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A CRITICISM

OF

MR. R. D. OLDHAM'S MEMOIR

"The Structure of the Himalayas and of the Gangetic Plain, as elucidated by Geodetic Observations in India"

BY

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CHAPTER I.

Along the southern fringe of the Himalayas, where they rise abruptly from the plains, and in the Gangetic plain itself, the force of gravity has been found to possess, in respect to intensity and direction, marked peculiarities whose meaning has, for long, been the study of geodesists. Neither Bouguer's nor Hayford's hypothesis completely explains the observed facts.

According to Bouguer's hypothesis, the crust of the Earth is sufficiently strong and rigid to withstand the condition of strain induced by the irregularly distributed loads of surface topography; elevations and depressions of the surface represent real excesses and deficiencies of matter. Hayford's hypothesis of Isostasy assumes that the crust has no rigidity; that where we find elevations or depressions, we are not to suppose real excesses or deficiencies of mass, but that every such irregularity of surface is accompanied by a subjacent compensating defect or excess of density, so that, at some stratum below the surface, there is a condition of equilibrium, each unit area of the stratum carrying the same load.

The Bouguer hypothesis fails completely to account for the facts observed in the Himalayan Gangetic region. Hayford's hypothesis, though it goes far towards interpreting them, still leaves us with unexplained residuals that cannot be justifiably considered as accidentals, due to purely local departures from the general law, until it has been shown that modifications of the initial hypothesis will not produce a closer agreement between the calculated and observed quantities. As based on this hypothesis, the theoretical values of deflection, as compared with the observed, at stations in the Himalayas and immediately at their foot are too small towards the north while, over north-west, north-central and north-east India, at distances of more than about 30 miles from the hills, the values are too large towards the north. This characteristic of the Hayford quantities and the magnitudes of the residuals they give indicate that the particulars of the hypothesis, which were found suitable to the phenomena observed in the United States of America, may still require some modification before we accept them as constituting the best approximation to the general law governing the actual distribution of densities in India.

Mr. Oldham, however, in his Memoir, "The Structure of the Himalayas and of the Gangetic Plain, as elucidated by Geodetic observations in India",* does not appear to consider that a reconsideration of the hypothesis may be necessary, but to be of the opinion that we need look no further than the Gangetic Trough, filled with alluvium, for the explanation of the anomalies of plumb-line deflection and intensity of gravity. His investigation is directed, in the main, towards an estimate of what the dimensions of this trough must be to suit the observed facts. The aim of the Memoir is, perhaps, the evolution out of the material afforded by geodetic determinations, of the shape of the trough rather than the solving of the problem presented by the gravitational anomalies. The reliance that can be placed, however, on details of structure deduced from geodetic anomalies depends on the degree of success with which these details explain the anomalies as well as on the nature of the methods of enquiry. Mr. Oldham's Trough, alone, will not explain many of the anomalies. Indeed it increases several of them, as at Agra, Hathras, Muttra, Gesupur, Allahabad, Kisnapur and Chatra. The existence of a great depression in front of the Himalayas is not doubted but, besides this depression, there are other causes of disturbance, without a knowledge of which the deflection and gravity anomalies, as they now stand, are not calculated to give reliable quantitative results as to the structure of the Trough.

By reason of the method in which the matter is arranged the following of the development of Mr. Oldham's investigation is a little difficult and it is not made easier for the uninitiated reader by the occurrence of several inaccuracies.

In the tabular statement on page 42, three of the quantities in the last column have been given the wrong algebraic sign and, on page 43, with reference to the compensated deflections given in Table 5, it is stated that "Major Crosthwait's calculations give rather smaller values for the northerly deflections". For three out of the eight stations dealt with, Major Crosthwait's results show *larger* northerly deflections. In connection with the same group of figures, it is stated that for stations outside the Himalayas, the differences show greater uniformity than for stations within the Himalayan region proper. But we find the difference for Siliguri is $+ 2''$ and that for Jalpaiguri is $- 3''$ showing a range of $5''$ for stations outside the Himalayas while the variation in the case of Himalayan stations is $4''$. On the same page, we find it stated that "the greater difference at Jalpaiguri is doubtless due to the inclusion in Major Crosthwait's calculations of the southerly pull of the highlands of the Assam Range and the Peninsula". But Major Crosthwait's calculations show $-8''$, that is $8''$ northerly deflection, at Jalpaiguri while Mr. Oldham's Imaginary Range gives only $-5''$. Crosthwait's more northerly attraction cannot be explained by the pull of southern highlands.

On page 66, there is a statement that at the southern stations included in Table 19 and distant 140 to 180 miles or so from the northern boundary of the alluvium, "the effect of the Himalayas.........is negligible". The calculated effect of the Himalayas at Noh, 138 miles from the edge of the hills, is $20''$; at Agra, at 168 miles distance, we have $17''$ and at Usira at 192 miles, $16''$. These quantities are not negligible. Mr. Oldham may have meant to refer to the compensated

* Memoirs of the Geological Survey of India, Vol. XLII, Part 2, Calcutta 1917.

Himalayas. Compensation will certainly reduce the effects given above, but by how much are they reduced in reality? What particular hypothesis of compensation is truly appropriate to the Himalayan-Tibetan mass? At the distances in question, what are the actual effects of the compensated Himalayas? These questions still await solution. Until we have before us the results produced by modifications of either the terms of the hypothesis or the initial assumption on which it is based, namely, that the Earth's crust has no rigidity, we shall not be in a position to say that Hayford's hypothesis represents the most probable approximation to actual conditions or to make the definite statement that, by reason of the compensation, the effect of the Himalayas, at 140 or 150 miles distance, is negligible.

In the footnote on page 67, Mr. Oldham writes that, at Pathardi and Nimkar, Major Crosthwait's 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".

Major Crosthwait's residuals of $-12''$ and $+5''$ refer to the Everest spheroid and depend on the assumption of a deflection of $4''$ to the south at the datum station, Kalianpur. In the same terms, the observed deflection at Pathardi is $-15''$ and at Nimkar $+4''$. The residuals derived from the Imaginary Range being $-9''$ and $+4''$, the effect of this Range at Pathardi is $-6''$ and at Nimkar $0''$. The effects calculated by Major Crosthwait are $-3''$ and $-1''$ respectively. Thus, at Pathardi, the Imaginary Range gives a larger northerly deflection than does the actual topography but at Nimkar, it gives a smaller. The indications are discordant. The statement that "evidently the Imaginary Range gives a larger deflection than the actual topography of this part of the actual range" is not very clearly supported by the two examples selected.

A change of the spheroid of reference, the use of the Bessel-Clarke instead of the Everest, will not alter the calculated effects of either the real or the Imaginary Range. Only the values of the observed deflections are altered by a change of spheroid.

It is to be noted that no reliable estimate of the relation between the effects of the Imaginary Range and the real Himalayan mass can be drawn from comparisons such as that made above. Major Crosthwait's quantities are derived from a consideration of all masses, Himalayan and otherwise, within 2564 miles of the station concerned. Mr. Oldham's Imaginary Range is intended to represent only the Himalayan mass and of this Range he takes into account only such part as falls within 100 miles of the station.

It may be noted also that, in connection with investigations such as that dealt with by the Memoir, it is not correct to say that "the Himalayas in Nepal Territory are quite unsurveyed". Maps on the scale of 1/1000000 based on accurate triangulation are available and reliable for geodetic purposes and it may be safely affirmed that Major Crosthwait's estimation of the effect of this part of the Himalaya is nearer the truth than that based on the Imaginary Range.

On page 81, the Bouguer anomalies for Kisnapur and Chatra are given as +0·033 dyne and +0·009 dyne, respectively, and the Hayford anomalies as +0·039 dyne and +0·005 dyne. These two sets of quantities are not directly comparable. The Bouguer anomalies are based on Helmert's 1884 formula for γ_0 while the Hayford quantities are dependent on that of 1901. (All the gravity determinations in India have now been referred to this later formula and the results published in Professional Paper No. 15, Survey of India, 1915. "The Pendulum Operations in India and Burma, 1908-1913"). Mr. Oldham recognises that "the anomalies allowing for compensation are not directly comparable with those in which it is not considered" (p. 29 of the Memoir) but, for the better understanding of the comparisons between Bouguer and Hayford anomalies, this point could, with advantage, have been more definitely emphasised.

On page 97, Mr. Oldham says it must be remembered that the northerly deflections at Datairi and Bostan "are only northerly if the deflection at Kalianpur is assumed to be as much as 4″ south". This is not the case. Any decrease in the assumed southerly deflection at Kalianpur will make the deflections at Datairi and Bostan still more northerly.

In calculating theoretical effects, Mr. Oldham has adopted methods of considerably less precision than those usually employed and the results would have had greater weight had they been supported by a clear exposition of the limits of error to which such methods may be liable. The main features of the procedure adopted are the substitution of an Imaginary Range for the actual contours of nature; the omission from the calculation of masses beyond 100 miles from the station under consideration, on the assumption that the effects of such masses are, by reason of complete local compensation, negligible; and the assumption that the Gangetic Trough, itself, is not compensated.

The Imaginary Range, representing the real Himalayan-Tibetan mass, is uniform in section from end to end. Figs. 1 and 2, facing this page and 3 and 4, facing page 5 show how the Imaginary shape compares with cross sections of the actual mountain ranges. In fig. 1 are the two sections given in the Memoir, across the mass from, possibly, Dehra Dun and Siliguri. The positions of the sections shown in figs. 2, 3 and 4 are marked on the map at the end of this Paper. These last three cross-sections indicate that one feature of Mr. Oldham's generalisation of the actual ranges is the accumulation of considerably more than the natural amount of mass along the edge of the hills and in proximity to the Gangetic plain in which the group of stations dealt with is situated.

A comparison between the deflection effects due to the Imaginary Range and those produced by the actual masses will be made later. Generally speaking, the Imaginary Range gives larger northerly deflections than do the real masses within 100 miles of each station and very much smaller northerly deflections than those produced by all the masses in the Himalayan-Tibetan region.

FIG. 1.—The cross sections given by Mr. Oldham.

