Survey of India.

PROFESSIONAL PAPER—No. 12.

ON THE ORIGIN
OF THE
HIMALAYA MOUNTAINS.

A CONSIDERATION OF THE GEODETIC EVIDENCE

BY

COLONEL S. G. BURRARD, C.S.I., R.E., F.R.S.,
SURVEYOR GENERAL OF INDIA.

CALCUTTA,
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PLATE I.

Showing the Pre-Tertiary Table-land to the south,
the Tertiary Mountains to the north,
and the intervening Alluvial Belt.

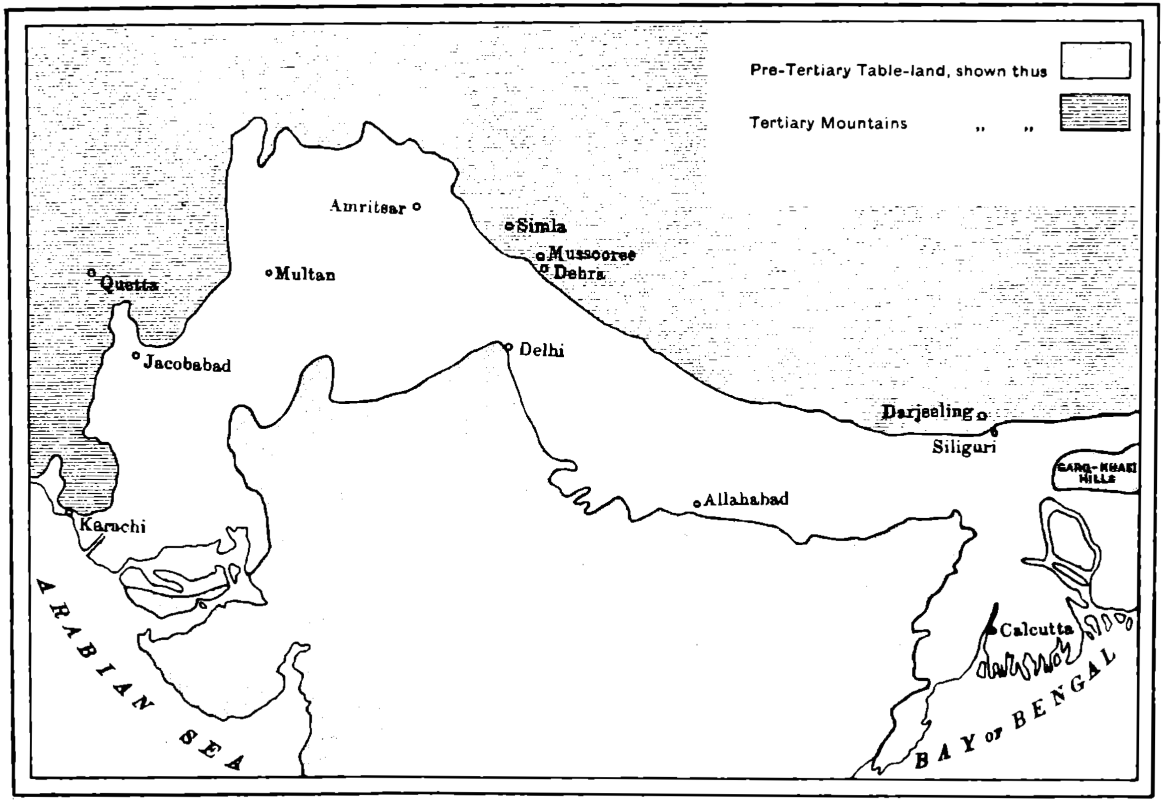

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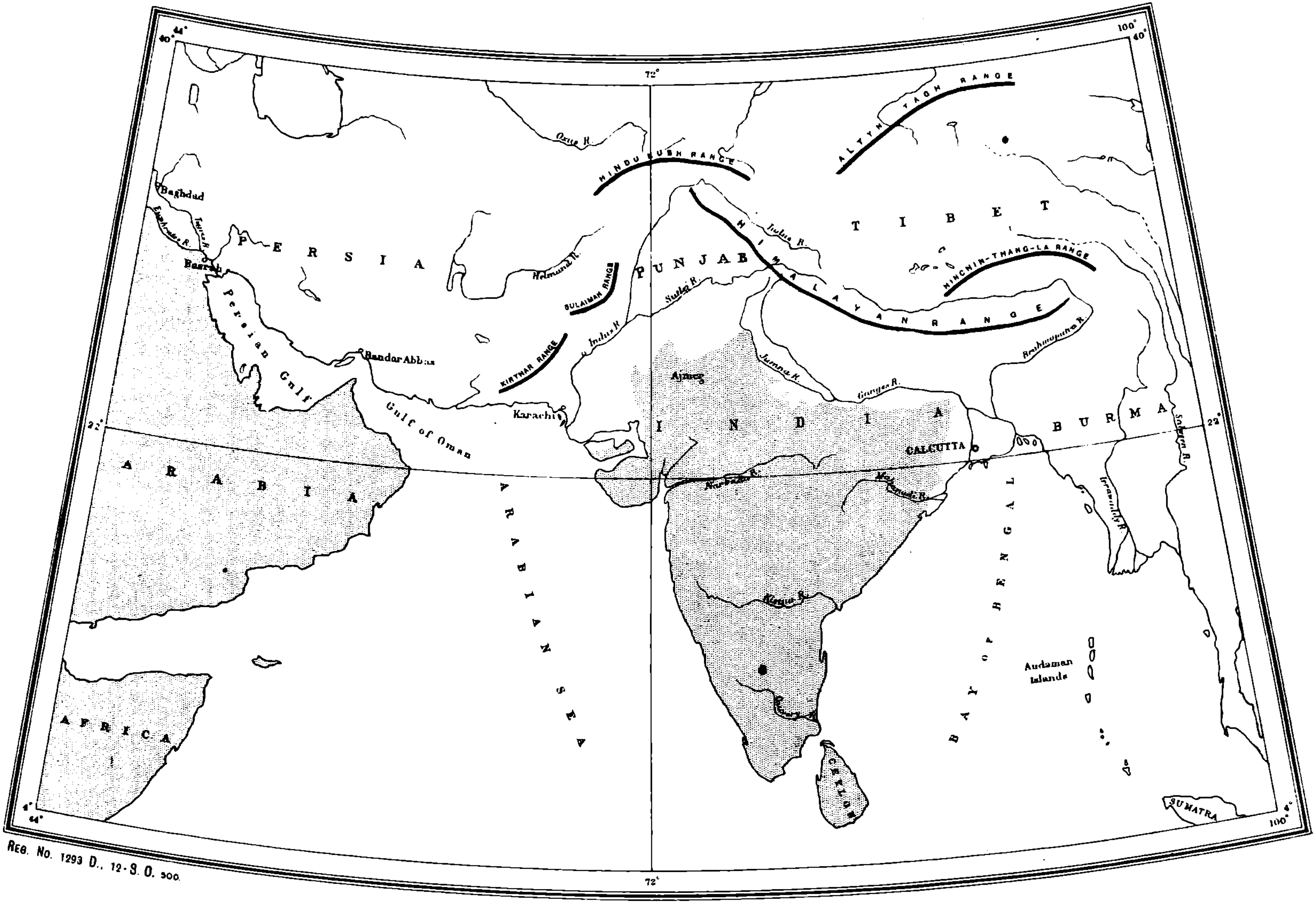
PLATE II



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NOTE.—Relics of Pretertiary continent are shown thus

1-8

On the Origin of the Himalaya Mountains.

A CONSIDERATION OF THE GEODETIC EVIDENCE.

(This paper is an amplification of a lecture given at a meeting of the Astronomical Society of India in Calcutta on February 9th, 1912.)

Throughout the Himalayas evidence exists of the crumpling of the Earth's crust; a portion of the crust has clearly been compressed into a smaller area of the spheroidal surface than it originally occupied. The outer crust has behaved as though it were a carpet; the Himalayan portion has been wrinkled and folded, and whilst undergoing changes of shape it has retained its original superficial area undiminished.

The origin of mountains is generally explained in text books as follows: mountains are wrinkles of the Earth's crust; the wrinkling is caused by the cooling and shrinkage of the core; the outer shell sinks down upon the contracting nucleus, the lateral compression produced throwing the crust into undulations.

In his *Physics of the Earth's Crust,* however, Osmund Fisher has shown that it is not possible to assume a shrinkage of the Earth's radius sufficient in magnitude to account for the wrinkling of the surface.

The following extracts illustrate an interesting geological interpretation of the Mountains of Asia :—

The great series of parallel plications in Asia are supposed to have been caused by a horizontal thrust from the north: the sediments of the Eurasian sea were forced against the northern coast of the once continuous Indo-African continental mass, which stood like a buttress in the path of the advancing earth-waves. (*H. H. Hayden : Sketch of Geography and Geology of Himalayan Mountains, page 48.*)

