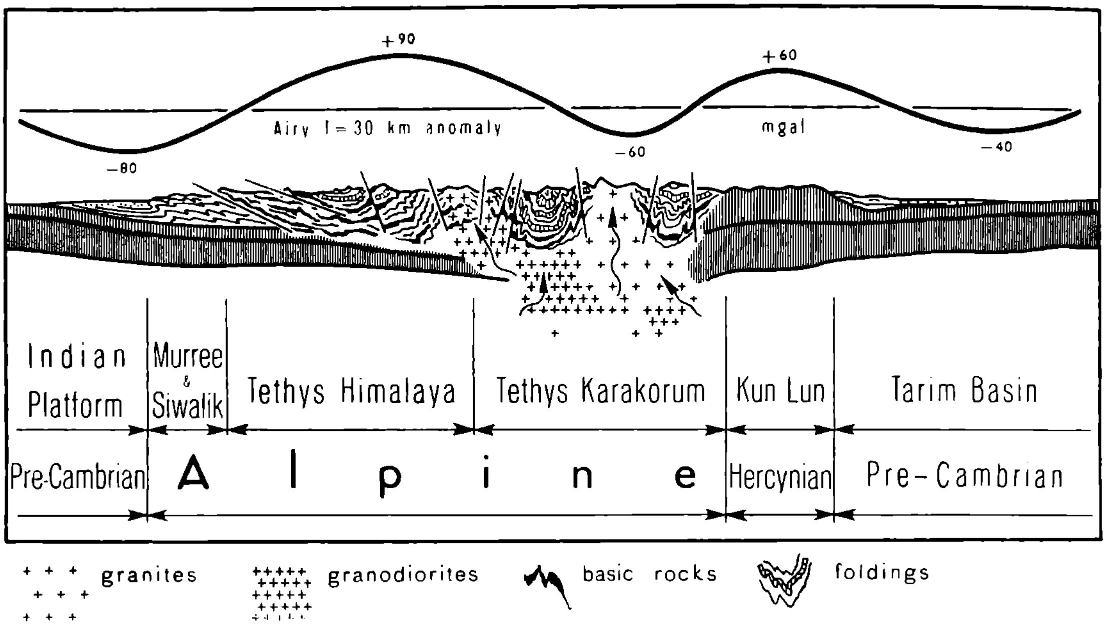


Fig. 55 - Hypothetical structure of the Himalayas, Karakorum and Kun Lun, and its possible relations to the observed isostatic anomalies of gravity

It seems that the foregoing statements support the affirmation as to the great tectonic importance of the granitic batholith in the axial part of the Karakorum; the batholith should have been placed in the axis of the geosyncline during the critical phase of its transformation into orogen, and should therefore be synorogenetic.

Once the view of synorogenic origin is accepted, the vastity and the continuity itself of the phenomenon leads us to acknowledge that it plays a fundamental role in the geological history of the Karakorum and that precisely at the most critical stage of transition from the phase of geosyncline to that of orogen. Indeed, one is prompted to ask whether an active role is to be attributed to the emplacement of these granites not only in the framework of the general balance of the exchanges between the materials of the earth's crust (or possibly exchanges in their phases, as pointed out for example by G. Kennedy, H. H.

Hess (1955) and G.P. Woollard (1959)) that both tend to raise the lighter and lower the heavier materials, but also in the framework of vertical and tangential stresses which are responsible for the foldings and thrusts that the Himalayas show so impressively and whose origin has, until now, very often been sought in the convergent movement of the surrounding rigid platforms only.

If these views should be confirmed, the orogenic process should be looked for in the intrusion in the axial part of the geosyncline of primary granites, which have migrated from more distant regions or resulting from local physical or chemical differentiation, to which secondary granites or gneisses, due to the melting of sedimentary rocks at the bottom of the geosyncline, may be added.

The rising of the axial part of the orogen would therefore be due to the direct action of the granitic intrusion, as has also been recently maintained by Soviet geologists (*see* for example Beloussov, 1955,-56,-59,-60); the horizontal stresses responsible for folding and thrusting should therefore be looked for partly in the lateral compression ensuing from the intrusion, and mainly in the gravitational plastic flowing of the upper layers, raised by the batholith itself.