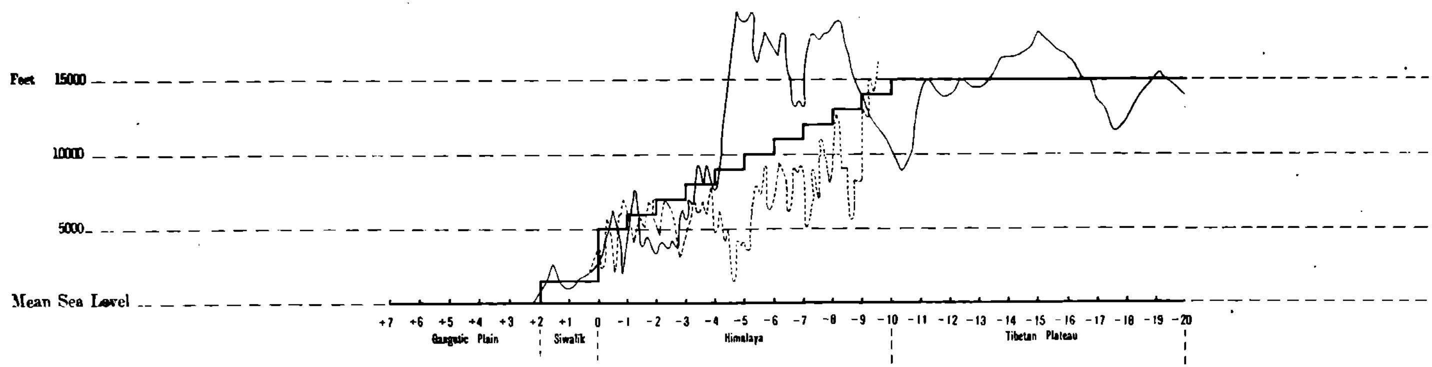
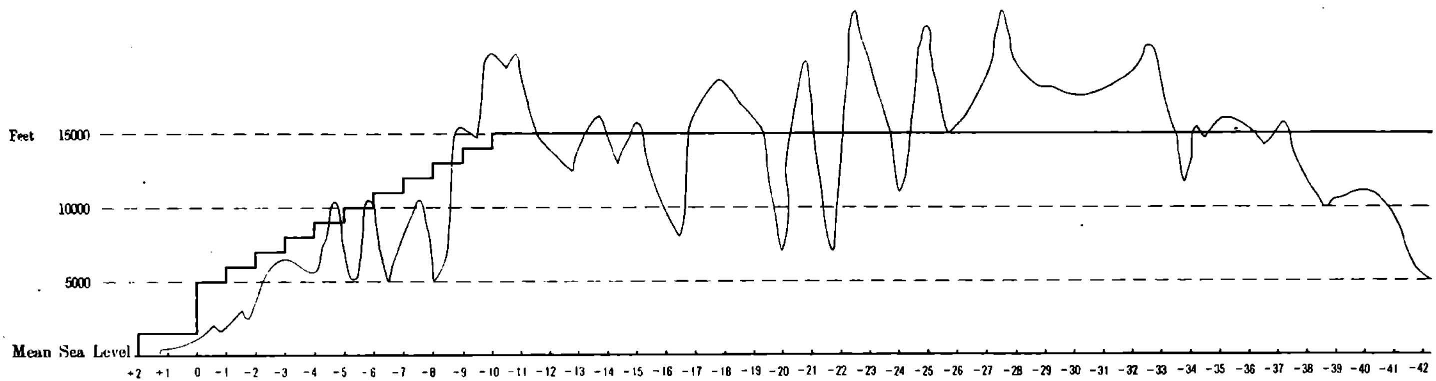


FIG. 2.—Section from Ranjitgarh to point Lat. 36°, Long. 79°.



In these figures the section of the Imaginary Range is shown by the thick line, the actual section of the mountain mass being shown by the finer line.

The unit of the horizontal scale represents 10 miles.

FIG. 3.—Section from Ramnapur to point Lat. 32°. Long. 83°.

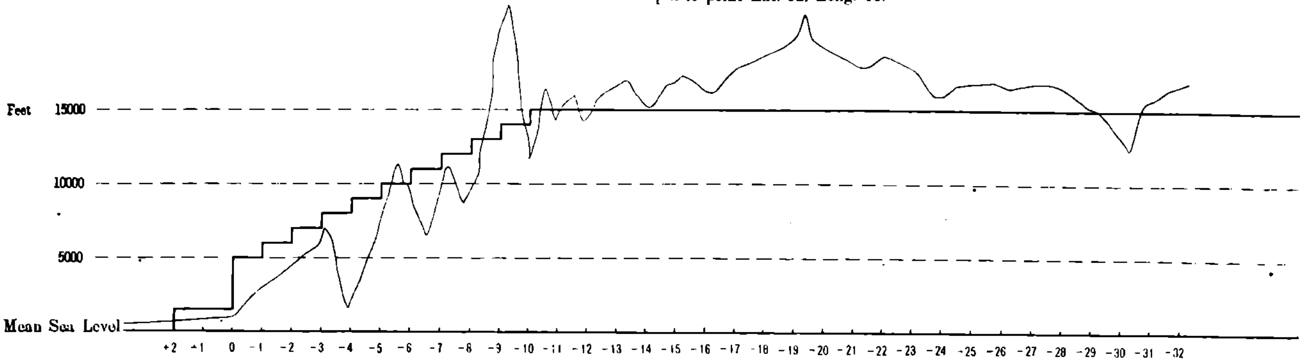
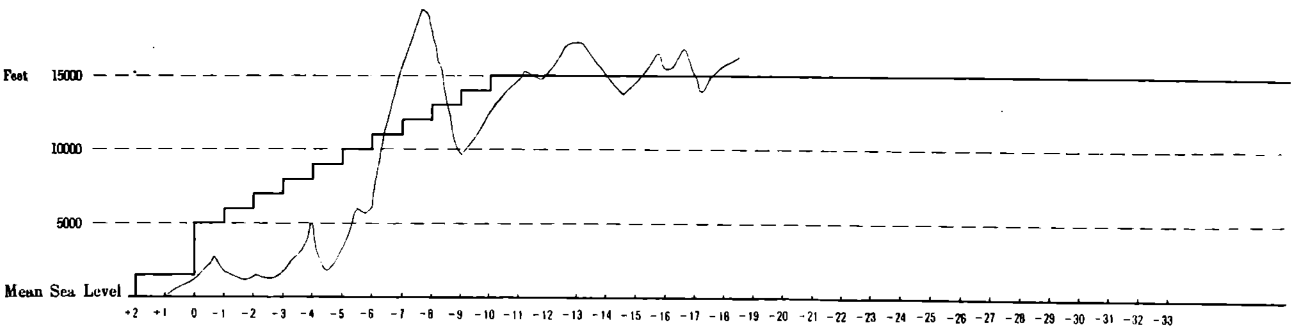


FIG. 4.—Section from Ramnagar to point Lat. 29°. Long. 85°.



In these figures the section of the Imaginary Range is shown by the thick line, the actual section of the mountain mass being shown by the finer line. The unit of the horizontal scale represents 10 miles.

The propriety of ignoring masses beyond 100 miles from each station and of asssuming that such masses have complete local compensation is discussed later. Hayford's hypothesis of compensation has been shown to be closely equivalent, in point of effects produced, to the actual conditions in the United States of America, but the same cannot be said of it in regard to the Indo-Tibetan area. Compensation in some form does undoubtedly exist here but it is almost certainly, not local, it is not uniform between sea level and the "depth of compensation" and it may not be complete. Our knowledge of conditions is too indefinite to allow of reliable quantitative estimates of local structural details being formed from the present Hayford deflection and gravity anomalies.

Mr. Oldham's assumptions involve a very marked difference between the conditions underlying the Gangetic Trough and those appertaining to all other masses. While the latter are considered to be completely and locally compensated, the former is not compensated at all. This assumption is at variance with the Hayford anomalies found at gravity stations in the Gangetic plain which tend, at first sight, to indicate over-compensation.

This procedure involves us in the anomaly of one part of the crust, tens of thousands of square miles in area, having a high degree of rigidity, capable of withstanding the strains set up by a deficiency equivalent to the weight of a stratum of rock averaging 1500 feet in thickness, while all surrounding parts of the crust are unable to support any strain at all, failure being prevented by a condition of isostatic flotation. The supposition of no compensation to the Gangetic Trough is difficult to reconcile with the assumption that the effects of all masses beyond 100 miles from the station are neutralised by complete local compensation.

This question of compensation is an all important one in the investigation of the actual thickness of the alluvium. If there be compensation of the deficiency of the alluvium, the gravity anomalies will indicate very much greater thicknesses than those deduced by Mr. Oldham. In Table 23 and some of the subsequent tables of the Memoir thicknesses of alluvium are calculated from the gravity anomalies. The density of the alluvium being taken to be 2·16, or four-fifths of normal crustal density, the anomaly is considered as due to a deficiency of density amounting to one-fifth of normal. On this basis, it is deduced that a thickness of 500 feet of alluvium would produce an effect of 0·0033 dyne and it is at this ratio that the calculations have been made. This ratio makes no allowance for the possibility of the compensation of the deficiency of density of the alluvium by appropriate excesses of density at lower depths.

Let us suppose the case of a station S, situated on a stratum of alluvium, 1000 feet thick, with the upper surface 500 feet above sea-level. Suppose the alluvium to stretch in all directions round the station to a distance of 60 miles and let the compensation depth be 70 miles.

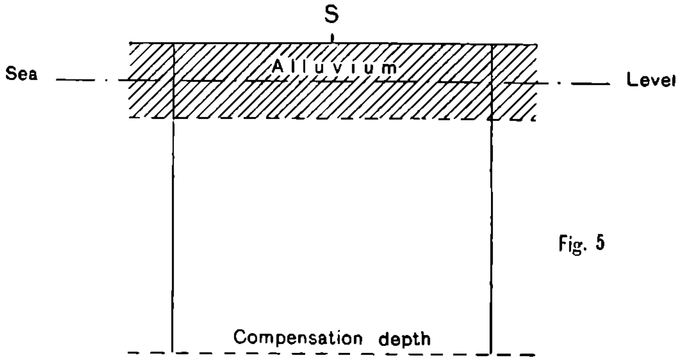


Fig. 5

The effect of the 1000 feet of alluvium below S, together with its subjacent compensation will be

$$+0\cdot0047 \text{ dyne.}$$

The Hayford correction for this station, 500 feet above sea-level, for the area up to 60 miles distance and for a density of the surface material $=2\cdot67$, will be

$$+0\cdot0078 \text{ dyne.}$$

The first of these quantities is the correction that should have been applied in deducing the theoretical value of gravity, the second is the correction actually applied. The difference of the two,

$$-0\cdot0331 \text{ dyne}$$

is the residual that would be apparent. This, if we use Mr. Oldham's ratio, would seem to indicate 475, say 500 feet of alluvium. The real thickness is 1000 feet. Its effect is partially masked by the compensation.

The following table gives a comparison of the real thicknesses of alluvium with those calculated by Mr. Oldham's ratio which postulates no compensation.