The whole southern border of Eurasia advances in a series of great folds towards Indo-Africa: these folds for long distances are overthrust to the south against the Indo-African table-land. (*Eduard Suess : The Face of the Earth, Vol. I, page 596, Sollas's translation.*)

As one stands in front of the overfolded chains of the Himalaya there seems to have been a movement of the whole mass of Asia towards the south. (*Griesbach : Geology of the Central Himalayas*).

In Volume II, page 195, *The Face of the Earth,* the great Austrian geologist calls the Peninsula of India "an obstructive fragment." This obstructive fragment is supposed to be opposing the advance of the Himalayan folds which are moving southwards from Siberia.

In plates No. I and No. II attached to this paper the fragment of the ancient continent is shown as a dotted area; the folds on the north are shown in plate I as a lined area. The dotted area represents an undisturbed relic of the Earth's pre-tertiary crust. (The scale of plate I is $\frac{1}{15,000,000}$).

Suess's interpretation of the orography of Asia is based upon two independent series of observations :—

(*i*) The plan of the mountain trend-lines.

(*ii*) The over-thrusting of the folds towards the south.

The argument from the plan of the trend-lines is this: the trend-lines of the mountain-ranges are curved alignments, they are arcs which are convex towards the obstructive fragment, *i.e.*, towards the south. They are a series of earth-waves advancing towards the south.

Five great arcs turned towards the south align themselves one after the other across the continent. (*Suess: Face of the Earth, Vol. I, page 505*).

It is true that the Himalaya Mountains and the mountains of Baluchistan take the form of arcs convex towards the south. But in my opinion the following great ranges are convex towards the north :—

the Hindu-kush,
the Ninchin-tangla,
the Altyn Tagh.

I have drawn these ranges upon plate II of this paper. The evidence of the trend-lines appears to me to be contradictory.

