MEMOIRS

OF

THE GEOLOGICAL SURVEY OF INDIA

VOLUME XLII, PART 2.

THE STRUCTURE OF THE HIMALAYAS, AND OF THE GANGETIC PLAIN, AS ELUCIDATED BY GEODETIC OBSERVATIONS IN INDIA. BY R. D. OLDHAM, F.R.S.

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CHAPTER I.

INTRODUCTORY.

The annual reports of the Great Trigonometrical Survey have contained occasional reference to certain peculiarities exhibited by geodetic observation near the outer edge of the Himalayas, and to a belt of lesser density as a reasonable explanation of them. These references had attracted little attention on the geological side, for those geologists who could understand them, and were also acquainted with the results of geological examination, knew that just such a belt of rock, of less than average density, did run along the foot of the hills, and though the form of the trough, in which it lies, differs from that suggested as an explanation of the geodetic peculiarities, it was clear that the effect of the known geological structure would be similar in kind to that revealed by geodetic observation, and there was no reason to suppose that it might not also be sufficient in amount.

Matters might have remained in this state but for the publication, in 1912, of a brief paper, by Sir S. G. Burrard, on the Origin of the Himalaya Mountains.[1] The explanation offered would probably have attracted little attention, and in due course have gone to join a respectable company in the limbo of forgotten theories,

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[1] *Survey of India.* Professional Paper No. 12. Calcutta, 1912.

had the paper not seemed to imply that the geodetic evidence necessitated the existence of a deep and comparatively narrow rift along the edge of the hills, filled with rock of lesser density than that on either side—with some suggestion of actual cavity—and at one place the figure of 20 miles was given for the depth of this rift.[1] Such at least was the interpretation which the paper seemed to bear, and the figure, mentioned for the depth, implied a diaclasm so far transcending in magnitude anything which has been established from observation, in the Himalayas or elsewhere, that its acceptance would have necessitated the revision of what had been regarded as well founded deductions from geological evidence. Diaclasms of three miles in depth are well established, and even five miles is not impossible, and these are the figures which had been regarded as the probable, and the extreme possible, limit of the faults along the southern boundary of the Himalayas. The assertion that the geodetic evidence pointed to, if it did not necessitate, the existence of a diaclasm of four times the extreme magnitude of which we had any indication in geological observation, naturally attracted attention, led to an examination of the grounds on which the assertion was based, and gave rise to a somewhat extensive literature, which, being mainly controversial, was mostly unprofitable.

I have no intention or desire to add to this literature; his main rift has been placed further south, and the figure of 20 miles has been explained away,[2] thereby removing the contradiction which appeared to exist between the geodetic and geological observation, yet the original statement cannot be regretted for it has drawn attention to the geodetic work of the Trigonometrical Survey and led to an examination of the light thrown by it on some interesting and doubtful points of geological structure, which it had not been possible to elucidate by geological observations alone. In the course of this examination I shall have occasion to refer to theories which have been offered in explanation of the origin of the Himalayas, but only so far as to indicate the influence which they might have on geodetic observations, and so afford a guide to the directions in which these should be examined; for the object of this investigation is not advocacy, or attack, of any

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[1] *Loc. cit* p. 11. "A rift in the sub-crust south of Mussooree and 20 miles deep would explain the large deflections in the interior of the Himalayas."

[2] *Proc. Roy. Soc.*, Series A. XCI, 1915, p. 229.

particular theory, but an attempt to add to the stock of fundamental facts, on which alone a successful theory can be built.

In the sequel it will be seen that, so far as the origin of the Himalayas is concerned, the observations help us but little on the way, though they do to some extent diminish our ignorance of the processes which have been at work, but in other directions they have very considerably added to our knowledge of the underground structure of the northern part of India, by converting what were merely conjectural possibilities into well founded probabilities. The investigation has been limited to the region of the Himalayas and the alluvial plain to the south of them, though this does not cover the whole ground of possible cooperation between geodetic and geological observation. The curious band of excess of attraction which crosses the northern part of the peninsula, for instance, may be found to assist in the interpretation of the geology of the country, but the data at present available do not admit of any definite conclusion being drawn, and its discussion has, consequently, been omitted, though it is not impossible that, when observations are more numerous and complete, it may be found to help in the elucidation of the origin of the Himalayas.

The completion of this work has been retarded by the call of other claims on my time, but the delay has enabled the attainment of more complete results. I have to acknowledge with gratitude the receipt of much assistance, in the communication of material, from Sir S. G. Burrard, Surveyor-General, and Dr. H. H. Hayden, Director of the Geological Survey, also to Mr. D. B. Mair, for assistance in the mathematical part of the investigation. The actual calculations were done on a machine, in all but the simplest cases, and are sufficiently accurate for the purposes of this investigation, though they do not pretend to the refinement required in geodetic work.

The first step to be taken in this investigation is a statement of the issues which are or may be affected by the new evidence, and from these all questions of stratigraphy or correlation must be excluded, as well as all those questions of structure which do not involve the distribution of large masses of rock of materially different densities. With this necessary restriction the following seem to be the conclusions which are well enough established to necessitate their acceptance in any discussion of the observations.

(1) Firstly, there is the indubitable fact that the elevation of the Himalayas has been accompanied by the compression of the rocks of which it is composed. It is not meant that the whole of the disturbance of the Himalayan rocks has been the consequence, or the cause, of the elevation of the Himalayas; the contrary is indeed almost certain,[1] but the general distribution of the rocks, in the larger anticlines and synclines, along the general course of the range, and the fact that the prevailing strike is in the same direction, point to a connexion between the disturbance of the rocks and the elevation of the range. In the Siwalik region of the foot-hills the connexion is incontestable, for here we find that the rocks, which must have been deposited in practically horizontal beds at a time when the elevation of the Himalayas was already in progress, are now folded, disturbed, and compressed in a direction transverse to the general course of the range.

(2) There is, along the outer edge of the Himalayas, a great fault, known as the main boundary fault, which separates the northern area of the rocks of the Himalayas from the southern area occupied by the Upper Tertiary Siwalik rocks of the Sub-Himalayas. This fault, as was originally shown by Mr. Medlicott, marks very closely the original limit of formation of the Siwaliks, and the boundary separating an area of elevation and denudation, to the north, from an area of subsidence and deposition, to the south. He also showed that the Siwaliks were formed under the same conditions as the marginal deposits of the Gangetic alluvium, that the material of which they were composed was derived from the Himalayan area,—in other words, that the Himalayan range had already been marked out as an area of special uplift in early pliocene times. Along the greater part of the length of the Himalayas this fault brings the indurated older rocks of the Himalayas into direct contact with the soft sandstones and shales of the Upper Tertiary series, and throughout this region we have two groups of rocks of very markedly different densities separated by a nearly vertical plane of separation. A condition like this cannot but have a marked influence on the direction and amount of the force of gravity and, as will be seen in the sequel, a study of this effect enables us to form an approximate estimate of the vertical depth to which the contrast extends. Between the Jumna and the

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[1] See *Manual of the Geology of India*, 2nd ed., p. 483; also *Records, Geol. Surv., India* **XLIII, p. 140.**

Sutlej rivers, older Tertiaries appear on the northern side of the main boundary fault and, beyond the Sutlej, the whole of the Tertiary system becomes involved in the mountain-forming disturbances. In this region the main boundary fault is no longer recognisable, having merged into one of a series of more or less parallel faults, of similar character, which traverse the area of Tertiary rocks in the outer Himalaya.

(3) Mr. Medlicott also showed that the main boundary fault was not the only feature of its kind, for a series of similar faults is found within the Siwalik area, which were regarded as marking successive limits between an area of uplift and erosion to the north, and of deposition to the south of the fault line. This conclusion was more fully worked out by Mr. C. S. Middlemiss[1] in the Sub-Himalayas of Kumaon and Garhwal, where he showed that not only was there a succession of faults within the Siwalik area, each of later date than the next one to the north and each in succession marking the limit of the region of Himalayan uplift, but that there was also a series of similar faults to the northwards, each in succession earlier than the one to the south and, presumably, marking the successive limits of the Himalayan area; and a similar conclusion is suggested by the geological structure of the Sikkim district.[2] From this it follows that, at any rate during the latter part of the period of elevation of the Himalayas, there has always been an abrupt limit of the region of compression and elevation, and that this boundary has progressively shifted southwards,[3] encroaching on an area of deposition and involving deposits of later date in the mountain-forming processes.

(4) The clearly defined character of the southern margin of the hills towards the plains, running with a regular sweep along the foot of the hills, and the absence of detached outliers rising out of the alluvium, irresistibly suggests that the boundary is determined by a structural feature similar to the main boundary and the faults in the Siwalik area, and though no direct measurement of the depth of the undisturbed alluvium is possible, the fact that it is identical with, and a continuation of, the Siwalik deposits

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[1] *Memoirs*, Vol. XXIV, pt. 2.

[2] *Memoirs*, Vol. XI, pt. 1.

[3] This statement necessarily refers only to the position of the successive boundaries, relative to each other. There is no means of deciding whether there has, or has not, been any general movement of the Himalayas northwards or southwards, whether in latitude or as regards distance from the rocks of the peninsular area.

affords a tolerably secure indication. The total thickness of the Siwaliks, in the Kumaon and Garhwal districts, was estimated by Mr. Middlemiss at an average of about 16,500 feet [1]; Mr. Medlicott estimated the thickness of the Siwaliks north of Hardwar at 15,000 feet,[2] and the whole thickness is not exposed on this section. We may therefore take it that the depth of alluvial deposits, being the continuation of these Siwaliks, is not likely to be materially less than 15,000 to 16,000 feet at the northern limit of the plains, and we may safely say that the alluvium at the northern edge of the plains is very improbably much greater or less than about three miles in depth.

(5) At the southern edge of the alluvial plain the thickness is small, the boundary is irregular, following the contour of the much denuded surface of the older rocks of the Peninsular area, which crop out, near the boundary, in numerous isolated patches and hills, rising from the surrounding spread of alluvium. All the features, in fact, suggest a gradual encroachment of the alluvium on an old land surface of rock, and a gradual southward growth of the depression in which the Gangetic Alluvium has been deposited.

Besides these well established conclusions, there are certain others of a more conjectural character, which need confirmation, or greater amplification, than the present state of geological knowledge—or in some cases any conceivable advance in it—can afford. Of these the following seem capable of elucidation by the data to be dealt with: namely—

(1) The question of whether the elevation of the Himalayan range was caused, or merely accompanied, by its compression. The natural conclusion would be that they were related to each other as cause and effect, but in which direction cannot be regarded as proved. Were the elevation due to a simple process of tumefaction, or swelling up, of the material underlying the range, this would set up internal strains in the elevated mass and a tendency to spread, which might result in compression and folding. This hypothesis has in fact been proposed and experimentally illustrated on the small scale,[3] but it has never been tested by actual

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[1] *Memoirs*, XXIV, p. 87.
[2] *Memoirs*, III, pt. 2, p. 118.
[3] E. Rayer, *Nature* XLVI, p. 224 (1892).

calculation of the relative magnitude of the stresses which would be set up, and of the resistance by which they would be opposed, nor does it seem that any such test could be satisfactorily applied, in view of the many unknown factors which would be involved. It will, however, be shown that the hypotheses, of elevation being due to compression or compression the result of elevation, each carry with them certain consequences in the underground distribution of matter, which would, in the case of the Himalayas, lead to results of recognisable magnitude.

(2) No direct measurement of the throw of the main boundary fault can be made, and of the similar faults within the Siwalik area measurement has only been effected in one case. Mr. Middlemiss was able to show that one of the faults, in the Ramganga Valley, must have a vertical throw of 6,380 feet, or 11,880 feet measured along the hade of the fault,[1] and as this is by no means the greatest of the faults we may take it that the throw at the main boundary must be at least as great, but beyond the fact that the throw of this fault must amount to several thousands of feet no more exact estimate is possible.

(3) Closely bound up with the last, is the depth of the pre-Tertiary floor of the Siwalik deposits within the Siwalik region. It has been generally accepted that the level is higher than in the alluvial area to the south, and that the elevation of the Siwalik hills has carried with it an elevation of the floor on which they rest. This conclusion is illustrated in some of the sections drawn by Mr. Middlemiss and in the generalised and diagrammatic section given in the "Manual"[2]; it is supported by the mode of occurrence of the inliers of older rock met with in the Tertiary area beyond the Sutlej, but it is by no means an inevitable conclusion in the region east of the Sutlej, where the main boundary becomes so well-marked a feature. If we consider the cross sections of the Siwalik area, those, for instance, which were reproduced in the "Manual," we find a compression of from 30 to 100 per cent., on comparing the original with the present horizontal extent of the beds. Now a series of deposits 15,000 feet in vertical thickness, if compressed to one-third less than their original extent would be thickened by no less than 7,500 feet. Actually the mean elevation of the Siwalik area over the plains to the south is not over

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[1] *Memoirs*, XXIV, p. 87.

[2] *Manual of the Geology of India*, 2nd edition, p. 473.

a couple of thousand feet, and on most sections even less, so that, even allowing for the extensive removal of material, and lowering of the hills, by denudation, there is a possibility that the floor of the Siwaliks is not materially higher, and may even be lower, than that of the alluvial deposits immediately beyond them.

(4) As has been stated, we have very good reason for supposing that the thickness of the alluvial deposits, along the southern edge of the hills, is not less than some 15,000 feet; we also know that the thickness near the southern edge is very small, but we have no direct knowledge of what takes place between these limits, whether the depth of alluvium is at its maximum near the northern edge and gradually diminishes to the southwards, or whether it increases to a maximum and then diminishes, or whether it continues with a considerable depth to near the southern edge and then thins out rapidly. In other words, we are unable to draw a cross section of the Gangetic trough [1] with any degree of certainty.

(5) Though the alluvial areas of the Gangetic and Indus drainage areas are continuous with each other, and the whole area is coloured uniformly on the geological map, it has been recognised that there is a considerable difference in the surface contour, in the arrangement of the river courses, and in the character of the deposits which form the surface of the two regions. From the Jumna eastwards to the junction with the Brahmaputra Valley is the great tract of the typical Gangetic alluvium, which bears all the characters of a plain of deposit and across which the rivers flow in courses determined by their own action and interaction. In the plains of the Punjab these features are largely absent, and the surface features suggest a much smaller thickness of alluvial deposit, a suggestion which is strengthened by the occurrence of inliers of older rocks, rising as hills in the centre of the alluvial plain.

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[1] The title of a paper by Sir S. G. Burrard, published in *Proc. Roy. Soc.*, Series A, XCI, p. 221, 'On the origin of the Indo-Gangetic Trough, commonly called the Himalayan Foredeep,' is liable to convey a wrong impression. The basin filled by the Indo-Gangetic alluvium is certainly not commonly called the Himalayan Foredeep, and the use of the terms as synonymous is improper. The word "foredeep" occurs in Prof. Sollas' translation of *Das Antlitz der Erde* as the English equivalent of the word *Vortiefe*, coined by Prof. Suess with the intention of conveying not only a description. but also a definite theory of origin. The word may be used without accepting this theory, but a term, which was invented to connote a definite theory of origin, cannot be used with propriety unless that theory is intended to be implied. I shall confine myself to the use of the word trough, which is purely descriptive and implies no theory of origin, and in using it shall refer only to the deep depression in the rock surface under the alluvial plain, not to the whole of the area which is mapped as alluvium.

(6) At the other extremity of the Gangetic plain we find the alluvium extending southwards, across the gap between the Peninsula proper and the plateau of the Assam range. The rocks of these two areas are similar in character and the Assam range must be regarded as, stratigraphically, part of the same geological area as the Peninsula. There is some geological suggestion that the stretch of alluvium, through which the Ganges and Brahmaputra reach the Bay of Bengal, forms no part of the depression, or trough, of the Gangetic plain of Upper India, and that the alluvium is a comparatively shallow covering over a rock barrier connecting the Rajmahal and Garo Hills.[1]

These are the geological problems in which elucidation may be helped by geodetic observations, they do not comprise the whole of those in which assistance from this line of research may be looked for, but the necessary observations are wanting for dealing with the others, and especially with the very important one of what has taken place in the regions at either end of the Himalayan ranges, where they pass into the mountain systems of Indo-China on the one hand and of Afghan Turkestan on the other.

[1] *Manual,* 2nd ed., p. 443.

CHAPTER II.

THE NATURE AND INTERPRETATION OF THE GEODETIC EVIDENCE.

Before dealing with the observations it will be well to devote some space to a consideration of the nature of the evidence and the bearing of the observations, when converted from their original object, of measuring the dimensions and form of the earth, to that of elucidating the structure of the outer portion which is called, for convenience and brevity, its crust. Though the treatment may be regarded as elementary by a portion of those who will read these pages, it is none the less necessary for two reasons, firstly because many may be unfamiliar with the nature and the meaning of the observations, and secondly because, for those who may be familiar with this aspect of the geodetic results, it is important to have a clear understanding of the possibility, and more especially of the limitations, of their application to the completion or checking of the results of geological observation, and it is this aspect of them which will alone be dealt with.

The geodetic observations which have to be considered may be described as measures of the direction and intensity of the force of gravity, and are of two classes. One deals with the deflection of the plumb-line from the direction which it would have on the surface of an ideal earth of perfectly regular form and uniform distribution of density, the other measures the variations in the attraction of gravity. Of these the first gives the horizontal and the latter the vertical component of the resultant of all the forces which produce a departure from the attraction which would be exerted by the ideal average globe.

The position of two places on the surface of the earth, with regard to each other, may be expressed in two ways, either by a difference in longitude and latitude, or by the length and direction of the shortest line connecting them. The determination of the first of these belongs to the methods of astronomy, the latter to those of trigonometrical survey, and the one could be converted into the other with equal accuracy if we knew with absolute accuracy the dimensions of the earth; but the principal problem of geodesy is the determination of these dimensions, on which depend the calculations by which the observations with the theodolite are converted into measures of distance and direction, and into differences of latitude and longitude.

Were the earth a perfectly regular spheroid, and of uniform constitution throughout, the problem would be a simple one, and a few comparisons, of measured distances with observed differences of latitude, would suffice to determine the form and size of the spheroid. But these conditions are far from being met with in practice. The difference in the astronomical position of two stations is determined by observations of the sun and stars, and a measurement of their angular distance from the vertical, as shown by the plumb-line, or from the horizontal, as shown by a fluid surface; the latter is that actually used, but the two are identical in result for the apparent horizontal plane and the apparent vertical line are always, and necessarily, at right angles to each other. Now the exact direction of the plumb-line, at any point, is determined not only by the attraction of the earth as a whole but by the attraction of local masses, and may be affected either by variations in the density of the rocks at, or below, the surface, or by irregularities in the form of the surface near the station. A mountain range, or a mass of rock of greater than average density, to the northwards of a station would attract the plumb-bob and cause the liquid surface to be tilted in such a manner that the latitude, as determined by astronomical observation, would appear to be less than the true latitude of a station situated in the northern hemisphere, and a similar excess of attraction to the south would make the apparent latitude greater than the true. Differences in the density of unseen portions of the earth can, obviously, not be allowed for; they must be searched for and detected by the discrepancies between astronomical and geodetic measurements; but it might be thought easy to calculate, and allow for, the effect of the visible masses of mountain ranges and the visible hollows of the ocean basins, and so it would be were mountains mere excrescences formed of material added on to the surface of the spheroid, or the oceans merely hollows carved out of its surface. Such, it has been found, is not the case; mountain ranges do not attract the plummet to anything like the extent they should do, nor do ocean basins cause it to be attracted away from them, and the explanation of this phenomenon has introduced two allied, though distinct, concepts of compensation and isostasy.

The word compensation we owe to Archdeacon J. H. Pratt,[1] but the notion, though not the word, was suggested at an earlier date, by Sir G. B. Airy.[2] Though the hypotheses regarding the constitution of the earth, used by these two investigators, differed radically from each other, the essence of the explanation was the same, that under every great protuberance of the earth's surface, such as a mountain range, there was a mass of density less than the average at that depth, and that the plumb-line was not merely affected by the attraction of the visible mass of the mountain range, but also by the defect in mass in the underlying portion of the earth, which would cause an apparent repulsion of the plummet and so neutralise, or compensate, in part or in whole, the direct attraction of the mountain range.

The most complete investigation of the effect of compensation, which has been published, is that carried out by Mr. J. F. Hayford, of the United States Coast and Geodetic Survey, in 1909.[3] Mr. Hayford adopted an hypothesis similar to that of Archdeacon Pratt, and assumed that compensation took the form of a defect of density, equal in amount to the excess of mass in the range and distributed uniformly through some definite depth which would be everywhere the same. The deflections which should be expected from the relief of the country surrounding each station, up to a distance of 2,564 miles, were calculated, and compared with the observed deflections, the difference being regarded as an unexplained "residual," and it was found by a series of trials, that these residuals were lowest if the depth of the layer, through which the defect of mass was supposed to be uniformly distributed, or "depth of compensation," was 113·7 km.; with a greater or less depth the "residuals" were larger, and from this it was concluded that the depth of compensation in the United States was somewhere close to 113·7 km., or 70·67 miles.

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[1] J. H. Pratt, On the Deflection of the Plumb-line in India, caused by the Attraction of the Himalaya Mountains and of the elevated regions beyond; and its modification by the Compensating effect of a Deficiency of Matter below the Mountain Mass. *Phil. Trans.*, CXLIX, 745-778 (1859).

[2] G. B. Airy, On the computation of the Effect of the Attraction of Mountain Masses as disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys. *Phil. Trans.*, CXLV, 101-104 (1855).

[3] The Figure of the Earth and Isostasy, *from measurements in the* United States, Washington, 1909.

This, which he called the solution *G*, was afterwards modified [1] on the inclusion of additional observations, and the depth of compensation increased to 122 km., but as the difference is trivial, and the earlier value has been used in the investigations published by the Great Trigonometrical Survey of India, and was used by Mr. Hayford himself in his investigation of the effect of compensation on the vertical force of gravity, it may be accepted as a close approximation to average conditions. The results of calculations based on it are so little different from those which would have been obtained from a slightly different depth of uniform compensation, that no useful purpose would be served by a revision of the calculations.[2]

It must not, however, be supposed that these depths of 113·7 or 122 km. have any real meaning; all that the calculations imply is that the effect of such compensation as actually exists is not materially different from that which would have resulted from a defect of mass equal to that of the material above sea level, if this were produced by a defect of density extending uniformly through a depth of 113·7 km. and everywhere proportionate to the excess of mass represented by the surface elevation above sea level. Any other form of distribution of density which would bring about the same result would be equally in accord with observation, and this conclusion is borne out by certain calculations made by Mr. Hayford. In addition to the hypothesis of uniform compensation he considered four others, namely—

(1) A compensation uniformly distributed between the depths of 25 and 35 miles.

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[1] Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy. Washington, 1910.

[2] In Mr. Hayford's calculation, as in other treatments, it is assumed that compensation should be applied directly to the elevations above, or depressions below, sea level. The sea level is, however, an artificial datum for these purposes and the differences of level should, strictly, be measured from a datum representing the mean level of the solid earth, or the mean level as it would be if the oceans were supposed to be solidified and condensed to the mean density of the rock forming their floor. This datum would lie at about 3,000 ft. below sea level and its introduction would require an extensive re-calculation of tables, which ought properly to be undertaken in a discussion of the effect of compensation, which included observations at stations near the sea coast. Where, as is the case in this investigation, the distances from the shore line are measured in hundreds of miles, and where, as will appear further on, the modification introduced by considering the effect of topography beyond a distance of one hundred miles is trivial, as compared with the differences indicated by observation, we may confine attention to the difference of effect due to difference of elevation above an arbitrarily assumed datum, such as the mean sea level, the effect of the mass of the crust below this level, but above the mean level of the solid spheroid, and of its compensation, being the same in amount at all stations.

(2) A compensation similarly distributed between the depths of 27 and 37 miles.

(3) A compensation produced by a defect of density decreasing uniformly from double the average value to zero; for this the depth which gave the best results was found to be 175·4 km.

(4) A compensation such as that suggested by Prof. Chambarlin, at first increasing and then decreasing at a variable rate; for this the depth which gave the best result was found to be 287·4 km.

Taking ten stations as typical of the different regions of the United States, and comparing the residuals with those resulting from the solution G, the mean differences were found to be ·25, ·22, ·19, ·09 seconds of arc, for the four hypotheses respectively, and the maximum differences were 1·13, 1·04, ·80, ·38 respectively. As the mean of the residuals resulting from the solution G was 3·04″ and the maximum 12·35″, it is evident that there are five different hypotheses of compensation, which vary widely in the assumed distribution of the compensation, but agree in giving it a mean depth of from 30 to 35 miles, and in giving almost identical results. This shows that the supposed depth, to which compensation extends, has no real meaning, and that, although the effect of compensation, as it actually exists in the United States, is on the average very much the same as would result from a uniform defect of density extending to 113·7 or 122 km, according to whether the earlier or later solution of the problem is accepted, any other distribution of density might be equally in accord with observations provided that the position of the centre of effect was not materially different. In this way we are introduced to the concept of the *locus of the centre of compensation.*

In any given mass, forming part of a visible protuberance on the earth's surface, or of the underlying portion through which the compensation is distributed, there will be a point, so situated that, if the whole of the mass were concentrated at that point, the effect at the station of observation would be the same as that actually produced by the sum of the effects of all the separate particles of which the mass is composed. This point may be called the *centre of effect*, and in the case of the defect of density by which compensation is brought about the expression *centre of compensa-*

tion is a convenient one. This centre of compensation must be clearly understood as something entirely different from the centre of gravity of the defect of mass by which compensation is produced, the two are not coincident in position, and the divergence, which will not be great in the case of distant topography, may or may not become important in the vicinity of the station, according as the distribution of the defect of density is concentrated in a layer of small, or distributed through one of great, thickness.

The calculation of the depth of the centre of compensation does not, therefore, give any direct information regarding the nature of the compensation, but an investigation of the effect of varying the assumed depth of the centre of compensation affords a ready means of seeing in what direction we may best look for an explanation of the departure of the observed from the calculated deflection of the plumb-line.

The general principle of this investigation can easily be determined. In Fig. 1 let A represent the centre of attraction of an elevated mass, whose compensation is distributed in an unknown manner, so that the centre of compensation lies at the point C, then, if the divergence of the line A C from the vertical is

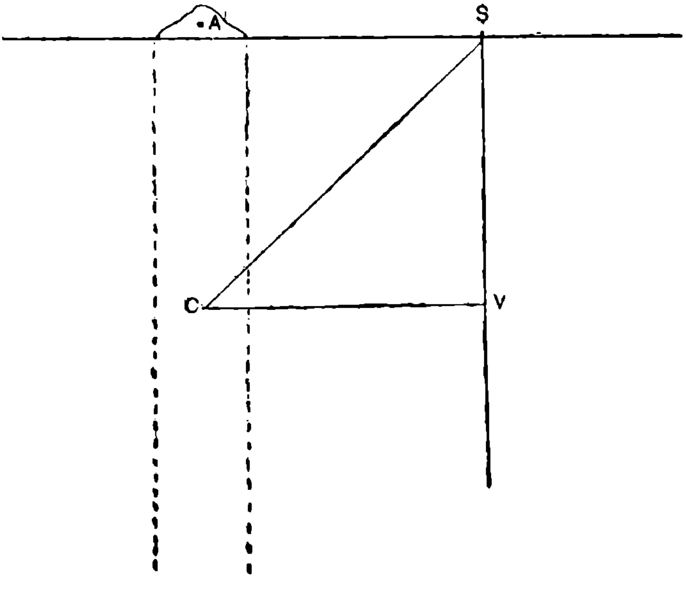

FIG. 1.

neglected, the effect of the compensation, at the station S, is represented by the formula

$$D' = \frac{m}{h^2} \sin^2 a \cos a$$

where D′ represents the deflection produced at S,

m, the mass whose effect is supposed to be concentrated at C,
h, the depth of C below the level of S, and
a, the angle of depression of C at A.

This expression has a limiting value of zero when *a* is 0° or 90° and attains a maximum when it has a value of about 50° 45′, or when the depth *h* is about 1·4 times the distance *r*. If this maximum effect, and the distance at which it is produced, are both expressed as 1·0, the proportion of this maximum effect which will be observed at other proportionate distances is given in Table 1.[1]

TABLE 1.—*Relation between distance and effect of the attraction of an under-ground mass.*

Distance.	Depression.	Deflection.
·1	86° 4′	·15
·2	83° 22′	·30
·3	80° 2′	·44
·4	76° 39′	·57
·5	73° 14′	·69
·6	69° 44′	·79
·7	66° 10′	·88
·8	62° 30′	·95
·9	58° 42′	·98
1·0	54° 45′	1·00
1·1	50° 35′	·98
1·2	46° 10′	·94
1·3	41° 23′	·85
1·4	35° 7′	·70
1·5	28° 52′	·53
1·6	21° 1′	·31
1·7	7° 38′	·04

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[1] This table has a further utility in that it may be applied to the effect of any defect or excess of mass at any depth below the level of the station, where the distances involved do not introduce the necessity of considering the curvature of the earth's surface, and where the dimensions of the mass are such that it may be regarded as centrobaric at all the distances involved. In the case of more extended masses the effect is the sum of the effects of all the separate small masses of which it is composed, and this effect would usually diminish the ratio between the distance of maximum effect and the mean depth of the mass, but not reduce this below equality. It is unnecessary for the present purpose to treat this matter in further detail; it is sufficient that the mean depth of the centre of such a mass will lie somewhere between 1·0 and 1·4 of the distances between the positions of maximum and zero effect.

While the effect of the compensation varies as indicated in Table 1, the effect of the attraction of the visible topography varies inversely with the square of the distance, and, for any particular distance from the station of observation, there is a definite ratio between the effect of the direct attraction of the visible topography and of its compensation, and this ratio is easy to determine. Referring again to Fig. 1, the effect of the attraction of the elevated mass, if the divergence of A S from the horizontal is neglected, as it usually may be, is represented by the formula—

$$D = \frac{m}{r^2}$$

where D represents the deflection produced at S—

m, the mass of the elevated tract,

r, the distance A S.

Similarly the effect of compensation, expressed in terms of r, instead of h as in the formula on p. 16 will be—

$$D' = \frac{m}{r^2 \sec^2 a} \cos a = \frac{m}{r^2} \cos^3 a$$

The ratio of the effect of attraction to that of compensation is, therefore, 1 : $\cos^3 a$ and the ratio to the net effect of attraction, and compensation, is, 1 : $1 - \cos^3 a$, which represents the compensation factor of Mr. Hayford, or the factor by which the calculated attraction must be multiplied to obtain the net effect, after allowing for compensation. This factor depends only on the angle a or, in other words, on the ratio between the distance from the station of observation and the depth of the centre of compensation, so long as the former of these is not large enough to necessitate the consideration of the effect of the curvature of the earth's surface.

As has already been pointed out, the centres of attraction and compensation, as the terms are here used, differ from the centres of gravity of the masses to which they refer; where the distance from the station is considerable, the two may be so nearly coincident as to become practically identical, but at lesser distances they may be largely divergent. To take the assumption, used by Archdeacon Pratt and Mr. Hayford, of a uniform defect of density, extending through a definite depth, then the centre of compensation would lie not far from one-half of that depth so long as the horizontal distance was such that the direct distance of the bottom of the column of rock from the station did not exceed that of the top by more than a small fraction of the whole. At lesser distances the effect of the portions near the top outweighs those near the bottom, because not only are they much nearer, but also their effect is more nearly in the horizontal plane, and, consequently, the centre of compensation comes nearer and nearer to the surface till, at the limit when the distance becomes zero, the depth of the centre of compensation also becomes zero.

It is obvious that if the compensation factor can be determined when the depth of the centre of compensation is known, the process can equally be reversed, and the corresponding depth of centre of compensation can be deduced from the factors. Taking the case of uniform compensation to a depth of 113·7 km., or 70·7 miles, we find that the depth of the centre of compensation at a distance of—

1·2 miles, is 4·5 miles.
2·4 ,, ,, 7·0 ,,
4·9 ,, ,, 10·9 ,,
10·0 ,, ,, 16·5 ,,
20·4 ,, ,, 23·5 ,,
41·5 ,, ,, 31·0 ,,
84·4 ,, ,, 35·5 ,,

allowing for the effect of the curvature of the earth in the last two cases.[1] The value obtained for the depth of the centre of compensation at 84·4 miles is just over half the total depth through which compensation is supposed to extend; at greater distances the depth is more or less than 35 miles, but in all these cases the three figures, to which the compensation factor was calculated, are insufficient to give more than approximate results.

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[1] It would seem that there is some small inaccuracy in the factors calculated by Mr. Hayford, so far as the neighbourhood of the station is concerned. This is shown by the fact that the factors, given on page 150 of his memoir, for a compensation confined to a layer between 25 and 35 miles from the surface, which are derived from those for uniform compensation from the surface to a depth of 113·7 km., give depths of less than 25 miles for distances of less than about 7 miles from the station; at greater distances the depth rapidly sinks to between 29 and 30 miles. As the depth of the centre of compensation could not, in any case, be less than 25 miles, there is evidently some mistake here, which may have partly arisen from working with too few decimals, but is more probably attributable to the fact that the supposed exact formula, from which the factors are derived, is itself merely an approximation, which fails when the depth of the column of rock is more than about three times the horizontal distance. The discrepancy may be left out of account, as it is confined to near-by distances, where the effect of compensation is in any case trivial.