TABLE I.

Real thickness of alluvium.	Apparent Hayford anomaly.	Thickness derived from Mr. Oldham's ratio.
feet	*dynes*	*feet*
1000	·0031	500
1500	·0047	700
2500	·0078	1200
5500	·0170	2600
12000	·0365	5500
20000	·0623	9500

In each case the station is supposed to be on the upper surface of the alluvium at 500 feet above sea-level and the alluvium to extend 60 miles in all directions.

It is thus seen to be essential, before attempting to deduce the real thickness of the alluvium, to have a correct idea of the actual degree of compensation.

The figures in Tables 23 and 27 of the Memoir, representing thicknesses of alluvium, deduced by Mr. Oldham from the gravity anomalies are dependent on the supposition that these masses are not compensated. The gravity anomalies, themselves, however, have been derived on the assumption of complete local compensation and it would be logical to interpret them in conformity with this hypothesis. The Hayford corrections which give rise to them are calculated upon a consideration of the visible masses. It would be more appropriate to regard the anomalies as the effects, still under the same initial hypothesis, of masses that are not visible than to conclude at once that they indicate departures from the hypothesis.

In discussing the quantities of Table 23, Mr. Oldham says (p. 79 of the Memoir) "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 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 3000 to 4000 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 15000 feet. The former of these figures would neutralise the effect of about 2000 feet of alluvium, the latter about 5500 feet to perhaps 7000 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 3000 to 5000 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".

Whether the effects of the two considerations do or do not neutralise one another need not concern us here. What is to be noted is that, though the value of the gravity anomaly, or difference of anomalies, may or may not be altered by taking count, on the one hand, of distant topography with its compensation and, on the other, of compensation of the trough, its meaning is now changed. It now, the trough being supposed compensated, means a certain thickness of *compensated* alluvium, far greater than the figure calculated by Mr. Oldham. The "compensation of the trough", otherwise, becomes meaningless. The consideration that the trough is compensated will now make the gravity anomalies indicate at least twice the thicknesses of alluvium given in Table 23.

The same mistake has been made in arriving at the figures of the last column of the table, "Thickness of the alluvium deduced from Hayford anomaly". The Hayford anomalies are derived on the hypothesis of complete local compensation and in conformity with this hypothesis, the gravity anomalies indicate very much greater depths than those arrived at by Mr. Oldham. For Roorkee, for example, Mr. Oldham has calculated a thickness of 6500 feet and for Gorakhpur, a thickness of 10500 feet. (In arriving at the figures in the table, to both of these quantities, an arbitrary correction of +3000 feet has been applied). Interpreting the Hayford anomalies at Roorkee and Gorakhpur in conformity with the Hayford hypothesis, we get thicknesses of 14200 and 22600 feet instead of 6500 and 10500 feet.

Mr. Oldham bases on Basevi's gravity determination at Moré and the latitude observations at Gogipatri and Poshkar in Kashmir the theory of overcompensation of the central Himalayan mass. References to publications of the Survey of India show that none of these determinations are suitable for use in investigations of crustal structure, far less can they be justifiably considered as sound bases for important deductions.

Mr. Oldham says, (page 110) of Basevi's work 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", and that Basevi's determination gives us a "good indication" of what the value of gravity is likely to be. Mr. Oldham is, here, under a misapprehension. Basevi's work has never been "discredited" and there never has been, on the part of responsible authorities, a question of "reinstating" his results. Opinion regarding them has not changed. His results are merely incomplete and they will always remain incomplete.

In Basevi's day no method had been devised of determining the amount of correction that should be allowed for flexure, or sway, of the stand supporting the swinging pendulum, and all his determinations have been rendered obsolete by modern apparatus and methods which permit of the determination of the necessary correction. There are no means of ascertaining what the flexure of Basevi's pendulum stand actually was at Moré or of applying such a correction to his Moré work as will justify the inclusion of the result in evidence as to mass distribution or the degree of compensation.

The redetermination of the value of gravity at one of Basevi's stations by means of modern apparatus does not enable us to apply appropriate corrections to his determinations at other stations, for the amount of the flexure varies from station to station with each fresh setting up of the pendulum stand. The particular stand used by Basevi at Moré was employed at only one other place, Mian Mīr. At Mian Mīr, the conditions, atmospheric and material, were very different from those at Moré. Moreover, in the interval between the two sets of observations, the stand had been subjected to experiences calculated to affect its rigidity and condition of molecular strain. The comparison between the modern determination and Basevi's result at Mian Mīr gives us an indication of the nature of the flexure of his pendulum stand at that place, but there is no justification for supposing that at Moré the flexure was the same in amount or even of the same order of magnitude as at Mian Mīr. The flexure correction for a heavy stand used elsewhere by Basevi appears to have varied from about 0·02 dyne to 0·10 dyne. Concerning the flexure of the light stand used at Moré, we have no knowledge except that at Mian Mīr its effect may have been about 0·11 dyne. We can form no idea of the characteristics of this stand, of the limits between which its flexure varied or of its behaviour under the exceptional conditions incidental to the Moré work. All that we can say is that if the flexure of the stand at Moré was the same as at Mian Mīr, the coincidence is most remarkable and improbable. We have no knowledge of what correction to apply to Basevi's Moré result so that we may be enabled to use it with confidence in discussions of compensation and mass distribution. The determination is unserviceable and will always remain so.

Mr. Oldham, on page 111, attaches weight to the fact that his value, —0·434, of the gravity anomaly at Moré agrees with —0·433 deduced by Borass and published in the Report of the International Association of 1909. He states that "the two values of the anomaly differ by only ·001 dyne and we may take it that the deficiency at Moré is not far from ·43 dyne". This conclusion is illogical. Both results are derived in the same manner from the same observations and the agreement does not prove that the deficiency is not far from ·43 dyne, but merely that the respective computations of the corrections for latitude, height, mass and flexure gave accordant quantities. It would have been surprising had they produced a discordance, seeing that both Borass and Oldham use practically the same arbitrary corrections for flexure. (Borass ·107, Oldham ·109). A disagreement of results would not have placed in doubt the value of the deficiency of gravity. It would have thrown suspicion on the accuracy of one of the two sets of computations.

Of Gogipatri and Poshkar, Mr. Oldham says "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 unfavorable 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".

As Mr. Oldham points out, these two latitude determinations have been rejected by the Survey of India and omitted from data judged suitable for geodetic purposes. They were included in earlier accounts of the operations in order to serve a useful purpose. It is important to place on record a statement of all work done under geodetic conditions, for the analysis and discussion of observations that have given faulty results is often productive of progress and improvement of methods and instruments. In order, however, that the publication of results of doubtful accuracy should not mislead, the records gave the observations in considerable detail. There was no mistaking the reliability that could be placed on the results. From the last account, however, the Gogipatri and Poshkar work has been rightly excluded. The omission is indication of untrustworthiness. The uncertainty in their accuracy is not, as stated by Mr. Oldham, small in amount and due to unfavorable weather conditions. The observations are burdened with large errors due, apparently, to instrumental defects. It is impossible to say how much the errors of the final latitude determinations may be. There is no foundation for the statement that it is "certainly less than one second of arc". By those qualified to judge, the observations have been declared unfit for geodetic purposes and reliable deductions cannot be formed therefrom.

The theory of overcompensation, put forward by Mr. Oldham, rests on Basevi's incomplete gravity determinations at Moré and the faulty latitude observations at Gogipatri and Poshkar.

CHAPTER II.

The introductory chapter of Mr. Oldham's Memoir deals mainly with what is already definitely known regarding the structure of the Himalayas and the Gangetic Plains, as well as with certain other geological matters, in respect to which the examination of the results of geodetic operations may, it is hoped, lead to the strengthening and amplification of our knowledge which, at present, is of merely a conjectural nature.

The following are given as established facts.

(i). The elevation of the Himalayas has been accompanied by the compression of the rocks of which they are composed.

(ii). A great fault, known as the main boundary fault, separates the rocks of the Himalayas from the Siwalik rocks of the Sub-Himalayas. This fault marks closely the original limit of formation of the Siwaliks, separating an area of elevation and denudation to the north from one of subsidence and deposition to the south. It brings, along the greater part of the length of the Himalayas, the older rocks of the Himalayas into direct contact with the softer sandstones and shales of the Upper-Tertiary Series, the plane of separation between the two groups of rocks of very different densities being nearly vertical.

(iii). A series of similar faults is found within the Siwalik area and these are regarded as marking successive limits between areas of uplift and erosion to the north and deposition to the south and as indicating that, at any rate during the latter part of the period of elevation of the Himalayas, there has always been an abrupt limit to the region of compression and elevation and that this limit has shifted progressively southwards.

(iv). The well defined character of the southern margin of the hills toward the plains suggests that it is determined by a structural feature similar to the main boundary and to the Siwalik faults and the thickness of the alluvium at the northern edge of the plains is probably about three miles.

(The inclusion of this estimate of the thickness of the alluvial deposits amongst well established facts may be questioned. Over no great length, if at all, do we find exposed the floor on which these deposits were laid. Estimates of the thickness of the unexposed strata must be conjectural and it is possible that in giving it a value of three miles, the total thickness of the deposits is underestimated. We only know that, at one point on the northern edge of the trough, the thickness is at least 15000 feet; that at Calcutta, a bore hole was taken down to 481 feet "but probably this represents only a small part of the deposit" (Enc. Brit. XI Edn., art. on India, Geology). The existence of the swatch of no ground off the mouth of the Hooghly points to the possibility that the thickness of the alluvium "is at least 1800 feet and may be much more" (ibid). At Agra a boring reached 480 feet without attaining the bottom of the alluvium. At Lucknow, a depth of 1336 feet from the surface was reached. Here "there was no indication of an approach to the base of the alluvial deposits" (ibid). Our knowledge of the thickness of the alluvium is, thus, very slight. Within the trough, the bottom of the deposits has nowhere been reached).

(v). At the southern edge of the alluvial plains the thickness is small and the boundary irregular, suggesting a gradual encroachment of the alluvium on an old land surface of rock and a gradual growth southward of the depression in which the alluvium has been deposited.

The further investigation of the structure of Himalayan and Gangetic regions soon leads to our being confronted by questions, insoluble by direct methods of observation but upon which, it is hoped, geodetic evidence may throw some light. Amongst these are the following;

(i). What is the relation between the elevation of the Himalayan region and the compression of the rocks of which it is built? Which is cause and which, effect?

(ii). What is the throw of the main boundary fault and of similar faults within the Siwalik area?