Now with regard to the second argument based on the overthrusting of folds, geologists have found that the Himalayan folds are overthrust towards the south. But the direction of movement of the range cannot be ascertained from such data. When folds are overthrust towards the south, they have the appearance of being pushed southwards from the north: but another explanation is possible, and that is that the sub-crust upon which the folds are standing erect is being moved northwards, and that the folds overbalance towards the south.

The great objection to Professor Suess's interpretation of the mountains of Asia is that it is opposed to the theory of "mountain compensation." In appendices I and II of this paper, I have discussed the results of geodetic observations. The mountains of northern India are largely compensated, more so I believe than are the mountains of central India. The Himalaya Mountains are compensated to a greater extent than they would be, if they had been crumpled up through "the whole southern border" of Asia advancing southwards towards India "in a series of great folds." (*Suess: Volume I, page 596.*)

If the whole surface of Asia is advancing towards India an immense excess of mass must be accumulating along the northern frontiers of India. The geodetic observations show that no very large excess of mass exists.

If folding of strata denotes the compression of a portion of the surface into a smaller area, the mountains so formed may not be isostatically compensated. It is true that the Himalayas may not be completely compensated, but still their excess of mass is considerably less than what it appears to be. They are largely compensated by deficiencies of matter beneath them.

Professor Suess does not admit that there is any deficiency of mass.

The existing state of observation does not justify us, in the face of so many contradictory facts, in regarding the existence of deficiencies of mass beneath the mountains as proved. It would be inconsistent with all geological observations. (*Suess: The Face of the Earth, Vol. IV, page 614.*)

Whilst the attraction of the Himalayas upon the plumb-line is partially compensated by deficiencies of mass underlying the mountains, its remaining effects are completely neutralised by the extraordinary deficiency of mass underlying the alluvial belt that is situated immediately to the south of the Himalayas. What is this extraordinary deficiency under the alluvial belt due to?

Professor Suess explains it as follows :—

All the figures determined by the plummet may be explained on the assumption that the foredeep is filled with sediment of a less density beneath which the ancient rocks dip from the south. (*Suess: The Face of the Earth, Vol. IV, page 614.*)

In my opinion it is not possible to explain the deflections of the plumb-line, recorded in table I, (page 11 of this paper), on any hypothesis of uncompensated mountains combined with a foredeep filled with light sediment.

The Himalayan line of low density.

Recent geodetic observations have brought to light the existence of a deficiency of matter at the foot of the Himalaya Mountains. The Himalayas rise suddenly out of flat alluvial plains, and our plumb-lines show that all round the base of the mountains there is a deficiency of matter resembling a deep invisible channel or trench. The Himalayan side of the trench appears to be a steep wall; the southern side of the trench has a gentle slope. But all is hidden from sight, buried under the alluvium.

The results of the plumb-line observations (see appendix No. 1) in the Indo-Gangetic plains (plate I) may be summarised as follows: the deflections of the plumb-line in the meridian show most extraordinary variations all along the foot of the Himalayas: between Kurseong and Jalpaiguri, for example, the deflection changes 45″ in 25 miles. As a rule, all over the earth, deflections of the plumb-line are smaller than the attraction of visible topographic features would lead us to expect. The attraction of the Himalayas is on the whole inconsiderable. But across this one long line at the Himalayan foot the change in the deflection is actually much larger than it would be, if the Himalayan mountains were exercising their entire attraction uncompensated. Between Kurseong and Jalpaiguri the change in deflection, calculated from the uncompensated topographic features should be 25″. On Hayford's hypothesis of isostasy this change should be 15″. The actual change observed is 45″.

Kurseong and Jalpaiguri are typical stations of the Eastern Himalaya. In the Central Himalaya we find at the foot of the mountains that the deflection of gravity changes 43″ between Birond and Nimkar. The change here in the deflection, as deduced from the topographic features uncompensated, is 31″. The change here in the deflection, as deduced from Hayford's hypothesis of isostasy, is 13″. The change actually observed is 43″.

If we go to the Western Himalayas, we find that at the foot of the mountains between Dehra Dún and Kaliana, the change in deflection, deduced from topographic features, is 29″, the change in deflection deduced from Hayford's hypothesis is 15″, the actual change in deflection as observed, is 30″. There is no question about these figures; the same results are obtained throughout the whole length of the Himalayas.*

Here we have an invisible channel. Across the channel there is a sudden change in the direction of gravity: in the regions to the north and south of the channel the direction of gravity alters very slowly.

On the origin of the line of low density.

The main point, that I wish to emphasise in this paper, is the existence of a line of low density, and my object would perhaps be more surely gained, if I now refrained from speculating upon the origin of the line. The existence of the line is a fact; its origin is conjectural. The existence of the line of low density is the significant fact of Himalayan geodesy.

In discussing the meaning of the line of low density, I have to make some assumption concerning the compensation of the Himalaya Mountains; without some assumption I cannot decide upon the exact numerical values of the plumb-line deflections which are to be exclusively attributed to the line of low density. I will therefore assume that the Himalayas are isostatically compensated in accordance with Hayford's hypothesis.†

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* *Sketch of the Geography and Geology of the Himalaya Mountains and Tibet*, 1907, page 52. The total deflection-change south of Dehra Dún is as great as south of Kurseong: the observed change quoted above is derived from latitude observations and is consequently the meridional component of the total change. Kurseong is south of the Himalayas, Dehra Dún is south-west: almost the whole deflection at Kurseong is in the plane of the meridian: at Dehra Dún the prime-vertical component is considerable.

† The significant fact is the *decrease* in the deflections, as we recede from the Himalayas. This decrease is independent of any assumption of compensation or want of compensation: no such assumption will account for it. I have to make some assumption as a working basis, and I assume complete compensation, but this does not affect the subsequent conclusions.