These figures apply equally to any depth of compensation, so long as the proportion between that depth and the distance is preserved, and for distances equal to or greater than the assumed depth of uniform compensation the centre of compensation lies very close to the centre of gravity of the column of rock, but at lesser distances approaches nearer the surface. Here, then, we have a useful guide to the investigation of observations; instead of dealing with hypotheses of compensation, and the cumbrous calculations which their investigation involves, we may first of all see what position of the centre of compensation accords best with observation, and then consider the hypotheses which are in accordance with this.

In carrying out this comparison it will be convenient to retain Mr. Hayford's system, and dimensions, of compartments, with the modification that the horizontal distance, with which we are now concerned, will not be the outer, but the mean effective, radius of the compartment, which lies at ·455 of the distance between the inner and outer boundaries, this being the distance from the station to the centre of effect of a difference of density distributed uniformly over the area of a compartment. If we assume a depth of the centre of effect equal to the radius of any zone then the ratio of depth to distance will be the same for each successive zone within or without that from which a start is made, and the angle of depression and compensation factor will be as given in Table 2, from which it may be seen that, for any given distance from the

TABLE 2.—*Compensation factors for various ratios of distance from station (r) to depth of centre of compensation (h).*

Ratio $\frac{r}{h}$	Angle a.	$\cos^3 a$.	Factor.
·2419	76° 24·1′	·013	·987
·3449	70° 58·2′	·035	·965
·4918	63° 48·7′	·086	·914
·7013	54° 57·5′	·190	·810
1·000	45° 0·0′	·353	·647
1·426	35° 2·4′	·549	·451
2·033	26° 11·5′	·723	·277
2·899	19° 1·9′	·845	·155
4·134	13° 35·0′	·918	·082
5·805	9° 37·7′	·058	·042
8·406	6° 47·0′	·979	·021
11·99	4° 46·0′	·990	·010

station, an increase in the depth of compensation is accompanied by a decrease in its effect, or in other words an increase in the net effect of the attraction of the visible mass and of its compensation.

From the general considerations which have been set forth we may conclude that the existence of a residual, or a divergence between a computed and an observed deflection of the plumb-line at any station may be explained in one or other of three different ways, or by a combination of more than one of them. It may indicate

(1) that the compensation of the visible topography is not exact, but either in excess or defect;
(2) that the compensation is exact, but lies at a greater or less depth than that assumed in the calculation;
(3) that there is an excess of density, either in the surface rock or at some depth from the surface, which has not been allowed for in the calculation.

One or other of these conclusions is indicated, and it is only by the comparison of a number of separate observations in the same region that a decision can be reached as to which is the most probable explanation of the observed deflections.

Before leaving this subject it will be necessary to devote a few words to the nature of the evidence available. In practice the deflection of the plumb-line from the vertical can only be determined in the two directions of the meridian and the prime vertical; the latter is more difficult than the former and more liable to small errors, the observations moreover are too few in number, in the region under consideration, to be made use of, but this is a matter of small importance, seeing that the general trend of the Himalayas, and of the Gangetic trough, approaches more nearly to an east and west, than to a north and south, direction; consequently, the effect on the plumb-line is much greater in a north and south than in an east and west direction. Only incidental reference will, therefore, be made to the few available determinations of the deflections in the prime vertical, and attention concentrated on the more numerous and important determinations of the deflection in the meridian; and in getting at the meaning of them it is important to remember that the published figures represent differences, not actual deflections. There is no known method of determining the departure of the plumb-line from the vertical at any one station, all that can be measured is the difference of the deflections at one station as compared with another. A station is therefore selected as the station of origin, in India it is Kalianpur, and the figures published represent the difference in deflection between the direction of the plumb-line at that station and the other station of observation. Further it must be noted that the calculation of the deflections necessitates the use of certain assumed figures as representing the mean dimensions of the earth, dimensions which are known with approximate, but not absolute, accuracy. In the publications of the Great Trigonometrical Survey the published deflections of the plumb-line are based on an assumed zero deflection of the plumb-line at Kalianpur, and the dimensions of the Everest spheroid, which has an equatorial diameter of 20,922,932 ft. and a flattening of 1/300·8. It seems certain that this is not the closest approximation possible to the true dimensions of the earth, and in the more recent publications of the Survey of India the Bessel-Clarke spheroid [1] has been adopted, which has an equatorial diameter 3,270 ft. greater than the Everest and a polar flattening of 1/299·15; but the deflections are still calculated and published in terms of the Everest spheroid, and will be used without any attempt to adjust them to more modern dimensions of the earth. Any such adjustment would only give an illusory appearance of accuracy, for the difference in the absolute deflection at Lambatach, the station most distant from the reference station of Kalianpur, does not amount to more than 3″ of arc, and the differences, with which we are concerned, would not be altered by more than a single second in any of the groups of stations considered, an amount which is trivial in comparison with the differences actually observed.

A more important correction, which will be applied, depends on the probable existence of a southerly deflection at the reference station of Kalianpur, where no deflection is assumed in the published figures. Of the reality of this southerly deflection there seems no possibility of doubt, but the amount is open to uncertainty. In 1905 Sir S. G. Burrard adopted a value of +6″, in 1912 a value of +4″ is used in Major Crosthwait's investigation and, being the latest authoritative estimate, it has been used and a correction of +4″ has been applied to the published figures. It

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[1] See *Phil. Trans.*, Series A, CCV, 1905, p. 299

is obvious that this constant correction does not affect the differences between the deflections, but it is convenient as bringing the deflections into closer approximation to their true values.

We may now pass on to the consideration of the variations in the attraction in a vertical direction. These are measured by comparing the period of a free-swinging pendulum at different stations; in practice many precautions have to be taken and corrections applied for temperature, pressure of the atmosphere, flexure of the support, etc., with which we are not here concerned, and in the result it is now possible to determine the vertical force of gravity at any particular station with a very high degree of accuracy. This result has been expressed in several different forms; at one time it was commonly expressed by the number of swings in twenty-four hours of a pendulum which would beat exact seconds at sea level on the equator, or it might be expressed by the acceleration which would be produced in a free falling body; more recently, however, it has become customary to express it in dynes per gramme of mass, the dyne being the unit of force which, acting on a mass of one gramme for one second, would produce a velocity of one centimetre per second. Numerically, the value in dynes is identical with the acceleration, expressed in centimetres and seconds, but it is sometimes more convenient to express the result as a force than as an acceleration.

Having obtained a local measure of the force of gravity, it is compared with the theoretical value of gravity at the station, and the difference expressed as an "anomaly" which is positive if the former is in excess, and negative if it is in defect, of the theoretical value; but before this can be done it is necessary to reduce the observed value to what it should be at sea level immediately under the station, and to reduce the accepted equatorial value of gravitation to the latitude of the station.

To take the latter question first, the mean value of the force of gravitation at the equator is not far from 978·03 dynes with an error of not more than ·01; the formula for the reduction from this to the latitude of the station depends on the form of the earth, which is not yet known with exactitude, but any error introduced by this cause would not vary largely within the limits of the groups of observations to be considered. The position is very similar to that of the deflections of the plumb-line, in neither case can the absolute values be determined with certainty, but the differences, between the observed values in the stations taken into consideration, may be depended on, and in both cases we have departures from the values reckoned, without consideration for the disturbances produced by local departures from a condition of uniformity, which are far in excess of any possible error in the factors used in the calculations.

The reduction of the observed value of the force of gravity to sea level is a matter introducing much larger possibilities of variation than the determination of the theoretical value at sea level. The corrections to be applied are as follows:—

(1) for the height of the station above sea level;

(2) for the attraction of the masses above sea level, but below the level of the station;

(3) for the attraction of masses which rise above the level of the station;

(4) for the effect of compensation of the elevated masses.

The first of these depends on the fact that the force of gravity decreases as the surface of the earth is left below. This correction can be applied with great exactitude and there is no doubt of the reality of its effect; it is sometimes referred to as the "free air" correction, as, in applying it, the whole of the underlying ground is supposed to be removed and the station left standing free in the air. Here it will be referred to as the correction for height.

The second correction is sometimes also called the Bouguer correction, a term which refers to the particular method of calculation adopted, by which the station is supposed to be situated on the surface of a level plateau. The combined effect of this and the correction for the actual irregularity of the surface, often referred to as the orographical correction, will here be referred to as the correction for visible mass, that is for the attraction of all the mass which lies above sea level at and around the station.

The fourth correction is a modern development, first applied by Messrs. Hayford and Bowie,[1] and a consideration of its effect is necessary for the understanding of the interpretation of the anomalies discussed further on.

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[1] The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity, by J. F. Hayford & W. Bowie. Washington, 1912.

Referring back to Fig. 1 the attraction of a mass, centred at C, is exerted at the station S in the direction C S. We have already considered the variation in the horizontal component, and in Table I the proportionate variation in this, with a varying distance of the station, is given ; it is obvious that these same factors apply equally to the vertical component of the force, if the angle is measured from the vertical, instead of the horizontal, plane. The effect of any small mass, situated on the vertical drawn through C, will reach a maximum value when the angle joining it to the station S makes an angle of about 54° 45′ with the vertical, and at any greater or less depth the effect will diminish in the proportions given in Table 1.

So far we have only considered the case of a single small mass represented by C, but it is obvious that every other similar mass situated at the same depth and distance from S will have the same effect ; and if, instead of the line C S, we consider, as is shown in fig. 2, the space included between the surfaces of two cones and

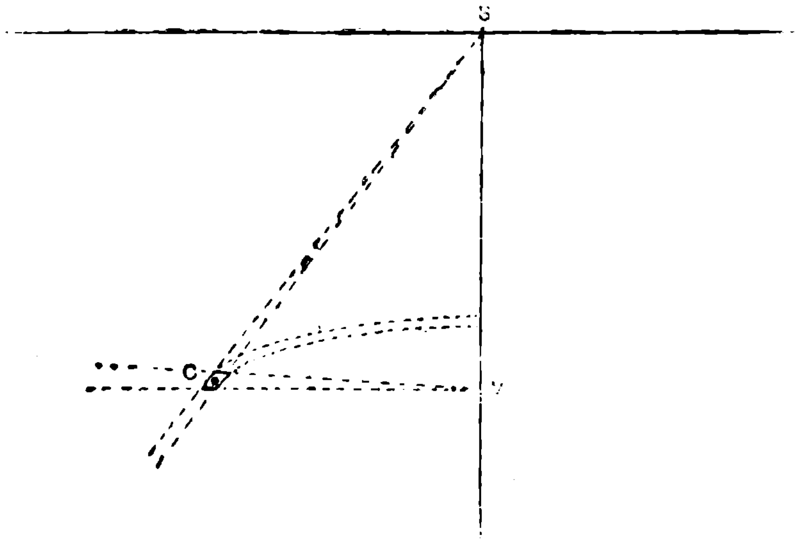

FIG. 2

two vertical radial plane surfaces, both diverging from each other at a very small angle, and instead of the horizontal line C V we take a very thin layer included between two horizontal planes represented by C V, we get a small volume, which may be treated as an ultimate particle, and of which the mass is directly proportional to the square of distance S C or S V. The effect at S being inversely proportionate to the square of the same distance, it results that the effect of the small portion of the thin horizontal slab is the same, whatever the depth of C may be below the level of the station S and, as the same is true of every portion of the circles included between the lines C S and S V at any depth, we reach the conclusion that the attraction, of any layer of rock included between two horizontal planes and a conical surface whose apex is at the station, will be proportionate to the thickness of the layer and the density of the rock, and independent of the depth of the layer below the station.

The formula by which this principle is translated into numerical calculation is

$$A = kd\,2\pi\,\delta\,(1 - \cos\alpha)$$

where

A is the attraction, expressed in dynes per gramme, at S,
k, the gravitation constant,
d, the thickness of the layer, measured in centimetres,
δ, the density of the rock,
α, the angle from the vertical of the outer surface of the cone;

and from this formula we may calculate, taking the value of k as about 6673×10^{-11}, that the pull exerted by 100 feet thickness of average rock, included in a cone whose outer surface makes an angle with the vertical of about

84°	is	·003 dyne,
66°	is	·002 ,, ,
45°	is	·001 ,, .

It may be pointed out that the volume or mass of these three cones is in the proportion of 1 : 5 : 90, while their effect is only in the proportion 1 : 2 : 3, and if the angle of the cone is taken at 90, that is, if the layer of rock is of infinite extent, and so of infinite mass, the effect is only increased to ·0033 dyne, so small is the influence of the more distant masses as compared with those nearly underneath the station.[1] Moreover these figures are not

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[1] It must again be noted that these statements and figures would only be true of a plane earth of infinite extent, and require modification when applied to a spherical or spheroidal earth, but within the distances and depths with which this investigation is concerned the effect of the curvature of the earth's surface is inappreciable.

only true of a simple layer of rock 100 feet in thickness, but are equally true of a proportionate excess or defect of density, distributed through a greater thickness in such a manner that the mass of any vertical column of rock, which wholly includes the cone, is in excess or defect by the equivalent of 100 feet of rock of average density.

This formula, and the figures derived from it, will be useful in comparing the effect which should be expected on different hypotheses of the nature and distribution of compensation. The way in which these differences arise will be most readily explained by a reference to fig. 3, which represents the case of a station S on the surface of an elevated plateau; it will be affected by the downward pull of the mass of rock lying between the level of S and sea level, represented by D D, it will also be affected by a defect of downward pull, due to the diminution of density by which the weight of the plateau above D D is compensated. To simplify the consideration of the relative effects of these two forces we will suppose that the variations of density are so distributed that the centre of effect of any column of small area lies at the depth A A in the case of the plateau, and of C C in the case of the compensation; and that the line S M represents that along which any given mass will produce a greater effect at S than if it were situated at a greater or less depth on the same vertical line.

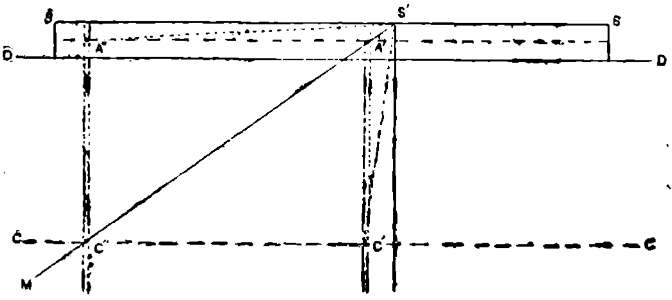

FIG. 3.

Now take the case of a small column so situated that the centre of attraction of the plateau at A′ is on the line S M, and the centre of compensation vertically below it at C′; here the effect of the attraction of the plateau is obviously larger in amount than that of the compensation, and the net effect will be a downward pull at S, which will increase the amount of the local measure of gravitation at that station. Conversely in the small column of rock situated so that the centre of compensation lies at C″, on the line S M, and of the attraction of the plateau at A″, the effect of the compensation is obviously in excess of the attraction of the mass above sea level, and the net effect at S will be a diminution of the local measure of gravity. Somewhere between these two points must come a limiting distance, where the effect of the attraction of the mass above sea level is exactly balanced by that of the compensation and the net effect at S reduced to zero; at lesser distances the effect of the elevated mass will exceed that of the compensation, and the net effect will be an increase in the local measure of gravity, but to a less extent than if there were no compensation, and at greater distances the effect will be reversed, and the net effect be a diminution of the force of gravity at S.

The distance from the station at which this reversal takes place depends in part on the height of the station and the surrounding topography above sea level, and partly on the depth and nature of the compensation. For the particular hypothesis of compensation used by Messrs. Hayford and Bowie the distance is about five or six miles ordinarily, but in the case of stations of great altitude may reach nearly twelve miles. An idea of the nature and amount of the effect of the direct attraction of an elevated mass and its compensation may be got from Table 3 (on next page), which shows the effect of the attraction of a circular plateau, of varying heights and dimensions, at a point in the centre of its upper surface, the values being expressed in dynes and calculated from the Hayford and Bowie tables.

Here we see that the effect of the mass of a circular plateau of 1,000 feet in height, contained within a radius of 1·4 miles, amounts to ·031 dynes, and that no appreciable increase results from an enlargement of the plateau to a radius of 100 miles, the more distant masses being so nearly on a level with the station that the vertical component of their attraction is negligible. If, however, we take the effect of compensation into consideration a reduction in the net effect becomes apparent beyond five miles from the station. For greater heights there is a continuous increase in the effect of the visible mass up to the limits considered in the table, but beyond a distance of 40 to 50 miles the further increase is very small, and may be ignored. The effect of the compensation on the other hand increases and the net effect, after reaching a maximum, goes on diminishing with an increase in the dimensions of the plateau.

TABLE 3.—*Attraction of a circular plateau, of varying radius and elevation, at a point centrally situated on its upper surface, due to the visible topography, and to the same, compensated in accordance with the Hayford and Bowie tables. All values positive and expressed in dynes.*

Radius in miles.	1,000 ft.		5,000 ft.		10,000 ft.		15,000 ft.	
	top.	comp.	top.	comp.	top.	comp.	top.	comp.
1·4	·031	*·031*	·118	·114	·172	·164	·196	·185
2·2	·031	*·031*	·135	·129	·215	·203	·260	·244
3·2	·031	*·031*	·146	·137	·250	·234	·321	·297
5·2	·031	*·031*	·154	*·141*	·282	·258	·383	·345
7·5	·031	·030	·159	*·141*	·301	*·266*	·422	·367
11·7	·031	·028	·163	·137	·315	·264	·452	*·373*
17·9	·031	·025	·165	·127	·325	·249	·473	·359
36·5	·031	·020	·168	·101	·335	·202	·494	·295
61·4	·031	·015	·170	·075	·338	·155	·502	·226
103·3	·031	·009	·170	·050	·341	·108	·508	·159

From the figures in Table 3, it will be seen that in the case of a plateau extending for distances measured by hundreds of miles, it may well be that the effect of compensation will completely neutralise that of the attraction of the visible mass, and the resulting attraction of gravity be the same as if the whole of the elevated mass were non-existent. We may also find in these figures an explanation of the fact that the anomalies of gravitation above sea level tend to be positive if the effect of the visible topography is ignored, and negative if it is considered, for in the first case no regard is paid to the increase in the local attraction due to the mass above sea level, and in the second a greater effect is attributed to it than it actually exerts. Further, it is obvious, from a consideration of fig. 3, that an increase in the depth of compensation would enlarge the limits within which the effect of the visible mass predominates over that of its compensation, and so increase the force of gravity at the station, while a lesser depth of compensation would have the reverse effect.

Taking all the considerations into account we may conclude that if, after allowing for the effect of the surrounding topography and its compensation, there is left a positive, or a negative, anomaly at any station, it may be due to one of three causes, and may indicate

1. that the compensation of the elevated masses is incomplete, or in excess;
2. that the real compensation is such that its centre of effect lies at a greater, or a lesser, depth than that of the compensation assumed in the calculation; or
3. that there is a local excess, or defect, of density in the matter lying below the level of the stations, independent of the effect of the elevated masses and their compensation.

The form in which the gravity observations of the Survey of India have been published has undergone greater changes than in the case of the deflection of the plumb-line. The older calculations are based on Prof. Helmert's 1884 formula for the theoretical variation of gravity with latitude, and on values of 5·6 and 2·8 for the mean densities of the earth, as a whole, and of surface rock, respectively. All the published anomalies, making allowance for the effect of height alone or of height and visible masses, were calculated on this basis, but, with the introduction of the consideration of the effect of compensation, different values for the density of the earth and of surface rock were adopted, namely 5·576 and 2·67 respectively, and Helmert's 1901 formula replaced the earlier one of 1884. The result is that the anomalies allowing for compensation are not directly comparable with those in which it is not considered. The difference in the densities used has but a small effect, except in the case of the Himalayan stations, but the 1901 formula gives a larger value for the theoretical value of gravity and, consequently, a negative change in the value of the anomaly which amounts, in the stations dealt with, to from —·022 to —·027 dyne.

There are, fortunately, a sufficient number of stations for which the Hayford anomalies have been calculated to serve most of the objects of this investigation, and these will be made use of, so far as possible, as they not only give a closer approximation to the absolute values of the anomalies but also to the differences between them. The other values of the anomaly of gravity, which are available for all stations, are comparable with each other, though not directly comparable with the Hayford anomaly, and afford an indication of the nature, and approximately of the amount, of the difference in the anomaly at any two stations and in this way will be utilised, as far as seems practicable.

So far, attention has been confined to the fact of compensation and the effect of variation in the depth at which it takes place; it will now be necessary to devote some space to a consideration of the manner in which compensation may be brought about, and to the cognate concept of isostasy.

The word isostasy was introduced by Major C. E. Dutton,[1] and by etymology implies merely the statical condition that the mass —or, more correctly, weight— of matter under every considerable portion of the earth's surface of equal area is the same, irrespective of the elevation of that area above or below sea level. The statement is not intended to apply to every small protuberance or depression in the surface of the land or bed of the sea, but to the general level, and involves, of necessity, a lesser density of the matter under an elevated region, such as a great mountain range, than under the plains at its foot, and a greater density under the depressed floor of the ocean. This leads to the same result as the concept of compensation, but the two are not synonymous, for the elevated regions of the dry land are continually suffering a loss of weight by denudation, while the material removed is deposited on the lowlands, and especially on the bed of the sea; in this way the load on one area is diminished, that on the other is increased and isostasy is destroyed, till the strain set up by this shift of load causes an underground flow of matter from the overburdened to the lightened area and so isostasy is re-established. From this it will be seen that the two principles of isostasy and compensation are related to each other in as much as the former necessitates the latter, and further that, whereas compensation merely expresses a static fact, isostasy, in spite of its name, implies

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[1] *Bull. Phil. Soc. Washington*, XI, p. 53 (1889).

a dynamic process,[1] which could only take place in a medium possessing a considerable degree of plasticity under the stresses to which it is exposed.

The various hypotheses which have been proposed, to account for the elevation of mountain ranges, excluding those which do not provide for compensation, may be divided into two categories, those which regard the elevations of the earth's surface as being supported by some form of tumefaction, and those which regard them as supported by some form of flotation. The earliest suggestion, that of Sir G. B. Airy,[2] was of the latter class; adopting the notion, still prevalent when he wrote, that the earth consisted of a comparatively thin solid crust floating on a fluid core, he showed that the crust would not be able to support the stresses set up by the weight of a great mountain range, which would break through the crust, and sink into the denser magma, till the buoyancy of this depressed portion was sufficient to support the weight of the range, and the difference in weight, between the depressed portion of the crust and the denser magma displaced by it, while supporting the range, would also produce that compensation which the observations indicated.

This hypothesis was afterwards adopted and developed by Rev. O. Fisher[3] who, taking the elevation of mountain ranges as due to compression, and consequent thickening, of the earth's crust, recognised that the additional weight thereby imposed on the mountain region would cause a depression of the crust into the underlying denser magma and give rise to a protuberance on the underside of the crust corresponding to the mountains on the upper.

Though both of these investigators based their explanation on the notion of a comparatively thin crust, floating on a fluid earth of greater density, it must be remarked that the latter condition is by no means essential, for the whole of the processes concerned would take place within the outermost 60 miles from the surface of the earth, leaving the odd 3,900 miles of the radius unaffected, so that, provided there was a fluid or even plastic layer, of greater density than the overlying crust, in that region which lies above a depth of 60 miles from the surface, all the requirements of the hypothesis would be fulfilled, and the constitution of the more

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[1] Major Dutton recognised that the term was inappropriate, but the word which would have expressed his intention was preoccupied in a different sense.

[2] *Phil. Trans.*, CXLV, 101-104 (1855).

[3] *Physics of the Earth's Crust*; 1st ed. 1881; 2nd ed. 1889.

deeply seated portions would not enter into consideration. It must also be remarked that any hypothesis which regards the elevation of mountain ranges as a result of compression, seems necessarily to involve some form of isostasy by flotation, in order to account for compensation, for if the whole of the thickening took place in an upward direction the mountains would be an uncompensated excrescence of additional matter, but if the thickening took place both upwards and downwards, and the outer crust consisted of less dense matter than that underlying it, there would be a defect of attraction which, at a sufficient distance, would neutralise the attraction of the mountain mass to a greater or less degree, according to the ratio of the excess and defect of matter. For complete compensation the two would have to be equal in mass, a condition which would imply complete isostasy and a support of the mountains by flotation.

Much the same effect, and the same considerations will apply to any form of hypothesis which attributes the elevation of the surface to an intrusion of fluid matter below it. Here again, if the whole effect was the raising of the crust between the upper surface and the intrusive mass, the range would be a mere excrescence of the surface and its attraction would be unmodified by compensation, unless we could assume that the intrusion was devoid of density, which is inconceivable, or that the displacement of the upper surface was accompanied by a downward displacement of the lower surface, leading to the replacement, under the upraised tract, of denser material by lighter. Any hypothesis of this kind, therefore, falls into the same great category as the supposition that the elevation of the range is due to a thickening of the crust by compression, in that it would imply an actual transfer of matter from a region outside, resulting in an increase of the mass of the outer crust underneath the upraised tract; and on any hypothesis involving this, it seems impossible to account for the accepted fact of compensation, without admitting that the upward protuberance of the upper surface is accompanied by a downward protuberance of the under surface of the crust, the "root" of Mr. Fisher's investigation, with the consequences of a displacement of the denser material under the crust by the lighter material of the crust itself, and an isostasy and support by flotation.

An hypothesis of this kind opens up a further possibility of a considerable departure from locally complete isostasy and a distribution of the load of the range, or of the flotation power of its root, over a considerable portion of the crust on either side of the range. This effect may work in one of two ways; if the growth of the upward protuberance exceeded that of the root there would be a local defect of support, which would be taken up by a depression of the crust on either side till the requisite support was attained. In this case the compensation of the range would be in defect, or in other words the mass of the range would be in excess of the defect of mass below it, while the tract on either side would be over compensated, so that the deep-seated defect of mass would exceed that of the visible elevation. This is a variation from a condition of the compensation of the range being complete, in the portion of the crust underlying it, which was actually investigated by Mr. Fisher; but it is also conceivable that the reverse might take place, and the development of the root be in excess of that of the range. In this case the surplus buoyancy would be taken up by a raising of the crust not only under the range but on either side of it, and the range would be over compensated while the tract on either side would show an excess of load over compensation.

This modification of the hypothesis of support by flotation has not, so far as I know, been investigated as yet, but its possibility cannot be excluded, and, if supported by the geodetic observations, is in some ways an attractive one. It would give a ready explanation of some of the features in the geological history of the Himalayas, such as the simple upward lift, of which there is evidence in the Deosai, north of Kashmir, in the plains of Hundes and elsewhere; the peculiarities and origin of the great boundary fault would find an easy explanation, as also the tilting of the surface of the gravel slope along the foot of the Hills, which is noticeable in many parts, and the fact that the range seems still to be rising.

An alternative group of hypotheses involves no addition to the material under the elevated tract, but regards the elevations of the visible surface as due to an actual swelling up of the matter under them, or, what comes to the same, a greater condensation under the more low-lying tracts of the surface. An hypothesis of this sort may be described as attributing the differences in level of different tracts of the earth's surface to some form of tumefaction, and the effect has usually been attributed to differences of temperature. This explanation has the defect of being apparently insufficient, quantitatively, to account for the facts, and even if it might suffice for the original formation of an elevated tract, with the accompaniments of compensation and a condition of isostasy, it would not provide for the maintenance, or re-establishment of the latter after disturbance by the removal of material by denudation from the higher and its deposition on the lower levels. Recently an hypothesis of tumefaction has been proposed by Dr. L. L. Fermor,[1] which appears to be more competent to account for the facts met with in nature; starting with the fact that igneous rocks of the same chemical composition may present themselves in different forms of mineral constitution, and that these forms vary in specific gravity, he concludes that this variation is the result of the conditions of temperature and pressure under which the different forms of rock consolidated, and distinguishes between the plutonic and the infra-plutonic forms of rock, which may originate from the same magma according to the pressure under which it cooled down to crystallisation. From this concept the consequence follows that in appropriate conditions of temperature and pressure, there might be a passage from one mode of mineral aggregate to another, of different density, accompanied by a corresponding change in volume. As the difference in density of the extreme forms of mineral aggregate may amount to as much as 20 per cent., it seems that we might find in an action of this nature a sufficient explanation for the elevation of even so lofty a range as the Himalayas and, in the opposite direction, for even the greatest depths of the sea, without having to invoke either too great a difference in density, or too large a bulk of material, to fall within limits which are justified by other observations. Dr. Fermor's hypothesis would also account for the maintenance of a mountain tract against the action of denudation, for the change in the deeper layers of the crust might easily be a progressive one, and to some extent dependent on the decrease in load.

We are not, however, here concerned with a discussion of hypotheses of mountain formation, but with the effect which an hypothesis of origin by tumefaction would have on the question of compensation. This, it will easily be seen, is provided for by the hypothesis, for the protuberance of the surface is the manifestation of a corresponding decrease in density below, and in this way compensation is provided for. It is also obvious that the denudation of the upraised tract and the deposition of the material removed

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[1] *Geol. Mag.* Decade VI, Vol. I, pp. 65-67 (1914); *cf.* also *Rec. Geol. Surv. Ind.*, Vol. XLIII, pp. 41-47 (1913) and XLII, pp. 133-207 (1912).

by denudation, on lower lying tracts may lead to departures from a condition of complete isostasy, but these will necessarily be in the direction of an excess of compensation in the hills and a defect in the plains; it is not conceivable that any hypothesis belonging to this class can account for the hills being under compensated or in other words showing an excess of load. In this way, then, we have a test which will distinguish between the two groups of hypotheses; so long as the geodetic observations indicate that the compensation of the hills is complete, or that the compensation is in excess of the visible mass of the range, we are free to choose between the hypotheses, but if they indicate an unmistakeable excess of mass in the hills, or a defect under the plains, after allowance has been made for compensation, the whole of one group is excluded. We are then restricted to the other, and can only choose between those hypotheses which involve an addition to the mass of the crust underlying the hills, whether this is brought about by the compression of the crust or by an underground migration of material from outside the limits of the range.

CHAPTER III.

THE IMAGINARY RANGE AND TROUGH.

In applying the general principles, outlined in the preceding chapter, and endeavouring to find the real meaning of the irregularities noticed in the geodetic data, two courses are open. The first is to take the whole of the stations, or a selected series of them, and calculate what the deflections should be at each, according to different forms of compensation, and then see which assumption gives the smallest average departure from observed results, or, more accurately, the least value for the sum of the squares of the differences between the observed and the calculated deflections. This is the method of geodesy, and is the only one admissible where minute numerical accuracy is essential, but it has the drawbacks of being extremely laborious, and of liability to degenerating into mere juggling with figures, unless great care is taken to keep in mind the exact significance of the calculations being gone through. Moreover, it is a method more suited to the final calculations of an investigation than to the preliminary stages, which may show that the more refined method would be no more than a vain attempt at a greater degree of precision than the nature of the data permits.

For these reasons it is necessary to discover simpler means of dealing with the problem, and this is to be found in ignoring the complicated contour of the actual Himalayas, and substituting for them an *Imaginary Range* which shall not differ too largely from the actual range, while simplifying the calculations necessary for estimating the consequences of various hypotheses. It will then be an easy matter to compare these results with those of observation, and so determine which of the hypotheses must be rejected, and which, if any, can be profitably pursued in greater detail.

It is not difficult to devise such an Imaginary Range as will render calculation easy, and at the same time be in agreement with the actual average contour of the Himalayas, that is with their average or generalised form, apart from the irregularities due to the erosion of the river valleys. Broadly speaking, the Himalayas proper, excluding for the present the foot-hills of the Siwalik area, rise abruptly on their southern margin to a height of about 5,000 to 6,000 feet above the level of the sea; in the interior of the range is the great plateau of Tibet, which, presenting very considerable irregularities of contour, may, in view of the distance separating it from the stations of observation with which we will be concerned, be regarded as a plain of about 15,000 feet of elevation above the sea level.[1] Along the southern edge of this plateau runs the great snowy range, including the highest peaks, and south of the snowy range comes the region of the lower Himalayas, where the summits do not rise to more than ten or twelve thousand feet above sea level. Though the distinction between these two regions, of the snowy range and the Lower Himalayas, is fairly well defined and somewhat abrupt, the average level of the ground shows a less abrupt change and in the Lower Himalayas themselves there is a gradual decrease in general altitude to about 5,000 feet at the southern margin of the hills, where the ground drops abruptly to the foot-hills, or Sub-Himalayas, of the Siwalik region. These may conveniently be represented in that portion of the range which will come into consideration, by a plateau of twenty miles in width, and fifteen hundred feet in elevation above the plains to the south. The generalised cross-section of the elevated mass of the Himalayas may therefore be represented as a plateau of 15,000 feet in elevation, bordered by an inclined plane of 100 miles in width, sloping from 15,000 to 5,000 feet of elevation, and a plateau of 1,500 feet in height by 20 miles in width. For purposes of calculation, it will be simpler to substitute for this inclined plane a series of steps each ten miles broad and 1,000 feet lower than the next step to the north. The Imaginary Range would then have a cross-section like that shown in fig. 4 (page 38), where two actual cross-sections of the Himalayan Range are also given, for comparison.

In the calculations regarding this Imaginary Range, it will be assumed to have an east to west direction, with the elevated plateau on the north and the plains on the south. This is not only in general agreement with the Himalayas, but will allow of deflections towards the range being expressed as northerly deflections, in accordance with the usual convention, by the minus sign, and

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[1] I have followed previous writers in accepting 15,000 ft. as the mean height of the central plateau; actually the mean height would be more correctly 16,000 ft. or a little more. As the elevation of the land south of the Himalayas is ignored in the calculations, and only the height of the hills above the sea considered, the difference is partly eliminated, and in any case would have but a very small effect at the stations at which observations have been made.