(iii). What is the depth of the pre-tertiary floor within the Siwalik region and how, in point of level, does this floor compare with that of the alluvial area to the south?

(iv). What is the cross-section of the Gangetic trough?

(v). How does the thickness of the alluvium in the Punjab plains compare with that in the Gangetic drainage area?

(vi). In the east, is the Gangetic trough closed by a rock barrier between the Rajmahal and Garo Hills?

CHAPTER III.

The "Centre of Effect."

In Chapter II, "Nature and Interpretation of Geodetic Evidence", Mr. Oldham introduces what he terms the centres of effect and of compensation. He says "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' ". There may be, it is true, such a point but this knowledge will not help us at all in actual practice. Its position, which need not necessarily be within the mass in respect to which it is the "centre", is determinable only after we know the shape and size of the mass and the effect it produces at a given point. But it is just the discovery of these factors relative to masses that constitutes the end toward which our investigation is directed.

The "centre" does not, as pointed out by Mr. Oldham, coincide with the centre of gravity and, for any given mass, the position of the centre varies with the situation of the station of observation. When considered relatively to several stations, a mass has no one "centre".

Nothing is gained by introducing the ideas of a "centre of effect" and "concentration of mass", dangerous conceptions to apply to investigations involving masses covering many hundreds of square miles, in that they are likely to lead to error. For example, Mr. Oldham says that "the effect of the compensation varies as indicated in Table I" of the Memoir. He has forgotten, here, that the quantities of this table are based on the assumption of mass concentrated at a point, the position of which is fixed and not dependent on the position of the station of observation. The figures of the table, consequently, do not apply to the distributed masses of either topography or compensation, in respect to which the situation of the "centre" varies with the distance of the station.

In the footnote on page 16, Mr. Oldham recognises the fact that the formula he uses and the tabulated quantities derived therefrom are applicable only to cases "where the dimensions of the mass are such that it may be regarded as centrobaric at all the distances involved". As some of the distances are small, the dimensions of such a mass must also be small. In our investigation, the masses to be dealt with cover thousands of square miles and, in respect to the stations of observation, cannot, either by reason of the area they cover, variations of density as in the stratum of compensation or irregularity of shape as in the actual topography, be considered as centrobaric. The "centre of effect" treatment is impossible.

It is stated, also, that examination 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. To this we cannot agree. The problem is essentially one of investigation into the distribution of mass. Any position of the centre of compensation will correspond to more than one hypothetical distribution of mass, so that varying the position of the centres of effect or compensation is not likely to lead to reliable conclusions as to the distribution of density.

Before examining the figures of Table 1 of the Memoir, let us consider briefly the position and the angle of depression of this "centre of effect".

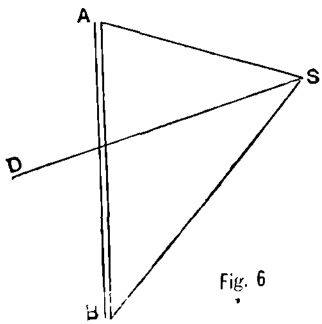


Fig. 6

If AB be a thin column of matter, the attraction exerted by it on the point S will act along the line S D which bisects the angle A S B. A simple proof of this will be found in Pratt's "Figure of the Earth" (4th Edition, Chap. IV).

The following investigation is due to Dr. Gilbert Walker, F.R.S.

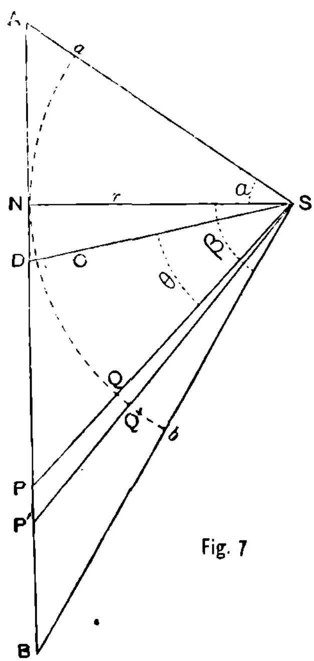


Fig. 7

Let A B be a thin cylinder of mass m per unit of length and S be a point at a distance $SN = r$ from AB.

Draw a N b, an arc of a circle with S as centre and S N as radius. Take an element PP′ of the cylinder and join P S and P′ S cutting the arc in Q and Q′.

Then it is easily seen that the attractions at S of the elements PP′ and QQ′ are equal if the mass of the arc $= m$ per unit of length.

Thus the attraction of AB = the attraction of the arc $a\,b$ and will act along S D bisecting the angle ASB.

If the centre of effect is on S D at C, distant x from S we have

$$AB = r\,(\tan\alpha + \tan\beta)$$

so that

$$\text{the attraction of AB} = \frac{\text{mass of AB}}{x^2} = mr\frac{(\tan\alpha + \tan\beta)}{x^2}$$

$$\text{the attraction of the arc} = 2\int_0^{\frac{\alpha+\beta}{2}} \frac{mr\cos\theta\, d\theta}{r^2}$$

$$= 2\frac{m}{r}\sin\frac{\alpha+\beta}{2}$$

$$\text{thus} \quad x^2 = \frac{r^2(\tan\alpha+\tan\beta)}{2\sin\frac{\alpha+\beta}{2}} = \frac{r^2\cos\frac{\alpha+\beta}{2}}{\cos\alpha\cos\beta}$$

$$\text{But} \quad SD = r\sec\frac{\beta-\alpha}{2}$$

$$\text{Therefore} \quad \frac{SC^2}{SD^2} = \tfrac{1}{2}\cos\frac{\beta-\alpha}{2}(\sec\alpha+\sec\beta)$$

This is only equal to unity when $\alpha=\beta=0$, that is to say when the column's length is zero. In all other cases the value is greater than unity, whence it follows that SC is greater than SD.

Thus it appears that for a thin column of matter, the centre of effect is situated outside the column and on a line bisecting the angle subtended at the station by the length of the column. Now consider the bearing of this latter characteristic on the effect of a compensating defect of mass disposed, with regard to the station, according to the assumption generally adopted. This assumption is that the compensating defect of mass is distributed with respect to depth, from the sea surface down to a depth to be determined from the observations. For masses thus placed, with the upper extremity of the column at the sea surface, it is obvious that the angle subtended at a station at sea level by the length of the column can never be as much as 90° and, consequently, the angle of depression of the "centre of compensation" must always be less than 45°. The angle of depression to the centre of a thin column near the station is greater than that to the centre of one more remote, so that the "centre of compensation" of a combination of several columns lies at an angle of depression less than that appropriate to the "centre" for the column nearest the station and this, we see, is never as much as 45°. Now the angles of depression of Mr. Oldham's Table I extend to 86° so that, obviously, they do not apply to the condition of compensation usually adopted, where the upper limit of the stratum containing the compensating mass is the sea surface. In all cases where the angle of depression is given as greater than 45°, the mass concerned cannot extend upwards as far as that surface, supposing the station to be at sea level. Mr. Oldham having specified no condition governing the position of the mass, this latter may, for any given value of the angle of depression, be disposed in an infinite number of ways, as shown at AB, CD, EF, GH, etc. in fig. 8. In both position and volume occupied, the mass is indeterminate. Also, if the masses CD and EF, for example, be limited by the same radial lines from S and both be tangential to a circle of the same radius with S as centre; both CD and EF, if of the same mass per unit of length, have the same effect at S, at the same angle of depression, though the depths of the two centres of effect are different.

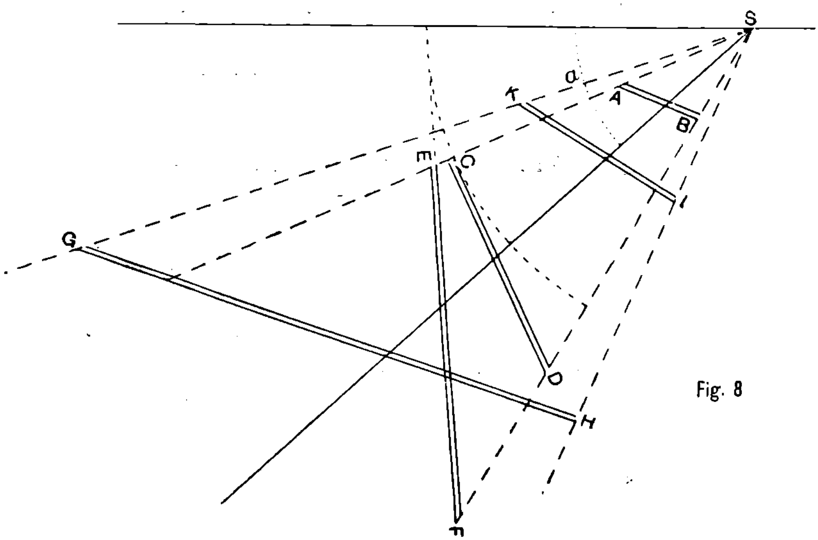


Fig. 8

The deflection anomaly at a station, thus, affords no definite indication of the depth of the "centre" of the mass creating that anomaly. Also, let it be remembered that, in the case of a given mass and a group of stations, the position and depth of the appropriate "centre of effect" is different for each station. In the case of masses extending over thousands of square miles and stations widely separated, "varying the assumed depth of the centre of compensation" will certainly not prove "a ready means" of explaining deflection anomalies.

Table I of the Memoir is entitled "Relation between distance and effect of the attraction of an underground mass". This is based on the formula

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

in which D′ represents the deflection produced at a station S by a mass m, h being the depth of C, the "centre of effect" of m and a, the angle of depression of C at S.

Proportionate deflections, appropriate to different horizontal distances of S from m, are given in terms of the maximum value of D′, as unit of deflection. Mr. Oldham's first step in compiling this table is to find the value of a which gives D′ a maximum value, by differentiating with respect to a the formula above. In this process $\frac{m}{h^2}$ is treated as a constant, that is, h as a constant, supposing the mass m to remain the same. If m is not constant the quantities of the table are not inter-related and, in consequence, meaningless. Treating h as a constant, D′ becomes a maximum when $a = 54° 45'$. Using this maximum value of D′ as unit, the values of deflection for other angles of depression have been calculated from the ratio

$$\frac{D'_a}{D'_{54° 45'}} = \frac{\frac{m}{h^2} \sin^2 a \cos a}{\frac{m}{h^2} \sin^2 (54° 45') \cos (54° 45')}$$

in which the suffixes denote the angle of depression concerned. Here again $\frac{m}{h^2}$ is treated as a constant. The point C is considered as invariable in position.