We have then the following data from the typical stations of Kurseong and Jalpaiguri :—

(*a*).—Jalpaiguri (height 280 feet) is in the plains 25 miles south of Kurseong (height 4,428 feet).

(*b*).—The decrease in the topographic deflection (uncompensated) between Kurseong and Jalpaiguri is 25″.

(*c*).—The decrease in deflection according to Hayford's hypothesis is 15″.

(*d*).—The observed decrease in deflection is 45″.

(*e*).—Of the 45″ as observed, 15″ are due to the Himalaya Mountains and their compensation : thus the unexplained Hayfordian residual is 30″.

(*f*).—Throughout 2,000 miles in length round the foot of the Himalaya mountains we have an unexplained change in deflection of 30″ in 25 miles.

Hypothesis of a synclinal trough.

It has been suggested by high geological authority that this decrease of 30″ in 25 miles, all round the foot of the mountains, is due to a synclinal trough, a foredeep, lying in front of the Himalayas. But this explanation does not appear to me to be adequate.

	Observed deflection.	Hayfordian correction.	Unexplained residual.
Kurseong (in the outer hills) ..	−46″	−23″	−23″
Siliguri (near the foot of the hills 12 miles south of Kurseong)	−18″	−12″	− 6″
Jalpaiguri (13 miles south of Siliguri) ...	− 1″	− 8″	+ 7″
Chanduria (50 miles south of Jalpaiguri) ...	+ 9″	− 2″	+11″

These are merely typical Himalayan deflections : to explain them by a hidden synclinal, we must assume the latter to be 70 to 80 miles wide and 6 miles deep under Siliguri, 2 miles deep under Jalpaiguri; rock composing the synclinal basin to have a density of 2·7, sediment filling the synclinal to have a density of 1·9.* It is doubtful whether the density of sediment, when under a pressure of a vertical column 6 miles high, would remain as small as 1·9; any increase in its value will require the depth of the supposed syncline to be increased.

As far as we can ascertain, the visible Himalayan folds are mostly compensated : it is then inconsistent to assume the existence of an immense synclinal fold, entirely uncompensated. If the Himalayas were uncompensated, the deflection at Kurseong would be 71″ instead of 46″ (see appendix I), and the deflection at Jalpaiguri would be 45″ instead of 1″. The observed deflections are smaller than they would be, if compensation did not exist; but the observed *decrease* in deflection is larger : that is the curious fact. This sudden decrease in deflection is a remarkable geodetic abnormality, and we cannot explain a geodetic abnormality by means of a normal geological fold.

If the large deflections of gravity, discovered in other parts of India, are analysed, they are seen to be due not to topographic features of the upper crust but to heterogeneity of the sub-crust. On the coasts we find plumb-lines deflected strongly towards the ocean and away from mountain coast-lines; throughout the Gangetic plains we find the plumb-lines deflected away from the Himalaya Mountains; throughout the north of the Archæan peninsula we find the plumb-lines deflected towards a hidden line of high density, that is a feature of the sub-crust, not of the topography. Many of the most important deflections that we have discovered are thus independent of topography, and it is even open to doubt now, whether the large deflections at the foot of the Himalayas are due to the Himalayas. If we may judge from geodetic observations generally, the line of low density round the foot of the Himalayas is a feature of the sub-crust and not of the topography.

* I assume densities 2·7 and 1·9, because they are most favourable to the idea of a syncline. The larger we make the difference between them, the less deep need our syncline be. In geological diagrams the rocks dipping under the alluvial plains are shown as Siwalik (density 2·2) not as Himalayan (density 2·67). If these diagrams are correct, the syncline must be 16 miles deep.

Hypothesis of Himalayan weight.

If we place a heavy weight upon a surface that yields, we find that the weight causes the surface to sink, and produces a kind of trough around it. Immediately under the weight the surface sinks, but it recovers its position towards the sides. This interpretation of the Sub-Himalayan line of low density, the existence of which has now been brought to light by geodetic observation, cannot however be upheld; it ascribes to the Himalayas a weight that we know they do not possess, and it offers no explanation of the visible Himalayan folds.

Hypothesis of horizontal displacement of compensation.

I have frequently been led by our results to consider whether the compensation of the Himalayas does not extent southwards beyond the base of the mountain range. The principal reason for this idea is that the negative anomaly at pendulum stations on the low-level plains south of the mountains is in close accordance with the anomaly found to exist at stations in the mountains 6,000 feet high.*

The following calculations will, however, show that the hypothesis does not account for the observed results:—

(a).—The residual and unexplained change in deflection, as observed in 25 miles, is 30″.

(b).—The change in the deflection produced in those 25 miles by the entire subterranean compensation of all the Himalayas is only 10″.

(c).—The extension of the compensation for a few miles beyond the base of the range could not account for the 30″ observed and unexplained.

(d).—At the base of the range the density of the crust underlying the outer Himalayas is according to the theory of isostasy less than the normal density of the crust by 0·03 or 0.04. A change of density such as this (from 2·75 to 2·72), even if it extends down to 70 miles, would not produce a change of deflection of 30″ in a horizontal distance of 25 miles at the Earth's surface.

Hypothesis of a rift.

In my opinion the line of low density is entirely different from a synclinal fold. I believe it to be a feature of the sub-crust, not of the upper crust.