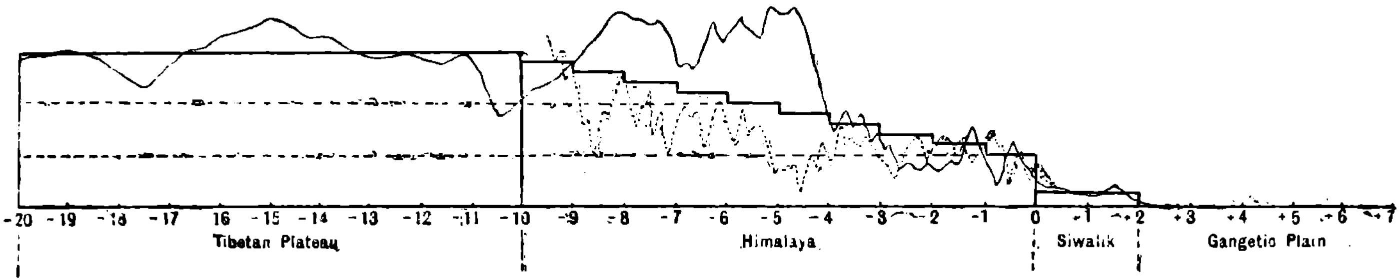

FIG. 4.—Cross section of the Imaginary Range; two actual cross sections of the Himalayas are represented, on the same scale, for comparison. Below is indicated the numbering of the stations, as used in the tabular statements.

deflections away from the range as southerly, by the plus sign. A series of supposed stations, at intervals of ten miles apart, can conveniently be distinguished in the same manner, the station at the edge of the hills, which is here regarded as coincident with the main boundary fault, being 0, those to the north being successively −1, −2, and so on, and to the south, in a similar manner as +1, +2, &c. The geodetic effect which should be looked for having been calculated for each of these stations, the results were plotted on squared paper and a curve drawn through the points, which will not be very widely different from the smoothed curve calculated for a set of stations similarly situated on the actual Himalayas.

Having decided on the cross-section of the Imaginary Range, it is necessary to decide on how much of it is to be considered in each calculation. The smaller the distance from the station which enters into the calculation, the simpler this will be, and there are three considerations which put a limit to the distance which can profitably be considered. The first of these is the fact that the attraction of any given mass of rock decreases with the square of the distance, so that its effect becomes negligible after a certain distance is exceeded. The second is the fact that the methods of geodetic observation can only give a differential, not an absolute, result. In practice some one station is taken as a station of reference, and the observations at other stations are expressed as differences from that station. Now the nearer two stations are to each other, the smaller will be the proportionate difference in distance of any point remote from both, and, consequently, the smaller the difference in the effect of the attraction at each of the two stations; and so, for any pair of stations there is a certain distance beyond which all masses affect each in so nearly equal degree that their effect may be neglected, so far as the consideration of the difference in deflection at the two stations is concerned. For a distance of 10 miles between the stations this limit would be about 50 miles, for a distance of 25 miles between the stations the limit would be about 100 miles, and for a distance of 100 miles the differential effect of topography more than 400 miles away would be trifling, even if the effect of compensation is ignored. The third consideration, limiting the distance from the station which need enter into calculation, is the fact that when the effect of compensation is considered, the effect of distant topography is almost or completely neutralised by its compensation.

In my earlier investigation of the effect of the Gangetic Alluvium on the Plumb-line,[1] only those masses lying within 50 miles of each station were considered, but in this more extended investigation the limit has had to be enlarged and in each case a strip running transverse to the range and extending 100 miles on either side of the station, and so much of this strip as lies within 100 miles of it, has been taken into consideration. In other words each station successively has been conceived as lying in the centre of a 200-mile square, and everything outside this limit has been put out of consideration. It will be shown, further on, that the effect of this limitation, of the area considered, is so small, in proportion to the effect produced by the area actually considered, that it may be left out of consideration for the purpose of this investigation.

We are now ready to take up the effect of different hypotheses of compensation as applied to the Imaginary Range and, as a starting point, the tabular statement No. 4 (page 41) gives the deflections which would be produced by the Range proper, excluding the effect of the Siwalik Hills, at a series of stations 10 miles apart, the masses within a square of 200 miles a side being alone considered, and as they would result (1) from the uncompensated effect of the visible mass and (2) allowing for the effect of compensation according to Mr. Hayford's factors for uniform compensation to 113·7 km.

Before proceeding further it will be useful to consider what modification in these figures would result from including a larger area in the calculations and, as an extreme case far exceeding anything to be met with in nature, I have supposed the stations to be situated in the centre of a square of 2,400 miles on the side, and the plateau, slope, and plain of the Imaginary Range, to be extended over the whole of the area thus taken into consideration. In these circumstances the uncompensated deflection at the station 0, on the edge of the hills, would be increased by 78″; at station 10, or at a distance of 100 miles from the edge of the hills, in either direction, the deflection would be increased by 69″; the difference would, therefore, be increased by 9″. If, however, the effect of the Hayford compensation be taken into account, the increased deflections would be reduced to just under 3″ at the edge of the hills and just over 2″ at 100 miles away, and the difference would be but

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[1] *Proc. Roy. Soc.*, Series A, XC, pp. 32-41 (1914).

TABLE 4.—*Deflections produced by the Imaginary Range due to the attraction of the visible masses; (I) uncompensated and (II) compensated by Hayford factors for depth 113·7 km.*

STATION No.	I Uncompensated.	II Compensated.
— 20	0	0
— 19	0	0
— 18	1	0
— 17	1	0
— 16	2	0
— 15	3	1
— 14	5	1
— 13	7	2
— 12	11	3
— 11	15	6
— 10	23	11
— 9	28	13
— 8	32	15
— 7	35	16
— 6	38	17
— 5	40	18
— 4	42	19
— 3	43	20
— 2	45	21
— 1	48	24
0	76	53
+ 1	34	15
+ 2	23	9
+ 3	17	5
+ 4	12	3
+ 5	9	2
+ 6	6	1
+ 7	4	0
+ 8	2	0
+ 9	1	0
+ 10	0	0

0·7″. It may be said that no reasonably admissible hypothesis of compensation could increase this difference by more than about 1″, and so the limitation of area, adopted for the purpose of simplifying calculation, is justified, for the effect of increasing the area would be much less in nature than in the artificial circumstances assumed for this calculation.

The same conclusion is reached by a comparison of the deflections, calculated as due to the Imaginary Range, with those of the actual topography of the Himalayas, and this can readily be done, since the necessary calculations have been made, for certain stations, and published by Major H. L. Crosthwait.[1] In Table No. 5 a list of these stations is given, together with their distances from the main boundary fault, and the deflections which were calculated for the actual station, as well as those at stations similarly situated on the Imaginary Range, allowance being made for the departure of the actual range from a due east and west direction. In each case the values are given (I) for the supposition that the visible masses are uncompensated and (II) for the supposition that the compensation is in accordance with Mr. Hayford's tables for uniform compensation to a depth of 113·7 km. Finally there is given the difference between the value for the Imaginary Range, and for the actual topography on each supposition, or the amount of deflection, northerly or southerly, which the latter gives as compared with the former.

TABLE 5.—*Comparison of deflections due to the actual topography, with those due to the Imaginary Range, at stations similarly situated, allowing (I) for the effect of the visible masses and (II) for the same as modified by the effect of Hayford compensation.*

STATION.	Distance from main boundary in miles.	Deflections due to the Imaginary Range, in the meridian.		Deflections calculated by Major Crosthwait.		Difference between the effect of actual and imaginary topography.	
		I	II	I	II	I	II
Lambatach	44 N.	— 33	— 14	— 71	— 9	— 38	+ 5
Kurseong	3 ,,	— 54	— 29	— 103	— 23	— 49	+ 6
Mussooree	3 ,,	— 40	— 19	— 86	— 17	— 46	+ 2
Birond	2 ,,	— 51	— 20	— 74	— 14	— 23	+ 6
Dehra Dun	6 S.	— 34	— 17	— 86	— 18	— 52	+ 1
Siliguri	12 ,,	— 30	— 13	— 84	— 11	— 54	+ 2
Jalpaiguri	33 ,,	— 14	— 5	— 77	— 8	— 63	+ 3
Kaliana	41 ,,	— 6	— 2	— 58	— 3	— 52	+ 1

It will be seen that the uncompensated deflections derived from Major Crosthwait's calculations show a large northerly deflection, in

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[1] Investigation of the Theory of Isostasy in India: *Survey of India, Professional Paper* No. 13, Dehra Dun, 1912. In addition to the results published in this paper, I am indebted to the courtesy of Sir S. G. Burrard, Surveyor-General, for the details of the calculations from which they were obtained.

excess of those due to the Imaginary Range, but this is due to the fact that Major Crosthwait's calculations include all topography within 2,564 miles of the station, and therefore the whole of the highlands of Central Asia, whereas those for the Imaginary Range only include topography within 100 miles distance. If we turn to the compensated deflections this great difference disappears and we find that Major Crosthwait's calculations give rather smaller values for the northerly deflections. At the stations north of the boundary fault, that is to say within the Himalayan region proper, the difference varies from 6″ to 2″, an irregularity which finds a natural explanation in the irregularity of the contour of the actual Himalayas and in the deep cut valleys which penetrate it. At stations outside the Himalayas, where these irregularities have less effect, a greater uniformity is observable and a closer agreement; the greater difference at Jalpaiguri is doubtless due to the inclusion in Major Crosthwait's calculation of the southerly pull of the highlands of the Assam Range and the Peninsula.

From this comparison two conclusions may be drawn. Firstly that the limitation, of the extent of topography considered, to that lying within 100 miles of the station is justified by the smallness of the effect of more distant topography, when the opposite effect of its compensation is taken into consideration; in none of the stations does the effect of the topography beyond 100 miles, and up to 2,564 miles, differ materially from about a couple of seconds of arc, and in every one of them it is in the same, northerly direction, so that no change is introduced in the difference between the calculated deflection for any pair of stations. Secondly it appears that the Imaginary Range will serve the purpose for which it was intended; that the deflections calculated from it are, on the average of the same order of magnitude as those which would be deduced from the actual topography; and that the departures from the deflections calculated from Mr. Hayford's tables which would result from a variation in the hypothesis of compensation will agree in character and order of magnitude with those which would result from the application of a similar hypothesis to the more complicated topography of a station, similarly situated, in the Himalayas.

No more than this is, at present, required, so far as the range representing the Himalayas proper is concerned; but for the greater part of its length the main range is bordered by a tract of lower hills, which have to be included in making a comparison between the effect of actual and imaginary topography. These are absent in the Sikkim area; elsewhere they lie south of the main boundary, and belong properly to the region of the Gangetic trough, but must be considered as part of the topography so far as they affect the deflection of the plumb-line. They will be simplified into a plateau of 20 miles in width and 1,500 feet in height above the plains, dimensions which conveniently, and approximately, represent the actual topography; and, as the mean density of the Siwalik rocks is about 2·2, and of the rocks of the main range about 2·7, the deflections will be estimated at eight-tenths of those which would result from Mr. Hayford's figures. In table No. 6 the deflections so obtained are given on the assumptions respectively, of no compensation, and compensation according to Mr. Hayford's tables; the difference does not in any case exceed one second of arc, and though there seems some reason, in this area, for not using the hypothesis of compensation, it will be safer to use the figures in the second column, which must be added to those obtained from other tables, when it is necessary to consider the attraction of the hills of the Sub-Himalayan region.

TABLE 6.—*Deflections due to an Imaginary plateau, representing the Sub-Himalaya or Siwalik Hills, assumed 20 miles broad by 1,500 feet in height and of density ·8 of average rock.*

STATION.	Uncompensated.	Compensated.
—5	+ 1	0
—4	+ 1	0
—3	+ 1	+ 1
—2	+ 2	+ 1
—1	+ 3	+ 2
0	+ 14	+ 13
+ 1	0	0
+ 2	— 14	— 13
+ 3	— 3	— 2
+ 4	— 2	— 1
+ 5	— 1	— 1
+ 6	— 1	0
+ 7	— 1	0
+ 8	0	0

Having formed an estimate of what the effect of compensation would be, if it is given the average value determined by observations in the United States of America, which may be accepted as not widely different from the average effect elsewhere, the next stage in the investigation is to calculate the result of supposing a departure from these average conditions in one direction or another. The first of these, to be considered, is a variation of the depth of compensation, still supposed to be uniform throughout the depth to which it extends, and the depths taken for calculation will be those for which Mr. Hayford has given tables, namely 162·3 km. or about 100 miles and 79·8 km. or about 50 miles.

In table No. 7, the result of calculation for these two depths is given, to the nearest whole second of arc, as well as the deflections resulting from Mr. Hayford's factors for uniform compensation to a depth of 113·7 km., or about 71 miles, and the differences between these values. The meaning of these differences being that, if the calculation had been made according to the Hayford

TABLE 7.—*Deflections which would be produced by the Imaginary Range on the supposition of uniform compensation to various depths.*

STATION.	ASSUMED DEPTH OF COMPENSATION.				
	162·3 km.	Diff.	113·7 km.	Diff.	79·8 km.
− 10	− 13	− 2	− 11	+ 3	− 8
− 9	− 16	− 3	− 13	+ 3	− 10
− 8	− 18	− 3	− 15	+ 3	− 12
− 7	− 20	− 4	− 16	+ 4	− 12
− 6	− 21	− 4	− 17	+ 4	− 13
− 5	− 22	− 4	− 18	+ 4	− 14
− 4	− 23	− 4	− 19	+ 4	− 15
− 3	− 25	− 5	− 20	+ 4	− 15
− 2	− 26	− 5	− 21	+ 4	− 17
− 1	− 29	− 5	− 24	+ 4	− 20
0	− 58	− 5	− 53	+ 5	− 48
+ 1	− 19	− 4	− 15	+ 3	− 12
+ 2	− 11	− 2	− 9	+ 3	− 6
+ 3	− 7	− 2	− 5	+ 2	− 3
+ 4	− 5	− 2	− 3	+ 1	− 2
+ 5	− 3	− 1	− 2	+ 1	− 1
+ 6	− 2	− 1	− 1	0	− 1
+ 7	− 1	− 1	0	0	0
+ 8	− 1	− 1	0	0	0
+ 9	0	0	0	0	0
+ 10	0	0	0	0	0

factors for a depth of 113·7 km., observation at a station 50 miles north of the edge of the hills would show a northerly deflection of 4″ in excess of that due to calculation, or, in other words, a "residual" of — 4″ if the depth of compensation were 100 miles and a defect, or "residual," of + 4″ if the depth were only 50 miles. From this it appears that a variation in the depth to which compensation extends, assuming it to remain similar in character to Mr. Hayford's assumption, would introduce residuals which would be northerly for a greater depth of compensation and southerly for a lesser one. These residuals would not, however, amount to more than three or four seconds of arc, unless a much greater depth of compensation is assumed than there is any reasonable justification for adopting, and further, the residuals would have their maximum value at the edge of the hills, decreasing in both directions but more slowly towards the interior of the range than beyond its limits.

TABLE 8.—*Comparison of deflections produced by the Imaginary Range for Uniform Compensation to depth 113·7 km., with those produced by various depths of Centre of Compensation.*

STATION.	COMPENSATION UNIFORM.	DEPTH OF CENTRE OF COMPENSATION.					
	To depth 113·7 km.	45 miles		35 miles		25 miles	
		Defl.	Diff.	Defl.	Diff.	Defl.	Diff.
— 10	— 11	— 14	— 3	— 12	— 1	— 9	+ 2
— 9	— 13	— 17	— 4	— 14	— 1	— 11	+ 2
— 8	— 15	— 19	— 4	— 16	— 1	— 13	+ 2
— 7	— 16	— 21	— 5	— 18	— 2	— 14	+ 2
— 6	— 17	— 22	— 5	— 19	— 2	— 15	+ 2
— 5	— 18	— 23	— 5	— 20	— 2	— 15	+ 3
— 4	— 19	— 24	— 5	— 21	— 2	— 16	+ 3
— 3	— 20	— 26	— 6	— 22	— 2	— 17	+ 3
— 2	— 21	— 27	— 6	— 23	— 2	— 18	+ 3
— 1	— 24	— 31	— 7	— 27	— 3	— 22	+ 2
0	— 53	— 61	— 8	— 57	— 4	— 52	+ 1
+ 1	— 15	— 20	— 5	— 17	— 2	— 13	+ 2
+ 2	— 9	— 12	— 3	— 9	0	— 7	+ 2
+ 3	— 5	— 7	— 2	— 5	0	— 3	+ 2
+ 4	— 3	— 4	— 1	— 3	0	— 2	+ 1
+ 5	— 2	— 3	— 1	— 2	0	— 1	+ 1
+ 6	— 1	— 2	— 1	— 1	0	— 1	0
+ 7	0	— 1	— 1	0	0	0	0
+ 8	0	— 1	0	0	0	0	0
+ 9	0	0	0	0	0	0	0
+ 10	0	0	0	0	0	0	0

The Hayford values for the effect of compensation depend, as has been pointed out, on a wholly empirical distribution of the variations in density, a distribution which would not accord with those theories of mountain formation, which, so far as they admit of compensation at all, demand a limitation of the effect to a certain layer, or, at least, a concentration of the greatest effect within these limits. A calculation was, therefore, made of the effect of an assumption of a uniform depth of the centre of compensation at 25, 35, and 45 miles below sea level; the result is given in the table No. 8 (page 46), in which the result of the Hayford compensation is also included, for comparison. Here, again, we see that a greater depth of compensation results in an increased northerly deflection; we also see that if the depth of the centre of compensation is as much as, or over, 35 miles the maximum difference is at the outer edge of the hills and decreases at stations further in, while a shallower depth gives an apparent southerly deflection, when compared with the result of the Hayford compensation.

So far the compensation has been supposed to be uniform in character and depth; we must now consider the effect of a variable compensation, such as would be introduced by an hypothesis involving the support of the range by flotation, and a thickening of the crust downwards into the denser matter below, as well as upwards into the air. The most complete investigation of such an hypothesis, is that of Mr. O. Fisher, and it will be convenient to adopt his constants, and then investigate the effect of a variation in them. According to these, the mean thickness of the undisturbed crust is 25 miles, and the difference in density between it and the subjacent magma is such that the general elevation above mean sea level would require a downward protuberance of 9·6 times as much to compensate, by its buoyancy, for the weight of the upward protuberance.

On this supposition the bottom of the crust would lie at a depth of 25 miles under the plain, and under the first step of the Imaginary Range it would lie at 34·1 miles, under the second step at 35·9 miles and so on, and the whole of the compensation would be concentrated in that part of the crust lying below 25 miles.

The result of calculation from this supposition is given in table No. 9 (page 48), which shows that, as compared with the Hayford compensation, it not only gives rise to considerable northerly differences or "residuals" at stations within the hills, a result which

TABLE 9.—*Comparison of the Deflections produced by the Imaginary Range for uniform compensation to depth 113·7 km., with those which would be produced on the hypothesis of support by simple flotation, using Fisher's constants.*

STATION.	UNIFORM COMPENSATION TO 113·7 KM.	SIMPLE FLOTATION.	
	Deflection.	Deflection.	Difference.
— 10	— 11	— 14	— 3
— 9	— 13	— 17	— 4
— 8	— 15	— 19	— 4
— 7	— 16	— 20	— 4
— 6	— 17	— 21	— 4
— 5	— 18	— 22	— 4
— 4	— 19	— 22	— 3
— 3	— 20	— 23	— 3
— 2	— 21	— 24	— 3
— 1	— 24	— 27	— 2
0	— 53	— 56	— 3
+ 1	— 15	— 16	— 1
+ 2	— 8	— 8	0
+ 3	— 5	— 5	0
+ 4	— 3	— 3	0
+ 5	— 2	— 2	0
+ 6	— 1	— 1	0
+ 7	— 1	— 1	0
+ 8	0	0	0
+ 9	0	0	0
+ 10	0	0	0

is the consequence of the greater average depth of the centre of compensation, but these differences are greater within the range than at its southern edge, and show a maximum at about 50 miles in. Moreover, the differences must be regarded as minimum values, since Mr. Fisher's constants, though arrived at by him on grounds independent of the particular hypothesis of mountain formation and support, represent a minimum value for the thickness of the crust and a maximum value for the difference in density between the crust and the underlying magma. If instead of 25 miles for the former a thickness of 30 miles is assumed, and instead of a difference of density such that for each 1,000 ft. of elevation representing 1·8 miles it be taken to represent 3 miles of "root," values which are not beyond reasonable limits, then the "residuals" become —7″ at the station 0, —8″ at station —5, and —6″ at station —10.

Actually, on any reasonable hypothesis of support by flotation the differences would probably lie somewhere between these two extremes, but nearer the lower than the higher value.

It has been pointed out that an hypothesis of support by flotation not only allows, but has a necessary consequence, of the likelihood that compensation would not be complete within the limits of the range, but might be partly distributed over the crust on either side. This want of balance may take place in two ways, and the one which will be considered first is a superelevation of a part of the range, accompanied by a bending down of the crust on either side. In table No. 10 the result of such a departure from complete local support by flotation is given on two separate suppositions, namely (1) that a tract 100 miles in width is superelevated by 1,500 ft. and that the defect in support is taken up by a depression of the crust on either side, gradually diminishing to nothing in 100 miles; and (2) that the same tract is superelevated by 3,000 ft.

TABLE 10.—*Corrections to the deflections due to the hypothesis of support by simple flotation, on two separate suppositions of partial support, corrected by depression of the adjoining tracts, supposed to be confined* (*A*) *to the topography and* (*B*) *to the compensation.*

Distance from southern edge of superelevated tract (in miles).	DEFLECTIONS RESULTING FROM HYPOTHESIS			
	No. I.		No. II.	
	(A)	(B)	(A)	(B)
50 N.	0	0	0	0
40	— 2	— 1	— 4	— 1
30	— 4	— 2	— 7	— 3
20	— 7	— 3	— 12	— 5
10	— 12	— 4	— 20	— 7
0	— 27	— 5	— 44	— 8
10	— 11	— 4	— 19	— 8
20	— 5	— 3	— 12	— 7
30	— 2	— 2	— 8	— 6
40	0	— 1	— 5	— 4
50	+ 1	0	— 3	— 3
60	+ 2	0	— 1	— 2
70	+ 3	+ 1	0	— 1
80	+ 4	+ 1	+ 1	0
90	+ 4	+ 1	+ 2	+ 1
100 S.	+ 4	+ 2	+ 3	+ 1

and the defect in support taken up by a depression of the crust on either side by the equivalent of 1,500 ft. gradually diminishing to nothing in 200 miles. In each case the figures given in table No. 10 must be added, algebraically, to those given in table No. 9 for the hypothesis of support by simple flotation, and so will increase or diminish the differences from the deflections due to the Hayford compensation, as the case may be.

The effect of the opposite supposition, that the buoyancy of the downward protuberance is in excess, and the surplus power of flotation absorbed by an upward bending of the crust on either side, would be practically the same in amount, but with the opposite sign, as that shown in the table No. 10, the surplus buoyancy being supposed to be of equal amount and extent as the surplus load considered in that table.

In considering the gravity observations a somewhat different course to that adopted in the case of the deflection of the plumb-line will be more convenient. The effect of the direct attraction of the visible masses is always determinable from the published observations, and different formulæ of calculation make very small differences in the amount to be allowed for this effect; the anomalies, or more properly the difference of anomaly between two stations in the same region, may therefore be looked upon as representing local differences in the density of the matter under the station, of which the most important is that due to the effect of compensation. It is, consequently, convenient to consider the effect of the compensation only, and the differences which would be introduced by varying the hypothesis.

The first of these comparisons to be made is that of the Hayford compensation with an hypothesis of support by flotation. This is given in table No. 11 (page 51), and a few words of explanation will show the use of this and the other tables; taking station 0, at the edge of the hills, and calculating the gravity which should be found at it according to the Hayford factors, we would have to allow for the effect of the visible masses and a further correction of — ·075 dyne for the effect of their compensation; but if the support had in reality been, as considered in the second column, one of simple flotation its effect would have amounted to — ·085 dyne, and the observed force of gravity would show a defect, or anomaly, of — ·010 dyne. At stations more than 50 miles into the hills this would be reversed, and a calculation based on the Hayford tables would show a

TABLE 11.—*Gravitation effect of the compensation only of the Imaginary Range (I) according to the Hayford tables and (II) on the hypothesis of support by flotation, using Fisher's constants. All quantities negative and expressed in dynes.*

STATION.	Hayford Compensation.	Fisher Constants.
— 20	·350	·310
— 10	·305	·280
— 5	·200	205
— 4	·180	·185
— 3	·155	·165
— 2	·130	·140
— 1	·105	·115
0	·075	·085
+ 1	·045	·060
+ 2	·130	·040
+ 3	·020	·025
+ 4	·015	·015
+ 5	·010	·010

positive anomaly, increasing at stations further into the hills till, on the plateau, it rises to as much as + ·040 dyne.

In the table No. 12 are given the gravitation effects of a compensation supposed to have a uniform depth of the centre of compensation of 25, 35, and 45 miles respectively, which shows the

TABLE 12.—*Gravitation effect of the compensation only of the Imaginary Range supposed to be centred at various depths. All quantities negative and expressed in dynes.*

STATION.	DEPTH OF CENTRE OF COMPENSATION.		
	25 miles.	35 miles.	45 miles.
— 20	·380	·330	·300
— 10	·345	·295	·265
— 5	·235	·200	·180
— 4	·210	·180	·160
— 3	·180	·155	·140
— 2	·150	·130	·115
— 1	·120	·105	·095
0	·085	·080	·075
+ 1	·060	·055	·055
+ 2	·040	·040	·040
+ 3	·025	·025	·030
+ 4	·015	·015	·020
+ 5	·010	·010	·015

extent to which the attraction of the visible masses is neutralised by a compensation whose centre of effect lies at these depths. And finally in table No. 13 are given the effect of the two modifications to the hypothesis of simple support by flotation which were dealt with in table No. 10. Here again a reversal of the suppositions and an assumption of over-compensation of the range, or part of it, balanced by a corresponding under-compensation elsewhere, would hardly affect the numerical value of the correction but would reverse its sign. In either case the values given in table No. 13 must be added, algebraically, to those given in table No. 11 for the hypothesis of simple flotation.

TABLE 13.—*Gravitation effect of two suppositions of departure from a condition of support by simple flotation.*

Distance from southern edge of superelevated tract.	GRAVITATION EFFECT OF SUPPOSITION.	
	I	II
50	+ ·035	+ ·080
40	+ ·035	+ ·075
30	+ ·030	+ ·070
20	+ ·025	+ ·060
10	+ ·015	+ ·045
0	+ ·005	+ ·025
10	— ·005	+ ·010
20	— ·010	— ·005
30	— ·015	— ·015
40	— ·020	— ·020
50	— ·020	— ·025
60	— ·020	— ·025
70	— ·015	— ·025
80	— ·015	— ·025
90	— ·010	— ·020
100	— ·010	— ·015

The Gangetic trough will be treated in a manner similar to that adopted in the case of the range, and the effect calculated of an Imaginary Trough, or rather series of troughs of different forms and dimensions; but before this can be done it is necessary to determine what value will be adopted as representing the mean density of the material with which they are filled, and this can be determined within narrow limits. The mean density of the superficial deposits of the Gangetic plain is about 1·8, but the deeper layers have certainly a greater density than this; at the same time they can hardly attain a greater density than that of the Siwaliks, which are composed of the same materials and have been subjected to the pressure of superincumbent deposits, as well as to the induration due to age and the compression to which they have been subjected in the course of the upheaval of the Sub-Himalayas. This fixes the upper limit of density at 2·2 and the probable mean density must lie somewhere between the two, though nearer the higher than the lower limit. In my earlier investigations a density of 2·1 was accepted, or a deficiency of two-ninths of the mean density of the rock forming the floor and sides of the trough; later a slightly higher density was adopted, for convenience of calculation, and the deficiency put at two-tenths of the mean density of the rocky floor of the trough, representing a density of 2·16.

Doubts have been expressed[1] as to the reality of so great a difference in density between the material forming the Himalayas and that which fills the Gangetic trough, and especially it has been urged that the material in the lower layers of the trough would be compacted, by the pressure of the superincumbent material and the percolation of water holding carbonate of lime in solution, till the difference in density between it and ordinary rock would be negligible. These objections might be valid where depths of many miles are postulated, but, as will be seen further on, there is no need to suppose that the Gangetic trough is anywhere more than 20,000 ft. in depth, and as the Siwalik rocks, which have been subjected to the pressure of superincumbent deposits of about the same thickness, have an average density of only 2·2 or not much greater than the mean density assumed for the whole of the deposits in the Gangetic trough, of which the Siwalik rocks are the most dense, it is evident that the deficiency of two-tenths, corresponding to a mean density of 2·16, does not err on the side of being too high.

At first sight it might seem strange that there should be so great a difference between the density of the rocks forming the Himalayas and the material filling the Gangetic trough, seeing that the latter is the debris of the former, but all the denser minerals of the former have been decomposed, oxydised and hydrated, and the hard quartzites of the Himalayas broken up, to form the soft sandstones

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[1] S. G. Burrard, *Prof. Paper, Surv. Ind.*, No. 12, p. 4 and T. H. Holland, *B.A., Report* 1914, p. 355.

and loose sands, silts and clays of the Siwaliks and Gangetic trough. Now the softer sandstones, such as the New Red, used for building purposes, have a density of 2·1 to 2·2, and river sand or clay both about 1·9, and as these types of rock represent the material of which the contents of the Gangetic trough is composed, the difference between its density and that of the Himalayas is about what would be expected from the difference in composition and state of aggregation.

The effect of such a mass of lighter material, at stations outside the trough, is that the attraction towards one side is not counterbalanced by that towards the other, and the material filling the Gangetic trough would exercise an apparent repulsion, causing a northerly deflection at stations to the north, and a southerly at stations to the south, of it. Within the limits of the trough the effect would depend on the position of the station and on whether, and to what extent, the effect of that portion lying on one side of the station exceeded that of the portion lying on the other.

TABLE 14.—*Deflections due to troughs, 50 miles broad, of various sections; density ·8 of average rock.*

STATION.	DEPTH UNIFORM.		DEPTH VARYING FROM		
	10,000 feet.	15,000 feet.	15,000 to 10,000 feet.	0 to 10,000 feet.	0 to 15,000 feet.
— 10	0	0	0	0	0
— 9	0	0	— 1	0	0
— 8	— 1	— 1	— 1	— 1	— 1
— 7	— 1	— 2	— 2	— 1	— 1
— 6	— 2	— 3	— 2	— 1	— 2
— 5	— 3	— 4	— 3	— 2	— 3
— 4	— 3	— 5	— 4	— 2	— 3
— 3	— 4	— 6	— 5	— 3	— 4
— 2	— 5	— 8	— 7	— 3	— 5
— 1	— 8	— 11	— 10	— 6	— 8
0	— 19	— 27	— 24	— 16	— 21
+ 1	— 6	— 9	— 6	— 1	— 2
+ 2	— 2	— 3	0	+ 2	+ 4
+ 3	+ 2	+ 3	+ 5	+ 6	+ 8
+ 4	+ 6	+ 9	+ 9	+ 8	+ 10
+ 5	+ 19	+ 27	+ 21	+ 8	+ 11
+ 6	+ 8	+ 11	+ 9	+ 3	+ 5
+ 7	+ 5	+ 8	+ 6	+ 3	+ 4
+ 8	+ 4	+ 6	+ 5	+ 2	+ 3
+ 9	+ 3	+ 5	+ 4	+ 2	+ 2
+ 10	+ 3	+ 4	+ 3	+ 1	+ 2

The underground form of the trough cannot be determined by surface observation of a geological character, and the readiest means of applying the geodetic results to the solution of this problem appeared to be the calculation of the effect of a series of troughs of various forms and dimensions, by the combination of which a series of cross sections could be built up and the calculated compared with the observed results. This has been done in tables 14 to 16; in table No. 14 (page 54) a width of 50 miles is assumed and we have the deflections which would be produced if it had a uniform depth with vertical sides, if it had vertical sides and a floor sloping upwards from a depth of 15,000 ft. on the north side to 10,000 ft. at the south, and if it had a vertical side on the north and a floor sloping gradually upwards to the surface at the southern edge. Table No. 15 gives the deflections which would be produced by a trough 100 miles in width, of uniform depth, or with a vertical side

TABLE 15.—*Deflections due to a trough 100 miles broad of various sections; density ·8 of average rock.*

STATION.	UNIFORM DEPTH.		DEPTH VARYING FROM 0 TO	
	10,000 feet.	15,000 feet.	10,000 feet.	15,000 feet.
— 10	0	0	0	0
— 9	0	— 1	0	— 1
— 8	— 1	— 1	— 1	— 1
— 7	— 1	— 2	— 1	— 2
— 6	— 2	— 3	— 2	— 2
— 5	— 3	— 4	— 2	— 3
— 4	— 3	— 5	— 3	— 4
— 3	— 4	— 7	— 4	— 5
— 2	— 6	— 10	— 5	— 7
— 1	— 9	— 14	— 7	— 11
0	— 21	— 29	— 18	— 25
+ 1	— 9	— 13	— 5	— 7
+ 2	— 6	— 8	— 1	— 1
+ 3	— 3	— 5	+ 2	+ 2
+ 4	— 2	— 2	+ 3	+ 5
+ 5	0	0	+ 4	+ 6
+ 6	+ 2	+ 2	+ 5	+ 8
+ 7	+ 3	+ 5	+ 6	+ 8
+ 8	+ 6	+ 8	+ 6	+ 9
+ 9	+ 9	+ 13	+ 6	+ 9
+ 10	+ 21	+ 29	+ 6	+ 9

on the north and a floor sloping gradually upwards to the south. Table No. 16 gives the deflections due to a trough 200 miles in width,

TABLE 16.—*Deflections due to a trough 200 miles broad, 20,000 ft. deep diminishing to nothing; density ·8 of average rock.*

STATION.	DEFLECTION.	STATION.	DEFLECTION.
0	— 40	15	+ 8
1	— 14	16	+ 7
2	— 7	17	+ 7
3	— 3	18	+ 7
4	0	19	+ 7
5	+ 2	20	+ 6
6	+ 4	21	+ 3
7	+ 6	22	+ 2
8	+ 7	23	+ 1
9	+ 8	24	+ 1
10	+ 8	25	+ 1
11	+ 8	26	0
12	+ 8	27	0
13	+ 8	28	0
14	+ 8	29	0

with a vertical northern side 20,000 ft. in depth and the floor sloping gradually upwards to the surface; in this case the calculation is extended to a distance of 100 miles beyond the limit of the trough to indicate the rate at which the effect of such a trough would die out as the southern limit of the Gangetic alluvium is left. In every case the trough is supposed to run east and west, and the northern limit is assumed to coincide with the southern boundary of the range, or with station 0; this enables the effect to be conveniently stated in the tables, and by combination, with reversal where necessary, of two or more of the cross sections given in the table, an approximation to any cross section which need be considered can readily be built up. Further, although the deflections have only been calculated for certain depths of trough, they may be determined for other depths by interpolation or extrapolation, which will not introduce any material error, at any rate between the limits of 5,000 and 30,000 feet of maximum depth.