The methods of determining the values of the angle of depression at which the deflection is a maximum and of calculating the proportionate deflections for other angles are applicable only to the case where a given mass is situated at a certain point C, invariable in position. They do not apply to the case where the position of C, the "centre of effect" is variable and dependent on the distance of the station of observation. Consequently, the figures of Mr. Oldham's Table I are inapplicable and teach nothing regarding the effects of topography or its compensation.

Moreover, without considering their applicability, examination will show that the three columns of figures are not in conformity with one another. Those given for "Depression" and "Deflection" require h, the depth of the point C, to be constant while the values of "Distance" and "Depression" when taken together show h, computed from

$$h = r \tan a$$

to vary from 0·23 when $r=1·7$ to 1·72 when $r=0·2$ (the value of a given in the table for $r=0·1$ appears to be a misprint). It would appear from this that, as the distance from the station of observation becomes smaller, the depth of the "centre of effect" increases. This is not the case and does not agree with the statement at the top of page 18, "at lesser distances............the centre of compensation comes nearer and nearer to the surface".

If we take PN in fig. 9 to be a thin column of matter, 70·7 miles in length (Hayford's Solution G depth of compensation) exerting an attraction on the point S, distant S N from P N, and if C be the "centre of effect" of P N with regard to S

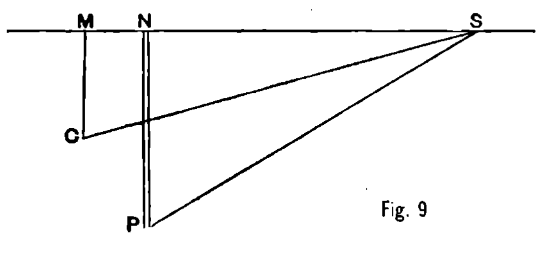


Fig. 9

we get the following quantities showing the relation between SN, SM, the distance of C from S and CM, the depth of C below S.

TABLE II.

SN distance of mass from station.	SM distance of "centre of effect" from station.	CM depth of "centre of effect" below station.
miles	*miles*	*miles*
20·4	27·68	20·82
10·0	17·53	15·22
4·9	11·65	10·87
2·4	7·91	7·64
1·2	5·53	5·44

These figures show the gradual change of position and decrease of depth of the "centre of effect" as the station of observation approaches the attracting mass.

The investigation into the relation between the effects of compensation and topography and the deduction of a compensation factor which are given on page 17 of the Memoir, are of no real usefulness, being based on the erroneous assumptions that the attraction due to the topography varies inversely as the square of the distance and that the effect of compensation can be represented by

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

the fact that the position of the "centre of effect" is not constant being ignored.

The attraction due to an element of mass varies inversely as the square of the distance but if the mass be composed of many elements distributed in a thin bar of infinite length, the attraction varies inversely as the distance of the point affected. In the case of the actual topography, the mass certainly can not be considered as concentrated at a point. The conditions are better represented by the long bar. The actual law of variation depending on the area and shape of the mass is, however, far more complex than the simple one of the inverse square.

The small tabular statement given on page 18, representing, it is stated, the relation between distance and depth of the centre of compensation is misleading. The figures do not apply to the case of uniform compensation extending to a depth of 70·7 miles. The figures have been derived as follows;

Fig. 10

Let PQ be a thin rod of matter and S be a point lying in the prolongation of QP so that

$$SP = r_1 \qquad SQ = r'$$

If the mass of an element of length of PQ be m, the total attraction of the rod on the point S is

$$A = m \left\{ \frac{r' - r_1}{r' r_1} \right\}$$

Again if the total mass of the rod be supposed concentrated at the point C in PQ, distant SC, $=$R, from S, then the attraction at S will be

$$A' = m \left\{ \frac{r' - r_1}{R^2} \right\}$$

$$\text{If } A = A' \quad \text{and} \quad r' = k r_1$$
$$\text{then} \quad R = \sqrt{k}\, r_1$$

In the system of zones used by Hayford in calculating the effects of topography and its compensation,

$$k = 1{\cdot}426.$$
$$\text{Hence} \qquad R = 1{\cdot}194\, r_1.$$

This quantity, R, has been called by Mr. Oldham the "mean effective radius" and, in the statement on page 18, the distances are the values of R for certain Hayford zones.

The next step has been to take Hayford compensation factors for each of these zones in turn and to equate them to $(1 - \cos^3 a)$ which, it is said, "represents the compensation factor of Mr. Hayford", a being the angle of depression of the centre of compensation.

Substituting the values of a derived from this equation in the expression

$$D = R \tan a$$

values of D are computed. The quantity D, it is claimed, is the depth of the "centre of compensation" for the zone whose mean effective radius is R.

The mistake Mr. Oldham has made is assuming that the "centre of effect" of a mass necessarily lies within that mass; that the centre of compensation lies vertically below the point indicating "the mean effective radius" of the topography.

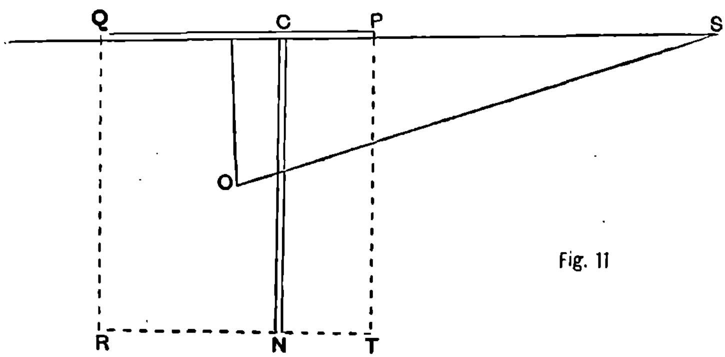


Fig. 11

In fig. 11., R = SC is the "mean effective radius" of the thin rod PQ. The average height of the surface topography being relatively small, C may be considered the "centre of effect" of a narrow strip of topography in the zone defined by P and Q. But when we consider the compensation underlying PQ, with its thickness of 70·7 miles, the case is different. If the compensating mass in PQRT be concentrated in the thin column CN, disposed vertically under C, the centre of effect of this mass will not lie in CN but outside it, as at O, and if α be the angle of depression of O at S, the relation

$$D = R \tan \alpha$$

where D is the depth of O below S, no longer holds good. In computing values of the depth, Mr. Oldham has failed to take cognizance of the fact that the horizontal distance to the "centre of compensation" is still an unknown quantity.

In Table II has already been given a statement of distances and depths of centres of effect. This is repeated below for the sake of easy reference.

TABLE III.

Distance of station from column representing concentrated compensation. 1	Horizontal distance of "centre of compensation" from station. 2	Depth of "centre of compensation" below station. 3	Compensation factor	
			as deduced from foregoing figures. 4	as given by Hayford. 5
miles	*miles*	*miles*		
20·4	27·68	20·82	0·723	0·721
10·0	17·53	15·22	0·860	0·859
4·9	11·65	10·87	0·931	0·930
2·4	7·91	7·64	0·966	0·965
1·2	5·53	5·44	0·983	0·983

These quantities assume the depth of compensation to be 70·7 miles or 113·7 km. The figures of cols. 1 and 2 show that the horizontal distances from the station to the compensating mass and from the station to the "centre, of compensation" are largely different. Mr. Oldham's values of the depth of the "centre", based on the equality of the distances to the mass and to the "centre", are seen to be incorrect. The same error has been made in calculating the quantities tabulated in Table 2 of the Memoir.

The numerical quantities given in cols. 2 and 3 of the table above are derived from the value 70·7 miles as the depth of compensation and the "mean effective radii" of the Hayford zones. Hayford's compensation factors have not been used in the calculations. Col. 4 shows the compensation factors deduced from the quantities given in cols. 1, 2 and 3, that is, for the case of a "topographical" mass, concentrated at C, being compensated by a defect of mass of the same amount concentrated at O (fig. 11.), the "centre of compensation". For purposes of comparison, col. 5 gives Hayford's values of the factors for the same zones.

On page 18 of the Memoir, it is stated that, "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 the centre of compensation can be deduced from the factors". It is to be remembered, however, that neither process is possible without a knowledge of the distance of the centre of compensation from the station of observation. It is the failure to recognise this that has led to the errors in the tabular statement following the sentence just quoted. The value of the factor cannot be deduced if we know only the depth of the centre. Before it can be determined, we require to know both depth and distance of this point. That is, we must have given us the shape and disposition of the mass. The reverse process is still further complicated. For even though the distance to the centre and the value of the factor were given, we yet could not determine definitely the depth, since it is possible to vary appropriately the size of the mass and the depth of the centre so as to give always the same factor.

The investigation is, however, of little use, for in practice all we have to work on are the observed deflection δ and the topographical effect D. The difference $\delta - D$ is the aggregate effect produced by the several compensating masses at various distances from the station of observation. Each of these masses has a different factor, the appropriate value of which we are unable to determine, being given only the ratio of nett results $\frac{\delta - D}{D}$. In practice we never know the compensation factor before we know or assume the characteristics of the mass to which it applies.

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CHAPTER IV.

The Imaginary Range.

In calculating theoretical effects, Mr. Oldham has departed in several respects from methods deemed appropriate by geodesists and the justification for such innovations ought to have received somewhat particular treatment. Results derived by methods of approximation are more convincing if supported by a discussion of their limitations and the errors with which they may be burdened. The Memoir suffers from the want of a clear exposition of the probable errors of computation resulting from the methods of procedure.

In his investigation Mr. Oldham replaces the complexity of actual masses by simple shapes and limits his calculation to embrace only masses within 100 miles of the station of observation. Substitution of simple forms for surface irregularities is used as a means of computation in the rigorous geodetic treatment also but, here, the topography is divided into compartments whose size is determined by the nearness to the station of observation, the nature of the ground and the limit of permissible error prescribed as a control and in each compartment the actual topography is reduced to a simple form with an approximation sufficiently close to justify acceptance of the results as closely representative of the effects of the real masses. The degree of approximation adopted by Mr. Oldham is of a much lower order and this, coupled with the exclusion of masses outside the 100-mile limit, leads to results which afford a doubtful foundation for the subsequent discussions. The soundness of any conclusions formed relative to invisible masses rests on the accuracy with which allowance is made for the effects of those visible. The visible topography constitutes the basis of the whole investigation and it is in connection therewith that approximations must be carefully controlled.

Mr. Oldham's Imaginary Range which is substituted for the Himalayas, some 1400 miles from end to end, is of uniform cross-section throughout its length and is considered to run from east to west. In the Memoir (page 38) is given this cross-section and, by way of comparison, two sections of the actual 1400-mile long Himalaya. When it is considered necessary, some allowance is made for the fact that the actual Himalayas have not an east and west direction.