Now if the Himalaya Mountains were being thrust southwards by a horizontal force (page 1), I do not think that a marked deficiency of density would be found existing in front of the advancing mountains. A long zone of low density is rather a sign of an opening; it is a sign rather of relief than of thrust, rather of expansion than of compression.

The parallelism of the northern and southern edges of the alluvial belt is shown in Plate I; and it gives rise to the idea that the alluvial belt is covering a crack in the Earth's crust. The extraordinary parallelism of the coasts of Arabia and of Baluchistan in the Gulf of Oman and in the Persian Gulf opposite Bander Abbas (see Plate II) seems also to be due to a crack, and it may be that one long crack has extended from Sumatra round the Arrakan coast across Northern India through the Persian Gulf to the Mediterranean.

There are thus two reasons for believing in the existence of a crack; one is the zone of low density skirting the Himalayas, the other is the parallelism of the mountains on the two sides of the alluvial belt.

* *Pendulum Operations in India, by Lenox-Conyngham. Page 105.*

$(g_0'' - \gamma_0)$ at Kurseong = —0·130, at Siliguri = —0·137. Similarly further west $(g_0'' - \gamma_0)$ at Mussooree (7,129 feet) = —0·115, at Hardwar (949 feet) = —0·114.

There seems nothing extravagant in the idea of a crack. If we ourselves were to construct a solid globe of heterogeneous materials, (differing in density, conductivity and coefficient of contraction) and if we were to heat it, we should not be surprised at seeing it crack as it became hotter. And if when it was very hot, we allowed it slowly to cool, we should again not be surprised at seeing it crack, as it cooled down.

The Earth's crust and sub-crust are heterogeneous: the underground temperatures are varying irregularly; rocks undergo chemical changes, as conditions of temperature and pressure vary. Strains must be set up, when the temperature varies irregularly in different parts of one sub-crustal shell: and further strains must be set up when the temperature varies irregularly with depth: cracks may be produced by strains and deformations.

Let us enumerate and consider the observed phenomena that we now wish to explain:—

(1).—A rock trough filled up with alluvium traverses Northern India (Plate I).

(2).—The edges of the trough are parallel (Plate I).

(3).—A line of deficient density, presumably in the sub-crust, is found to traverse the whole trough.

(4).—The Earth's surface north of the trough is heavily wrinkled.

(5).—The surface south of the trough is not wrinkled.

(6).—The mountain-wrinkles north of the trough are compensated by deficiencies of density beneath them; (but these deficiencies are not comparable in degree with the deficiency underlying the line just south of the base of the mountains).

(7).—The trends of the main granite ranges of the Himalayas, Karakoram and Hindu Kush and of the minor ranges are parallel to the line of low density and to the edges of the alluvial belt. (Plates I and II).

(8).—The mountain folds north of the trough are overthrust towards the south.

When I come to consider these observed phenomena, I have to confess with regret that I am ignorant of the geological data: I am consequently limited to regarding the problem from a geodetic point of view. In order to explain the geodetic observations I have to assume, firstly, that the sub-crust has cracked and opened, and secondly, that after this opening has occurred the northern edge of the crack has been forced northwards by strains and deformations.

It is I think evident that the Himalayan sub-crust must have contracted in area. The wrinkling of the Himalayas furnishes evidence that the upper crust has been compressed into a smaller area than it originally occupied, and this I think must have been brought about by the contraction of the sub-crust upon which the upper crust was lying.

The contraction of the sub-crust cannot have been due to loss of heat, because it is proved by mountain compensation that as the sub-crust contracted in area, it decreased in density. Decrease in density means increase of volume. As the sub-crust contracted in area, it increased in volume by vertical expansion and chemical change.

The main Himalayan range itself is composed largely of granite, and the latter may owe its elevation to vertical expansion following upon the relief of pressure which occurred when the superincumbent sediments were lifted off it by folding: or the granite may have been forced vertically upwards by the deformation of the sub-crust. These vertical movements of rock material may have been associated with horizontal shrinkage in the sub-crust.

When ancient rocks that have been buried in the crust for long ages are disturbed, and when the pressure upon them is relieved, their density is diminished, and those chemical changes and vertical expansions take place * that lead to the appearance of mountain-compensation.

* In 1905 an earthquake occurred at Dharmsala, and its effects were felt at Dehra Dún, nearly 200 miles distant. A line of precise levelling had been carried from the plains across the Siwalik area into the mountains at Dehra Dún shortly before the earthquake. After the earthquake had occurred, the levelling was revised from Saharunpore (height 700 feet) to Mussoorce (6,900 feet). The revision of the levelling showed that the whole Siwalik area (breadth 25 miles) had been raised 0·4 foot. *See page 342, Volume XIX, Great Trigonometrical Survey of India.* On page 395 it is recorded that the earthquake may be attributed "to a real up-lift of the Earth's crust". I calculate that an area of atleast 5,000 square miles was probably up-lifted. This area skirts the northern edge of the supposed crack. The up-lift at Dharmsala was probably greater than at Dehra Dún, but it could not be measured, as no bench-marks existed there.

If the sub-crustal shell cracks, and its northern portion then shrinks and moves away from the southern, the following results will ensue :—

(*i*) the surface towards the north will become wrinkled by the sub-crust's contraction ;

(*ii*) the crack will become filled with alluvium;

(*iii*) the surface folds on the north will become overthrust towards the south ;

(*iv*) if we regard the wrinkles alone, they will in places contain some local excess of mass, but if we regard the whole combined area of wrinkles and crack together, the amount of surface mass will be normal.