In these tables two features are noteworthy; one, that in every case we have a high northerly deflection at the foot of the hills, which decreases rapidly both northwards and southwards, but more rapidly in the latter direction, especially in the case of a floor sloping upwards to the south; the other that, at a distance from the edge of the hills which varies with the form of the floor, the northerly gives way to a southerly deflection which, in the case of a uniformly sloping floor, soon settles down to a value approximately proportionate to the amount of the slope, and nearly constant in amount right up to the southern limit, after which it rapidly diminishes and becomes negligible at stations more than 30 miles beyond the boundary.

The figures given in the tables are all based on the assumption that the defect in density of the material filling the trough is not compensated. It is by no means certain that a structural feature like this would have a separate compensation of its own, apart from the general compensation of the surface-relief, but it is not unreasonable to suppose that a defect of density, and consequently of weight, which may amount to the equivalent of 3,000 ft., or more, of average rock and having a horizontal extent of many hundreds of miles, would be compensated in the same way as a corresponding irregularity in the surface of a region composed of average rock.

The amount of the correction which would be introduced in this way has not been calculated in every case, but in the case of a trough 100 miles in width and 15,000 ft. in depth at the northern edge, diminishing to nothing at the southern, the deflections, supposed to be compensated according to the Hayford tables, would be as shown in table No. 17 (page 58) where the values, if compensation is not considered, are repeated from table No. 15, for comparison. It will be seen from this that the character of the curve of variation in deflection is not materially altered, but the reduction of effect beyond the limits of the trough is more rapid than when compensation is not considered; the deflections within the limits of the trough are reduced by about one-fifth at the deep northern edge, and by nearly one half in the southern portion of the trough, while they are practically unaffected in that part where the effects in opposite directions nearly balance each other. The general effect of introducing the consideration of compensation would be to increase the estimate of the maximum depth by about one quarter at the northern edge, and of the slope of the floor of the trough, near the southern, by about four-fifths; consequently, deflections which would give a maximum depth of 15,000 ft. and a uniform slope of the floor, if regarded as due to the effect of the trough without compensation, would give a maximum depth of about 18,000 ft. at the north and a slope of about 270 ft. to the mile in the

TABLE 17.—*Deflections due to a trough 100 miles broad, 15,000 ft. deep at the northern, diminishing to nothing at the southern, edge, supposed to be (I) uncompensated (II) compensated according to the Hayford tables for uniform compensation to depth 113·7 km.*

STATION.	DEFLECTIONS.	
No.	Uncompensated.	Compensated.
— 5	— 3	— 1
— 4	— 4	— 1
— 3	— 5	— 2
— 2	— 7	— 3
— 1	— 11	— 6
0	— 25	— 20
+ 1	— 7	— 4
+ 2	— 1	0
+ 3	+ 2	+ 2
+ 4	+ 5	+ 3
+ 5	+ 6	+ 4
+ 6	+ 8	+ 4
+ 7	+ 8	+ 5
+ 8	+ 9	+ 5
+ 9	+ 9	+ 5
+ 10	+ 9	+ 5
+ 11	+ 5	+ 2
+ 12	+ 3	+ 1
+ 13	+ 2	+ 1
+ 14	+ 1	0
+ 15	+ 1	0

southern part of the trough, and, therefore, would necessitate a cross-section whose floor did not have a uniform slope, but would

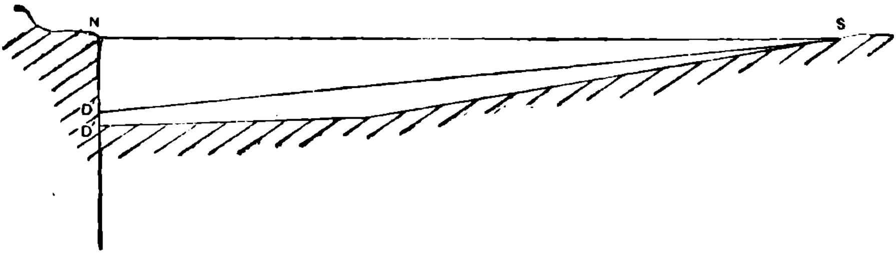

FIG. 5.—Showing the effect of separate compensation of the trough on the interpretation of the deflections. If NDS represents the cross section which would be indicated if there were no separate compensation, then ND'S represents the interpretation if compensation is considered.

need to carry the depth at the northern limit outwards at a lesser, and then upwards at a steeper slope to the southern margin as is shown in fig. 5 (page 58). From this it will be seen that the effect of introducing the concept of compensation would not materially alter the conclusions drawn from the observations if it is not considered; the exclusion of compensation would merely reduce the depth by about one quarter in the deeper and by nearly one half in the shallower southern part of the trough, and slightly modify the general form of the cross section.

The gravitational effect of the alluvium is easily dealt with; the anomaly having been calculated on the assumption that the whole of the alluvium consisted of average rock, there would be, apart from other causes, an apparent defect of gravity, due to the diminished attraction of the alluvium, whose density is only about four-fifths of the rock by which it was assumed to be replaced. As a layer of average rock of indefinite extent exerts an attractive force equivalent to ·0033 dyne for each one hundred feet of thickness, it follows that the gravitation effect of a depth of 15,000 ft. of alluvium, of sufficient extent, would exert an effect of — ·100 dyne. If the boundary of this trough were vertical the effect at the boundary would be exactly half this value, and at intermediate distances the effect would be as shown in table No. 18.

TABLE 18.—*Gravitational effect of the defect in density of a vertical-sided trough of alluvium, 15,000 ft. in depth, and density ·8 of average rock. All values negative and expressed in dynes.*

STATION.	DEFECT OF GRAVITY.
— 5	·000
— 4	·001
— 3	·002
— 2	·003
— 1	·005
— ·5	·011
0	·050
+ ·5	·089
+ 1	·095
+ 2	·097
+ 3	·099
+ 4	·100
+ 5	·100

An examination of this table shows that the effect of the limitation of the trough is barely noticeable at distances of over ten miles from the edge, and even at a distance of only five miles it has still nearly nine-tenths of the value which it would have at an infinite distance. Put differently, we may conclude that eighty per cent. of the total effect of a great expanse of alluvium, having a depth of 15,000 feet, is exerted by that portion which lies under a circle of five miles radius from the station, and ninety per cent. by that which lies within a distance of ten miles. As the limitation is even closer with a lesser depth, it follows that we may leave the effect of more distant alluvium out of consideration and, except close to the main boundary, regard the effect of the alluvium as directly proportionate to its depth under the station and as amounting to about ·006 dyne for each 1,000 feet of depth.

As in the case of the deflections, the effect of the trough may be subject to modification, if the invisible defect of density is compensated in the same way as a corresponding irregularity of the surface. The effect of this modification would be to diminish the negative attraction of the trough, and a calculation for the case of a trough 100 miles in width with a maximum depth of 15,000 feet at the northern limit, diminishing regularly to nothing at the southern, showed that the effect, using Mr. Hayford's tables, would be—

at the northern edge	+ ·013 dyne
at 35 miles from the northern edge	+ ·037 ,,
,, ,, ,, southern ,, ...	+ ·024 ,,
at the southern edge	+ ·014 ,,

and for comparison with these figures the uncompensated effect of the same trough may be given ; it would be

at the northern edge	— ·100 dyne
at 35 miles from the northern edge	— ·067 ,,
,, ,, ,, ,, southern ,, ...	— ·033 ,,
at the southern edge	·000 ,,

The effect of the compensation, it will be seen, is not proportional to the depth of the trough under the station of observation on account of the depth of the centre of compensation, which makes the effect felt to a greater distance than that of the trough itself. The modification in the conclusions drawn, if compensation is not considered, would be least at the northern edge of the trough, and would lead to the depth being under-estimated; this modification would increase in amount in a southerly direction and at about 20 miles from the southern edge, the negative effect of the trough would be neutralised; still further south the effect of the compensation would outweigh that of the trough and produce a small positive effect on the force of gravity.

Calculations were not made for other sections and dimensions of the trough, as an estimate, sufficiently accurate for the purpose of this investigation, may be made for any section of trough which will have to be considered, and, besides, there is the uncertainty of whether the trough should be considered as having a separate compensation of its own.

One more condition must be considered; besides the possibility of the separate compensation of the trough there is the possibility that its origin is due to a depression of the crust into, or a subsidence of the crust due to a removal of, the denser material below. In either case there would be a replacement of denser by less dense material of the same shape and form as the trough itself, but situated at some depth below it, as is illustrated in fig. 6.

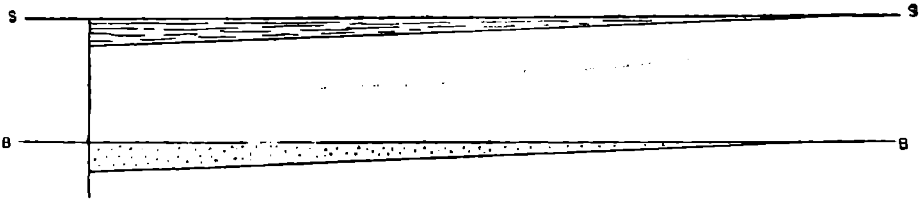

Fig. 6.

An hypothesis of this form has actually been investigated by Mr. O. Fisher, [1] who supposed the depression of the Gangetic trough to be due to a bending down of the earth's crust in partial support of the weight of the mountain range, but the same result might be brought about in other ways. On any form of hypothesis, which involves an isostasy and support of the range by flotation, it is conceivable that the support might not be completed under the range itself, but partly transferred to the crust on either side, with the consequence of an equal displacement of the denser material under the crust by the lighter material of the crust itself. The bearing

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[1] *Phil. Mag.*, Jan. 1904, pp. 14-25.

of this hypothesis on the support of the Himalayas will be dealt with further on; here its effect on the observations in the region of the alluvial plain will alone be considered.

To begin with, it is evident that no question of separate compensation of the trough need be introduced, as it would be merged in the general compensation of the range and trough combined, and we need only take into consideration the effect of the deficient density of the alluvium filling the superficial depression, and of the buoyancy of the corresponding depression of the lower surface of the crust. For the purpose of calculation the two will be assumed to be of equal dimensions, with a depth of 20,000 feet at the edge of the hills and a width of 200 miles; corresponding approximately to the dimensions of the Gangetic trough in the region of its greatest development. The thickness of the crust will be taken as 25 miles, and the difference in density between it and the underlying material as one-tenth of the density of the crust, so that each 10 feet of depression has a buoyancy to support the weight of a thickness of 1 foot of rock.[1]

Taking these constants, and considering the deflection of the plumb-line first, the effect of the depression of the under side of the crust, expressed to the nearest whole second of arc, would be

at the northern edge	— 4″
„ middle	+ 2″
„ southern edge	+ 1″

The effect of the corresponding depression on the upper side of the trough, supposed to be filled with alluvium, would be

at the northern edge	— 40″
„ middle	+ 8″
„ southern edge	+ 6″

The general character of the deflections is, therefore, similar in both cases, but whereas the change from northerly to southerly deflection takes place at about forty miles from the northern edge, in the alluvial trough, the northerly deflections produced by the depressed under-surface of the crust would extend for fully fifty miles, before the southerly deflections set in. At the extreme

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[1] This difference is slightly less than that adopted by Mr. Fisher (*Physics of the Earth's Crust*, 2nd ed., p. 168), which gives a ratio of 1 : 9·57. The difference is trivial and as that adopted by Mr. Fisher is, if anything, a little too great, the simpler ratio has been adopted to ease calculation.

northern edge it will be seen that the depressed tract gives a deflection which is only one-tenth of that due to the alluvial trough, but the latter drops in value much more rapidly in amount than the former, and in the central and southern portions of the trough, where all but a very few of the stations are situated, the effect of the depressed lower surface of the crust ranges from one quarter to one-sixth of the effect of the alluvial trough on the upper surface, if the two are supposed to be of equal dimensions.

In one respect this is not likely to be the case, for the boundary of the alluvium does not mark the limit of the depression. To the south of the alluvial boundary the general level of the country continues to rise for some distance and, if the origin of the trough is that assumed by the hypothesis just considered, the width of the depressed lower portion of the crust must be taken at 250 to 300 miles. In this case the effect near the centre of the alluvial area would be reduced by from one-quarter to one-third, and the effect at the southern limit of the alluvium increased in about the same proportion; the effect, therefore, of the depressed lower portion of the crust may be taken as round about one-fifth of the effect of the alluvial trough over the greater part of the plain. Only in the northern part of the alluvium, for a distance of at most 60 miles from the northern edge, would the ratio of the two separate effects differ materially from this proportion, and it is just in this region that the deflections give the least satisfactory and certain indications of the form of the floor of the trough.

The effect of the depressed lower portion of the crust on the force of gravity at the surface may be simply and easily expressed, with sufficient accuracy for present purposes. The defect in mass of the depressed lower portion of the crust is ·1 of the whole, that of the alluvial trough is ·2, the defect in attractive power is therefore one half as great in the one case as in the other; but besides this we have to take into consideration the effect of the greater distance from the surface in the former case, which will have the effect of diminishing the apical angle of the cone covering two circles of the same radius. Taking this radius at 100 miles, and it is needless to take a larger radius seeing that the trough is only 200 miles broad, we find that a disc of the lower surface of the crust would produce an effect of ·76 of the amount which a disc of the same total mass would produce at the surface; and as the mass is taken at one-half, the ratio of the effect of the alluvial trough to that of the depressed lower portion of the crust is as 1·0 to 0·4, except near the northern margin where, in the last thirty miles or so, it falls to about ·3 of the effect produced by the trough.

The figures which have been calculated for the particular dimensions of trough considered, apply with proportionate variation to any other dimensions of a trough of similar form, and the ratio, between the effect of the superficial trough and of the depressed lower surface of the crust, would not be materially altered. We may, therefore, apply the results obtained to the conclusions, drawn from observation, and find that the depth of the trough, deduced from the deflections on the assumption that the whole effect is due to it alone, would have to be reduced by about 14 to 20 per cent., if the total effect is resolved into its two components, and that the reduction would have to be about 28 per cent. in the case of the gravity observations; but apart from this there would be no material alteration in the general form of the trough. Consequently the adoption of this hypothesis of origin of the trough would not lead to any modification in the conclusions drawn as to the general form of the trough, though it would lead to a reduction in the estimated depth of the alluvium by somewhere about one quarter, at most, of the estimate which would be formed if the whole effect was attributed to the trough alone.

CHAPTER IV.

THE UNDERGROUND FORM OF THE FLOOR OF THE GANGETIC TROUGH.

The latitude stations on the Gangetic alluvium are ranged across the plain in four series running north and south, and a more scattered group in the Punjab. Of these five series, only two are complete, in the sense that they are continued across the northern boundary of the alluvium into the region of the Himalayas, but it will be more convenient to begin with another series, which forms a remarkably complete series, extending from the northern boundary of the alluvium across the plain, and into the Peninsular rock area to the south, in the neighbourhood of the 81° meridian of east longitude.

TABLE 19.—*Latitude Stations near 81° Longitude.*

STATION.	Distance from N. and S. boundaries of the alluvium.	Calculated Deflections.		Observed Deflections.
		I	II	
Manichauk	14 — 176	— 13	— 13	— 15
Pathardi	14 — 168	— 13	— 13	— 15
Ghaus	16 — 156	— 12	— 12	— 13
Basadela	20 — 156	— 10	— 9	— 9
Dadawra	16 — 180	— 12	— 12	— 11
Ramuapur	24 — 200	— 7	— 6	— 7
Masi	32 — 164	— 2	— 3	— 6
Jarura	48 — 160	+ 2	+ 2	— 2
Imlia	60 — 160	+ 6	+ 7	+ 3
Nimkar	80 — 130	+ 8	+ 9	+ 4
Utiaman	80 — 140	+ 8	+ 9	+ 9
Etora	96 — 114	+ 9	+ 10	+ 9
Parewa	96 — 114	+ 9	+ 10	+ 11
Sora	110 — 96	+ 10	+ 10	+ 12
Pariaon	140 — 48	+ 10	+ 10	+ *10*
Dewarsan	144 — 80	+ 10	+ 9	+ 9
Kanakhera	164 — 40	+ 10	+ 9	+ 9
Pavia	180 — 16	+ 9	+ 9	+ 8
Potenda	40 S.	+ 1	+ 1	+ 6
Karara	76 ,,	0	0	+ 4
Amua	88 ,,	0	0	+ 5

A list of these stations is given in table No. 19 (page 65) with the addition of four stations, ranged along the northern fringe of the alluvium to the eastwards of the meridional series. It is in no case possible to measure the exact distance of any of these stations from the main boundary, as this runs through Nepal territory to the north of this section, but the distance from the outer edge of the hills can be determined with sufficient accuracy, and a comparison of the section at the western end of Nepal with that along the road to Khatmandu, shows that the width of the Siwalik tract is probably about 20 miles, so that the main boundary may be taken as lying at that distance from the outer edge of the hills and, where it needs to be taken into consideration, this must be added to the distance of each station from the outer edge of the hills as given in the table No. 19. In this table are also given the distances from the southern boundary of the alluvium, the figures in each case being approximate and measured to the boundaries of the alluvium as drawn on the general geological map of India on the scale of 32 miles to the inch.

The deflection, actually observed at each station, is given, to the nearest whole second, in the last column of the table, and the first thing to be noticed is the presence of a considerable southerly deflection at the stations beyond the alluvium to the south. The distances of these stations from the boundary are too great for the deflections to be attributable to the effect of the alluvial trough, and we may look for their cause in the " hidden range " or belt of underground excess of density which has been found to exist in the northern part of the Peninsula.

Turning to the stations on the alluvium, and comparing the observed values with the calculated deflections given in tables 14 to 16, we see that, so far as the southern half of the section is concerned, they indicate a trough deepening steadily from south to north at about 130 ft. to the mile, and that this slope is continuous for over 100 miles from the southern edge, so that in this way we reach an estimated depth of over 13,000 and probably about 15,000 feet. The northern part of the section gave more trouble, for here the effect of the Himalayas, which is negligible at the southern stations, becomes considerable. As it was impossible to calculate the effect of the actual topography at each station it seemed best to assume that the effect would not be very different from that of the Imaginary Range, allowing for Hayford compensation, at a station situated at a corresponding distance, reckoned from the main boundary; at the stations nearest to the hills a small additional correction was included, for the effect of the attraction of the foot-hills of the Sub-Himalayan region. The figure allowed in this way, for the effect of the attraction of the Himalayas, is a little less than the reality, but the difference would not exceed one second of arc, or at most a couple, at any of the first six stations, included in the table No. 19, and is negligible at the rest.[1]

Allowing for this effect, a first attempt at calculation, on the supposition that the slope of the floor of the trough continued regularly up to the main boundary, showed that this would give too small northerly deflections at the northern stations, nor were matters much improved by supposing that the maximum depth was continued outwards from the main boundary for some considerable fraction of the width of the trough, before the upward slope commenced. It became evident, therefore, that the maximum depth of the trough could not be at the northern edge, but must be somewhere out towards the centre, though nearer to the northern than the southern edge; a supposition was accordingly adopted, that the trough had a depth of 15,000 feet at the main boundary, increasing to 20,000 feet at 50 miles away and then decreasing to nothing in 150 miles. The result of this calculation is given in the column headed I, but at a later period, when the study of other sections had revealed a possibility that the trough attains its greatest depth close to the outer edge of the visible hills, another assumption was made, that the maximum depth was 25,000 feet at the outer edge of the hills, that the floor sloped regularly upwards from this to the southern edge of the plain, and on the north rose abruptly upwards to a depth of 20,000 feet diminishing to 15,000 feet at the main boundary. The result of this supposition is given in the column headed II.

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[1] We have a check on the correctness of method of arriving at the allowance to be made for the effect of the trough, and any other invisible influence, in Major Crosthwait's calculation of the residuals at Pathardi and Nimkar. On the same basis of reference as is here used in the text, the residuals, after allowing for the effect of visible topography and its compensation, are —12″ and +5″ respectively, the values derived by using the Imaginary Range were —9″ and +4″. The use of the Bessel-Clarke spheroid would introduce a change of 1″ in the values of the residuals. Evidently the Imaginary Range gives a larger deflection than the actual topography of this part of the actual range, but it must be remembered that the Himalayas in Nepal territory are quite unsurveyed.

Comparing the calculated with the observed deflections, it will be noticed that either supposition gives results which are in very fair agreement with reality; only in the stations from Masi to Nimkar is there any considerable irregularity, but these stations are situated in the tract where northerly are passing into southerly deflections, and where a small variation in the assumed form of the trough would lead to considerable changes in the calculated deflections. Apart from this, the general course of the variation, as well as the actual values, of the calculated and the observed deflections are in very good agreement; at the northern stations the calculated deflections are in slight defect, and the same is true of the stations in the southern half of the section, but the former of these is easily accounted for by the probable excess of the northerly attraction of the Himalayas over that allowed for in the calculations, or both the deficiencies could be eliminated by assuming a rather greater depth of the trough, but no real benefit would accrue from any attempt at obtaining a closer agreement between calculation and observation.

This study of one of the groups of latitude stations serves to illustrate at once the method which will be followed, and the limitations of any attempt to derive geological information from geodetic observations. The method, though differing in form, is essentially the same as that adopted in geodetic work; a certain assumption is made, calculation is made on that basis and the results of calculation and observation compared, another assumption is then made and fresh calculations made until the average difference between the calculated and observed values of the deflection is reduced to the smallest amount. In geodetic work proper the closeness of agreement is tested by comparing the sum of the squares of the individual differences, and adopting the supposition which gives the smallest value to this sum, as the one which most closely approaches the average conditions. This method is the only oneadmissible where a large number of observations, extending over a large area, have to be dealt with; it is not only unnecessary, but would give a wholly illusory appearance of precision, if applied to a limited number of observations, and to the extraction of the information for which we are in quest.

Here we must start with those conditions which represent a near approach to the average, and apply to them a correction for local departure from the average, in this case represented by the defect of density in the Gangetic trough, and it will be seen that either of the suppositions considered in table No. 19, if combined with the average conditions assumed in calculating the observed deflections, would largely reduce the differences between the calculated and observed values. They may therefore be regarded as approximations to the actual form of the trough, but it is not possible to obtain a closer approximation, with any degree of certainty, owing to the uncertainty in which we are as to the density of the alluvium in the lower layers of the deposit, as to the nature and extent of the separate compensation of the trough, and as to the presence and character of any independent cause which would affect the direction of the plumb-line. The effect of the last two elements of uncertainty has been dealt with in the last chapter, and need not be enlarged on here. With regard to the possible increase in density of the lower layers of the alluvium, the depth, indicated by the observations, of 20,000 to 25,000 feet, even if allowance is made for the possible increase due to a separate compensation, is not so great as to necessitate or suggest a condensation of the sands and clays of which the alluvium is composed to a much greater density than the 2·16 which was assumed as the mean density of the deposit, and against this must be placed the fact that the upper layers have certainly a considerably lower density than that assumed as the mean of the whole deposit.

Allowing for all these possible modifications of the conclusions come to if the whole of the deflections, so far as they are not accounted for by the visible topography, are due to the alluvial trough, the fact remains, that the published deflections agree so well with those which should result from a cross section and dimensions of the trough which are in accord with those suggested by a wholly independent line of research, as to render it probable that this is the preponderating, if not the sole, influence at work; and we reach the conclusion that the maximum depth of the trough lies at, or a little south of, the edge of the hills and need not exceed about 25,000 feet; it can hardly be less than 20,000 and is not likely to exceed 30,000 feet, so far as the indications of this group of latitude stations are concerned.

The northern part of the section, which was not represented in the group just considered, is covered, further west, by a very complete group of stations in and around the Dehra Dun; it will, however, be best to defer the consideration of these observations and confine attention to the southerly continuation of the series, across the alluvial plain. This series forms a double line of stations stretching across the alluvium and ranged on either side of the 78° meridian, which will be most conveniently treated as two separate series and are given in the table No. 20 in two columns,

TABLE 20.—*Latitude Stations near 78° Longitude.*

STATION.	Distance from Main Boundary.	Observed Deflections.		Deflections due to the Range.
Sarkara	32		—8	—6
Nojli	38	—10		—5
Sirsa	56		—5	—2
Kaliana	58	—3		—2
Bansgopal	76		—1	—1
Datairi	92	—2		
Bostan	104	—1		
Sankrao	108		+4	
Chandaos	124	+3		
Salimpur	124		+4	
Noh	144	+4		
Agra	168	—1		
Usira	200	—2		
Gurmi	200		+6	
Majhar			+7	
Kesri		+10		
Algi			+6	
Pahargarh		+4		

of which the left hand one includes the western, and the right hand one the eastern, stations; the actual deflections are given, and in the last column the amount of deflection attributed to the attraction of the Himalayas. For two of the stations in this series, Kaliana and Bansgopal, Major Crosthwait has calculated the effect of the visible topography, of which the Himalayas form all but a small proportion, and obtained a deflection of —3″ at Kaliana, as against —2″ in the table: at Bansgopal the agreement is complete.

The eastern stations are situated well out in the alluvial plain and exhibit much the same features as the series near the 81° meridian. The point of passage from the northerly to southerly deflections lies at about 70 miles from the main boundary, a somewhat greater distance out from the edge of the hills than in the series just dealt with. The southerly deflections at the stations further south are smaller in amount than further east, but it must be borne in mind that this series of stations lies not far from where the general course of the boundary of the alluvium runs about north-north-west; the deflections due to the trough would, therefore, be more nearly east and west than north and south and the component in the meridian, which is that measured by latitude observations, is necessarily reduced in amount. Still further south larger deflections come in, but here the effect is partly, and probably mainly, due to the southerly deflections in this part of the peninsular area, with which we are not here concerned.

The western series exhibits some peculiarities which it is not easy to explain, though they are doubtless connected with the narrowing of the alluvial area on the continuation of the line of the Aravalli hills. The northerly deflection is maintained for a distance of a hundred miles from the main boundary, and only beyond this distance does a small southerly deflection come in at a couple of the stations in the alluvium. Then, we have the northerly deflections at Agra, and further south the southerly deflections of the northern peninsular area. It is evident that on this section there are other influences at work counteracting the effect of the trough; or, in other words, that the trough is of smaller dimensions than further east, and no longer has that preponderating effect which was there met with, and it is noteworthy that the stations of Datairi and Bostan, where the northerly deflections show that there is no regular shallowing of the alluvium in a southerly direction, or that it is insignificant in amount, are situated on the direct continuation of the line of the main range of the Aravallis, which may reasonably be expected to continue under the alluvium with much the same surface contour as they show further south.

A third series of latitude stations is situated near the 85° meridian but does not extend across the alluvium, and in its southern portion is affected by some local cause leading to abnormal deflections. In spite of these drawbacks the series gives some information and needs notice. A list of the stations is given in table No. 21 ranged in order of distance from the outer edge of the

TABLE 21.—*Latitude Stations near 85° Longitude.*

STATION.	Distance from edge of Hills.	Observed Deflections.
Pahladpur	60	+ 10
Jalapur	72	+ 10
Dubauli	96	+ 11
Nuaon	110	+ 12
Mednipur	140	+ 12
Bihar		+ 17
Mahar		+ 14
Teona		+ 15
Hurilaong		+ 15
Chendwar		+ 7
Bulbul		+ 13
Mahwari		+ 8

Himalayas, so far as the stations within the alluvial plain are concerned, and in order of latitude in the case of those situated on rock to the south of the alluvial plain. The alluvium here is about 150 miles in width, and, on the road section to Khatmandu, the main boundary lies about 24 miles from the outer edge of the hills; the total width of the Gangetic trough is, therefore, about 170 miles. The southern boundary of the alluvium exhibits a peculiarity in this region which, as will be seen, may not be without influence on the deflections of the plumb-line at stations near its southern boundary; just at the 84° meridian the boundary turns nearly due southwards to the line of the Son River, and eastwards of this numerous outliers of rock rise through the alluvium between the main continuous rock area and a line running about E. N. E., on the continuation of the line of the Son Valley. Over this area the alluvium, between the hills rising from it, is probably nowhere of great depth, and the region as a whole should be included in the rock, rather than the alluvial, area. One station, Bihar, is situated on a small outlier, which is the last visible towards the continuous alluvial plain, another, Teona, is close to the line where it approaches the N-S stretch of the boundary, and a third, Mahar, is on a hill about 15 miles from the line bounding this archipelago of inliers.

Turning to the consideration of the deflections we find that the stations of the alluvial plain show southerly deflections of about 12″; the most northerly is about 60 miles from the outer edge of the hills and probably about 80 from the main boundary. This group of stations indicates an upward slope of the floor of the trough at about 200 feet per mile, or a little less, which would correspond to a maximum depth of about 20,000 feet, and so far the observations accord with what was found further west. The southern part of the section, however, shows some remarkably anomalous features; instead of a decrease of southerly deflections at, and beyond, the southern limit of the trough, we find the very high southerly deflection of 17″ at Bihar and at Teona of 15″. It might be possible to explain these deflections by the effect of the alluvium alone, if we assumed that the upward slope of the floor of the trough was not continuous to the southern margin, but ended in an abrupt rise of some 1,500 to 2,000 feet, an explanation which is not geologically impossible, for the boundary of the rock area, between Teona and Bihar, lies on the continuation of the Son Valley, the line of flexure marking the boundary between an area of elevation, to the south, and of depression, to the north. This structural feature is of great geological age, but it is not impossibly continued under the alluvium to beyond Bihar, and movement may have taken place along it during the formation of the Gangetic trough.

Though not impossible, this explanation is decidedly improbable, even if looked at from a geological point of view alone; regarded as an explanation of the high southerly deflections at Bihar and Teona it might be sufficient, it might even suffice for that found at Mahar, but it fails altogether when the southern stations are considered. Hurilaong, for instance, gives a deflection of 15″, but if the 17″ at Bihar were entirely due to the alluvium, the deflection at Hurilaong should not exceed 4″, at Bulbul 2″ and at Chendwar and Mahwari less than a second; even at Mahar it would take some forcing of the hypothesis to get a deflection of more than 10″. It is evident, therefore, that something besides the alluvium is at work, and that we are within the range of influence of an excess of density, in the rock area to the south of Bihar.

The high southerly deflection at Bihar is, therefore, made up of two parts, of which some 9″ or 10″ may be attributed to the effect of the trough and the remainder to some other cause, such as an underground excess of density to the south. At the stations north of Bihar the effect of this last-named cause must be small; it may be felt, to the extent of a couple of seconds or so, at Mednipur, Nuaon, and possibly Dubauli, but at the stations further north it can have no appreciable effect, and the observed deflections may be ascribed principally, if not wholly, to the effect of the Gangetic trough.

The easternmost group of latitude stations is ranged near 88° of longitude; in table No. 22 a list of those which lie in or near the alluvial plain is given, ranged from north to south. In deciding on the assumption to be made in calculating the deflections which should be expected we encounter the difficulty that, owing to the absence of a belt of foot-hills corresponding to the Siwaliks, it is impossible to form any direct estimate of the depth of the trough next the hills. The gravity determinations, as will be seen, indicate that this is not materially different from the depth in the Dehra Dun region, and so we may take it at about 15,000 feet; the width is less easily determinable, as, though the alluvium extends continuously to the sea-face of the Gangetic delta, the real boundary of the trough probably lies on a line connecting the northern end of the Rajmahal Hills with the western end of the Garo Hills. Here, as has already been mentioned, there is some geological ground for supposing the existence of a ridge of rock, covered by a comparatively shallow layer of alluvium, the crest of which might lie about 20 miles north of Charaldanga,

TABLE 22.—*Latitude Stations near 88° Longitude.*

STATION.	Distance from Main Boundary (in miles).	Calculated Deflections.	Observed Deflections.
Kurseong . . .	4 N.	—44	—46
Siliguri	12 S.	—19	—18
Jalpaiguri . . .	30 „	— 2	— 2
Lohagara . . .	52 „	+ 5	+ 6
Chanduria . . .	76 „	+ 7	+ 8
Charaldanga . . .	120 „	+ 1	+ 5
Madhupur . . .			+ 8

or about 100 miles south of the main boundary, but would probably be more nearly under that station. It will, consequently, be convenient to assume a width of 100 miles and a maximum depth of 15,000 feet for the trough in this region, and the deflections which should result from the effect of such a trough, combined with the effect of the Imaginary Range, are shown in the table.