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LIST OF ABBREVIATIONS

Acad. Sci. Paris; Comptes Rendus	Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences. Paris.
Accad. Naz. Lincei, Cl. Sci. fis. mat. e nat.; Rend.	Rendiconti dell'Accademia Nazionale dei Lincei, Classe di Scienze fisiche, matematiche e naturali. Roma.
Acta Geol. Acad. Sci. Hungaricae	Acta Geologica Academiae Scientiarum Hungaricae. Budapest.
Akad. Nauk SSSR	Akademiya Nauk SSSR. Moskva.
Akad. Nauk SSSR; Bull. Sov. po Seism.	Akademiya Nauk SSSR; Bulleten Sovieta po Seismologii. Moskva.
Akad. Nauk SSSR Doklady	Akademii Nauk SSSR Doklady. Moskva.
Akad. Nauk SSSR; Geofiz. Inst. Trudy	Akademiya Nauk SSSR; Geofizicheskovo Instituta Trudy. Moskva.
Akad. Nauk SSSR; Geol. Inst.	Akademiya Nauk SSSR; Geologicheskii Institut. Moskva.
Akad. Nauk SSSR Izv.; Ser. geofiz.	Akademii Nauk SSSR Izvestiya; Seriya geofizicheskaya. Moskva.
Akad. Nauk SSSR Izv.; Ser. geol.	Akademii Nauk SSSR Izvestiya; Seriya geologicheskaia. Moskva.
Akad. Nauk SSSR; Seism. Inst. Trudy	Akademiya Nauk SSSR; Seismologicheskovo Instituta Trudy. Moskva.
Amer. Geophys. Union; Trans.	Transactions of the American Geophysical Union. Washington, D. C.
Annales Acad. Sci. Fenn.	Annales Academiae Scientiarum Fennicae. Helsinki.
Annali Geofisica	Annali di Geofisica. Istituto Nazionale di Geofisica. Roma.
Asiatic Soc. Bengal; Jour.	Journal of the Asiatic Society of Bengal. Calcutta, India.
Boll. Geodesia e Sci. Aff.	Bollettino di Geodesia e Scienze Affini. Istituto Geografico Militare. Firenze, Italia.
Bull. Géod.	Bulletin Géodésique. International Association of Geodesy. Paris.
Bur. Central Séism. Intern.; Trav. Sci.	Publications du Bureau Central Séismologique International; Travaux Scientifiques. Strasbourg, France.
Canadian Min. Metall. Bull.	Canadian Mining and Metallurgical Bulletin. Montreal, Quebec.
Carnegie Instit.	Carnegie Institution of Washington. Washington, D .C.
Chicago Univ. Press	Chicago University Press. Chicago, Mich.
Com. Glaciol. Ital.; Boll.	Bollettino del Comitato Glaciologico Italiano. Italia.
Deutsche Geod. Komm.	Deutsche Geodetische Kommission. Potsdam, Deutschland.
Deutsch. Geol. Gesell.; Zeitschr.	Zeitschrift der Deutschen Geologischen Gesellschaft. Hannover, Deutschland.
Dominion Obs. Ottawa; Contrib.	Contributions of the Dominion Observatory. Ottawa.
Dominion Obs. Ottawa; Pubs.	Publications of the Dominion Observatory. Ottawa.
Dublin Inst. for Advanced Studies; Geophys. Mem.	Geophysical Memoirs. Dublin Institute for Advanced Studies, School of Cosmic Physics. Dublin.
Empire Surv. Review	Empire Survey Review. Crown Agents for Oversea Governments and Administrations. London.

Endeavour — Endeavour. Imperial Chemical Industries Limited. London.

Geofisica e Meteor. — Geofisica e Meteorologia. Società Italiana di Geofisica e Meteorologia. Genova, Italia.

Geofisica Pura ed Appl. — Geofisica Pura ed Applicata. Istituto Geofisico Italiano. Milano, Italia.

Geogr. Journal — The Geographical Journal. Royal Geographical Society. London.

Geol. Mag. — Geological Magazine. Stephen Austin and Sons. Hertford, England.

Geol. Rundschau — Geologische Rundschau. Stuttgart, Deutschland.

Geol. Soc. America; Bull. — Bulletin of the Geological Society of America. New York, N. Y.

Geol. Soc. London; Quart. Jour. — Quarterly Journal of the Geological Society of London. London.

Geol. Surv. Canada; Bull. — Bulletin of the Geological Survey of Canada.

Geol. Surv. India; Mem. — Memoirs of the Geological Survey of India. Delhi, India.

Geol. Surv. India; Rec. — Records of the Geological Survey of India. Delhi, India.

Geophysics — Geophysics. Society of Exploration Geophysicists. Tulsa, Okla.

Geophys. Inst. Potsdam; Abhandl. — Abhandlungen; Geophysikalisches Institut Potsdam. Springer Verlag, Berlin.

Geophys. Prosp. — Geophysical Prospecting. European Association of Exploration Geophysicists. The Hague, Netherlands.

Gerlands Beitr. Geophysik — Gerlands Beiträge zur Geophysik. Akademische Verlagsgesellschaft Geest & Portig K.-G. Leipzig, Deutschland.

Himalayan Jour. — Himalayan Journal. Calcutta, India.

Indian Jour. Meteorology Geophysics — Indian Journal of Meteorology and Geophysics. India Meteorological Department.

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Ist. Topografia Geodesia Univ. Trieste; Pubbl. — Pubblicazioni dell'Istituto di Topografia e Geodesia dell'Università di Trieste. Trieste, Italia.

Jour. Geophys. Research — Journal of Geophysical Research. American Geophysical Union. Washington, D. C.

La Ricerca Sci. — La Ricerca Scientifica. Rivista del Consiglio Nazionale delle Ricerche. Roma.

L'Universo — L'Universo. Istituto Geografico Militare. Firenze, Italia.

Moskov. Obsch. Ispitat. Prirodi; Bull.; Ser. geol. — Bulleten Moskovskovo Obschestva Ispitateliei Prirodi; Seriya geologicheskaya. Moskva.

Nederland. Mijn. Genoot. — Koninklijke Nederlandse Mijnbouw-kundig Genootschap. Den Haag, Nederland.

Nederland. Akad. Wetensch.; Proc. — Proceedings Koninklijke Nederlandse Akademie van Wetenschappen. Amsterdam, Nederland.

Nederland. Akad. Wetensch.; Verh. — Verhandelingen Koninklijke Nederlandse Akademie van Wetenschappen. Amsterdam, Nederland.

Notgem. Deutsch. Wiss. — Notgemeinschaft der Deutschen Wissenschaft. Karl Siegismund Verlag. Berlin.

Obs. Ksara; Mém. — Annales de l'Observatoire de Ksara; Mémoires. Ksara, Liban.

Petermanns Mitteil. — Petermanns Geographische Mitteilungen. Gotha, Deutschland.

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Priroda — Priroda (Nature). Akademiya Nauk SSSR. Moskva.

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