These phenomena are now visible in Northern India. No contraction of the Earth's radius need then be assumed to account for the Himalayan wrinkling.

The geodetic evidence (see appendices I and II of this paper) leads me to believe that the extreme northern zone of the Indo-Gangetic alluvial plains overlies a great rift in the sub-crustal shell of the Earth, that the rift has opened towards the north, and that, as it has opened, it has crumpled up the thin superficial carpet of sediment into the Himalayas, the Karakoram and the Hindu Kush.

During the tertiary period it was the older sedimentary rocks that were crumpled and raised ; in recent times a further opening of the rift has caused folds to appear in the tertiary deposits at the foot of the mountains.

With regard to the overthrusting of surface folds towards the south, if this overthrusting has been caused by a horizontal thrust from the north (see page 1), then the thrust must have acted in the upper superficial crust : if however the overthrusting has been due, as I have suggested on page 2, to the sub-crust shrinking northwards and leaving the folds to over-balance towards the south, the force must have been acting in the sub-crust, that is in the Earth's shell lying immediately below the upper-crust. The question at issue is, at what depth is the horizontal thrust acting, which produces wrinkles in the crust?

I have hitherto been referring to the rift, as though the same original crack had continued slowly to open. But if I may judge from the geodetic observations there has been a succession of cracks in successive sub-crustal shells. Each crack appears to have been followed by a further shrinkage of the crust towards the north.

On each successive occasion that the rift has become deeper, it has opened further north than before. Only by such an hypothesis am I able to explain the apparent steepness of the subterranean wall on the north side of the rift, and the gentleness of the subterranean slope on the south side.

Earthquakes and Volcanoes.

So long as the Himalayan area was under or near the sea, the rise of the mountains was accompanied by volcanic outbursts ; now that the Himalayas are in the interior of a continent, volcanic activity has ceased.

But the Sub-Himalayan region is still liable to frequent earthquakes, from Assam and Nepal to Kashmir.

The alluvial plains of Northern India shown as a belt in Plate I are also frequently affected by earthquakes. I have with me no catalogue of earthquakes, but a reference to a catalogue will support what I write from memory. Calcutta on the east of the belt has suffered from earthquakes, and Lakhpat on the extreme west has suffered. A few years ago an earthquake destroyed Bellpat, a town situated on the flat alluvial plains of Upper Sind; Delhi, Lahore, Peshawar have suffered in turn.

The Indus is said to have deserted its bed in Sind in consequence of an earthquake about A.D. 962, and the old city of the plains, Brahmanabad, was destroyed by an earthquake. *

* *R. D. Oldham : Geology of India, page 452.*

In 1819 a great subsidence was caused north of Cutch by an earthquake, and a considerable area was submerged.* Earthquakes occurred again in Southern Sind in 1844 and 1845.

The frequency of earthquakes throughout the alluvial plains of Northern India is in striking contrast with the freedom from earthquakes that the Indian Peninsula enjoys.

On the Eastern side of India on the supposed line of the rift an eruption occurred at Krakatoa near Java in 1888.

A raised beach 9 feet above sea level at Foul Island and 22 feet at Cheduba Island near the coast of Burma are attributed to an earthquake, as also is the submergence of 60 square miles near Chittagong in Eastern Bengal.†

A volcanic eruption took place at Cheduba on February 27th, 1881.

On the western side of India earthquakes have occurred at Gwadar on the Mekran coast and in the Persian Gulf.

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* *R. D. Oldham: Geology of India, page 11.*
† *Idem, page 12.*

Appendix No. I.

THE EVIDENCE OF THE PLUMB-LINE.

In a paper on *Himalayan Attraction*, published in 1901,* I drew attention to the fact that there existed in the crust a line of high density crossing India in latitude 23°. The existence of this line of density had been proved by observations of the plumb-line. Subsequent observations have indicated that between the line of high density and the Himalaya Mountains there exists a line of low density, which has all the appearances of being a deep rift. Since 1901 many observations of the plumb-line have been taken, valuable results have been accumulated, and pendulum observations have been commenced; our results moreover have been illuminated by the writings of Suess and of Hayford and by the calculations of isostasy.

The lines of high and low density are very different in their effects. For 200 miles on either side of the line of *high* density the plumb-lines are deflected towards it about 5″ or 7″ (tables V to XI of this Appendix), but there is no sudden change. From 100 miles north of the line to 100 miles south the deflection of the plumb-line changes perhaps 12″, that is, about 1″ in 16 miles. Across the line of low density the deflections of the plumb-lines alter suddenly, perhaps 1″ or even 2″ in a mile.

The deflection of the plumb-line has been observed in many places in India, and the results have been published in the volumes and professional papers issued by the Survey of India, but hitherto no correction for isostasy has been applied. According to the hypothesis of compensation, as first propounded by Pratt, the mass of the Himalaya was held to be compensated by deficiencies of matter beneath the mountains. According to the more recent hypothesis of isostasy the mountains are supported by hydrostatic pressure.

It has been recognised for many years by geodesists in India that the Indian Ocean is completely compensated by underlying excesses of matter and that the Himalaya mountains are partially compensated: these two facts are almost beyond dispute. But we have been unable to come to any conclusions as to—

(*a*) the precise amount of Himalayan compensation,

(*b*) the depth to which that compensation extends,

(*c*) the distribution of that compensation with depth.