So far as the stations from the north down to Chanduria are concerned the agreement is very close, and the correctness of the method of calculation is confirmed by Major Crosthwait's calculations which give residuals, after allowing for the effect of visible topography and its compensation, of — 7″ at Siliguri, + 6″ at Jalpaiguri, and + 10″ at Chanduria, as compared with deflections of — 5″ + 3″ and + 8″ allowed for the effect of the assumed trough in obtaining the figures of table 22. Southwards of Chanduria there is a considerable discrepancy at Charaldanga, but here it must be remembered that the width assumed for the trough was only 100 miles; if the width is taken at 120 miles, the southerly deflection at Charaldanga would be increased to about 5″, provided that the effect of the alluvium to the south was small, and this is not an improbable supposition.

The large southerly deflection at Madhupur, which is continued, though in lesser amount at Calcutta, may well be due to another cause than the effect of the alluvium. These stations lie in a region where the geological structure, confirmed, as will be seen further on, by the gravity observations, indicates that the depth of the alluvium is probably small, and that we are outside the limit of the Gangetic trough proper. At Calcutta a boring, which reached a depth of 481 feet, met with deposits indicating the proximity of a rock area, and it is probable that, over the tract separating the Peninsula from the Assam Hills, the depth of the alluvium is to be measured by hundreds, rather than thousands, of feet, so that it can have little effect, either on the deflection of the plumb-line or the force of gravity. We must, in fact, regard this area as belonging, so far as deep-seated structure is concerned, to the Peninsular area, and not to the Gangetic trough.

At the stations north of Charaldanga the deflections are sufficiently accounted for on the supposition of a trough shallowing from a depth of about 15,000 feet near the hills to a shallow depth of alluvium at about a hundred and twenty miles to the south of them, and the conclusion may be drawn that the southern boundary of the deep trough sweeps across, under the alluvium of the Ganges and Brahmaputra rivers, in an easterly or north-easterly direction from the point where its course ceases to be defined by the boundary between rock and alluvium. Whether the trough extends up the valley of the Brahmaputra cannot at present be decided; the geological evidence of the rocky hills in the alluvium, and the structural analogy which exists between the Assam Hills and the Salt Range, at opposite ends of the Himalayas, both suggest that the deep trough does not extend up the valley of the Brahmaputra, and this conclusion is to a certain extent borne out by the easterly deflection of the plumb-line at Jalpaiguri.

At this station Major Crosthwait's calculations show that the effect of the visible topography and its compensation should produce no deflection in either direction, yet observation shows that there is an easterly deflection amounting to 18″ or 13″, according to the Everest and the Bessel-Clarke spheroids, respectively. As this deflection is not due to visible topography we must look to some underground cause, of which a very probable one is to be found in the fact that the station lies near the eastern limit of the Gangetic trough, if this is presumed not to extend up the Brahmaputra Valley. In this case there would be the whole of the trough to the west of the station, unbalanced by any similar extension on the east, and so an easterly deflection would be produced. The magnitude of this deflection is greater than anything met with in the southern part of the trough, further west, and indicates an upward slope, of the bed of the trough, which may amount to as much as 300 to 400 feet per mile, or about 4° of arc, if the whole of the deflection is due to the effect of the trough.

The gravity observations in the alluvial plains have been dealt with by Dr. H. H. Hayden,[1] who showed that they indicated a gradual shallowing of the trough in a southward direction, but it will be well to review the more complete evidence, which is now available. In table No. 23 (page 77) a list of the gravity stations in the region of the Gangetic trough is given, arranged in three natural groups; the first a series ranged from north to south, along the 78° meridian; the second, a more extended group, covers the central portion of the trough, where it reaches its maximum development; and the third ranged along the 88° meridian. The

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[1] *Rec., Geol. Surv. Ind.*, XLIII, 163-167 (1913).

TABLE 23.—*Gravity Stations in the Gangetic alluvium.*

STATION.	Approximate distance from north and south boundary of alluvium.	Bouguer anomaly for height and mass.	Hayford compensation of the Imaginary Range.	Resulting thickness of the alluvium.	Thickness of the alluvium deduced from Hayford anomaly.
Roorkee	10 :	— ·107	— ·020	13,000	9,500
Nojli	30 :	— ·095	— ·014	12,000	..
Kaliana	40 :	— ·058	— ·008	7,500	4,000
Meerut	70 : 30	— ·027	..	4,000	2,500
Khurja	100 : 30	— ·042	..	6,500	5,500
Gesupur	100 : 10	— ·020	..	3,000	2,000
Aligarh	120 : 40	— ·026	..	4,000	4,000
Hathras	130 : 30	— ·006	..	1,000	1,500
Muttra	150 : 10	000	..	0	1,000
Agra	170 : 0	— ·004	..	500	500
Gorakhpur	50 : 120	— ·101	..	15,000	13,500
Majhauli Raj	60 : 100	— ·079	..	12,000	12,000
Muzaffarpur	60 : 70	— ·061	..	9,000	9,000
Sultanpur	100 : 70	— ·040	..	6,000	..
Arrah	100 : 50	— ·083	..	5,500	7,000
Buxar	110 : 40	— ·023	..	3,500	5,000
Moghalsarai	150 : 20	— ·013	..	2,000	2,500
Allahabad	160 : 20	+ ·002	..	0	..
Sasaram	150 : 0	— ·002	..	0	2,000
Siliguri	10 :	— ·137	— ·045	14,000	9,000
Jalpaiguri	30 :	— ·096	— ·020	11,500	6,000
Kesarbari	50 :	— ·043	— ·008	5,000	..
Ramchandpur	80 :	+ ·001	..	0	..

first column of the table gives the name of the station, the second the approximate distance from the northern and southern boundaries of that portion of the Gangetic trough which is covered by the Gangetic alluvium. These distances, consequently, differ from those used elsewhere, which are measured from the main boundary on the north, the difference being due to the fact that the position of the main boundary is uncertain for a large portion of its course, where it runs through the territory of Nepal, and partly to the fact, which will appear further on, that the northern boundary of the alluvium marks a distinct break in the floor of the trough, in that portion of the range where the Siwalik region, the foothills of the Sub-Himalaya, is distinctly developed. On the south the distances are measured from the boundary of the trough proper, so far as it can be inferred from surface observations, excluding the spreads of, presumably shallow, alluvium with inliers of rock rising from it, which belong more properly to the rock area of the Peninsula than to the Gangetic alluvium. The third column of the table gives the Bouguer anomaly, or the difference between the observed value of gravity at the station and the theoretical value, after allowing for the effect of latitude, altitude, and the attraction of the mass above sea level, reckoned as rock of average density.

This anomaly is negative at every station but two, where its positive value is so small as to be practically non-existent; in other words, there is everywhere an apparent defect of gravity. At the stations nearer to the Himalayas a part of this defect is due to the compensation of the range, and in the case of these stations the fourth column gives the amount which this compensation would be in the case of the Imaginary Range, a figure which is slightly, but not materially, less than the compensation of the actual range as calculated by Mr. Hayford's tables. After allowing for this there still remains a defect which may be due to various causes, of which one is the defect of density of the Gangetic alluvium as compared with an equal bulk of average rock, and in the fifth column is the depth of alluvium, to the nearest 500 feet, which would be equivalent to the anomaly of gravity at the station.

It must not be supposed that these figures necessarily represent the actual depth of the alluvium, for they might be modified in various ways; the adoption of the later formula for the variation of gravity with latitude would increase them by about 3,500 feet; the newer densities would introduce only a very slight change at any of the stations, but the effect of distant topography, beyond a radius of 100 miles, and its compensation, which is not taken into consideration, introduces a further correction to the depth of the alluvium. The amount of this last correction has been published in the case of only one of the stations, Arrah, where it is ·028 dyne, and at Dehra Dun, to the north of the group included in the table, it is ·057 dyne; as the effect is in both cases negative it would reduce the numerical value of the anomaly and consequently the apparent depth of the alluvium by from 4,000 to 8,000 feet. All these corrections would, however, affect the stations to much the same extent and, though they would alter the absolute value of the inferred depth of the alluvium, would have little effect on the differences, or at any rate the differences between any two adjacent stations.

Confining attention to these differences alone, it will be seen that in the first group there is a steady decrease in depth as the distance from the northern boundary increases and the southern boundary is neared; the second group repeats the same feature, as does the third, though here the position of the southern boundary can only be inferred from the geological structure of the rock area on either side of the alluvium which stretches southwards to the delta of the Ganges, and from the geodetic observations themselves.

The gravity observations, then, agree with the observations of the deflection of the plumb-line in bearing out the conclusions, which had been drawn from geological examination, as to the general upward slope of the floor of the Gangetic trough from north to south; and the fact that the gravity observations indicate a thickness of less than 500 feet at stations near the southern margin, where the thickness of the alluvium is either known, or may be presumed, to be small, suggests that the various corrections, which have been referred to above, neutralise each other, so that the figures given in the table may be regarded not merely as comparative, but as not far from the actual depth, or at least of about the same order of magnitude as it. There are, however, two considerations which may introduce a modification of this conclusion.

The first of these is the effect of distant topography and its compensation. As has been mentioned, this is greater by about ·030 dyne at Dehra Dun, just north of the stations included in the table, than at Arrah, and as the difference is probably very largely due to the greater proximity of Dehra Dun to the Himalayas, it is also probably greatest at the northern stations of each group, and decreases progressively in the southern. As the effect of this correction would be to decrease the apparent thickness of the alluvium, it is evident that the variation in its amount would decrease the difference between the apparent depths at the northern and the southern stations; and, as the thickness at the southern edge must necessarily be nothing, the result would be an apparent decrease in the depth at the northern stations of each group by some 3,000 to 4,000 feet.

Secondly, we have to consider the effect of a separate compensation of the trough. The amount of this effect is indicated by the figures given on page 62 which show that it would amount to about ·015 dyne at the southern margin, and to about ·040 at thirty or forty miles from the northern margin, or more where the trough has a greater width than 100 miles or a greater maximum depth than 15,000 feet. The former of these figures would neutralise the effect of about 2,000 feet of alluvium, the latter about 5,500 feet to perhaps 7,000 in the central portion of the trough; and so, the difference between the northern and the southern stations, or the apparent depth at the northern stations of each group, would be increased by about 3,000 to 5,000 feet.

From this it will be seen that the modifications introduced by these two considerations practically neutralise each other and the figures in the table remain as the closest approximation to the actual depth of the alluvium which can be attained by this method.

In the last column of the table No. 23, another series of figures is given, based on the Hayford anomalies, where these are available. The thickness given here is not directly deduced from the anomalies, because these are positive at several stations, indicating a negative thickness of the alluvium, which is impossible. The positive anomaly reaches its maximum at Agra, where it is equivalent to the effect of about 2,500 feet of alluvium, and if the thickness at Agra is made equal to 500 feet to bring it into accord with the depth of the alluvium, which is known to be 480 feet at that place, a correction of 3,000 feet must be made to the thickness deduced at the other stations, assuming that the difference in the anomaly is due to a difference in thickness of the alluvium.

In this way the figures in the last column were obtained, and it will be seen that they follow the same general course as those in the preceding column, but indicate a lesser depth at the northern stations. Here, however, it must be remembered that the Hayford anomaly includes the effect of distant topography and its compensation, and if allowance is made for this, the figures in the last two columns would come into very fair agreement with each other, as close, probably, as can be expected. In both columns there are some departures from a regular decrease in depth as the southern margin of the alluvium is approached, departures which may be due to local variations in the force of gravity, quite unconnected with the trough, and also to irregularities in the form of its floor, which may be considerable when expressed in feet, though subordinate to the general slope of the floor. The western group, in its southern half, runs close to the margin of the trough, which here has a course of about N.N.W.—S.S.E., and in its northern half suggests a depth of about 15,000 feet at the outer edge of the Siwalik hills—the northerly continuation of this section across the Dehra Dun being dealt with further on. The central group, situated where the trough attains its maximum breadth, indicates that the maximum depth may reach 20,000 feet or more. The eastern group indicates a depth of about 15,000 feet at the northern boundary, and also the existence of a rock barrier, covered by no great depth of alluvium, connecting the Peninsular area with the Assam Range. This last conclusion is in agreement with the deduction which has already been drawn from the deflection of the plumb-line, and is of interest as showing that the broad expanse of alluvium, which stretches southwards to the Gangetic delta, forms no part of the Gangetic trough.

A confirmation of this deduction is to be found in the gravity observations at the two stations of Kisnapur and Chatra. These are situated on the alluvium, but, in spite of this, both have positive anomalies, the Bouguer being + ·033 and + ·009 dyne, and the Hayford + ·039 and + ·005 dyne, respectively. The high positive anomaly at Kisnapur is evidently the result of a deep-seated excess of density in the rock underlying the alluvium, but its magnitude, and the smaller positive anomaly at Chatra, show that the alluvium cannot have any great thickness, comparable to that in the Gangetic trough, for if there were any great thickness of alluvium the negative effect of the defect in density would more largely neutralise the deep-seated excess of density in one case, and in the other would make the anomaly negative, instead of positive. We may, therefore, reasonably conclude that the alluvium, spread over the gap between the north-east corner of the Peninsular area and the hills of Assam, is of no great thickness, and forms no part of the Gangetic trough, in the sense in which these words are used here, although it has to be coloured the same as the plains of Upper India on a map showing the surface geology.

There remains one station in the alluvial plain which requires separate notice, as the results are somewhat anomalous. This is the station of Monghyr, near the southern margin of the alluvium, where the width of the plain has diminished to ninety miles. Though situated close to the southern edge of the alluvium it gives a Bouguer anomaly of — ·031, and a Hayford of — ·024 dyne, and, as it is difficult to believe that there can be a thickness of over 4,000 feet of alluvium under this station, we must fall back on the supposition that the anomaly is due to a more deep-seated deficiency of density. A similar, though smaller, defect of density at the station of Sasaram, included in table No. 23, suggests that in both cases the anomaly may be due to a deep-seated defect of density in the rocks below the alluvium.

However this may be, the solitary exception, if it be an exception, does not affect the general conclusions which have been drawn from the gravity and latitude observations, conclusions which are besides in agreement with the inferences from geological observations. It is, of course, possible that the results might be due to a defect of density in, or below, the rocky crust of the earth, of an amount and variation similar to that which has been attributed to variations in the depth of the alluvium, but this explanation is not probable, and is inapplicable in the case of the deflections at stations near the main boundary, for these could not be explained by any deep-seated cause, but require a defect in density immediately below the surface, such as would necessarily result from the known facts of geological structure. We may take it, therefore, that the results of geodetic observation at stations on the Gangetic alluvium indicate, firstly, that the southern margin of the Gangetic trough is very much as marked on the map, Pl. 12; secondly, that a large area of alluvium east of the Aravallis does not, properly speaking, belong to the trough, but is merely a thin covering of alluvium laid down upon, and obliterating the unevenness of, an irregular land surface; thirdly, that the alluvium east of the Rajmahal Hills, stretching southwards to the Gangetic Delta and eastwards into the valleys of the Brahmaputra and Barak, also lies outside the limits of the Gangetic trough, and is formed by a comparatively thin covering of alluvium, whose thickness may be measured by hundreds, instead of thousands of feet, and, fourthly, that the Gangetic trough proper, reaches a depth of 15,000 to 20,000 feet towards its northern edge, and that its floor has a fairly regular upward slope to the southern margin.

The geodetic stations in the Punjab plains are fewer in number and more scattered, than those on the Gangetic alluvium, yet, interpreted in the light of the latter, they give some interesting information. A list of the latitude stations, ranged in order of their distance from the main boundary, is given in table 24, from which it will be seen that there is first a northerly deflection, which becomes southerly with increasing distance, increases in amount to a maximum at Amritsar, and then diminishes. This is exactly the character of the change in the deflections noticed in the Gangetic trough, though there spread over a greater distance, and the similarity is more striking if the stations of Sawaipur and the three others following it are left out of count; these, as will be seen by reference to the map, are detached from the rest, and it is doubtful whether the southerly deflections are due to the trough, or to some cause independent of it, such as has been met with south of the Gangetic trough, in the northern part of the Peninsular rock area. To some such cause must be attributed the southerly deflections at the last three stations in the list, which lie within the area mapped as alluvium, but in a region where geological observations show that there is probably no great depth of alluvial cover on the rock floor, and where it is difficult to believe that the southerly deflections can be due to the effect of an alluvial trough.

TABLE 24.—*Latitude Stations in the Punjab.*

STATION.	Approximate distance from main boundary.	Observed deflection in the meridian.	Resulting deflection normal to range.	Deflection due to range.	Remainder.
Ranjitgarh	30	− 2	− 2	− 5	+ 3
Isanpur	50	0	0	− 2	+ 2
Shahpur	55	+ 5	+ 7	− 2	+ 9
Amritsar	85	+ 8	+ 12		+ 12
Sangatpur. . . .	90	+ 5	+ 7		+ 7
Rakhi	110	+ 3	+ 5		+ 5
Khimuana . . .	120	+ 1	+ 1		+ 1
Sawaipur	140	+ 3			
Tasing	190	+ 4			
Ram Thal . . .	200	+ 3			
Garinda	230	+ 3			

Omitting these, we have a fairly compact group of latitude and gravity stations which deserve more detailed study, but before this can be done it is necessary to convert the recorded deflections, which were measured in the meridian, into the corresponding deflections normal to the general course of the range, here somewhat north of north-west; it is then necessary to allow for the attraction of the range, the figure used being the deflection calculated for the Imaginary Range at a similarly situated station, and by deducting this from the observed deflection we obtain a remainder, given in the last column of the table, which may be treated as the effect of the trough. Here we see that at the first two stations there is a small deflection away from the range, indicating that they lie a little beyond the point at which the effect of the trough changes from a northerly to a southerly deflection, but these two stations are situated at opposite extremes of the group; at the more centrally situated station of Shahpur, at about the same distance from the main boundary, we have a deflection of 9″ which increases to 12″ at Amritsar, representing a slope of about 250 feet per mile of the bottom of the trough; at the more distant station of Sangatpur this has dropped to 7″ and at Khimuana to 1″ from which we may conclude that both these stations lie outside the limits of the trough, and, consequently, that the alluvium forms a comparatively thin covering over the rocky floor.

Turning to the gravity observations, a list of which is given in table No. 25, we find a high negative anomaly at Pathankot, a lesser one at Ludhiana, and small positive anomalies at the other three. Taking the highest of these positive anomalies as the zero and interpreting the difference of the others as due to the lesser density of the alluvium, we obtain the thickness given in the last column, where allowance has been made, in the case of Pathankot, for the effect of the compensation of the range. Here again we find that the stations of Mian Mir and Ferozepore, at

TABLE 25.—*Gravity Stations in the Punjab.*

STATION.	Distance from outer edge of hills.	Bouguer anomaly.	Equivalent thickness of alluvium.
Pathankot . . .	1	— ·179	23,000
Ludhiana . . .	30	— ·048	8,500
Mian Mir . . .	90	+ ·004	500
Ferozepore . . .	90	+ ·006	0
Montgomery . . .	180	+ ·003	500

about the same distance from the main boundary as Khimuana, seem to lie on a comparatively thin covering of alluvium, which is 8,500 feet thick at Ludhiana and 23,000 feet at Pathankot. From these figures we may conclude that the trough is, on this section, less than 100 miles broad, but has a depth which is comparable with, and possibly quite as great as, that of the much broader trough in the Gangetic region; further, if we take the stations of Mian Mir and Pathankot, the gravity observations give a mean slope of the floor of the trough of about 250 feet per mile, or just about the same as is indicated by the deflection at Amritsar, a station which lies between the other two, and close to where the southern edge of the depression seems to lie.

The conclusions drawn from the Bouguer anomalies require some modification when the Hayford anomalies are used. At Mian Mir and Pathankot these are + ·040 and — ·077, respectively, giving a difference of ·117 dyne, equivalent to the effect of about 17,500 feet of alluvium. The large positive anomaly at Mian Mir precludes this interpretation and the actual anomaly at Pathankot represents a depth of only 11,500 feet, if the anomaly is solely due to this cause. The positive anomaly at Mian Mir shows that the alluvium cannot have any great thickness here, but the anomaly itself must be due to an excess of density in the rocks below the alluvium, and may be deep-seated enough to account for part of the high southerly deflection at Amritsar; some such cause is necessary if the depth of alluvium at Pathankot, deduced from the Hayford anomaly is approximately correct, for this would give a mean slope of only about 120 feet per mile to the floor of the trough, and produce a deflection of not more than 6″ to 7″ away from the range.[1]

The geodetic observations in the Punjab, like those further east, give different numerical results according to the way they are dealt with, but, in spite of this difference in the dimensions of the trough, they agree as to its general form and show that the depression, now filled with alluvium, which has been traced along the southern edge of the Himalayas from near the 89° meridian, continues westwards at least as far as 74°; and that it there maintains the same general character of deepening regularly from the

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[1] At this station the adoption of the Bessel-Clarke spheroid would increase the southerly deflection by about 3″ (S. G. Burrard, *Phil. Trans.*, Series A, CCV, pp. 301 and 308).

outer edge towards the hills. The section is not complete but it is probable that the maximum depth is not at the northern boundary of the trough though nearer to it than to the southern, and probably close to the outer edge of the hills, as is found to be the case on the section through the Dehra Dun. The westerly extension of this trough cannot be traced for want of observation, but it is natural to expect that it dies out as the point is reached where the Salt Range impinges on the Himalayas, just as it seems to die out in the east where the Assam range, in a similar manner, bridges the angle between the Himalayas and the ranges separating India from Burma.

The geodetic observations also show, in confirmation of the deduction which was drawn from geological evidence, that the great spread of alluvium in the Punjab differs from that of the Gangetic plains, in that it is formed by a comparatively thin covering over the rocky floor, and only when the hills of the western frontier are approached do we find indications of a trough comparable with that which borders the Himalayas; but this is a matter which cannot be dealt with here.

The observations, dealt with so far, are confined to that portion of the Gangetic trough which lies south of the limit of the hills, and only incidental reference could be made to the form of that portion of the trough which lies within the Siwalik area, between the outer edge of the hills and the main boundary. There are only two series of geodetic observations which cross this boundary, one near the 88° of longitude, where there is only a narrow fringe of hills between the main boundary and the edge of the plain, and the other near the 78° of longitude, where there is an exceptionally complete series of latitude and gravity observations in the Dehra Dun and in the Himalayas on the one hand, and the plains on the other.

Taking the latitude observations first, these are included in table No. 26 (page 87), to which the two northernmost stations of the series in table No. 20 are added, in order to bring the two series into relation with each other. In the table No. 26 the distance of each station from the main boundary, and from the southern edge of the Siwalik hills is given in the second column, these distances being in every case measured in a direct line, normal to the course of the boundaries, and expressed in the nearest whole mile. In the case of the first three stations two values are given for the

TABLE 26.—*Latitude Stations in and south of the Dehra Dun.*

STATION.	Approximate distance from main boundary and outer edge of Siwaliks.	Deflections due to Imaginary Range, Siwaliks and Trough.		Observed deflections.
		I	II	
Rajpur	0 & 5 : 19	— 43	— 42	— 44
Dehra Dun, old	1 & 6 : 14	— 33	— 36	— 33
Dehra Dun, new	2 & 7 : 13	— 35	— 33	— 33
Dehra Dun, E. Base	10 : 9	— 25	— 26	— 26
Shorpur	12 : 5	— 23	— 27	— 25
Khajnaur	13 : 6	— 24	— 26	— 23
Lachkua	13 : 2	— 24	— 27	— 25
Bullawala	14 : 1	— 24	— 27	— 25
Amsot	15 : 5	— 24	— 25	— 25
Hatni	16 : 3	— 23	— 26	— 26
Sarkara	32 : 20	— 10	— 10	— 8
Nojli	38 : 22	— 8	— 7	— 10

distance from the main boundary, this being due to the fact that, immediately east of Rajpur, the general course of this boundary is interrupted and thrown southwards for a distance of about five miles, the exact distance being indeterminable as the boundary is covered over with recent or sub-recent gravels. As a consequence of this, a single value cannot be given for the distance from the main boundary of the stations close to this change in its course ; Rajpur, for instance, is a station on the main boundary, so far as the hills to the westwards are concerned, but lies about five miles north of the main boundary so far as it is affected by those to the eastwards.

In the last column of the table is given the observed deflection at each station, and in these it will be noticed that from the Dehra Dun E. Base to Hatni they give practically identical deflections, in spite of the increasing distance from the edge of the main range ; the only exception is the station of Khajnaur, at which the northerly deflection is in slight defect, as compared with the other stations, a defect doubtless due to the position of the station on the northern slope of the Siwalik Range, where it is subject to a purely local southerly attraction which would easily account for the small defect in the northerly deflection. Form this uniformity in the deflections over so broad a strip it is evident that there is some cause at work, counteracting the decrease in deflection which would otherwise take place with increasing distance from the main boundary, and the first supposition which was investigated was that this cause is the attraction of the mass of the Siwalik plateau, above the general level of the plain. The figures given in table No. 6 show that this would produce a southerly deflection of about 14″ at the northern boundary, decreasing to zero in the centre, about coincident with the position of the Dehra Dun E. Base station, and a northerly deflection in the southern half, increasing to about 14″ at the southern edge. This effect was added to that of the Imaginary Range and of a trough of uniform depth of 15,000 feet; and the sum, converted into the meridian, by allowing for the departure of the course of the range from due east to west in this region, is given in column I of the table.

It will be seen that the figures are in very fair accord with the result of observation, except in the case of the two stations at Dehra Dun, but here the uncertainty as to the precise course of the main boundary, under the surface gravels north-eastwards of the stations, introduces so great an uncertainty into the calculation of the deflections to be expected at them, that these two stations might well have been left out of account in this connexion. Apart from this, the hypothesis not only gives about the same difference between the deflections at Rajpur and at the Dehra Dun E. Base station, and the group beyond it in the Siwalik hills, but provides for the same uniformity of deflection, at all distances between 10 to 16 miles from the main boundary, which is exhibited by the actual deflections; and this uniformity would not be seriously disturbed by a difference of anything under 5,000 feet in the assumed depth of the trough, though the actual figures, and the difference between the calculated values at Rajpur and Hatni, would be somewhat increased or diminished as the case might be. An assumption that the depth of the trough decreased continuously with increased distance from the main boundary would seriously disturb this uniformity, for it would introduce a rate of decrease in the northerly deflections which would more than counterbalance the effect of the Siwalik plateau, and require a distinctly greater northerly deflection at the Dehra E. Base station than at those further removed from the main boundary. From this we might conclude that the depth of the trough at Rajpur is somewhere about 15,000 feet and that this depth is maintained in a southerly direction to a distance of 30 or 40 miles from the boundary, before the shallowing of the trough begins.

This, however, is not the only possible explanation, or the only supposition which will fit in with the facts. If we supposed the depth of the trough under the Siwaliks to be about 10,000 feet the effect of the defect of density through this depth would be approximately equal in amount to that of the Siwalik plateau, but opposite in sign. The two would, in these circumstances, neutralise each other, and if we then supposed the trough to be deepened outside the Siwaliks, or, in other words, the floor of the trough to form a step upwards under the outer edge of the Sub-Himalayan region, we would have much the same effect produced as in the supposition just examined. In reckoning the effect of such an hypothesis as has been outlined it will be necessary to make some modification in the distance from the outer edge of the hills, as given in table No. 26, for the two stations Lachkua and Bullawala. The distances given in the table are measured from the outer edge of the visible hills, as marked on the one 1-inch map, but it is not reasonable to suppose that a rise in the floor of the trough, if it exists, would follow all the sinuosities of the boundary between the hills and the gravel slope at their base, and these two stations are situated where the outer edge of the hills takes a distinct curve inwards from its general course. If we suppose that the rise in the floor of the trough spans this inward bend, these two stations would lie at some three or four miles from the course of the rise, or from the edge of the deeper trough. Making this allowance, and assuming a depth of 10,000 feet under the Siwalik plateau and of 15,000 feet outside it, we get the figures given in column II of the table, which will be seen to agree almost equally well with the results of observation as those in column I. A slightly closer agreement might be obtained by varying the assumed depth of the trough outside and within the Siwalik area, but no real advantage would be obtained by trying to attain a greater degree of precision than the method permits.

As has already been pointed out, the calculations, both of the observed deflections and of the deflections which are to be expected on any given hypothesis, involve the adoption of certain assumptions, which in no case exactly agree with what is found in nature, but are approximations to the conditions which are either known, or may be expected, to exist. A variation in these assumptions would produce a change in the absolute value of the deflections given in the table, but any such variation, if applied to every station, would produce a similar change in all, and the differences would be little affected, or in many cases not affected at all. Consequently we may take it that the form of the underground floor of the Gangetic trough is similar in kind to one or other of the two assumptions involved in columns I and II of the table. We may be certain that the Siwalik region does not cover a deepening of the trough; but whether the floor continues underneath it with very little change of level, or whether there is a marked drop, and deepening of the trough just outside the limits of the Siwaliks, cannot be determined from the latitude observations alone.

The gravity stations in the Siwalik region of the Dehra Dun are seven in number, and for two of these only, Rajpur and Dehra Dun, has the Hayford anomaly been published. A list of these stations is given in table No. 27, where two other stations to the south are included, in order to bring the series into connection with the stations in the alluvial plain, which have already been dealt with. As before, the first column gives the name of the station, the second its distance from the main boundary, the Bouguer anomaly of gravity is given in the third column and the gravitation effect of the compensation of the Imaginary Range in the fourth. Finally the depth of the trough is given, to the nearest 500 feet, on the supposition that the whole of the unexplained residue of the anomaly is due to the defect in density of the material contained in the trough. These depths were obtained from table No. 18, where the effect of a 15,000 feet deep trough is given, the depth in

TABLE 27.—*Gravity stations in and south of the Dehra Dun.*

STATION.	Distance from main boundary.	Bouguer anomaly.	Hayford compensation of Imaginary Range.	Residue expressed as depth of Trough.
Rajpur	0	— ·124	— ·073	15,000
Kalsi	0	— ·098	— ·073	7,500
Dehra Dun	2	— ·126	— ·067	12,000
Fatehpur	6	— ·100	— ·056	7,500
Hardwar	7	— ·114	— ·053	10,000
Asarori	9	— ·112	— ·048	10,000
Mohan	14	— ·104	— ·039	10,000
Roorkee	25	— ·107	— ·024	13,000
Nojli	38	— ·095	— ·015	12,000

table No. 27 bearing the same proportion to 15,000 feet as the unexplained anomaly to the deficiency of gravitation which should be met with at a station similarly situated on a trough 15,000 feet in depth.

The first point to be noticed in the table is that the depth of the trough at Rajpur is given as 15,000 feet, which happens to be exactly the figure assumed at the outset as somewhere near the actual throw of the main boundary fault, but, as has been explained, no great importance can be attached to the precise figure. The second point to be noticed is that the western stations of Kalsi and Fatehpur give much smaller depths of the trough and, at first sight, seem to indicate that the throw of the main boundary fault in this section is only about one half as great as on the Rajpur-Dehra Dun section. The correctness of this conclusion is, however, open to doubt, owing to the unknown effect of the break in the general course of the main boundary just east of Rajpur, and this doubt is confirmed by a consideration of the Hayford anomalies. These have positive values, of + ·003 at Dehra Dun and + ·022 at Rajpur, thus following the general rule that the Hayford anomaly has a positive value as compared with the Bouguer, but the amount of the difference is greater than at stations further removed from the Himalayas ; and, moreover, the anomaly is greater at Rajpur than at Dehra Dun. There are two possible explanations of these differences, between the Hayford anomalies at Rajpur and Dehra Dun and between the Bouguer anomalies at these and stations further west ; they may be due, either to a variation in the depth, and consequent effect, of the trough, or to a difference between the real and the calculated effect of the compensation of the range, for all other changes, introduced by the difference in the method of calculation, as well as by the effect of any cause not considered in the calculations, would affect both stations in exactly, or very nearly exactly, the same degree and direction.

From this it appears that these stations, close to the main boundary, cannot be used with any degree of safety in determining the form of the trough, or in other words, they belong more properly to the region of the range and will be more profitably dealt with in that connexion. It also follows that the gravitation observations close to the main boundary cannot be used to confirm or qualify the results obtained from the deflections.

Southwards of the stations just considered, and now at a sufficient distance from the edge of the range proper to make it probable that the difference between the actual and the calculated effect of the compensation will not be great, come the three stations of Asarori, Hardwar, and Mohan, all situated on the line of the Siwalik Hills, and all indicating a depth of about 10,000 feet. Southwards of these again come the two stations in the alluvium indicating a depth of 13,000 and 12,000 feet. Here again it is not the exact figures which are important, although it has been shown that they are probably of much the same order of magnitude as the actual depths, but the very definite indication of an increase in depth of the trough to the south of the edge of the Siwalik Hills. The amount of this difference is 3,000 feet as between the stations in the Siwaliks and Roorkee, but Roorkee is separated by about 15 miles of plain from the Siwalik Hills, and the stations to the southward indicate a progressive decrease in depth at the rate of about 250 feet per mile for some forty miles from Roorkee. If this average slope continues northwards from Roorkee towards the hills, the actual rise in the floor of the trough may well amount to the 5,000 feet assumed when dealing with the deflection of the plumb-line.