Only so much of the Imaginary Range as falls within the 100-mile limit has been taken into consideration for the purpose of calculating deflections. This procedure is not quite logical. The Imaginary Range being supposed to be an "average or generalised" Himalaya, the whole and not merely a small part of it should have been taken into account when endeavouring to deduce results representative of the Himalayan effects. Or, having decided to deal with the effects of only those masses lying within 100 miles, the "average or generalised" form appropriate to each station should have been derived from the actual topography within that distance.

Table IV gives, for thirty-three latitude stations, the calculated deflections due to masses beyond 100 miles distance from the station. Mr. Oldham introduces in his Memoir ninety-four latitude stations but for only thirty-three of these have the requisite calculations of the effects of distant masses been carried out as yet.

TABLE IV.

Effects of masses beyond 100 miles from the station of observation.

Station.	Deflection.	Station.	Deflection.
	″		″
Lambatach ...	− 53	Usira ...	− 33
Kurseong ...	− 65	Kesri ...	− 33
Mussoorie ...	− 57	Pahargarh ...	− 31
Murree ...	− 30	Datairi ...	− 39
Birond ...	− 50	Hurilaong ...	− 41
Dehra Dun ...	− 57	Chendwar ...	− 45
Siliguri ...	− 62	Chanduria ...	− 62
Jalpaiguri ...	− 61	Madhupur ...	− 47
Kaliana ...	− 53	Ranjitgarh ...	− 34
Pathardi ...	− 59	Isanpur ...	− 34
Nimkar ...	− 44	Amritsar ...	− 40
Sora ...	− 44	Khimuana ...	− 33
Kanakhera ...	− 39	Sawaipur ...	− 31
Bansgopal ...	− 42	Tasing ...	− 35
Noh ...	− 38	Ram Thal ...	− 29
Agra ...	− 35	Kalianpur ...	− 33
Calcutta ...	− 51		

This statement shows the nature of the topographical effects disregarded by Mr. Oldham in his investigation of invisible masses below the Gangetic Plain. The stations mentioned cover an area of about 1100 miles by 200 miles and occur in five groups distributed between Longs. 75° and 88°. As will be seen, the effects vary from −29″ to −65″, showing a range of 36″. Between Ranjitgarh and Amritsar, 65 miles to the south, about the meridian of 75° there is a difference of −6″; between Dehra Dun and Agra, 200 miles apart on the 78° meridian, we find a change of +22″; between Pathardi and Gurwani (not given in the table) 240 miles apart in Longitude 82½°, there is a change of +22″ while between Jalpaiguri and Calcutta, 270 miles to the south, in about Longitude 88°, we have a difference of +10″. Between Sawaipur in the western portion of the area and Chanduria in the eastern, there is a change of −31″. These effects, large in amount and showing considerable variation, cannot be termed insignificant. They are due to masses whose existence is undoubted and being so, they ought to be taken into account before we proceed to discuss the attraction of invisible masses about which we, as yet, know little or nothing. In Mr. Oldham's investigation they are eliminated by assuming that the isostatic compensation is such that the effects of masses beyond 100 miles are completely neutralised. Assumed data or assumptions regarding data, if not supported by independent external evidence, are justifiable only if the results of the investigation in which they are used, will give, in some way, proof of their correctness or, if the results are never declared except linked with a statement of the assumption. Mr. Oldham uses the assumption that surface masses outside the 100-mile limit are completely compensated as a stepping stone from which to proceed to the branch enquiry into the form of the Gangetic Trough. The results of this latter can shed no light on the propriety of the initial assumption which still remains, for all that these results can tell us, unconfirmed and the investigation, accordingly lacks stability. From other sources, the assumption receives but little support. The testimony of geodetic observations in India is adverse rather than favorable to the hypothesis of complete compensation as stated by Hayford. It does not justify the assumption of complete compensation in researches into the absolute nature of details of mass distribution, such as those dealt with in Mr. Oldham's Memoir. In this, the only statement made in vindication of the assumption is that the effect of compensation determined by observations in the United States of America "may be accepted as not widely different from the average effect elsewhere". Mr. Oldham gives no evidence in support of this assertion which is not accepted by geodesists, so far as India is concerned. In 1912, Major Crosthwait wrote* "with a view to comparing results in the two countries, the following tables have been prepared showing the mean residual for each group, or region :—

U. S. A.

Group	S.E.	...	mean residual	−0·74″
,,	N.E.	...	,,	−1·04
,,	Central	...	,,	−1·66
,,	W.	...	,,	−4·02

India.

Region No. 1,	Himalaya Mountains, mean residual ...	−16″
2,	Plains at the foot of the Himalaya Mountains	− 2
3,	N.E.	+ 8
4,	Central	+ 5
5,	N.W.	+ 4
7,	W.	− 3
8,	E.	− 2
9,	S.	+ 1

Speaking generally, it would appear that isostatic conditions are much more nearly realised in America than in India, *i. e.* if we are to take the smallness of the residuals as an indication of the completeness of isostatic compensation. In India we have an example of a continent where very large natural convulsions have taken

* Professional Paper No. 13, Survey of India, 1912.

place, in recent geological times, producing upheavals of the crust on a scale quite unknown in any other part of the globe. In U.S.A. disturbances have been comparatively slight. Taking these facts into consideration and granting that there is always a tendency towards isostatic equilibrium, is it not reasonable to suppose that while the attainment of equilibrium is already far advanced in America, in India it is still in an immature state, and compensation is by no means so perfect ?"

In the Introduction to Professional Paper No. 15 (1915), Survey of India, by Capt. H. J. Couchman, Col. Lenox-Conyngham said "if we try to make out that under the hills there is isostatic equilibrium we are confronted by great deviation from equilibrium under the plains at their foot, or vice versa, so that we are forced to the conclusion that we are not merely dealing with an isostatic equilibrium constantly disturbed by the effects of wind and weather and constantly readjusting itself, but that there are other forces at work which are, in certain regions, continually lifting the mountains higher and higher and allowing the material washed down from their sides to sink deeper and deeper".

As indicating that complete compensation in the Indian area is not yet accepted in its entirety, we may quote, from the same Professional Paper, Capt. Couchman's conclusions ;— "It is almost certain that the Himalayas and other high mountains of India are compensated to a great extent. It is possible that this compensation extends into the plain". "The Central Indian plateau may or may not be compensated, the residuals by the two methods agreeing closely with each other".

In the Journal of Geology, Vol. XXII, No. 4 (May-June, 1914), Prof. Barrell wrote, after comparing plumb-line deflections in the United States of America with those in India, "the major elements of the relief, the Himalayas, the plateau of India and the surrounding ocean basins are, of course, largely compensated, but these figures show that in detail the hypothesis of complete isostasy is very far from the truth". "It may be concluded therefore that the convergence of geodetic evidence shows the crust to be competent to sustain loads measured by the weight of several thousands of feet of rock extending over circular areas some tens of thousands of square miles in area. This is a measure of crustal strength twenty, fifty or even a hundred fold greater than that advanced in recent years by the leading champions of high isostasy".

In the Journal of Geology, Vol. XXIV, No. 7 (Oct.-Nov. 1916), Prof. Hobbs says "It is possible to assume that a tendency to attain to isostatic adjustment exists within the earth's outer shell as a consequence of diastrophic action and that at any given time large areas, such as the greater portion of the United States are measurably compensated. In areas more recently disturbed and at a more rapid rate (western section of the United States or the Himalayan region) which still betray their lack of stability in earthquakes, no such state of isostatic compensation can be postulated".

The knowledge we have at present of the nature of the compensation of the Himalayan-Tibetan mass is not sufficient to permit of the quantitative estimation of local irregularities of density in India. The hypothesis of complete local compensation has been tested and found to be inappropriate. Observations at Himalayan stations show large discordances between observed and calculated effects. We find, for example, at Lambatach, in Long. 78°, that the observed deflection is —30″. By the hypothesis of complete compensation it should be —9″; the observed value is three times as large as the theoretical. At Mussoorie, also in long. 78°, observations show a deflection of —33″ against the theoretical —17″; the observed value is twice as large as the calculated. At Birond, long. 80°, the respective quantities are —40″ and —14″; observations giving a value nearly three times as large as theory. At Kurseong, long. 88°, similarly, we find —47″ against the calculated —23″ and at Murree, long. 73½°, an observed value of —16″ with a theoretical —10″. The magnitudes of the differences between the results of observation and theory, as compared with the theoretical effects, are so large that we are not justified in attributing them to local causes until we have reconsidered the hypothesis of compensation. (It is improbable that a reconsideration of the problem on the basis of the existing data would lead to any notable advance in this respect. Geodetic research has, so far, been able to touch only the mere fringe of the mass covering some 450,000 square miles and averaging, possibly about 13,000 or 14,000 feet in thickness between the plains of India and the divide between the rivers of Central Asia and those discharging into the Indian Ocean. Along the 1,400-mile southern fringe, deflections in the meridian have been determined in four localities and the value of gravity in three. For the rest of the enormous area we have no data as yet).

The one hypothesis of compensation that has been tested leaves us with large residuals. It is unreasonable to conclude at once that these are due to local causes rather than to an inappropriate assumption regarding compensation and regional distribution of density. Research has not yet advanced far enough to enable us to appraise correctly the attraction exerted by the Himalayan-Tibetan masses and consequently, we cannot clear deflections observed along the margin of these masses of the effects caused by them and so proceed to deduce from remaining residuals the magnitudes and shapes of local disturbing elements. In this light, weight cannot be attached to the results of an investigation into the shape of the Gangetic Trough which starts with the unsupported assumption that the Himalayan-Tibetan masses are completely compensated in such a way that their effects at stations in the Gangetic area are entirely neutralised.

In his calculation of theoretical deflections, Mr. Oldham has substituted for the actual Himalayas an Imaginary Range and has taken into consideration only so much of the mass of this range as falls within 100 miles of the station considered. The shape of the range, based on but two cross-sections of the actual Himalaya, represents only very roughly the contour of the real mass. No direct comparison has been made between the Imaginary Range effects as calculated by Mr. Oldham and those computed in the rigorous manner from the actual contours. It is argued that, because the resultant small quantities derived by combining the attraction due to the imaginary masses with the neutralising effect of compensation do not differ largely from the similar small quantities deduced from all masses, Himalayan and other, within 256·4 miles of each station and their compensation, the Imaginary Range closely represents the real Himalayas. But it does not follow that because the compensated effects of two masses are equal, the masses themselves and their uncompensated effects are equal or even of the same order of magnitude. M_1 does not necessarily equal M_2 because

$$M_1+C_1 = M_2+C_2.$$

In Table 5 of the Memoir is given, for eight stations, a comparison of the deflections calculated from the Imaginary Range with those computed by the orthodox method embracing all masses within 256·4 miles of the station. This table is reproduced below with correct signs introduced in the last column of figures. As given in the Memoir, for three of the eight stations the signs are wrong.