The existence of a certain degree of compensation is so obvious that almost any assumptions of amount, depth and distribution lead to diminutions of observed anomalies. The following hypotheses have been considered,—that the Ocean is slightly over-compensated,—that the Himalayas are compensated to the extent of $\frac{3}{4}$ths,—that the depth of compensation varies with the height of the mountain,—that the degree of compensation decreases with depth,—that the degree of compensation varies with the geological age and the constitution of the mountains.

Whilst we have been considering this problem, and have been learning to realise its difficulties, Mr. Hayford has shown how different hypotheses can be actually and practically tested.

* *The Attraction of the Himalaya Mountains upon the Plumb-line, 1901.*

The conclusions that Mr. Hayford has reached after a long series of laborious calculations are,

— that compensation is generally complete,

— that it extends to a uniform depth of about 113·7 kilometers,

— that it is uniformly distributed in depth.

The importance of Mr. Hayford's results was at once recognised in India, his hypotheses have been adopted and the effects of isostasy upon both plumb-line and pendulum are being computed.

Major H. L. Crosthwait has already computed for 100 latitude stations the deflections of the plumb-line in the meridian, that would exist, if Hayford's hypotheses are correct. He has also computed for 18 longitude stations the Hayfordian values of deflections in the prime vertical. I am going to make use of Major Crosthwait's results in this appendix, but before I do so, I have to express my obligations to him for the very thorough and systematic way in which he has conducted these difficult and laborious computations.

The zero of verticality. *

The station of origin is Kalianpur, and at Kalianpur there exists a southerly deflection of the plumb-line due to some subterranean cause. Major Crosthwait has calculated the topographic deflection at Kalianpur and finds it to be 32″·4 North. The expression "topographic deflection" denotes that deflection of the plumb-line which would exist at Kalianpur if mountains and seas were entirely uncompensated. Major Crosthwait finds that if Hayford's conditions of isostasy were existing the deflection at Kalianpur would be — 0″·04 North. The actual deflection at Kalianpur is from 4″ to 6″ South. In 1905, I obtained for the value of this deflection 6″ South.† I have discussed this value with many authorities: the opinion is unanimous that the deflection is from 4″ to 6″ South. *I feel convinced also that this deflection cannot be less than 4″, and that it may be 6″.* In South India our longitude arcs show seaward deflections at coast stations: in order to obtain seaward deflections in the meridian at stations on the southern coast (Punnae) a southerly deflection of 6″ at Kalianpur must be assumed.

Latitude observations have recently been taken in northern Baluchistan, where the stations are far-removed from Himalayan and Oceanic influences.

Lenox-Conyngham's section in plate VI of his *Pendulum Operations in India* shows that a southerly deflection is to be expected at Quetta and Jacobabad.

The observed deflections deduced from the spheroid (a = 63,78,190 metres, e = $\frac{1}{299\cdot15}$) are

Khojak	—	2″
Quetta	—	1″
Dumb	+	1″
Sultan ka Gót		0

Dumb and Sultan ka Gót are near Jacobabad, and should have southerly deflections.

The results from Baluchistan therefore support the view that the deflection in the meridian at Kalianpur is 4″ south.

It may be argued that as I am discussing the theory of isostasy my conclusions will depend upon the value of the standard deflection adopted for Kalianpur. This will not, however, be the case. It has to be remembered that the deflections over Northern India show two extraordinary anomalies; the first of these is the persistence over a great area of northerly deflections, *i.e.*, of deflections more northerly than that at Kalianpur. The second anomaly is the persistence over an immense region of more *southerly deflections than at Kalianpur.* The value of the deflection adopted for Kalianpur affects these two anomalies differently; it improves the one, it intensifies the other.

As, however, the unfortunate existence of a powerful source of hidden attraction near our standard station of origin does create uncertainties, I shall in this paper not base any conclusions on *absolute* values of observed deflections. I shall deal only with observed differences of deflection, so that the question of the deflection at Kalianpur may be eliminated.

In the following tables the values of the deflection have been derived as follows:‡

Topographic deflections: Major Crosthwait calculated for each of his 118 stations the deflection which all topographical features within a radius of 2,564 miles would produce, if the density of the superficial crust were everywhere 2·8. The topographic deflection at Kalianpur was calculated by him to be $-32''\cdot4$. As Kalianpur is our standard station, the topographic deflections entered in the tables are *differential* from Kalianpur. Thus for Birond, Major Crosthwait found that the total absolute "topographic deflection without compensation" was $-75''\cdot3$, and that the topographic deflection at Birond with regard to Kalianpur was $-75''\cdot3+32''\cdot4=-42''\cdot9$.

Hayfordian deflections were computed from the isostatic hypothesis of Hayford. The question of Kalianpur does not enter now, because the Hayfordian value for the deflection in the meridian at Kalianpur is only $-0''\cdot04$. The Hayfordian values represent *the deflections that would exist in nature if all topographic features were isostatically compensated.*

* References to the question of the zero of verticality are printed in this paper in small type.

† Philosoph. Transact. Royal Society, Series A, Vol. 205, 1905, page 313.

‡ The negative sign denotes a deflection towards the north, the positive towards the south.

The observed deflections have been obtained by deducting the geodetic values of latitude and longitude from the astronomical values. The geodetic values have been computed through the triangulation on the assumption that the deflection at Kalianpur is + 4″ in the meridian, and 0″ in the prime vertical. The computations are based on the Clarke-Bessel spheroid*:—

equatorial radius 6,378,190 metres

ellipticity $\frac{1}{299 \cdot 15}$

India is divided by geologists into three great regions (*vide* Plates No. I and No. II):—

(1) First region: Tertiary Mountains, Himalaya, Tibet, Baluchistan.