The gravity observations may also be treated in another manner. At the four stations of Rajpur, Dehra Dun, Roorkee, and Kaliana, we have both the Bouguer and Hayford anomalies, from which it is easy to obtain the correction from the one to the other at those stations. If, then, these corrections at the four stations are plotted on squared paper, the stations being ranged according to their distances from the main boundary, a curved line can be drawn through the four points which will approximately indicate the correction which would be applicable to a station at some other distance from the main boundary, and by applying this correction to the published Bouguer anomalies, we can get an approximate value for the Hayford anomaly, which should be correct to the first two places of decimals. The values obtained by this method are given below, where an asterisk means that the anomaly is an estimated one; the figures are:—

	Distance.	Anomaly.
Rajpur	0 miles	+ ·022
Kalsi	0 ,,	+ ·047
Dehra Dun	2 ,,	+ ·033
Fatehpur	6 ,,	+ ·01*
Hardwar	7 ,,	— ·01*
Asarori	9 ,,	— ·01*
Mohan	14 ,,	— ·02*
Roorkee	25 ,,	— ·043
Nojli	38 ,,	— ·04*

Here, as before, the irregularity shown by the first four stations is probably connected with the distribution of the compensation of the range, and will be dealt with in the next chapter. At the other stations the anomalies show the same feature as the Bouguer values, and indicate an increase in the negative anomaly of about ·03 dyne as between stations in the Siwaliks and the nearest ones on the alluvial plain. Interpreted as an effect of the alluvium, this means an increased depth of about 4,500 feet.

The general result, then, of an examination of the geodetic observations in the Dehra Dun is that the observations of the deflection of the plumb-line require that the magnitude of the main boundary fault shall be of the order of near 10,000 feet vertical throw; they suggest the possibility, though they cannot establish the existence, of a rise in the floor of the trough coincident with the outer limit of the Siwalik Hills; they show that if such a step exists it must mean a rise of some thousands, probably near 5,000 feet; that in this case the throw of the main boundary fault will be near the lower limit indicated, but will be near the upper limit if the floor of the trough continues under the Siwalik area with no material change in level. Finally, they exclude the possibility of a deepening of the trough under the Siwalik area as compared with its depth under the plains to the south.

The gravity observations, on the other hand, do not enable us to determine the depth of the trough at the main boundary; though they indicate that the main boundary fault has a throw of several thousand feet, they do not enable us to decide, directly, between the two alternatives presented by the observations of the deflection of the plumb-line. Indirectly, however, they do give an answer, for they indicate most unmistakeably that there is a very considerable drop in the level of the floor of the trough at, or near, the southern edge of the Siwalik Hills, amounting to something like 5,000 feet in vertical difference, with a depth of somewhere about 10,000 feet on the one side and about 15,000 feet on the other, of the step.

Taken together, these observations indicate that the boundary of the outer hills, if we could obtain a deep section, would be of very much the same character as the main boundary fault, thus confirming the suggestion, first made by Mr. H. B. Medlicott[1] and subsequently worked out in much greater detail by Mr. C. S. Middlemiss,[2]

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[1] *Mem. Geol. Surv. Ind.*, Vol. III, pt. 2 (1864).
[2] *Mem. Geol. Surv. Ind.*, Vol. XXIV, pt. 2 (1890).

that the series of longitudinal faults, traversing the Siwalik region, represent successive positions of the boundary between hill and plain, and that the outermost boundary of the hills marks the position of a similar fault, the latest in date of the whole series.[1]

It is now possible to summarise the conclusions drawn from the separate groups of observations and to draw a generalised cross-section of the trough, as is shown in figure 7. This does not represent any one cross-section, for no one cross-section is complete, but, by a combination of the geodetic and geological evidence of different sections, it is possible to represent diagrammatically the general type of section which would be met with, subject to minor variations, at almost any part of the length of the trough. On the north we have the range of the Himalayas proper, and near the southern edge of it a series of faults, which mark the successive boundaries between hill and plain. The outermost and latest of these faults traverse the region where the deposits of the plain have been compressed, folded and elevated into the foot-hills of the Siwalik zone, the outer limit of which is probably marked by a similar fault.

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[1] In Vol. VII of the *Records of the Survey of India*, p. 151, particulars are given of the deflection of the plumb-line at two stations between Rajpur and Mussoorie. The deflections, in the meridian and the prime vertical, are

Mussoorie	36″·5 N	28″·2 E.
Jharipani	52″·5 N	33″·6 E.
Spur Point	53″·2 N	31″·3 E.
Rajpur	47″·7 N	31″·3 E.

It will be seen that the deflections at Jharipani and Spur Point are distinctly greater than at Rajpur; part of this excess is doubtless due to the effect of quite local topography, but these stations are situated rather less than a mile and about half a mile, respectively, from the outcrop of the main boundary fault, that is, in positions where the effect of the trough would be markedly less, and lesser deflections looked for, were the plane of the boundary fault vertical. Not so, however, if the fault had a hade towards the hills, as is indicated by the surface geology; in this case the maximum effect of the trough would be met with to the northwards of the outcrop, and there would not be the same rapid falling-off of the deflections as in the case of a vertical plane of separation between the denser and the less dense rocks. Seeing that a hade of 30° from the vertical would bring the fault directly under Jharipani at a depth of 7,000 to 8,000 feet, figures in good accord with the geological and the geodetic observations, the effect of the trough would be at least as great at Jharipani and Spur Point as at Rajpur, the effect of the range would not be materially different and that of the quite local topography perhaps a little greater. The large deflections at the new stations are, therefore, in complete accord with what was to be expected, and confirmatory of the structure which had been deduced from geological examination.

These observations did not reach me in time to be embodied in the text; the absolute deflections are liable to modification in the manner which has been indicated, and are actually different from the figures printed above, but this does not affect the differences between the deflections at the different stations.

FIG. 7.—Generalised cross-section of the Gangetic trough. This does not represent any individual cross-section but is a diagrammatical representation of the general type ; to the left is the Siwalik region with its successive boundary faults, which now forms part of the mountain system of disturbance ; to the right is the alluvial trough proper, the floor of which at first slopes downwards to the point of maximum depth, and then gradually upwards to the southern limit of the alluvium.

Leaving the hills, the section enters the area of the alluvial plain and there is an increase in depth of deposit ; beyond this the section becomes uncertain for a while and there are two possibilities, one that the floor of the trough slopes upwards from a maximum depth at the edge of the hills, the other that the trough gradually increases in depth for a while before the upward slope of the floor commences, as is indicated in the figure. In either case the greater part of the width is occupied by a sloping floor, rising to the southwards and ending in a rock area, rising above the level of the plain in some sections, and in others covered by a layer of alluvium.

The position of the southern boundary has been referred to when dealing with the different groups of observations. At the eastern end the boundary seems to bend round to the northwards, and the trough to terminate where the Assam range impinges on the boundary of the Himalayas. The next locality where the boundary of the deep trough can be fixed is to the south of Jalpaiguri, where it evidently runs near to the stations of Chanduria and Ramchandpur ; the exact position here is doubtful as the deflection suggests that the boundary lies to the southward of, and the anomaly of gravity that it lies very nearly under, or a little to the northward of, Ramchandpur. The distinction between the deep trough and the shallow covering of alluvium must in any case be an indefinite one and cannot be defined with accuracy, but the trough here has a width of certainly 80, and possibly over 100, miles.

In a westward direction the southern boundary of the trough is fixed by the boundary of rock and alluvium at Monghyr and thence sweeps across to Sasaram, the stretch of alluvium to the southward of this line, with rock islands rising from it, being evidently of only shallow depth. From Sasaram westwards the boundary of the trough follows the general course of the boundary of the peninsular rock area, keeping clear of the irregularities and deep indentations of the alluvial boundary, till, west of the 80° meridian, it trends more northwards and from Agra to Delhi runs about north-north-west. In this part of the course the latitude stations help but little, as the effect of the trough on the plumb-line would be in a nearly westerly direction, but the gravity observations enable us to place the boundary not far west of Hathras, Chandaos, and Gesupur; the great spread of alluvium, with rocky hills rising from it, to the westward of this line being merely a covering, of a few hundreds of feet at most, over the rocky floor.

From Delhi, where the last outlier of the Aravalli Hills disappears below the alluvium, the boundary of the trough must bend nearly west, for we find it running south of Rakhi and close to Ferozepore and Lahore; the further course cannot be traced with certainty, but the trough appears to be represented as far west as the station of Ranjitgarh, and probably terminates on the west as the Salt Range is reached, just as it ends up on the east where the Assam Range impinges on the Himalayas.

From the southern edge of the trough the floor slopes downwards towards the hills, reaching a depth of probably over 20,000 feet in the broadest part of the trough between 80° and 84°. Near 78° the greatest depth has sunk to not more than 15,000 feet, but further west the maximum depth of alluvium seems to increase again and may rise to as much as 20,000 feet under the plains of the upper Punjab.

We have, therefore, a fairly symmetrical trough, ranged along the whole of that part of the length of the Himalayas which is not complicated by the junction or contact of other ranges; and it is to be noted that the symmetry is in reality greater than appears on the map, for the very marked break in the even sweep of the boundary, and the prominence culminating near Delhi, are not entirely, and need not be in any way, connected with an irregularity in the displacements by which the trough was produced. The prominence lies on the direct continuation of the Aravalli hills, which still stand out, in the southern portion, as a distinct range of hills, rising above the general level of the country on either side, and the termination of the range to the northwards is not in any way connected with its structure, but solely due to a gradual lowering of the general elevation, which has allowed the alluvium to invade the valleys to a greater and greater extent, leaving the higher peaks standing out as rocky inliers in the alluvium, till the range finally disappears in the last exposure of rock at Delhi. There is, however, nothing to suggest that the range does not continue northwards under the alluvium, with the same irregular surface and general elevation above the rock surface on either side, and the geodetic observations indicate the same conclusion. The northerly deflections at Datairi and Bostan occur on the direct continuation of the line of the main range of the Aravallis, and beyond them the gravity observation at Meerut indicates a smaller negative anomaly, which may be interpreted as a lesser depth of alluvium than is found in other similarly situated stations. Still further in the direction of the Himalayas the comparatively small northerly deflection at Sarkára suggests a lesser depth of alluvium under this station than under similarly situated stations further east; and if the line is continued into the Himalayas it strikes a region where the geological structure has suggested the possibility of an original extension of the Aravalli range into what is now the Himalayan region[1]; the geodetic observations have supported this suggestion and converted what was only a bare possibility into something more than a probability.

The existence of a structural feature of such magnitude as the Aravalli Range, extending across the region where the Gangetic trough was subsequently brought into being, would have a twofold effect. In the first place it would introduce a variation in the strength of the earth's crust, and so a difference in the resistance which it would offer to the forces by which the trough was produced, and in the second place the mere fact of the original greater surface elevation of the range would result in the country on either side being soonest brought below the level of the formation of alluvium, and so give rise to an indentation in the boundary and a projection of rock into the alluvial area, quite apart from any possible difference in the amount of the surface warping, by which the trough was produced. In this way the northerly deflections at Datairi and Bostan, which it must be remembered are only northerly if the deflection at Kalianpur is assumed to be as much as 4″ to the south, represent the absence of a regular shallowing of the alluvium to the southwards, or the presence of very considerable irregularities of the under surface, no less than a deficiency of depth, so that the influence of uneven distribution of density in the underlying crust ceases to be masked by the effect of the trough.

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[1] *Manual*, 2nd ed, p. 483.

To the eastwards there seems to be a much smaller interruption of the regular sweep of the boundary of the trough in the north-eastern extremity of the peninsular area, to the south of Monghyr, which may be due to an original greater elevation of the land surface as compared with the regions on either side.

Excluding these departures from symmetry, for which quite obvious and adequate causes are apparent, the trough forms a remarkably symmetrical structure extending along the southern face of the Himalayas, from the Salt Range on the west to the Assam Range on the east. A structural feature exhibiting a symmetry and dimensions so closely coincident with those of the Himalayan range can hardly be wholly independent in its origin, and any attempt to account for the formation of one must take cognisance of the origin of the other. This is a matter which will be dealt with further on, but it must be pointed out that the trough, whose form and dimensions have been investigated, is something apart from the great spread of alluvium, stretching from the delta of the Ganges to that of the Indus. To this spread of alluvium the term Indo-Gangetic may be applied with perfect propriety, but it would evidently be incorrect to apply that name to the trough seeing that in no part of its course does the river Indus touch or even approach the deep alluvial trough along the foot of the Himalayas.

There is some reason to suppose that a deep trough filled with alluvium, similar to that which has been dealt with, though smaller in size, runs along the foot of the hill ranges of the western frontiers of India proper, which might be called the Indus trough, as that river traverses it from end to end. The other may be appropriately described as the Gangetic trough, seeing that three-quarters of its length and more than that proportion of its area lie within the drainage of the Ganges, but there is no reason to suppose that the two troughs are connected. Apart from the observations which have been dealt with, the outcrops of old rocks in the Chiniot, and other, hills which rise from the alluvium, point to the presence of a rock barrier, stretching under the plains of the Punjab to the Salt Range and separating the two deep troughs.

CHAPTER V.

THE SUPPORT OF THE HIMALAYAS.

The geodetic stations in the Himalayas, with the exception of a few isolated observations which will be dealt with separately, are ranged along the southern edge of the hills, covering some ten degrees of longitude and a distance of forty miles in from the edge of the hills. The latitude stations are given in table No. 28, arranged in a series of groups, in order of groups from west to east, and, in each group, of their distance from the main boundary. In this table is also given a calculation of the deflections which should be expected at each station, in accordance with the assumptions of imaginary topography which have been used in the preceding chapters. These deflections are given in three elements; firstly the effect of the attraction of the Imaginary Range, supposed to be compensated according to Mr. Hayford's factors for a uniform compensation

TABLE 28.—*Deflections which would be produced at Latitude Stations in the Himalayas on the assumption used in the text.*

STATION.	Miles from main boundary.	DEFLECTIONS NORMAL TO THE RANGE DUE TO			
		Range.	Siwaliks.	Trough.	TOTAL.
Kidarkanta	40	— 19	+ 1	— 5	— 23
Lambatach	36	— 19	+ 1	— 5	— 23
Bahak	26	— 20	+ 1	— 8	— 27
Bajamara	18	— 21	+ 2	— 11	— 30
Mussooree	3	— 31	+ 8	— 21	— 44
Banog	3	— 31	+ 8	— 21	— 44
Rajpur	0 & 5	— 41	+ 11	— 23	— 53
Birond	2	— 32	+ 10	— 26	— 48
Kaulia	32	— 19	+ 1	— 5	— 23
Mahadeo Pokra . .	30	— 20	+ 1	— 5	— 24
Phallut	32	— 19	0	— 5	— 24
Tonglu	20	— 21	0	— 7	— 28
Senchal	9	— 25	0	— 11	— 36
Kurseong	4	— 29	0	— 15	— 44

extending to a depth of 113·7 km.; secondly, the effect of the attraction of the Siwalik plateau, where it exists; and, thirdly, the effect of the Gangetic trough, using in each case the cross-section which has been adopted in Chapter IV as most appropriate to the position of each station. The combined effect of these three separate causes is given as the deflection, normal to the range, which should be expected at each station. This deflection requires a further correction, as the general course of the range varies, at the different stations, from nearly east and west to nearly north-west and south-east, and, before the calculated deflections can be compared with those actually observed in the meridian, it is necessary to make an allowance for the direction of the course of the range at each station. This has been done in table No. 29, where the calculated deflections, in the meridian, are compared with those actually observed by the Great Trigonometrical Survey and the difference given in the last column, a minus sign meaning that the northerly deflection, which is found at every station, is in excess, and a plus sign that it is in defect of the calculated deflection.

TABLE 29.—*Latitude Stations in the Himalayas.*

STATION.	Distance from main boundary.	Calculated Deflections.	Observed Deflections.	Difference.
Kidarkanta	40	— 18	— 26	— 8
Lambatach	36	— 18	— 30	— 12
Bahak	26	— 22	— 24	— 2
Bajamara	18	— 24	— 24	0
Mussooree	3	— 35	— 32	+ 3
Banog	3	— 35	— 29	+ 6
Rajpur	0 & 5	— 42	— 44	— 2
Biroud	2	— 38	— 40	+ 2
Kaulia	32	— 21	— 29	— 8
Mahadeo Pokra . . .	30	— 22	— 34	— 12
Phallut	32	— 24	— 33	— 9
Tonglu	20	— 28	— 38	— 10
Senchal	9	— 36	— 31	+ 5
Kurseong	4	— 44	— 47	— 3

In interpreting these figures it must be remembered that the observed deflection at any station may depart from the average deflection, at a similarly situated station on an average range, by some seconds of arc, owing to the effect of the irregularity of topography in the immediate vicinity of the station. The stations furthest in the hills are situated on peaks, and are not so much affected by this cause as those near the outer edge of the hills, where the effect is considerable. The stations of Mussooree and Banog, for instance, are situated on a ridge with a deep-cut valley on the north, and would therefore show a southerly deflection as compared with similarly situated stations on an imaginary representative of an average Himalaya, and the difference in the observed deflections at the two stations seems sufficiently accounted for by the local topography, which makes the effect of the valley to the north greater at Banog than at Mussooree. At Rajpur, which is situated at the southern foot of this ridge, the effect of the valley to the north is less, and here we have a northerly difference; the mean of the three gives a small southerly difference, or residual, if the effect of the trough has been correctly estimated.

The most conspicuous characteristic of the figures is the excess of observed over calculated deflection in a northerly direction, exhibited at all the stations in the interior of the hills, amounting to from 8″ to 12″, and the smallness of the differences at the outer stations, where the positive differences are as numerous as the negative. Though these characteristics are common to all the groups, it will be well to examine each separately.

In the western group we have first the two stations of Kidarkanta and Lambatach, at a mean distance of a little under 40 miles from the main boundary and giving a difference, or residual, of northerly deflection amounting to about 10″; next the two stations of Bahak and Bajamara, at about 20 miles from the boundary, give a difference of 2″ and 0″ respectively, and thirdly the three stations of Mussooree, Banog, and Rajpur, all within 3 miles of the main boundary, give a mean difference of about 3″ southerly. In all these cases the differences depend in part on the effect of the trough, and the dimensions adopted for this were those which have been deduced as probable ones, namely, 10,000 feet depths under the Siwalik area and 15,000 feet under the plains beyond. The adoption of these figures was largely governed by the fact that tables had been calculated for those depths, and the estimate is probably somewhat in excess of reality; if this excess amounted to as much as 25 per cent., probably an extreme value, the northerly deflections at the three outer stations would be reduced by about 4″ and the mean difference, or residual, altered from + 2″ to — 2″. This change would also affect the stations further in, whereby the differences at Bahak and Bajamara would be altered by — 2″, and at Lambatach and Kidarkanta by — 1″, but there would still remain a difference of about — 3″ as between the outer and the central, and about — 10″ as between the outer and the inner, stations of this group. So, too, a change in the estimate of the effect of the range would alter the estimated deflections at all stations, and only change the value of the differences, of the estimated residuals, by a small fraction of their total amount.

In this group of stations Major Crosthwait's calculation of the effect of the actual complicated topography surrounding two of the stations gives us a good check on the correctness of the conclusions drawn from the method of investigation which has just been outlined. At Lambatach he found a residual of — 18″, using the Bessel-Clarke spheroid, after allowing for the effect of the visible topography and its compensation, but not for the effect of the trough. This latter would account for about — 4″ of Major Crosthwait's residual, leaving — 14″ still unaccounted for, as compared with — 12″ in table No. 29. At Mussooree the residual was — 18″; the effect of the trough, as estimated in table No. 28, is — 17″ in the meridian, leaving a residue unaccounted for of — 1″ as against the + 3″ indicated in table 29. Major Crosthwait's figures thus make the northerly residual of deflection at Lambatach greater by 5″ than at Mussooree, a difference which is increased by some 10″ to 12″ if the effect of the trough is included, bringing it into fair agreement with the difference of — 15″ in table 29. We may therefore conclude that the increase in the unexplained residual of northerly deflection is a real one and amounts to about 10″ at 40 miles into the hills on this section.

The two stations in Nepal show an excess of northerly deflection amounting to about 10″, at a distance of 30 miles from the main boundary, and the same is noticeable in the more complete section in Sikkim, where the difference between the observed and the calculated deflections amounts to — 9″ at Phallut and — 10″ at Tonglu. At the station of Senchal the difference between calculated and observed deflections is + 8″, but the situation of this station is altogether exceptional, and the observed deflection departs largely from the average of similarly situated stations from purely a local cause. Due north of Senchal the deep-cut valley of the Rangit penetrates the range of the Himalayas, and about N.N.E. of the station is the larger valley of the Tista, similarly penetrating the range. I am unable to determine the exact amount of the defect of attraction due to these valleys, but an approximate estimate, made from the 32-mile contoured map of India, shows that the northerly deflection at Senchal is in defect by an amount which is of the order of 10″ to 12″ of arc, as compared with the average of stations at the same distance from the outer boundary of the hills, or with what would have been found at a station situated twenty miles or so west of its actual position. Applying this correction to the observed deflection we find that there remains a small northerly residual of unexplained deflection at this station, instead of the considerable southerly difference shown in table 29.

The effect of these deep-cut river valleys must be felt, though to a lesser degree, at Kurseong, but is there neutralised by the purely local topography, which gives an excess of attraction amounting to about — 4″ of arc, and at this station the difference between the estimated and observed deflections amounts to — 3″.

In this group we have only a single check on the estimates, in Major Crosthwait's calculation of the residual at Kurseong, where he made it amount to — 23″, of which — 15″ would be accounted for by the estimate of the effect of the trough adopted in table 28, leaving an unexplained residue of — 8″ to be accounted for in some other way. In part this is doubtless due to the estimate of the effect of the trough being too small, but the difference between the actual and the assumed dimensions cannot possibly amount to 50 per cent., as would be required if this was a complete explanation, and part of the northerly residual must remain unexplained after full allowance has been made for any possible effect of the trough.

In both the eastern and the western series of stations we have the same feature of only small differences between the actual and the calculated deflections at stations near the outer edge of the hills, if we allow for the effect of the lesser density of the material filling the Gangetic trough, and a high northerly residual of unexplained deflection at stations situated 30 to 40 miles in. This difference amounting to 10″ to 12″ is repeated in the three stations situated between the two groups and may be accepted as not only real, but directly connected with the structure and compensation of the range, rather than with four independent, fortuitous, variations in the density of the rocks which in every case act in the same direction and to the same amount.

In searching for an explanation of these peculiarities it is natural to turn in the first place to a modification of the hypothesis of compensation and a reference to table 8 shows that no help is to be got from supposing an alteration in the depth to which uniform compensation extends, for an increase in depth leads to a larger northerly residual at stations near the edge of the hills than at those further in, and a lesser depth merely gives a nearly uniform southerly residual. Table 9 shows that the adoption of an hypothesis of support by flotation gives some help, for it would give a northerly residual, as compared with calculations from Mr. Hayford's tables, of some 3″ greater than at a station situated outside the range, but as regards stations within the range, situated as are Lambatach and Mussooree, it would merely give a nearly uniform residual of about — 3″. It is obvious, therefore, that the explanation must lie in a departure from a locally complete compensation, and table No. 10 shows that, without going beyond the bounds of an easily accepted departure from the conditions assumed in the other tables, we can account for all the difference which is actually found between stations some thirty or forty miles apart. A supposition of this sort also allows of the passage from northerly to southerly residuals, which is suggested by the figures in table No. 29; but it is useless to pursue this matter further till the gravity observations have been dealt with.

Meanwhile it can be said that the measurements of the deflection of the plumb-line show that, northwards of about 30 miles from the edge of the Himalayas proper, the hills are superelevated, or, otherwise, that the compensation is in defect; but the amount of this departure from normal conditions depends largely on the manner in which it is distributed between the surface topography and the compensation, and this will be considered further on.

Besides the latitude stations, which have been considered, there are three others, separated by a long interval and situated in the north-western extremity of the range. Two of these are in the interior of the hills, on the southern edge of the valley of Kashmir, and will be more conveniently considered further on, the third is the station of Murree, situated near the edge of the Himalayas proper, but separated from the alluvium of the Punjab by some 80 miles of low hills. At this station a northerly deflection of 16″ was observed, of which 10″ are accounted for by the effect of the visible topography and its, Hayford, compensation, leaving a residual of 6″ of northerly deflection, which is reduced to 2″ if the Bessel-Clarke is substituted for the Everest spheroid. Here we find a very different condition from that met with in the stations further east, such as Mussooree, where the Hayford residual is 11″ greater than at Murree, and the difference may reasonably be attributed to the difference in geological conditions. The station of Murree is situated on rocks of the lower part of the Tertiary system, as developed in the Himalayas, and in the deep embayment of the exposure of these rocks, which marks the junction of the Himalayan system of disturbance with that of the ranges beyond the western frontier. The main boundary is not of the same sharply defined character as further east, but south of Murree is a broad expanse of middle and upper Tertiary rocks, and the eastern extremity of the Salt Range. The effect of the trough would be much smaller than on the eastern sections, so far as the deflection of the plumb-line is concerned, and in the absence of other stations for comparison, it is impossible to discover how far the small northerly residual, actually found, is due to the effect of the trough, and how far to an excess of the actual over the calculated attraction of the range, such as was suggested by the eastern stations. In either case the isolated position of the station, with none others near it for comparison, or as a check, makes it impossible to make any further use of the observation, which is, at least, not inconsistent with the conclusions drawn from the stations further east.

A list of the gravity stations in the Himalayan and Siwalik regions is given in table No. 30 (page 106), arranged in groups from west to east, as in the case of the latitude stations. It will be convenient to begin with the eastern group, where the station Sandakphu at about 26 miles in from the main boundary, gives a Hayford anomaly of + ·048 dyne, equivalent to the effect of the attraction of about 1,500 feet of rock at the surface, or of the equivalent of about half as much again, if the effect is due to a deficiency of compensation. At the other two stations we have only the Bouguer anomalies, but an approximate estimate can be made of the Hayford anomalies at these stations, either by applying the Hayford compensation of the Imaginary Range, as given in table No. 11, or by plotting the corrections to the Bouguer anomaly at Sandakphu, and the two stations of Siliguri and Jalpaiguri, and drawing a curve

TABLE 30.—*Gravity Stations in the Himalayas.*

STATION.	DISTANCE FROM THE		Elevation.	Bouguer anomaly.	Hayford anomaly.
	Main Boundary.	Boundary of hills.			
Moré	110 N.	150	15,427	— ·435 ?	
Simla	16 N.	34	7,043	— ·119	
Kalka	1 S.	11	2,202	— ·085	
Mussooree	3 N.	21	6,924	— ·110	+ ·049
Rajpur	0	18	3,321	— ·124	+ ·022
Kalsi	0	18	1,684	— ·098	
Dehra Dun	2 S.	12	2,239	— ·126	+ ·003
Fatehpur	6 S.	10	1,434	— ·100	
Hardwar	7 S.	0	949	— ·114	
Asarori	9 S.	8	2,467	— ·112	
Mohan	14 S.	0	1,660	— ·104	
Sandakphu	26 N.		11,766	— ·150	+ ·048
Darjeeling	15 N.		6,966	— ·143	
Kurseong	3 N.		4,915	— ·130	

through the three points, from which the correction at intermediate stations can be estimated. Either method gives a Hayford anomaly of between + ·02 and + ·03 dyne at Darjeeling and of between ·00 and + ·01 dyne at Kurseong. These results are necessarily approximate, but they are sufficiently near the values which would be derived from detailed computation to show that there is an increase in the force of gravity at Sandakphu, as compared with Kurseong, amounting to a departure of + ·05 dyne from the difference which should result from the hypothesis of compensation adopted in the calculations.

The northerly residual of deflection at the two latitude stations of Phallut and Tonglu, situated about 6 miles on either side of Sandakphu, makes it almost certain that the gradient of increase in the anomaly of gravity will continue to the northwards beyond Sandakphu, and that stations further into the hills would show even higher positive anomalies, though it is impossible to say for what distance this increase would continue. Now a gradient of increase in the excess of gravity of ·05 dyne in 30 miles, if continued, would give rise to a deflection of about 9″, if the anomaly were produced by a want of adjustment in the compensation. The actual residual deflection being about 10″, there is as close an agreement between the result of the gravity observations and of the deflection of the plumb-line as can be expected, and the want of adjustment between topography and compensation in this part of the range may be accepted as a fact, the consideration of its interpretation and origin being deferred for the present.

In the western group we have no gravity determinations, of which the Hayford anomaly has been calculated, further into the hills than Mussooree, three miles in from the main boundary, and the same distance in from the outer edge of the Himalayas proper. At this station the Hayford anomaly amounts to + ·049 dyne; at Rajpur, close to the main boundary, the same anomaly was found to amount to only + ·022 dyne, a remarkable difference to find in so short a horizontal distance. Part of this difference is the result of the method of calculation, combined with the fact that Mussooree is situated on the crest, and Rajpur at the foot, of a steep-sided hill, with a difference of level amounting to over 3,500 feet. In the method of calculation adopted, each separate small compartment is supposed to be separately compensated, but it is highly improbable that the compensation can vary as rapidly as the topography in a case like this, and if it varied more slowly the amount would not be largely different in the near-by compartments at each station; the result being that the actual calculation makes the effect of compensation too great at Mussooree and too small at Rajpur, thus increasing the difference between the anomalies at the two stations. Though part of the difference may be explained away in this manner, it is insufficient to account for more than a part, and probably a small part, and so we are driven to find another explanation, which is provided by the defect of density in the Siwalik rocks. If the trough in which they lie is supposed to be 10,000 feet deep, it would produce a difference of about — ·03 dyne at Rajpur as compared with Mussooree, and about — ·02 dyne at Dehra Dun as compared with Rajpur, or about the same differences are found in the calculated anomalies, which take no cognizance of the effect of the trough. We may conclude, therefore, that the actual excess of gravity at Mussooree and Rajpur is much the same and, interpreted as a defect of the compensation, appropriate to the averaged topography of the region, amounts to something less than ·05 dyne.

At Dehra Dun the anomaly is very small, but at this station a negative anomaly should have been expected, on account of the effect of the lesser density of the Siwalik rocks, which certainly extend for some thousands of feet under this station. If the thickness is taken at 10,000 feet and the distance of the station from the boundary of the trough at between 2 and 3 miles, the defect in the attraction of gravity would amount to about ·05 dyne, or much the same as the excess at Mussooree. It will be shown that the excess of gravity, which may be attributed to the want of adjustment of the compensation, decreases in the stations southwards of Dehra Dun, and so we may reasonably conclude that it will be less at that station than at Mussooree, but if the trough is 10,000 feet deep under Dehra Dun, there would need to be an excess of gravity apart from the effect of the trough of not less than the anomaly at Mussooree, and so again we find that the depth of the trough under the Dehra Dun is somewhat under 10,000 feet.

To the southwards of Dehra Dun are some gravity stations at which the Hayford anomaly has not been calculated, but can be estimated approximately by comparison of the corrections at the stations already considered, with those in the plains to the south. Accepting the figures given on p. 92, we find that at Asarori and Hardwar there is an anomaly of — ·1 dyne; as the effect of the trough would amount to at least — ·04 to — ·05 dyne, there is left an excess of gravity of from + ·03 to + ·04 dyne at these stations. At Mohan the anomaly, exclusive of the effect of the trough, is about — ·02, and the effect of the trough will be much the same as at Hardwar, leaving an excess of gravity of about + ·02 to + ·03 dyne. At Roorkee, the Hayford anomaly has been calculated as — ·043 dyne, and if this is directly interpreted in terms of the depth of alluvium necessary to produce the same effect, it represents a thickness of about 6,500 feet, but if interpreted in the terms of difference from Dehra Dun, indicates a depth of about 6,000 feet greater than at the latter station. In the last chapter a figure of 13,000 feet was indicated as the approximate depth indicated by the geodetic data, a figure which agrees very well with that indicated by deduction from the geological structure, and a comparison of this figure with those given in the last sentence suggests that the defect of compensation, found in the stations to the north, still exists under Roorkee, though the effect is reduced in amount to not more than + ·02 dyne. Here, however, we have reached a region where too many corrections of unknown amount have to be applied for the result to be of any real value, but the stations to the northward, in the Dehra Dun district, indicate a gradually increasing excess, as the range is neared, of gravity, which may be interpreted as an increasing defect of compensation.

Northwards of Mussooree there are no gravity stations, but in the group to the westward we have the station of Simla, situated about 13 miles further into the hills than Mussooree, whether we measure the distance from the main boundary or the outer limit of the hills. At Simla the Bouguer anomaly only has been calculated, which is negative and larger in amount than at Mussooree by ·009 dyne; as has been explained, the various corrections required to convert this into the Hayford anomaly would be very much the same at both stations, with the exception of the effect of the compensation of the range itself, and a reference to table No. 11 shows that this effect should be greater at Simla than at Mussooree by somewhere about ·035 dyne. From this it results that we should have expected the Bouguer anomaly at Simla to be greater than at Mussooree by not less than about ·035 dyne, whereas the excess of negative anomaly is just short of ·01 dyne, and it is, consequently, reasonable to conclude that the Hayford anomaly at Simla would certainly be positive and larger in amount than at Mussooree, probably somewhere near + ·08 dyne.