TABLE V.

Station.	Distance from main boundary in miles.	Deflection, due to the Imaginary Range, in the meridian.		Deflection 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 „	−44	−29	−103	−23	−49	+ 6
Mussoorie ...	3 „	−40	−19	− 86	−17	−46	+ 2
Birond ...	2 „	−51	−20	− 74	−14	−23	+ 6
Dehra Dūn ...	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

In this table, the quantities under *I* are appropriate to uncompensated, and those under *II* to compensated masses.

From these figures Mr. Oldham concludes 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", and that "the Imaginary Range will serve the purpose for which it was intended", that is to represent the real Himalayas.

This conclusion rests on the quantities of the last column of the table. It implies the assumption that these quantities correctly represent the effects of all masses beyond 100 miles from the station, that is, that the deflections calculated from the Imaginary Range agree with those deduced rigorously from the real masses within the 100-mile limit. The correctness of this assumption is not discussed and it is not established that the effects of the Imaginary Range may be taken as representing closely those of the real masses. The best test, a direct comparison of uncompensated effects, has not been made.

The quantities in the last column of the table, headed "Difference between the effect of actual and imaginary topography" show at once that, in some way, the Imaginary Range is not satisfactory. Supposing, for the moment, that the figures given as the deflections due to the Imaginary Range really do represent the effects of masses within 100 miles of the stations, then the quantities of the last column show the consequences of taking into the calculation all masses between 100 miles and 2564 miles distance. It would appear, then, from the tabulated quantities that in the case of Lambatach, Kurseong, Mussoorie, Birond and Siliguri, the masses beyond 100 miles have the effect of increasing the northerly deflections if no compensation be assumed but of decreasing them if there be compensation. Now such a result would be possible if the extension of the distance limit brought into consideration masses, to the south of the station and just beyond the 100 miles, much larger than those at a similar distance to the north. If in the 100—2564 mile zone, the distant northern masses were large and the nearer were small while to the south the nearer masses were large and those more remote, small, it might possibly result that the effect of this zone would be to increase the northerly deflection if the masses were taken as uncompensated but to decrease it if compensation were assumed. But at the stations just mentioned, we know that these conditions of mass distribution, to the south especially, are very far from being realised and that extension of the zone, covered by the calculations, to beyond 100 miles will cause an increase in the deduced northerly deflections whether masses be supposed compensated or not and we are therefore forced to conclude that the initial supposition, that the deflections due to the Imaginary Range represent the effects of the actual masses within 100 miles, is not correct in respect to five of the eight stations of the table. This failure of the nature of the calculated results to accord with what the actual mass distribution tells us to expect points at once to the necessity of a more searching test of the suitability of the Imaginary Range and a reconsideration of its shape.

Mr. Oldham has not perceived this teaching of the figures of the table. The effects of the Imaginary Range have not been further examined in their relation to those either of the Himalayas proper or of actual masses within 100 miles of the station. Table 5 of the Memoir gives merely a comparison between the imaginary deflections and those due to all masses, continental and oceanic, within 2564 miles of each station and it cannot establish the similarity of the Imaginary Range to the Himalayan-Tibetan masses.

The following table gives a comparison between the deflections calculated from the actual masses and those due to the Imaginary Range. In this, for the purposes of comparison, the actual masses comprise only the mountain mass on the continental side of northern India; they do not include the plains of northern India and the Punjab nor the masses of peninsular India.

TABLE VI.—Comparison between Deflections calculated from the actual masses and from Mr. Oldham's Imaginary Range.

Station.	Distance from the foot of the hills, in miles.	Deflections due to the actual masses.			Deflections due to the Imaginary Range.	Difference between "actual" and "imaginary" effects.		
		within 100 miles from the station.	in the Himalayan-Tibetan area.*	within 2564 miles of the station.		Difference col. 6—col. 3	Difference col. 6—col. 4	Difference col. 6—col. 5
1	2	3	4	5	6	7	8	9
Lambatach ...	44 N	− 22″	− 57″	− 70″	− 33″	− 11″	+ 24″	+ 37″
Kurseong ...	3 „	− 39	− 82	− 93	− 54	− 15	+ 28	+ 39
Mussoorie ...	3 „	− 33	− 72	− 84	− 40	− 7	+ 32	+ 44
Birond ...	2 N	− 27	− 62	− 70	− 51	− 24	+ 11	+ 19
Dehra Dūn ...	6 S	− 47	− 85	− 97	− 34	+ 13	+ 51	+ 63
Siliguri ...	12 „	− 23	− 66	− 76	− 30	− 7	+ 36	+ 46
Pathardi ...	13 „	− 7	− 50	− 58	− 28	− 21	+ 22	+ 30
Jalpaiguri ...	33 „	− 18	− 58	− 68	− 14	+ 4	+ 44	+ 54
Kaliana ...	41 „	− 5	− 39	− 52	− 6	− 1	+ 33	+ 46
Bansgopal ...	70 „	− 2	− 28	− 37	− 4	− 2	+ 24	+ 33
Nimkar ...	86 „	− 2	− 28	− 35	− 1	+ 1	+ 27	+ 34
Datairi ...	88 „	− 1	− 23	− 33	− 1	0	+ 22	+ 32
Sora ...	120 „	0	− 26	− 35	0	0	+ 26	+ 35
Noh ...	138 „	0	− 20	− 30	0	0	+ 20	+ 30
Agra ...	168 „	0	− 17	− 26	0	0	+ 17	+ 26
Tasing ...	180 „	0	− 17	− 26	0	0	+ 17	+ 26
Usira ...	192 S	0	− 16	− 25	0	0	+ 16	+ 25

* The area denoted as Himalayan-Tibetan is shown on plate I.

The quantities in cols. 7, 8 and 9 show how the Imaginary Range compares with the real masses. Col. 7 shows that, as compared with the real masses within 100 miles, the imaginary have too great an effect. The differences in this column amount to a fairly large percentage of the rigorously calculated deflections given in col. 3. The fact that both the imaginary and the real masses within 100 miles give no deflection at the more distant stations does not necessarily indicate equality. It means only that both masses are too small to produce significant effects at the distances involved. The differences in the case of the nearer stations show that the want of agreement between the Imaginary Range and the real masses is considerable.

The following statement of some of the discordances between imaginary and rigorously calculated differential effects shows the dissimilarity between Mr. Oldham's Range and the real Himalaya.

TABLE VII.—Differences of Deflection.

Stations.	Calculated from the Imaginary Range.	Calculated from actual masses within 100 miles.	Calculated from the Himalayan-Tibetan mass.
Lambatach—Dehra Dūn ...	+ 1″	+ 25″	+ 28″
Birond—Dehra Dūn ...	− 17	+ 20	+ 23
Lambatach—Jalpaiguri ...	− 19	− 4	+ 1
Kaliana—Dehra Dūn ...	+ 28	+ 42	+ 46
Kaliana—Pathardi ...	+ 20	+ 2	+ 11
Siliguri—Jalpaiguri ...	− 16	− 5	− 8

Before we can deduce the dimensions of the Gangetic Trough, we must be in a position to form an estimate, in which we can place some reliance, of the actual effects produced by this feature. We must eliminate, from the results of the observations, the effects of all masses other than those of the trough, the real effects, that is to say, not the effects according to this or that hypothesis.

Mr. Oldham argues that the compensated effects of his Imaginary Range, as they are nearly the same as those deduced by rigorous methods embracing the real masses in a wide area, may be accepted as the actual effects of the Himalayan-Tibetan mass. He considers the rigorously calculated quantities to be real effects. This has never been claimed for them. They are the results of an enquiry as to what geodetic evidence there was in India in favour of a certain hypothesis of compensation found to be suitable to the United States of America. The outcome of the enquiry is that this hypothesis does not explain satisfactorily the gravitational phenomena observed in India. It cannot be taken as representing the best approximation to the laws governing the actual conditions of compensation. Constituting a most valuable guide and criterion, they are only the first step in the investigation of the terms of these laws.

Mr. Oldham appears to hold that any change of hypothesis will not produce much alteration of the results. This may be true so long as we adhere to the assumptions underlying Hayford's hypothesis, namely that the compensation is everywhere complete and local, that is to say, that the crust of the Earth is a failing structure, having no rigidity. But the rejection of this initial assumption in favour of a certain degree of rigidity of the crust, producing regional compensation, either complete or otherwise, would lead to marked changes in the calculated quantities. The nature and magnitudes of gravitational residuals in India, derived on Hayford's hypothesis, do not permit of their being considered as accidentals but indicate the necessity of rejecting Hayford's assumption and of formulating a new hypothesis which will afford a more satisfactory explanation in general of the observed facts. In the meantime, theoretical quantities, calculated on Hayford's hypothesis, cannot be regarded as real Himalayan-Tibetan effects for the purpose of arriving at quantitative estimates of other geological structures and the substitution of an Imaginary Range for the real masses, while introducing uncertainty into the computations does not bring us nearer to the reality of results.

CHAPTER V.

The effect of the Gangetic Trough.

It has been generally conceded that along the foot of the Himalayas and roughly parallel to them there lies a great depression, probably deep toward its northern edge and shallow toward the southern and filled with alluvial deposits. In calculating the amount by which, theoretically, the direction of the plumb-line is affected by surrounding masses the fact of this depression has not been taken into account, for its dimensions must be, at present, conjectural and it is undesirable that the theoretical effects of visible determinate masses should be entangled with those of bodies whose magnitudes are unknown though their existence is not doubted.

It was recognised, also, that the effect of this depression would tend to increase the northerly deflections at stations along the foot of the Himalayas and, thus, to reduce the differences between the results of observation and theory. But any deficiency of mass, whatever its shape, underlying the Gangetic plains will tend to produce this effect, so that the mere fact of the reduction of the residuals, by itself, gives no reliable indication of the nature of the depression. For such indications it is necessary to examine the character of the residuals and to see to what extent a suggested hypothesis of deficiency provides an explanation of the salient features, one of which is the striking change that occurs in the residuals all along the length of the mountain mass as we recede to a short distance into the plains from its foot. There is a very rapid fall, in a northerly sense, in the value of the residual between Dehra Dūn and Kaliana, Birond and Bansgopal, Siliguri and Jalpaiguri. To produce this fall, a deficiency of mass, widespread throughout the Gangetic area, as in the trough, is insufficient. There seems to be demanded, in addition, a great deficiency concentrated within a small horizontal distance, possibly in the strip defined by the pairs of stations referred to above.