From this it will be seen that the progressive increase in the defect of compensation, as compared with the hypothesis on which the Hayford tables are based, is repeated in this part of the outer Himalayas, and that the magnitude and rate of increase is not very largely different in the two regions if we take the outer edge of the hills as the starting point for measuring distances. If, on the other hand, we take the position of the main boundary as the zero datum for distance, the anomalies are larger in the western group by close on ·05 dyne. Here we have a distinct suggestion that the main boundary, which may be regarded as a dominant feature of geological structure, is not continued into the region of compensation, but is confined to the outer portion of the crust.

This suggestion is an important one, and an attempt was made to test it by a detailed examination of the observations in the Dehra Dun district; the result showed that the apparent discrepancies between the observations were distinctly diminished if the compensation was regarded as distributed with reference to the general course of the range, rather than if it was distributed with reference to the sinuosities of the course of the main boundary; but the result showed that there were also variations in the force of gravity which must be attributed to some other cause, one of which might be a variation in the depth of the trough. There are in fact too many corrections of unknown amount to justify a detailed discussion of the inconclusive results, from which only one conclusion could be drawn, that neither the course of the main boundary, nor that of the outer boundary between hill and plain, coincided in detail with the limit of the compensation of the range.

We have seen that from the outer edge of the hills inwards, there is an excess of gravity, or a defect of compensation, which increases continuously as far as the observations extend, and that these show no indication of the progressive increase coming to an end. Yet it cannot go on for ever, and sooner or later the excess of gravity must diminish and ultimately disappear, and the principle of general isostasy requires that the excess of gravity, which has been established, should be balanced by a corresponding defect on one or both sides, of the under supported tract. To the southwards we can get no direct evidence, owing to the preponderating effect of the defect of density in the alluvial trough, the amount of which cannot be estimated with accuracy. To the northwards we shall have precise information when the observations made by Dr. F. de Filippi's expedition are published, but in the meanwhile we have a good indication of what the nature of these results is likely to be in Capt. Basevi's determination of the force of gravity at Moré. The results obtained by this observer, after having been discredited, have been reinstated and, the cause of the discrepancies between his values and those of later observers having been detected, it is once more possible to make use of his results. Every correction which has to be applied was used by Basevi, with the exception of that for flexure of the stand, the necessity for which had not been recognised, nor means devised for measuring its amount. Had he followed the usual practice of having pillars built at each station it would have been impossible to allow for this correction, but instead he used a strongly braced wooden stand, which was transported from station to station, and later observations, at stations where this stand was used, have so far indicated a fairly constant flexure correction of about ·04 dyne, with variations up to ·01 dyne on either side of the average. Had this stand been used at Moré we should be able to determine the force of gravity, within a limit of ·01 dyne, but it was replaced at this station by a lighter tripod, whose flexure would be different, and greater in amount than in the case of the standard stations; fortunately, however, the same stand was used at Mian Mir, and a later observation by Col. Lenox Conyngham showed that Basevi's determination was in defect by ·109 dyne at that station, a difference which may be attributed to the flexure of the stand used at that station and at Moré.

The published discussion of Capt. Basevi's observation indicates a defect of gravity, or negative anomaly, amounting to 24·11 swings of a pendulum which would beat seconds at the equator, after allowing for the effect of latitude, altitude and attraction of the visible masses above sea level.[1] Converted into modern standards the anomaly becomes ·545 dyne, to which the correction found at Mian Mir may be applied, making the actual anomaly about — ·434 dyne. As the formulæ on which this result is based have been superseded by others, believed to be more accurate, it will be safer to use the more modern value published in the Report of the 1909 meeting of the International Geodetic Association, where the anomaly is given as — ·433 dyne, an allowance of ·107 dyne being made for the flexure of the stand.[2] The two values of the anomaly differ by only ·01 dyne and we may take it that the deficiency at Moré is not far from ·43 dyne, omitting the third decimal figure as meaningless in the circumstances of the case.

This deficiency of gravity represents the effect not only of the compensation of the range but also that of the distant topography. The exact amount of this last has not been calculated in detail, but some estimate can be based on the fact that at Dehra Dun the effect of topography beyond a radius of 104 miles from the station amounts to — ·055 dyne on the Hayford hypothesis, and will not be materially different on any other admissible hypothesis of compensation. At Moré the effect of distant topography would certainly be greater than at Dehra Dun, but is not likely to be twice as much; if it should be as much as — ·100 dyne it would leave — ·33 dyne for the effect of the compensation of the range, a value which is not materially different from the effect of compensation within 100 miles of a station situated 150 miles from the edge of the Imaginary Range, namely about — ·33 dyne if the Hayford

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[1] Account of the Operations of the Great Trigonometrical Survey of India, V, p. 147, 1879.

[2] *Comptes Rendus de la seizième conférence générale de l' Association géodésique Internationale.* Vol. III, pp. 222 & 236 (1911).

tables, and about ·29 dyne if the Fisher constants, are used. The compensation of the actual range should somewhat exceed that of the imaginary, for the average level of the ground round Moré is more than the 15,000 feet assumed, but the difference cannot be great, and we may conclude that if the effect of distant topography is as much as —·100 dyne the range is just about completely compensated if the Hayford hypothesis is used, but that if the Fisher constants are adopted it is distinctly over-compensated. If the effect of distant topography is less than ·100 dyne, as seems more probable, then the defect of gravity becomes greater than can be accounted for on either hypothesis, and we reach the conclusion that the range is over-compensated at Moré, just as it is under-compensated at the stations in the outer hills.

Whether compensation is or is not in excess at Moré it is evident that the defect of compensation, which was so conspicuous in the outer hills, has disappeared, and that the station is either within, or on the borders of, the region of excess of compensation which is required to balance the defect met with further south.[1]

The conclusion drawn from the gravity observation at Moré is to some extent supported by the observations at two latitude stations situated on the southern border of the valley of Kashmir. These latitude stations were not included in the final account of the Operations of the Great Trigonometrical Survey, on account of a small uncertainty in their accuracy, due to unfavourable weather conditions, but, as this inaccuracy is certainly less than one second of arc, the results may be safely used for the purpose of this investigation.[2] The western station, Poshkar, is described as situated on a well-marked peak at the end of a spur that projects into the Kashmir valley from the Pir Panjal range, and is evidently situated on the small inlier of Panjal rocks, marked

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[1] It may be pointed out that, when discussing the Hayford anomalies of gravity in the alluvial plain, it was necessary to apply, what was in effect, a correction of —·02 dyne, to avoid the obtaining of a negative value for the depth of alluvium. It is not impossible that this represents a real correction to the method of calculation made use of, in which the ocean basins are assumed to be compensated in the same manner, and within the same depth, as the continental elevations, an assumption which is by no means necessarily correct. All that need be considered here is, that any correction of this character would change very slowly in amount, at stations in the interior of a continental area, and would have the effect of increasing the negative value of the anomaly at Moré.

[2] See Operations, etc., XI, 1890, pp. 18 &27, and Synopses of the Results of the Operations, etc., Vol. VII, 1879.

on Mr. Lydekker's map, in the position ascribed to the latitude station. The eastern station, Gogipatri, is described as being on one of the long slopes from the Panjal range. Both stations are in the region of the Karewah deposits, south of the newer alluvium of the valley, and the observations gave a deflection of + 11″ at Poshkar and — 1″ at Gogipatri, using the Everest spheroid and a deflection of + 4″ at the reference station of Kalianpur; deflections which become + 15″ and + 3″ respectively if the Bessel-Clarke spheroid is adopted.

These southerly deflections were attributed by the Trigonometrical Survey to the effect of the southerly attraction of the Pir Panjal range, yet it is doubtful whether this cause would, in itself, be sufficient to produce an actual southerly deflection, though it would necessarily reduce the amount of the northerly deflection due to the Himalayas as a whole. An approximate estimate, based on the 32-mile contoured map of India, gives the outward attraction of the mass between the stations and the plains as about + 20″ and the inward attraction of the masses towards the main range as about — 22″, allowing for the Hayford compensation of the visible masses in both cases, the greater proximity of the hills in the former case about counterbalancing the greater mass in the latter, with the result that only a small deflection in either direction is to be expected.

From this it is evident that the northerly residual of deflection, found at stations up to about 30 miles in from the main boundary further east, has disappeared at these two stations, and this suggests that they lie in the region where the northerly residual, resulting from the defect of compensation in the outer hills, is passing into the region where the excess of compensation in the central part of the range would give rise to southerly residuals. This deduction derives some support from the indications of a general recent uplift of the hills to the north of the valley, but any such inference is rendered unsafe by the fact that the southerly deflection, at both stations, may be due to the effect of the alluvium filling the depression of the valley of Kashmir, which, as in the case of the Gangetic alluvium, would cause an apparent repulsion, or southerly deflection, of the plumb-line. This cause is, indeed, the only obvious explanation of the great difference in the deflections observed at the two stations, for the Poshkar station is just south of the greatest development of the alluvial deposit, which is not only narrower to the north of Gogipatri, but probably shallower also; as suggested by the inliers of rock in the Karewa region to the west, and in the alluvium east of Srinagar.

The unknown amount to be attributed to this cause makes it impossible to determine the amount or direction of the residual of deflection, if the alluvium is taken out of consideration; but the observations do throw some light on an interesting point of geological structure, for they enable us to form some estimate of the depth of the depression of the valley of Kashmir. If we take the difference in the deflections to be entirely due to the effect of the alluvium we find that this is 12″ in the meridian, which is equivalent to about 17″ at right angles to the direction of the boundary of the alluvial deposit, and this, adopting the same density of deposit as in the Gangetic trough, would necessitate a depth of about 10,000 feet, or more. The estimate must be taken as very approximate, and subject to several qualifications, the most important of which are, firstly, the fact that the alluvium will not be altogether without effect at Gogipatri and, as the estimate is of a difference, this would necessitate an increase in the absolute depth; and secondly, the possibility that the southerly attraction of the Pir Panjal range may be greater at Poshkar than at the other station, thus lessening the amount of the difference in deflection which should be attributed to the effect of the alluvium, and so diminishing the thickness to be attributed to it. These two qualifications, therefore, introduce corrections in opposite directions and, as it is probable that both must be considered, they will, to a certain extent, neutralise each other, yet after making every reasonable allowance, there remains the conclusion that the depth of the depression under the valley of Kashmir is of such an order of magnitude as to bring its floor down to, if not below, sea level.

We can now summarise the separate conclusions which have been reached, and attain an understanding of the general distribution of the compensation of the Himalayas. In the central part of the range the compensation is in excess of the load which it is supposed to support; in the outer Himalayas, at a distance of 30 to 40 miles in from the edge of the hills, it is in very considerable defect; and somewhere between these two regions must come a tract where the compensation and topography are in adjustment with each other, where, in other words, the anomaly of gravity should be zero, proper allowance being made for the effect of compensation. Towards the outer edge of the hills the defect of compensation diminishes and the anomaly must ultimately become zero once more.

A variation of this kind in the adjustment between topography and compensation, or between load and support, is with difficulty intelligible, except on the supposition of a support of the range by flotation, and certainly finds easiest expression in terms of that hypothesis. In the centre of the range the downward protuberance of the crust is over-developed and there is an excess of buoyancy, tending to make the range rise, the excess of load in the outer hills would then be an indication that such rise has taken place, carrying with it the outer hills, till the load thrown on the central tract became large enough to check the further uplift and leave the main range at a lower elevation than that which would result from the protuberance beneath it, while, on the flank of this central tract, the outer hills are upraised beyond the height which they would attain by the effect of the support immediately below them. The general distribution of the stresses set up in the mountain range, by this want of adjustment between load and support, would be as shown by the arrows in fig. 8; in this diagram the points O O represent the points at which there is a complete adjustment of the

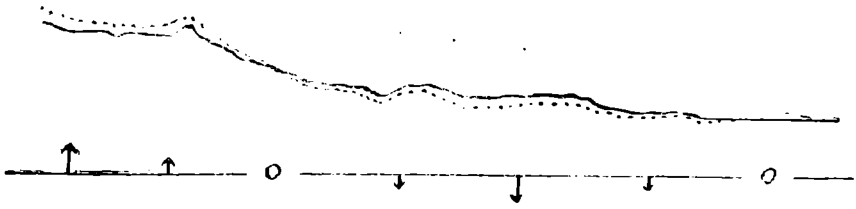

FIG. 8.

FIG. 8.—To illustrate the adjustment between topography and compensation in the Himalayas. In the central region, to the left of the diagram, the compensation is in excess of the load, producing an upward stress, as indicated by the arrows; in the outer region compensation is in defect, and there is a downward stress. The firm line represents the actual contour of the ground, the dotted line, that which it would have if the adjustment between topography and compensation, of load and support, were everywhere exact and complete.

compensation to the topography, not necessarily coincident with the zero points of the Hayford anomaly; to the left there is an excess of compensation, resulting in a tendency of the range to rise as indicated by the arrows; between the two zero points the compensation is in defect and the excess of load results in a tendency for the hills to sink. The same conclusions may be otherwise depicted in the outline of the topography where the firm line represents the section of the range as it actually exists, and the dotted line that which it should be if the topography were everywhere adjusted to the compensation.

One more conclusion may be drawn from the distribution of stresses indicated in the diagram. If the crust has sufficient strength to bear the load imposed on it by the superelevation of the outer hills, it is improbable that the adjustment would cease at the right hand zero point; the load on the tract between the two zero points would tend not only to hold down the central portion of the range from rising but also to bear down the crust on the right into the plastic, denser, layer below, and so we might expect to find a defect of gravity outside the range, quite apart from that due to the defect in density of the alluvium. It will be shown, further on, that there is some indirect evidence of the existence of such a depression of the under side of the crust, but there is no possibility of getting any direct confirmation of it from observations in the alluvial area, for the effect would be masked by that of the trough; and as our only estimate of the depth of the trough, except close to its margins, is derived from the geodetic evidence, any attempt, based on this evidence, to separate out the one effect from the other would be merely arguing in a circle.

The local departures from a condition of equilibrium between topography and compensation, which have been found in the Himalayas, indicate a degree of rigidity, and strength, of the crust greater than that which has sometimes been attributed to it, and this might lead to doubt as to the correctness of the inferences which have been drawn. On this point we have, fortunately, the recent elaborate investigation of the rigidity of the earth's crust by Prof. J. Barrell,[1] in which, after dealing with geological and geodetic data in the United States and elsewhere, he concludes that the crust is strong enough to support a load of over 3,000 feet of rock, har-

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[1] *Journal of Geology*, Vols. XXII and XXIII *passim*, 1914-15.

monically distributed over a wave-length of nearly 400 miles,[1] a degree of strength which is much greater than is needed to allow of the local departures from equilibrium which are met with in the Himalayas.

It will be of interest to find where the position of the right hand zero point of fig. 8 lies with regard to the outer edge of the Himalayas. In this connexion we have a suggestion in the fact that the Hayford anomaly near the outer edge of the hills, after allowing for the effect of the Gangetic trough, seems to have a small positive value, of the order of ·01 dyne, on both the Dehra Dun and the Sikkim sections. Too much weight must not be attached to this coincidence, as the actual compensation will not be identical with that adopted in the tables computed by Messrs. Hayford and Bowie, but it is suggestive of the conclusion that the zero point, where the uplift of the outer Himalayas comes to an end, lies beyond the edge of the hills, and under the northern part of the alluvial plain.

This conclusion receives some support on the geological side. Everywhere along the foot of the hills there is a gravel slope, composed as a rule of much coarser material, and having a steeper surface gradient, than the alluvial plain beyond. This gravel slope known in part of Upper India as the *bhabar*, is the result of deposit of coarser material by the streams as they leave the hills, and the steeper surface gradient has generally been attributed to the steeper slope of deposit of this coarser material, as compared with the finer silt of the plain proper. On some sections, however, the increase of surface gradient towards the hills results in a slope too steep to be accounted for in this way, and almost everywhere we find the streams cutting their way through the old gravel deposits at a lower level, and on a lower gradient, than the general slope of the surface. To some extent this may be due to climatic change, but this explanation does not seem adequate, and there remains a distinct suggestion, even where there is not a practical certainty, that there has been a general tilting of the surface and an uplift on the side towards the mountains. It is important to note that this surface tilt is too even and regular to be referred to any compression, folding, or similar process; it is not analogous

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[1] Vol. XXIII, p. 30. Not, be it observed, in addition to the weight of the crust itself. This is supposed to be everywhere isostatically supported; it is only the unsupported excess or defect which is borne by the strength of the crust.

to the disturbance which the strata have undergone in the Siwalik hills, but is a general tilt, which may reasonably be attributed to a general displacement of the crust, and to a continuation of the general uplift which is indicated in the outer hills, which, in this case, must extend beyond the limits of the hills into a region where its further progress can only be traced by inference from the geodetic data. It may also be pointed out that this interpretation is in accordance with, and may in some respects be regarded as a confirmation of, the conclusions, independently reached, that the great boundary faults of the sub-Himalayan region are the result of tectonic processes in the outer part of the crust, and do not extend downwards to its lower limit.

The conclusions which have been elaborated, as to the excess of support in the central part of the Himalayas, and the uplift which has thereby been superimposed on the mountain building processes in the outer hills, are of great importance in attaining an understanding of what these processes are, and to what causes they may be attributed. In one respect the question of the origin of the mountains may be regarded as having been put in a new light, for, hitherto, it has been usual to regard the visible range as the primary problem and the provision of support, or compensation, as a secondary one; but, in the light of the results of geodetic work in the Himalayas, the order must apparently be reversed, the primary phenomenon being the production of an excess of buoyancy under the range, in virtue of which the range is uplifted, and the range itself becomes but a secondary, though the most conspicuous, effect of the processes at work.

CHAPTER VI.

SUMMARY AND CONCLUSIONS.

The various groups of geodetic stations have now been considered in detail, and the conclusions, which may be drawn from each, have been indicated, but it is still necessary to review these as a whole and to consider how far they help in the solution of the problems, still in doubt, which were indicated in the opening chapter as those in which the geodetic evidence might help.

These questions will most conveniently be taken in the reverse order to that adopted in stating them, and it may be said that the geodetic observations fully support the two conjectures, that a rock barrier extends, at no great depth below the surface of the alluvium, from the peninsular rock area to that of the Assam Range to the east, and to the Salt Range to the west.

We have also found complete confirmation of the geological deduction that the depth of the alluvium along the outer edge of the Himalayas is great, amounting to about 15,000 to 20,000 feet towards the northern boundary of the alluvial plain, figures which are in complete accord with those deduced from the geological examination of the Siwalik hills.

This agreement, between the results of two wholly independent and different lines of research, leaves little room for doubt that we have reached a correct interpretation of the underground form of the Gangetic trough from near its northern limit to the southern boundary, and that its maximum depth is about 15,000 to 20,000 feet, possibly more on some sections, probably less on others, but in most cases lying within the limits named. From this maximum depth, at a distance of from 10 to 30 miles from the northern edge of the plain, the floor slopes upwards, with a fairly uniform slope, to the southern limit, whether this is marked by the reappearance of solid rock, at the northern boundary of the Peninsular area, or by the hidden barriers under the alluvial plains, over which the drainage of the Ganges and Brahmaputra reaches the Bay of Bengal on the one hand, or the rivers of the Punjab flow down to the Indus and so into the Arabian Sea on the other.

The underground form of the trough in its northern portion, along the edge of the Himalayas, is less clearly defined. On only one section, that of the Dehra Dun, do the observations extend across the Siwalik area to the Himalayas proper, and here they indicate that the maximum depth of the alluvium lies not far from the outer edge of the Siwalik hills, but whether actually at the boundary or at some distance from it is not established. Under the Siwalik area there is a distinct shallowing of the trough, probably abrupt and coincident with the outer edge of the hills, and, at the northern boundary of the Siwalik region, the floor of the trough rises abruptly along the main boundary fault, the throw of which is indicated as something less than 10,000 but probably over 7,000 feet.

Another section, which traverses the whole width of the alluvium near the 81° meridian, but stops short at the foot of the hills, indicates much the same conclusions, that the floor of the trough rises rapidly under the Siwalik area, though here the maximum depth may be 50 miles or more from the edge of the hills. A third section, near the eastern end of the trough, where the Siwalik zone is unrepresented, or covered by alluvium, indicates an increase in depth from south to north almost up to the outer edge of the hills, though a larger number of observations might put the maximum depth somewhat south of the station nearest the hills, at which the largest depth is indicated.

The structure indicated on these sections may reasonably be extended to others, and in it we find a confirmation of the deduction, which had been drawn from geological data, that the underground form of the trough near its northern limit, as well as the nature of the northern boundary, is radically different from what is to be found under the southern part of the trough. To the south of the present line of maximum depth the trough has been formed by simple subsidence and the alluvium deposited on an old land surface, preserved with little or no change in its original form. To the north, the rise is not only more rapid, but more irregular and determined mainly by tectonic processes, connected with the origin of the hills, which have profoundly altered the original form of the floor of deposition, and involved some of the originally undisturbed deposits in the folding and faulting of the process of mountain formation.

Incidentally we find a confirmation of the interpretation which had been accepted, rather than demonstrated, that there is a rise in the floor of the trough under the Siwalik area, and indirectly of the deduction that the outer edge of the hills marks the position of a structure similar in character to the faults which traverse the Siwalik area, and form its northern boundary for a large portion of the length of the Himalayas.[1]

There remains only the question of whether the compression, which the rocks of the Himalayas have unquestionably undergone, is the cause, or merely the accompaniment, of the elevation of the range. The treatment of this question is impossible without considering that of the origin of the Himalayas and a discussion, which need not be detailed, of the explanations which have been offered, of the origin of the Himalayas, and of the closely connected problem of the origin of the Gangetic trough.

It has already been shown that there is some suggestion of the boundary faults, and with them of the tectonic processes which have modified the underground form of the floor of the trough, being phenomena of the upper part of the crust alone, and independent of the more deep-seated changes in the distribution of density on which the compensation depends.[1] This being so, it is obviously possible that the same conclusion might be extended to the whole of the trough, and its existence be regarded as due to processes which were confined to the upper part of the crust proper, with the result that there would be neither need nor reason to look for any more deep-seated cause of origin. The magnitude and extent of the trough seem to make any such localised cause inappropriate, and the radical difference in the form and boundary of the southern part, as compared with the northern fringe, makes it probable that an entirely different set of processes have been at work, and that the trough as a whole may be due to deep-seated and widespread forces, involving the crust, as a whole, and the material which underlies it. In this case we cannot ascribe the trough to any deformation of a part of the crust, such as has profoundly modified the form, and defined the boundary, on the north, but rather to a general subsidence of the crust, increasing in amount from south to north.

In searching for a cause, which could have produced this depression, we must first of all reject the notion that it can be a direct downward pressure due to the weight of the alluvium. The notion

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[1] *Supra* p. 109.

that the deposit of sediment on the surface of the earth must cause a subsidence, in consequence of the additional load, is one which has had some vogue; it is unnecessary here to discuss the justification of this idea, it is sufficient to point out that the cause is obviously inapplicable in the case of the Gangetic trough. Not only is the surface of the alluvium at a lower level than that of the rock areas to the north and the south, but the density of the material is very considerably less than that of the rocks on either side; consequently the load borne by the crust in the region of the Gangetic trough must be less than in the Himalayas to the north, or in the peninsular rock area to the south, as is proved by the result of gravity observations in the alluvial plain. But though the weight of the sediment cannot have been the originating cause of the depression of the Gangetic trough, it may well have had considerable influence in determining the magnitude of its dimensions, for if there had been some other cause capable of forcing down the level of the crust to a given depth before the resistance to further movement became equal to the force, then the addition of a load of alluvium would enable the same force to lower the level to a greater extent than if the hollow had been left empty or only filled with water. The amount of this extra depression would depend on the balance between the force and the resistance; if both remained appreciably constant, within the limits of movement involved, the weight of the alluvium would enable this to be carried about five times further than would otherwise be the case, so that the Gangetic trough, taken as 15,000 feet deep, would only have had a depth of about 3,000 feet had it not been filled with alluvium as fast as it was formed.

One such possible cause has been indicated by Mr. Fisher. He pointed out that if material is removed by denudation from the surface of a range, and deposited by its side, the centre of gravity of that portion of the crust comprising the two regions would be shifted laterally, and, on the assumption of a crust supported by flotation, there would be a disturbance of the condition of equilibrium, so that the centres of gravity and of buoyancy would no longer lie on the same vertical line. As a result, a couple would be set up, tending to raise the range and depress the crust alongside it, till the loss of buoyancy under the range, and the gain under the plain, led to a re-establishment of a condition of equilibrium and, as a further result, a depression of the surface would be formed along the foot of the range, which would grow in depth, and in breadth, as the range increased in height. The reasoning is perfectly sound from a mechanical point of view; given a crust of some degree of strength and rigidity, supported by flotation, the processes conceived will follow with logical necessity, and it is interesting to note that the results of this purely mathematical investigation agree remarkably with the deductions which result from geological examination as to the character of the southern margin of the alluvium, the history of its gradual extension to the south, and the radical contrast in character between the southern and northern margins of the trough. The only doubt is as to whether the cause invoked by Mr. Fisher would be quantitatively sufficient to produce the results, and with regard to this it may be pointed out that the action, which he conceived, would be reinforced by the effect of an increase in the buoyancy under the range, such as has been indicated in the preceding chapter, so that it is possible for the combined effect of the two causes, working in the same direction, to have given rise to the depression of the Gangetic trough, though neither of them would, independently, have been sufficient.

The only test which we can apply to this interpretation is to be derived from the geodetic data. It is evident that a depression of the lower surface of the crust, with the consequent displacement of denser by less dense material, would produce an effect on the plumb-line and the pendulum, it would cause a northerly deflection to the north of the trough, and a southerly deflection to the south, and would give rise to a defect of gravity, greatest along the line of maximum depression and decreasing on either side. These effects, it will be noticed, are similar in kind to those produced by the alluvial trough, but, being much smaller in amount, are so effectively masked by those due to the alluvium itself that it is difficult to disentangle them. An attempt was made, by a comparison of the results derived from the deflections and the gravity observations, to separate out the effect of a possible depression of the crust as a whole from that of its upper surface, the attempt led to an apparent confirmation of the hypothesis, but it involved too many considerations of very doubtful validity to justify the space necessary for its exposition. There are, however, within the area of the alluvium some observations, otherwise difficult to understand, which find an easy interpretation in this way, namely, the very considerable defect of gravity at Monghyr and the lesser defect at Sasaram, which cannot be attributed to the alluvium, but could find an explanation in a depression of the crust into the denser material below, though whether this explanation is valid cannot be established.

It is outside the alluvial area that the test of the hypothesis must be looked for; the boundary of the alluvium would not necessarily coincide with that of the trough, for south of the alluvium the general level of the surface continues to rise, and in this region we may look for effects to be recognisable, which would be masked by others, of greater magnitude, in the alluvial plain. Now the investigation by Sir S. G. Burrard of the deflection of the plumb-line in India, published in 1901,[1] showed that along the northern edge of the peninsular area the deflections were all to the southwards, and that further south comes a belt in which northerly deflections prevail. His investigation established the conclusion that these facts could only be explained by the existence of a belt of excess of gravity, or as he expressed it a Hidden Range, traversing the Peninsula in a direction approximately parallel to the Himalayan Range, and having its crest directly under the station of Kalianpur. This conclusion has since been supported by the gravity observations, and by Major Crosthwait's determination of the residuals of unexplained deflection at a number of stations in India. The highest positive anomalies of gravity are at Kalianpur and Seoni; between these stations and the alluvial plain, positive anomalies prevail, but of lesser amount; and the line of separation between those stations at which Major H. L. Crosthwait obtained a southerly, and those which show a northerly, residual, also runs through these two places and follows almost exactly the course of the "Hidden Range" as indicated by Sir S. G. Burrard in 1901. In the diagrammatic representation, reproduced in fig. 9, of this belt of greater density it is shown as comparatively narrow and steep-sided, and in this form the result would not accord very well with observation, a mass of the form indicated would produce effects distributed very much as shown by the figures in table No. 1, immediately over the crest there would be no deflection, then a gradual increase to a maximum and a gradual dying out again as the distance increased. Actually, however, the observations suggest the existence of local

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[1] Survey of India, Prof. Paper No. 5, Dehra Dun, 1901.

irregularities of deflection superimposed on a general southerly deflection, which remains fairly constant over a wide tract of country; this condition would be satisfied if we supposed the belt of greater density to have the form indicated by the dotted lines in fig. 9, that is to say, instead of being narrow and steep-sided, to be broad with a gentle slope downwards on either side. If the excess of gravity along the crest of the range is taken as equivalent to about ·04 dyne, and the zero point at a distance of about 200 miles, the southerly deflection would be about 3″; and if the slope of the Hidden Range were continued into the depression under the Gangetic alluvium, in the manner which will be suggested immediately, this deflection would continue in fairly constant amount up to and beyond the boundary of the alluvium.

So far as I know, the only suggestion, which has yet been made, to account for the origin of this Hidden Range, is that the excess of density is due to an intrusion, or series of intrusions, of dense basic or ultrabasic rocks.[1] To this the same objection applies as to any ascription of the effect to a comparatively narrow belt of excessive density, and we must look elsewhere for an explanation of the origin of this feature, which seems marked out, by its courses and position, as in some way connected with the origin of the Himalayas. One such explanation follows, as a natural consequence from Mr. Fisher's interpretation of the origin of the Gangetic trough. Granted the existence of a floating

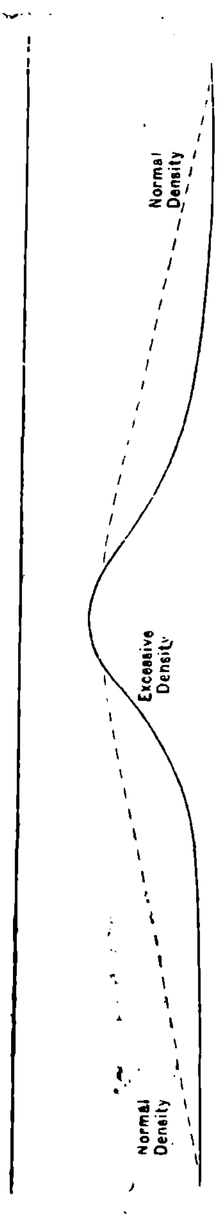

FIG. 9.—Diagram representing the "Hidden Range" of excessive density in the northern part of the Peninsula. The firm line reproduces the original diagram; the dotted line the modification suggested as being in better accord with the observations.

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[1] T. H. Holland. Presidential address to section C. *British Association Report* 1914, p. 358.

crust, of sufficient strength to enable it to be forced downwards into the denser matter underlying it, in the manner which has been outlined, it is improbable that so large a depression would at once die out into a condition of equilibrium on the further side from the hills. The very strength of the crust which enabled the depression to be formed would be likely to uplift the crust, on the further side, beyond the point of equilibrium, before it finally sank down into a normal condition, unaffected by the exceptional circumstances connected with the Himalayan range. In this way the depression of the Gangetic trough would be bordered on the south by a tract where the crust was uplifted, as a whole, with the consequence of the rise of the denser matter from below into the hollow formed in the under surface of the crust, and so give rise to precisely the phenomenon which Sir S. G. Burrard found necessary to invoke, in order to account for the observed deflections of the plumb-line.

The argument of the last paragraph may be made clearer by reference to fig. 10, where a cross-section is depicted, from the centre of the Himalayas to about the centre of the Peninsula, covering about 10° of latitude or a distance of some 700 miles. In this figure the actual relief of the surface is indicated on a somewhat exaggerated vertical scale, in order to make it recognisable; below is represented, on an equally reduced scale, the under surface of the crust, adopting Mr. Fisher's constants of a thickness of 25 miles for the undisturbed crust, and a ratio of 9·6 : 1 between the prominences on the under and upper surface of the crust, respectively.[1] In this part of the figure there are two lines, one firm and the other dotted, of these the dotted line represents the under surface of the crust as it would be if there was at every point a complete compensation of the surface irregularity, the firm line represents the form of the under surface of the crust as it would have to be in accordance with the departures from exact compensation which have been established or inferred. The treatment is in fact the reverse of that adopted in fig. 8, in which the adjustment was made by an alteration of the surface level, and the hills supposed to be either held down or uplifted.

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[1] It is obvious that the dotted line, which represents what the under surface should be, were the inequalities in the surface and the Gangetic trough completely compensated under every point, may also be regarded as representing the proportionate amount of the compensation, irrespective of any theory of how it is brought about.

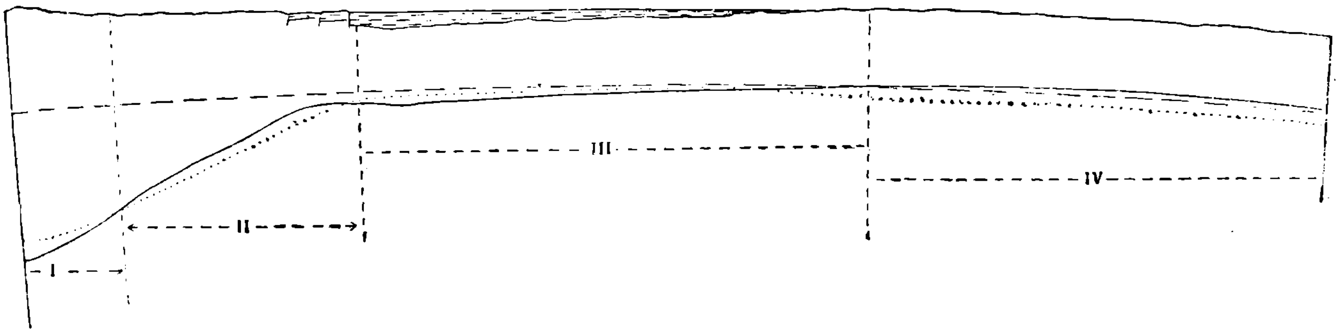

FIG. 10.—Cross section of the Himalayas, Gangetic trough and part of the Peninsula. Above is represented the actual form of the ground and the cross section of the Gangetic trough on a natural scale of curvature of the earth. Below, the broken line represents the assumed original lower surface of the undisturbed crust; the dotted line represents the form of the under surface as it would be if the balance between load and support were everywhere exact, and no local departures from average density in the crust; the firm line represents the actual form of the under surface according to the interpretation elaborated in the text. I is the region of excess of support; II the region of defect of support, where the surface is superelevated by the surplus buoyancy of region I, which is held down by the excess of load in the region II; III is the region of depression of the crust caused by tilting due to the overload of region II; IV is the region where the hills are nearly uncompensated and the crust is uplifted by the downward tilt of region III, to form the " Hidden Range" of Burrard. The length of the section represents a distance of about 700 miles; vertical scale of the upper surface is exaggerated by about one half, of the lower surface reduced by about one-third.

Turning now to the interpretation of these two lines, we see on the extreme left of the figure, that the firm line is below the dotted one, representing the greater depth of "root" required to produce the excess of compensation which exists in this region. To the right, but still within the region of the hills, this excess of compensation disappears and we enter a region where the crust is uplifted, as a whole, by the excess of buoyancy to the left, the hills are still compensated to a large extent, but not completely, and the defect may reach a maximum of about the equivalent of 2,000 feet of rock, or one-sixth to one-fifth of the whole amount of what would be complete local compensation of this portion of the range. Further to the right, this uplift gradually dies out and a condition of equilibrium is reached, at a point somewhat beyond the outer limit of the visible hills, but not maintained, for the weight of the tract which has been uplifted by the excess of buoyancy in the central region bears down the crust on the side towards the plains, and causes the crust to be depressed below the level of equilibrium, giving rise to the depression of the Gangetic trough. This depression reaches its maximum limit and then the buoyancy of the crust, further away from the hills, causes it to bend upwards, till a condition of equilibrium is again reached, at a point which seems to lie not far from the southern boundary of the alluvium, where it attains its greatest development and width, but to lie south of the boundary in the region of the Aravalli hills, and where the Rajmahal hills project into the alluvial area west of the Gangetic delta. Further to the right the condition of equilibrium is, once more, not maintained, but the downward tilt of the crust to the left is continued as an upward tilt to the right, with a corresponding rise of the under surface of the crust, till the weight of the unsupported crust beyond puts an end to this uplift, and the crust bends downwards again into a condition where the influence of the Himalayan range is no longer felt.

It will be seen that this development of the consequences which would result from the hypothesis of a floating crust, supported on a denser, plastic, but not necessarily liquid, substratum, is in close accordance with the larger features of the structure of the country south of the Himalayas. It provides for the trough, for the elevation of part of the earlier deposits formed from the waste of the hills on the north of this trough, and for a gradual extension, by progressive regular subsidence, to the southwards, as the range itself grew in magnitude; it provides also for that belt of positive anomaly of gravity, traversing the Peninsula, with its comcomitant effect on the plumb-line; and it may be added that the strength of the crust, required to produce these effects, is much the same as that deduced by Prof. Barrell from the geodetic work in North America.[1] This agreement, between the results of conclusions drawn from observation and those obtained by deduction, lends considerable support to the hypothesis on which the deductions were based, but it must be confessed that the Himalayas are the only range where anything like this agreement has been found, yet even this may rather strengthen than weaken the support, for it may well result from the magnitude of the range, which is not attained by any other mountains of the world. It is conceivable that only in the mountain system, of which the Himalayas form the culminating member, do the gravitational stresses set up by the processes of mountain formation reach a magnitude which enable them to dominate all other influences, and to produce a simplicity and magnitude of structure, obscured in other cases by the action of other influences and resistances, which become more prominent with the decrease in the magnitude of the gravitational stresses.[2]

We have seen that, the phenomena actually observed, in the region lying in and to the south of the hills, are in agreement with, and are easily explained by, the hypothesis of a solid and somewhat rigid crust supported by flotation on a substratum of denser material; but when we come to consider more especially the range itself, difficulties arise in the acceptance of Mr. Fisher's explanation of a simple thickening of the crust by compression. In his investigation the crust is supposed to be compressed as a whole and, recognising that the resistance of the lower part would be less than that of the upper, the neutral zone was put at two-fifths of the thickness from the upper surface, so that all above this would be thickened upwards and all below in a downward direction. In these circumstances the downward protuberance would be half as large again as the upward one, which would give an insufficient

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[1] *Journal of Geology*, XXIII, p. 30 (1915).

[2] Too little is known of the Andes, the only other mountain system of comparable magnitude, to admit of comparison with the Himalayas. [Since this was written, some particulars of deflection of the plumb-line in the Andes have been published, indicating that it varies in much the same manner, and to about the same extent, in these two ranges, which are of very much the same magnitude, in the portions which have a predominating share in the effect on the plumb-line. *Geog. Jour.* XLVII, 464-467, & XLVIII, 180-181, (1916).]

support by flotation, and the range would sink, carrying with it the crust on either side till a condition of equilibrium was attained. This explanation carries with it the necessity of a depression on both sides of the range; it renders the elevation of the marginal deposits almost impossible, and is in contradiction to the excess of support which is actually found in the central Himalayas. The latter condition could, however, easily be met by putting the neutral zone at a higher level. If placed so that the amount of the crust below were ten times that above, which would correspond to a depth of about two and one-third of a mile in a crust of 25 miles in thickness, the downward protuberance would exceed the upward one in just about the proportion necessary to provide a small excess of flotation.

In some respects a neutral zone so near the surface would be welcome, for some of the complicated structures, which have been revealed by geological survey of the more highly disturbed regions of the earth, certainly seem easier of explanation if we can consider the relief from compression as having taken place in a downward, rather than an upward, direction, and it is equally easier to accept these structures as having been brought upwards from a depth of a couple of miles than from five times that depth. On the other hand, a neutral zone so near the surface seems to give an inadequate cover for the production of a complicated folding of hard rocks, such as could only take place, without crushing and fracture, under a heavy superincumbent load of rock. A more important objection to this explanation is the fact that, though it would provide an adequate amount of support, it would not provide for the alternate defect and excess of compensation, which is revealed by observation, for, so long as the neutral zone is maintained at the same absolute level, preserving the same proportion between the thickness of crust above to that below it, the relative dimensions of the upward and downward protuberance would remain unchanged, and the hills would be uniformly over- or under-compensated, as the case might be.

A relief from this difficulty may be obtained in several directions. In the first place if the neutral zone maintained a nearly constant depth from the surface, instead of the same fraction of the total thickness of the crust, the downward protuberance under the central range would be developed in greater proportion to the upward one, and the excess of buoyancy attained. The distribution of resistance to compression, needed to bring this condition about, would be somewhat peculiar, but by no means impossible, yet it must remain merely a suggestion, in the absence of any means of testing it. Another possibility is that, in addition to the thickening of the crust by compression, its density is actually reduced in some way or other, and here Dr. Fermor's suggestion of the passage of rocks, belonging to the same norm, from a mode of greater density to one of lesser, affords a feasible explanation, but, like the previous one, it must remain a mere suggestion.

Neither of these suppositions involves the implication of any fresh material, from outside the portion of the crust covered by the hills, in the process of mountain formation, but the excess of support under the main range might equally be accounted for by an invasion, of the tract under the hills, by material from outside, whether by the injection of acid intrusions, or by a differential movement of the lower and upper parts of the crust, such as could be described indifferently, according to the point of view, as an over-thrust of the upper portion towards the south, or an under-thrust of the lower towards the north.

It is in the last-named direction that the easiest relief occurs from the difficulties arising from a limitation of the cause to the area actually covered by the range. The attribution of part of the downward prominence to an invasion of material from outside the limits of the range, would enable the neutral zone to be brought down to a level which would remove any difficulty in explaining the production of complicated folding of the rocks, but it is important to note that any process of this sort can only be subsidiary to the effect of compression, and that we cannot, on the hypothesis under consideration, attribute the whole, or even the major part, of the elevation of the range, to the invasion of material from outside. The case can be put simply enough : using Mr. Fisher's constants, the total thickness of the crust under the range would have to be just about twice as much as the normal thickness of the undisturbed crust, but these constants, as has been pointed out,[1] represent what may be regarded as a minimum value for the thickening, which may amount to three times the normal thickness ; the hypothesis, therefore, demands a compression of from one-half to two-thirds of the original horizontal extent of the crust. The actual amount of compression, indicated by geological structure, cannot be estimated with

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[1] See p. 48.

accuracy but, allowing for all possible over-estimates, it cannot be put lower than one-third, and is probably not much over one-half, of the original extent. It will be seen that the two estimates overlap, so that it is just possible to account for the support of the range, by compression limited to the area covered by the hills; on the other hand, if we take the highest estimate derived from the hypothesis and the lowest possible from observation, the downward prominence produced by compression would have to be reinforced by an equal bulk of material, of similar density, to provide sufficient support for the visible range. These may be regarded as the extreme limits, and the most natural conclusion is that, although simple compression might account for the whole of the support, or might be unable to account for more than one-half, the conditions lie somewhere between these two limits, and probably nearer to the first than the second, so that we may take it that, on the hypothesis which is being considered, the greater part of the support of the range would be provided by the compression, which it has certainly undergone, though a small portion may be attributable to the invasion of material from outside.

The specific question which had been put, of how far the elevation of the Himalayas is the direct result of the compression which they have undergone, seems to have been answered. An hypothesis has been found which is in accord with observation, not only within the limits of the range itself, but in the regions outside the range, where structures closely related to it in geographical extent and, presumably, in origin, are met with. But before this hypothesis can be accepted as in any degree satisfactory, it is necessary to examine the other explanations which have been offered at various times, and it will be of interest to pursue the hypothesis which has been discussed somewhat further, to see whether a satisfactory explanation can be found of the compression which it makes mainly responsible for the elevation of the Himalayas.

To take this last question first, it must be confessed that Mr. Fisher's investigation gives no conclusive answer. He rejected the obvious suggestion that it was due to the contraction of the earth by cooling; the cause may be a real one, it provides a force very many times more than adequate to produce the effect required, but the possible range of motion is almost equally in defect of that necessary to account for the compression which has taken place.

He next investigated the possibility of an expansion of the crust by the injection of dykes; this process seems just about able to produce the amount of force required, but here again the range of motion is inadequate. He finally suggested the existence of convection currents, rising under the ocean beds, flowing outwards along the under surface of the crust towards the continents, and giving rise, by a drag on the under surface of the crust, to compression in the continental areas. This cause, granted the existence of the currents, would produce an ample range of movement, but it is doubtful whether it could produce sufficient force to give rise to a yielding and compression of the crust. The drag exerted by such a current on the underside of the crust would be proportionate to three factors, the co-efficient of friction, the rate of flow, and the length of the tract along which the flow takes place; of these the first would be small, the second probably also small, but the third would be some hundreds of miles, and therefore large, so that the stress, accumulated along a length of the crust, might attain a magnitude sufficient to give rise to compression of the weaker portions of the crust.[1] It seems that, granted the existence of the currents postulated, the effect might be produced, but the conclusion is by no means established, and the postulate has by no means been accepted, very largely on account of the nomenclature adopted.

The notion of convection currents connotes, and was certainly intended to imply, a degree of fluidity which appears difficult to grant, but it is important to observe that similar movements might take place in a material which exhibits none of the properties associated with a fluid, as it exists on the surface of the earth. A material having the properties of the asthenosphere of Prof. Barrell,[2] would have sufficient power of yielding, to long continued stresses, to permit of the existence of movements analogous to convection currents, and so provide the motive power required. Though possible, however, this explanation can hardly be regarded as probable, or even satisfactory, but it is at least a feasible one, and not more unsatisfactory than any other which has been offered as yet.

Of these the first to be considered is that of Prof. Suess which, being incorporated and developed in his great work on the

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[1] *Physics of the Earth's Crust*, 2nd ed., 1889, p. 320.
[2] *Journal of Geology*, XXII, 1914, p. 655.

Face of the Earth, has attained a certain vogue, and a considerable amount of influence on geological thought and speculation. This explanation is based on the hypothesis of an originally highly heated solid globe gradually cooling by radiation from the surface, and the effects of surface deformation are attributed to the compression, to which the outer layers of the earth would be subjected, by the gradual contraction of such a globe. In explaining the actual forms, assumed by the surface, great stress is laid on the supposed directions from which pressure was applied, and to which movement took place. In the case of the Himalayas it is specially argued [1] that the form of the range, and of the associated ranges on the eastern and western frontiers of India, can only be explained if pressure was applied from outside towards the steady mass of the Peninsula, and is inconsistent with the supposition that the pressure and movement came from the south. On this view of the case the peninsular area naturally became a foreland, and the Gangetic trough a foredeep ; but the whole of the reasoning, on which the conclusion is based, is permeated by two mechanical fallacies.

The first is the possibility of a one-sided application of pressure ; but pressure can only exist if there is some resistance, and the resistance necessarily gives rise to an equal and opposite pressure. If these opposing pressures exceed the resistance of the material, compression, and consequent movement, will take place, but the direction and form, which this yielding will assume, is dependent solely on the nature of the resistances, and the amount of movement needful to relieve the pressure. The other fallacy is the possibility of absolute movement, and this will be most easily explained by reference to a diagram ; in fig. 11 let A B be two

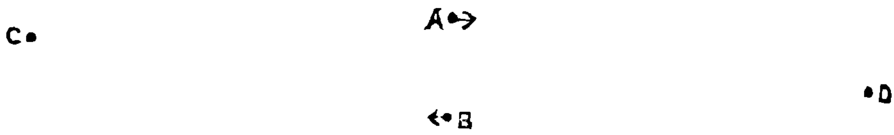

FIG. 11.

points near the outer limit of the Himalayas, C a point well away to the northwards and D one well away to the southwards, and

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[1] *Das Antlitz der Erde*, III (2), p. 707. English translation IV, p. 614.

suppose the distance between C and D to be reduced. Then, in the first place, we can only determine the change in distance, and cannot say whether C has moved to the right or D to the left, except by reference to some more distant point, such as the north pole, which again can only be fixed by reference to some still more distant points such as the sun or stars, which obviously have nothing to do with what goes on between C and D. Next, as regards this tract, we may suppose the tract to be uniformly compressed, in which case all the distances are proportionately reduced and the positions of A and B relative to each other are unchanged; or we may suppose the distances from C to A and from D to B to remain unchanged, those from C to B and from D to A being shortened, and in this case the effect will have a different aspect according as it is viewed from C or D. From the side of C it will seem that A has been unmoved while B has been underthrust to the left, but from the side of D the reverse action will seem to have taken place, and A to have been overthrust to the right; so far, however, as A and B are concerned it is only the relative movement which comes into consideration, and the result in either case is the same. From this we see that, as regards the processes which take place within the hills themselves, the question of whether the surface has been overthrust to the south or the lower layers underthrust to the north, is meaningless; the form of the range, and of the structures developed in the rocks of which it is composed, depends on the power of resistance, and the direction in which yielding takes place most easily, and not on the supposed direction from which pressure is applied. In other words the form of the range depends entirely on the distribution of resistances within the hills themselves, and the answer to the question of the direction in which this relief has taken place, depends entirely on the point of view from which it is regarded.

This matter has been dealt with as it seems important to clear it up, for the fallacies referred to are widespread and deep-seated and permeate a great deal of geological and other reasoning. The whole of the arguments based upon them are meaningless, so far as the origin of mountain ranges is concerned, but the fundamental objections to Prof. Suess' theory are, that it fails to provide a sufficient range of movement, and is incompatible with the existence of compensation. The first of these objections can be put simply; given a solid, heated globe, cooling into space, it is possible to calculate the amount of contraction which it has undergone, if certain constants are known. These are, the original temperature of solidification, the co-efficient of contraction, the conductivity, and the temperature gradient; none of these are known exactly, but they are known to lie within certain possible limits, and calculation, based on these, shows that, on this hypothesis, the total decrease in the circumference of the globe, since it became solid, might be as small as a couple of miles and cannot be more than about ninety. In other words the whole of the contraction, which could have taken place throughout geological time, is not greater than the compression of the Himalayas alone, within the limit of the Tertiary epoch.

The other objection is an even more important one; it was foreseen by Prof. Suess, and anticipated by a denial of the existence of compensation. In the case of the Himalayas he must be credited with a greater intuition than many of his successors and followers, for he recognised the fact that an alluvial trough, of the form which had been inferred from geological examination, would account for a large part of the facts on which the concept of the compensation of the range had been based; from this it was not a long step forward to the suggestion that the whole of the facts might be accounted for in this manner, and the absence of any compensation of the range asserted.[1] The position, though difficult, was still tenable at the time when he wrote, but in the light of subsequent observations, and of the investigation of the form and dimensions of the trough in chapter IV, must now be definitely abandoned. There can be no doubt, at the present time, that the Himalayas, as a whole, are compensated, though there are local departures in one direction or the other from exact equilibrium. This being so the only hypothesis of mountain formation which is consistent with a solid, rigid, globe is one of tumefaction, all hypotheses which refer the origin of mountains to compression, due to contraction, being excluded by the impossibility of providing for compensation.

Another explanation of the origin of the Himalayas and the Gangetic trough, which has attracted some attention of late years, is that offered by Sir S. G. Burrard.[2] Like that of Prof. Suess

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[1] *Das Antlitz der Erde* III (2), p. 707, English translation IV, p. 614.

[2] On the Origin of the Himalaya Mountains. *Survey of India, Prof. Paper*, No. 12, Calcutta, 1912.

it is based on the hypothesis of a solid heated, cooling globe, but differs in recognising that this hypothesis necessitates the existence of a zone of tension underneath the outermost layers of the crust. The fact that this consequence follows inevitably from the hypothesis, was first pointed out by Mr. Mellard Reade,[1] and once stated is so axiomatic that it immediately met with general acceptance. If we suppose a cooling globe, in which the cooling has only reached a certain distance down from the surface, we have an outer shell, which is contracting and so reducing its circumference, surrounding a central core, which remains unaltered in dimensions, and in these circumstances the outer shell must be thrown into a state of tension. Only in the outermost layers will the general reduction of the bulk of the globe, under the layers which, being already fully cooled, are incapable of further contraction, lead to the existence of compression, and it has been abundantly shown that the zone of tension must be of much larger dimensions than that of compression.[2] Sir Sidney Burrard, however, makes a somewhat different use of this deduction from his predecessors, and considers that the depression of the trough was produced by a withdrawal of material towards the Himalayas, and the range to have been produced by the invasion of the material so withdrawn. Such, eliminating the details of the mechanism invoked, is the essential character of the hypothesis; it seems to involve a greater tensile strength in the zone of extension than can easily be granted, greater certainly than that of any known rocks, as met with near the surface of the earth; but so little is known, or can be known, of the physical properties of the material of the earth, when subjected to the temperatures and pressures which exist in its interior, that we cannot summarily reject the explanation, on this ground alone.

In developing his explanation Sir S. G. Burrard is as insistent on the direction of movement as Prof. Suess, though he insists on the exact opposite, and maintains that the Himalayas are due to an underthrust of the sub-crust from the southwards, instead of an over-thrust of the upper layers from the north. This matter has been dealt with already and it has been shown that the distinction is meaningless, so far as the processes which have taken place within the range itself are concerned; but it is not meaningless

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[1] Origin of Mountain Ranges. 1886, p. 123.

[2] *Cf.* O. Fisher, *Physics of the Earth's Crust*, 2nd ed., 1889, ch. VIII, for a discussion of this matter and references to earlier literature.

as regards the region to the south of the range, now occupied by the Gangetic trough, and if this trough is really due to a withdrawal of material towards the hills, we have a process which is the converse of that suggested by Mr. Fisher. In the one case the crust is supposed to have been borne down, displacing a certain amount of denser material from beneath it, in the other the underlying material is supposed to have been withdrawn, leading to a settling down of the lighter material above, and as the form of the resulting trough, developed in Sir S. G. Burrard's latest exposition of his explanation,[1] is practically identical with that resulting from the present investigation, the geodetic effects would be identical in either case, and we have no criterion for discrimination between the two interpretations.

Nor do we get any help from the geological evidence. There is no indication that the region of the Gangetic trough is one of tension, as suggested by Sir S. G. Burrard, but equally there is no certainty that it is not; within the region of the alluvium all evidence, one way or the other, has been obliterated, and only by consideration of the associated phenomena can a criterion be obtained. It has been shown that the view which regards the origin of the Gangetic trough as a consequence of the process of the elevation of the range, and the disturbance produced in the equilibrium of a floating crust, is in agreement with the geological and geodetic observations along the border of the alluvium and in the country beyond; the same cannot be said of the alternative explanation. On the southern side it is not incompatible with the facts, and might give rise to the phenomenon of the Hidden Range of excess of gravity; on the northern, in the region of the Himalayas, there are the same fundamental objections, which were pointed out in dealing with Prof. Suess' explanation, that the hypothesis does not admit of a sufficient range of movement to account for the structure, and that it is inconsistent with the existence of compensation, and more especially of the alternate excess and defect of compensation, of the range. So far, however, as the explanation refers the origin of the Himalayas to an invasion of the region of the hills by the lower layers of the crust, independent of the deformation which has taken place in the upper layers, it is in accord with the investigation which has been developed in this memoir; for it has been shown that the facts, as they are known, seem

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[1] *Proc. Roy. Soc.*, Series A, XCI, 1915, p. 233.

incapable of complete explanation without invoking some such action, though the ultimate cause to which it is due has not been established.

The same action is provided for by Mr. Bailey Willis, who attributed the origin of the mountain ranges of Asia to the greater density, and weight, of the crust under the Pacific and Indian Oceans, and to an underground transfer of material, from the oceanic to the continental regions, in consequence of the pressure set up by this difference of weight.[1] At a later date a similar explanation was adopted by Mr. J. F. Hayford, who puts the action as taking place within narrower horizontal limits.[2]

So far as this undertow is supposed to occur at a depth below that in which the contortion of the rocks, now lying near the surface, took place, it is in effect similar to that of Mr. Fisher's convection currents; but while these supply a continuous action, ample to provide for all the range of movement required, the alternative process only provides for a limited and insufficient range of movement, and in both cases it is questionable whether the pressure requisite to produce compression could be communicated to the upper layers of the crust. If, on the other hand, the compression is supposed to take place within the layer involved in the movement of the undertow, the range of motion might be sufficient, but the pressures developed, especially when supposed to be transmitted, through a long horizontal column of material, appear to be utterly inadequate. As has been pointed out before, we know too little of the conditions actually existing in the interior of the earth to reject this explanation as impossible, but, in view of the many difficulties in the way of acceptance, it cannot be regarded as a satisfactory and sufficient explanation of the facts revealed by observation.

One more explanation of the origin of mountain ranges, which may be referred to, is the suggestion of Mr. Mellard Reade.[3] He pointed out that if the average temperature of a tract of the earth's crust was raised, it would expand, not merely in a vertical but also in a horizontal direction, and that the cubical expansion of the whole tract would most naturally find relief by yielding along a

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[1] *Research in China*, Vol. II, Chap. VIII, 1907.

[2] *Science*, new series, XXXIII, 1911, pp. 199-208; *Journ. Geol.*, XX, 1912, 562-578.

[3] The Origin of Mountain Ranges. London, 1886.

line of weakness, where the rocks would be compressed, and thickening of the crust take place. If the temperature then sank, the material would not return to its original position, but the contraction be relieved by a general subsidence of the superincumbent rocks and a compressive extension of the lower layers. On an increase of temperature again taking place, relief would once more be found along the original lines, and the disturbance and thickening of the crust accentuated, till, by a repetition of the process, the largest mountain ranges might be formed.

There can be no question that this cause is capable of producing much more than the pressure required, and a sufficient range of movement. It is a cause which might quite conceivably act, but, with the masses involved, the process would be slow, so slow in fact that even the vast periods, which have been deduced from the study of radioactive minerals, would seem insufficient for the production of the effect.

The explanations which have been passed in review do not by any means complete the list of those which have been proposed, but they serve as types, and the difficulties which lie in the way of the acceptance of each of them apply equally to the variants of the type. The general result of the examination is that, while the general distribution of the excesses and defects of gravity agrees best with the supposition of a somewhat rigid crust, supported by flotation on a denser yielding layer, we can, neither on this nor any other hypothesis of support, find an explanation of the origin of the Himalayas, which can be regarded as complete and satisfactory; nor does it seem possible to offer any alternative which can be accepted. In spite of this negative result the investigation has not been in vain; it was undertaken with no expectation of attaining a solution of the problem of the ultimate cause, to which the elevation of the Himalayas is due, and it has not failed this want of expectation; but it has yielded a fresh criterion, which must be met before any hypothesis can be regarded as acceptable. The conclusions, however, must not, at present, be extended to other ranges of a different type of structure, without corroboration of independent observations, and even in the case of ranges of similar general geological structures, but very different magnitude, such as the Alps, it is not impossible that the difference of scale may seriously vitiate an application of the conclusions, drawn from a study of the greatest range on the surface of the earth. If the conclusions, drawn from a study of the Himalayas, are corroborated by the study of other mountain ranges, an important step forward will have been made, and the problem will become one of accounting for the excess of support, of which the mountains themselves are but a secondary result and manifestation.

INDEX TO GEODETIC STATIONS.

In this list L signifies a latitude, G a gravity, station. Latitudes and longitudes are given to the nearest whole minute. There is some confusion in the longitudes, as the old and revised values of the longitude of the Madras Observatory differ by nearly 3′. The published longitudes of gravity stations are all referred to the revised value; those of the latitude stations usually, but not in every case, to the old values. The published longitudes are given without correction, except in those cases where the latitude and gravity stations are identical, or so close to each other that the use of a different reference for the longitude would lead to confusion. In these cases the longitude of the latitude stations has been revised to the new value; in all others the published figure has been retained, as the small discrepancy is immaterial.

Station.		Latitude.		Longitude.		Elevation (feet).	Table.	Page.
		°	′	°	′			
Agra	G.	27	10	78	1	535	23	80
,, ...	L.	27	10	78	3	550	20	71
Aligarh . . .	G.	27	54	78	1	612	23	
Allahabad . . .	G.	25	26	81	55	288	23	
Amritsar . . .	L.	31	38	74	55	770	24	84, 85
Amsot . . .	L.	30	23	77	44	3,140	26	
Amua	L.	24	0	80	32	2,113	19	
Arrah	G.	25	34	84	39	188	23	78, 79
Asarori . . .	G.	30	14	77	58	2,467	27, 30	92, 108
Bahak . . .	L.	30	45	78	16	9,715	28, 29	101, 102
Bajamara . . .	L.	30	46	77	56	9,681	28, 29	101
Banog . . .	L.	30	29	78	3	7,433	28, 29	101
Bansgopal . . .	L.	28	33	78	34	677	20	70
Basadela . . .	L.	27	24	82	17	366	19	
Bihar	L.	25	13	85	31	391	21	73
Birond . . .	L.	29	15	79	45	6,967	5, 28, 29	
Bostan . . .	L.	28	31	77	33	758	20	71, 97
Bulbul . . .	L.	23	38	84	26	3,352	21	73
Bullawala . . .	L	30	7	77	59	2,432	26	89
Buxar	G.	25	35	83	59	207	23	
Calcutta . . .	L.	22	33	88	24	18		75
Chandaos . . .	L.	28	5	77	54	699	20	96

Station.		Latitude.		Longitude.		Elevation (feet).	Table.	Page.
		°	′	°	′			
Chanduria . . .	L.	25	44	88	25	160	22	75, 95
Charaldanga . .	L.	24	53	88	26	149	22	74, 75
Chatra . . .	G.	24	13	88	23	64		81
Chendwar . . .	L.	23	57	85	29	2,817	21	73
Dadawra . . .	L.	27	43	81	43	420	19	
Darjeeling . . .	G.	27	3	88	16	6,966	30	106
Datairi . . .	L.	28	44	77	41	767	20	71, 97
Dehra Dun . . .	G.	30	19	78	3	2,239	27, 30	74, 78, 79, 90, 92, 107, 111
,, , Old . .	L.	30	20	78	3	2,289	26	88
,, , New . .	L.	30	19	78	3	2,240	5, 26	88
,, , E. Base .	L.	30	17	78	1	1,958	26	87, 88
Dewarsan . . .	L.	26	16	80	21	439	19	
Dubauli . . .	L.	25	40	85	20	189	21	
Etora	L.	26	54	80	42	429	19	
Fatehpur . . .	G.	30	26	77	44	1,434	27, 30	91, 92
Ferozepore . . .	G.	30	56	74	37	647	25	84, 96
Garinda . . .	L.	27	56	75	4	1,204	24	
Gesupur . . .	G.	28	33	77	42	691	23	96
Ghaus	L.	27	21	83	6	296	19	
Gogipatri . . .	L.	33	52	74	43	7,752		113, 114
Gorakhpur . . .	G.	26	45	83	23	257	23	
Gurmi . . .	L.	26	36	78	33	575	20	
Hardwar . . .	G.	29	56	78	9	949	27, 30	92, 108
Hathras . . .	G.	27	37	78	3	587	23	96
Hatni	L.	30	13	77	52	3,096	26	87, 88
Hurilaong . . .	L.	24	2	84	24	1,378	21	73
Imlia	L.	27	19	81	8	428	19	
Isanpur . . .	L.	30	38	76	9	874	24	
Jalapur . . .	L.	26	4	84	23	232	21	
Jalpaiguri . . .	G.	26	31	88	44	268	23	105
, . . .	L.	26	31	88	44	280	5, 22	76

Station.		Latitude.		Longitude.		Elevation (feet).	Table.	Page.
		°	′	°	′			
Moghalsarai . . .	G.	25	17	83	6	257	23	
Mohan . . .	G.	30	11	77	55	1,660	27, 30	92, 108
Monghyr . . .	G.	25	23	86	28	154		81, 124
Montgomery . .	G.	30	40	73	6	557	25	
Moré	G.	33	16	77	54	15,427	30	110, 111
Murree . . .	L.	33	55	73	27			104
Mussooree . . .	G.	30	28	78	5	6,924	30	107
,, . . .	L.	30	28	78	4	6,937	5, 28, 29	94, 101, 102, 104
Muttra . . .	G.	27	28	77	42	562	23	
Muzaffarpur . .	G.	26	7	85	25	179	23	
Nimkar . . .	L.	27	21	80	32	486	19	67
Noh	L.	27	51	77	41	710	20	
Nojli	G.	29	53	77	40	879	23, 27	92
,, ...	L.	29	53	77	40	929	20, 26	
Nuaon . . .	L.	25	35	84	14	251	21	
Pahargarh . . .	L.	24	56	77	44	1,641	20	
Pahladpur . . .	L.	26	4	85	27	175	21	
Parewa . . .	L.	26	38	81	12	380	19	
Pariaon . . .	L.	25	50	81	22	346	19	
Pathankot . . .	G.	32	17	75	39	1,088	25	84, 85
Pathardi . . .	L.	27	26	82	45	320	19	
Pavia	L.	25	27	80	47	481	19	67
Phallut . . .	L.	27	13	88	3	11,815	28, 29	102, 106
Poshkar . . .	L.	34	2	74	32	8,323		112, 113
Potenda . . .	L.	24	37	81	0	993	19	
Rajpur . . .	G.	30	24	78	6	3,321	27, 30	90, 92, 107
. . .	L.	30	24	78	6	3,500	26, 28, 29	87, 88, 94, 101
Rakhi	L.	29	17	76	0	785	24	96
Ramchandpur . .	G.	25	41	88	33	132	23	95
Ram Thal . . .	L.	28	30	75	3	951	24	
Ramuapur . . .	L.	28	22	80	31	541	19	
Ranjitgarh . . .	L.	32	35	74	40	900	24	96
Roorkee . . .	G.	29	52	77	54	867	23, 27	92, 108

Station.		Latitude.		Longitude.		Elevation (feet).	Table.	Page.
		°	′	°	′			
Salimpur . . .	L.	27	47	78	33	645	20	
Sandakphu . . .	G.	27	6	88	0	11,766	30	105
Sangatpur . . .	L.	31	18	75	5	779	24	84
Sankrao . . .	L.	28	2	78	35	670	20	
Sarkara . . .	L.	29	16	78	35	761	20, 26	97
Sasaram . . .	G.	24	57	83	59	340	23	82, 124
Sawaipur . . .	L.	29	39	75	6	697	24	83
Senchal . . .	L.	26	59	88	20	8,600	28, 29	102
Seoni	G.	22	5	79	29	2,032		124
Shahpur . . .	L.	32	2	75	8	830	24	84
Shorpur . . .	L.	30	13	77	58	2,916	26	
Siliguri . . .	G.	26	42	88	25	387	23	105
” . . .	L.	26	42	88	25	401	5, 22	75
Simla	G.	31	6	77	10	7,043	30	109
Sirsa	L.	28	55	78	35	739	20	
Sora	L.	26	17	81	12	400	19	
Spur Point . . .	L.	30	25	78	6	..		94
Sultanpur . . .	G.	26	16	82	5	314	23	
Tasing . . .	L.	27	53	76	15	2,050	24	
Teona	L.	24	35	84	10	740	21	72
Tonglu . . .	L.	27	2	88	8	10,073	28, 29	102, 106
Uaira	L.	26	57	77	40	810	20	
Utiaman . . .	L.	27	0	81	12	386	19	

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