In the following table, as a matter of interest, are shown the theoretical deflections obtained if we take into consideration, in addition to visible topography, a Gangetic trough such as that supposed by Mr. Oldham, all masses, including that of the trough, being taken as compensated according to Hayford's hypothesis with a compensation depth of 113·7 km.

The general shape of the trough, shown on Plate I is that suggested in Mr. Oldham's Memoir. The density of the alluvium above sea-level is taken at 2·16 and, below sea-level, at all depths the deficiency of density from normal is taken as equal to

$$(2{\cdot}67 - 2{\cdot}16) = 0{\cdot}51.$$

The calculations embrace all masses up to 2564 miles distance.

Complete compensation has been applied to the trough and its alluvium in consistency with the treatment of all other masses. There is no reason for excepting it, as Mr. Oldham has done, from the operation of the general hypothesis.

CORRECTION.

For main heading over cols. 3 and 4 of Table VIII, *read* :—

" Calculated effects of alluvium in Trough area alone ".

TABLE VIII.

Deflection effects deduced by taking into consideration a Gangetic Trough in addition to surface masses.

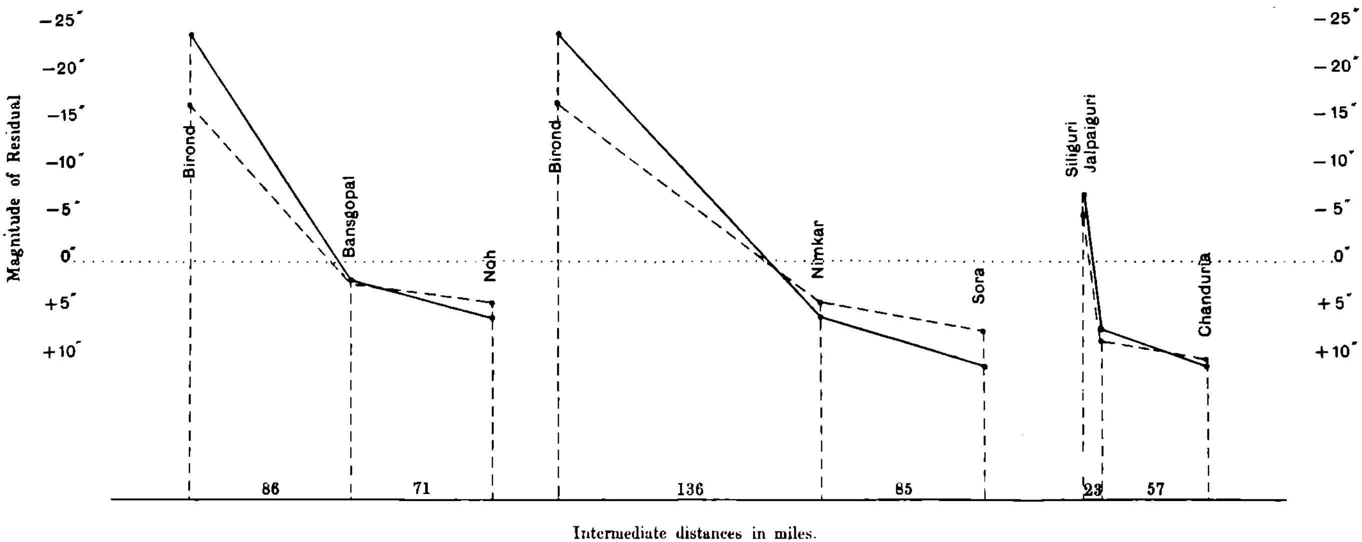
Station	Observed deflection	Calculated effects of Trough alone		Total calculated deflections		Residuals	
		Uncompensated	Compensated	Supposing no trough	Supposing a trough	Col. 2—Col. 5	Col. 2—Col. 6
1	2	3	4	5	6	7	8
	"	"	"	"	"	"	"
Ranjitgarh ...	+ 2	− 1	+ 1	− 5	− 6	+ 7	+ 8
Amritsar ...	+ 11	− 2	0	− 1	− 2	+ 12	+ 13
Khimuana ...	+ 3	+ 1	+ 1	0	+ 1	+ 3	+ 2
Sawaipur ...	+ 6	+ 1	0	0	+ 1	+ 6	+ 5
Ramthal ...	+ 4	+ 1	0	+ 1	+ 1	+ 3	+ 3
Isanpur ...	+ 3	− 1	0	− 1	− 1	+ 4	+ 4
Tasing ...	+ 6	+ 1	0	+ 1	+ 2	+ 5	+ 4
Lambatach ...	− 27	− 5	− 1	− 9	− 11	− 18	− 16
Mussoorie ...	− 30	− 7	− 2	− 17	− 20	− 13	− 10
Dehra Dūn ...	− 31	− 6	− 2	− 18	− 20	− 13	− 11
Kaliana ...	− 1	0	+ 1	− 3	− 2	+ 2	+ 1
Noh ...	+ 5	+ 4	+ 1	− 1	+ 1	+ 6	+ 4
Agra ...	0	+ 5	+ 2	0	+ 2	0	− 2
Usira ...	− 1	+ 4	+ 1	0	+ 2	− 1	− 3
Kesri ...	+ 10	+ 2	0	+ 1	+ 1	+ 9	+ 9
Pahargarh ...	+ 4	+ 2	0	+ 1	+ 1	+ 3	+ 3
Birond ...	− 38	− 12	− 5	− 14	− 21	− 24	− 17
Bansgopal ...	+ 1	+ 1	+ 1	− 1	− 1	+ 2	+ 2
Nimkar ...	+ 5	+ 4	+ 2	− 1	+ 1	+ 6	+ 4
Kanakhera ...	+ 10	+ 8	+ 2	0	+ 3	+ 10	+ 7
Pathardi ...	− 11	− 12	− 6	− 3	− 10	− 11	− 4
Sora ...	+ 11	+ 10	+ 4	0	+ 4	+ 11	+ 7
Hurilaong ...	+ 15	+ 4	0	+ 2	+ 2	+ 13	+ 13
Chendwar ...	+ 7	+ 3	0	0	0	+ 7	+ 7
Siliguri ...	− 18	− 3	− 1	− 11	− 13	− 7	− 5
Jalpaiguri ...	− 1	− 2	− 1	− 8	− 9	+ 7	+ 8
Chanduria ...	+ 9	+ 3	+ 1	− 2	− 1	+ 11	+ 10
	Mean residuals without regard to sign ...					8	7
	Mean residuals with regard to sign ...					+ 1·5	+ 1·7

So far as the trough effects at each station can be made out from the Memoir, the uncompensated values shown in col. 3 differ from those given by Mr. Oldham. The discrepancies have not been examined. They may be due to each station having been conceived "as lying in the centre of a 200-mile square and everything outside this limit has been put out of consideration," in Mr. Oldham's investigation

Diagrams showing variation of residual on moving from the Hills down on to the Gangetic Plain.

The black line represents the case where the Trough is not considered.

The red line represents the case where the Trough is considered.



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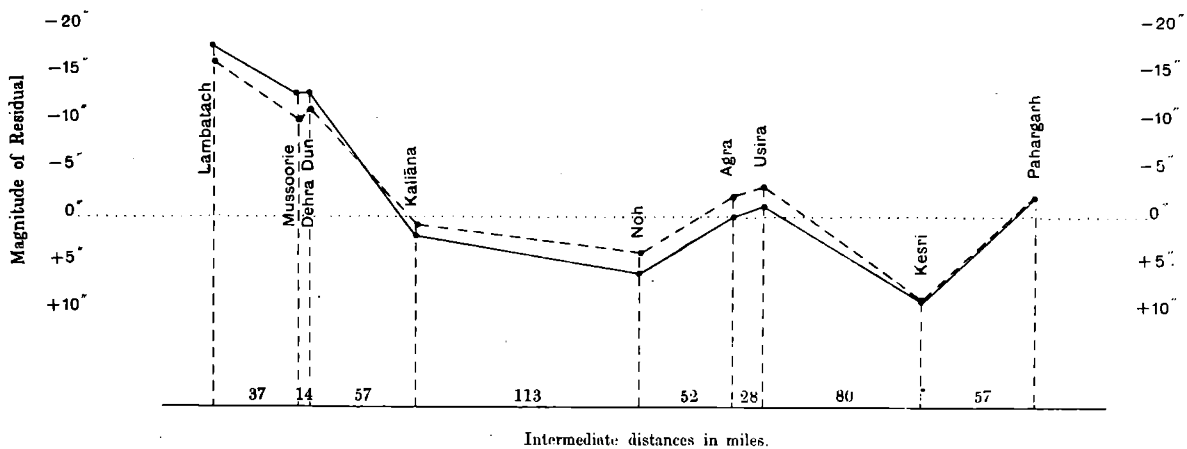

whereas, here, the whole extent of the trough is taken into account. Mr. Oldham limited the area to be considered to the 200-mile square, arguing that the effects of masses outside this limit, when combined with those of complete compensation, were negligible. But as, subsequently, he considers the alluvium of the trough to have no compensation, the argument and the imposing of the 100-mile limit are inapplicable to the trough and the omission to take count of this would lead to error.

Col. 5 shows the calculated deflections produced by surface masses and their compensation, the existence of the trough being ignored. Col. 7 shows how the observed differ from the calculated values. Cols. 6 and 8 give the corresponding quantities for the case where a trough of the shape and depth suggested by Mr. Oldham, and its compensation are taken into account in addition to the surface topography.

Regarded simply as series of residuals, there is little difference between the quantities of col. 7 and those of col. 8. The latter show no marked improvement, as a whole on the residuals of col. 7. There is, as was to be expected, some reduction of the northerly residuals at stations to the north of the trough, at, for example, Lambatach, Mussoorie, Dehra Dūn, Birond, Pathardi and Siliguri but, except at Birond and Pathardi, the reductions are slight. It will be noticed that the introduction of the trough has not had the effect of removing the abrupt change in the residuals along the northern fringe of the Gangetic Plain. We still find, between Dehra Dūn and Kaliana, Birond and Bansgopal, Siliguri and Jalpaiguri, the rapid variation which contributed to the evolution of Sir Sidney Burrard's rift theory. The diagrams on the opposite page show, at a glance, what effect the trough has on the deflection residuals. There is no marked general improvement and the characteristic anomaly, the rapid fall in the value of the residual, remains unexplained, a problem still awaiting solution.