(2) Second region: the extensive alluvial plains that lie between the tertiary mountains on the north and the pre-tertiary plateau on the south.

(3) Third region: the elevated pre-tertiary Peninsula.

I will now summarise the geodetic evidence that has been accumulated in the three geological regions.

First Region: Himalaya Mountains.

TABLE I

Deflections of the plumb-line.

Stations in the Himalayas.	Latitude.		Longitude.		Height.	Computed deflection in the meridian.		Observed deflection in the meridian.
						Topographic without compensation.	On Hayford's hypothesis.	
	°	′	°	′	Feet.	″	″	″
Birond ...	29	15	79	45	6,967	— 42·9	— 14·3	— 38
Dehra Dún ...	30	19	78	6	2,240	— 53·5	— 17·9	— 31
Kurseong ...	26	52	88	18	4,428	— 70·6	— 22·7	— 46
Lambatach ...	31	1	77	57	10,474	— 38·5	— 9·4	— 27
Mussooree ...	30	28	78	7	6,937	— 54·0	— 17·4	— 30

Suess assumes a foredeep filled with light sediment; the deflections according to Suess should be larger than the topographic; they should be equal to the topographic + the effects of the foredeep. It will be seen that the deflections as actually observed are considerably less than the topographic, but are greater than the Hayfordian.

Lambatach is in the interior of the Himalayas; the other four stations are on the southern border. Lambatach is 42 miles north of Mussooree: the deflection has decreased between Mussooree and Lambatach—

by 16″ according to topographic calculations,

by 8″ according to Hayford's hypothesis,

by 3″ according to observation.

A rift in the sub-crust south of Mussooree and 20 miles deep would explain the large deflections in the interior of the Himalayas.

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* Philosoph. Transact. Royal Society A, Vol. 205, 1905, page 218.

The following table shows the ratios of computed to observed deflections :—

TABLE II

Ratios of deflections.

Station.		Topographic to observed.	Hayford to observed.
Birond	...	1·1	0·4
Dehra Dún	...	1·7	0·6
Kurseong	...	1·5	0·5
Lambatach	...	1·4	0·3
Mussooree	...	1·8	0·6
Mean	...	1·5	0·5

The observed deflections are twice as great as the Hayfordian values. They are however only half as great as the Suessian values.

On the border-line between first and second regions.

TABLE III

Deflections.

Station.		Latitude.	Longitude.	Height.	Computed deflection in the meridian.		Observed deflection in the meridian.
					Topographic without compensation	On Hayford's hypothesis.	
		° ′	° ′	Feet	″	″	″
Pathardi	...	27 26	82 45	320	—31·5	— 3·3	—14
Siliguri	...	26 42	88 27	401	—52·0	—11·5	—18

Suess's values being equal to the (topographic + the foredeep) would be greater than the topographic.

TABLE IV

Ratios of deflections.

Station.		Topographic to observed.	Hayford to observed.
Pathardi	...	2·2	0·2
Siliguri	...	2·9	0·6
Mean	...	2·6	0·4

The observed deflections are more than twice as great as the Hayfordian values. They are however only one-third of the Suessian values.

Kurseong (table I) is in the outer hills, Siliguri (table III) at the foot, 12 miles south; the deflection decreases between Kurseong and Siliguri—

by 19″ according to topographic calculations,
11″ according to Hayford's hypothesis,
28″ according to observation.

The actual decrease is considerably greater even than the topographic decrease. In *penetrating* the hills to Lambatach we found the actual decrease *smaller* than was to be expected: in *emerging* from the hills to Siliguri the actual decrease is far *greater* than was expected.

Second Region.

TABLE V.

The Indo-Gangetic alluvial plains (Northern portion).

Station.	Latitude.		Longitude.		Height.	Computed deflection in the meridian		Observed deflection in meridian.
						Topographic.	Hayford.	
	°	′	°	′	Feet.	″	″	″
Amritsar	31	38	74	55	770	− 8	− 1	+11
Bansgopal	28	33	78	34	677	−11	− 1	+ 1
Datairi	28	44	77	41	767	− 8	− 1	0
Kaliana	29	31	77	42	828	−25	− 3	− 1
Jalpaiguri	26	31	88	47	280	−45	− 8	— 1
Nimkar	27	21	80	32	486	−12	− 1	+ 5
Noh	27	51	77	41	710	− 6	− 1	+ 5
Ranjitgarh	32	35	74	40	900	−12	− 5	+ 2
Chanduria	25	44	88	25	160	−31	− 2	+ 9

Along the northern portion of the Indo-Gangetic alluvial plains, the topographic calculations show a northerly deflection towards the mountains averaging 15″ to 20″: the Hayford hypothesis gives a small northerly deflection throughout. The observations bring to light a marked southerly deflection that cannot be accounted for by the hypothesis of isostasy.*

Jalpaiguri (Table V) is in the plains 13 miles south of Siliguri (Table III): between these two stations the deflection decreases—

by 7″ according to topographic calculations,
by 4″ „ „ Hayford's hypothesis,
by 17″ „ „ observation.

The *actual* decrease observed is again considerably greater even than the topographic. Between Kurseong and Jalpaiguri we have evidently crossed an extraordinary line of deficiency in the crust or sub-crust: so marked is this line that the observed change in the deflection of the plumb-line between Kurseong and Jalpaiguri (45″) is almost twice as great as the topographic change (26″) calculated from the whole mass of the Himalayas without compensation. The observed change (45″) is three times as great as Hayford's hypothesis gives (15″).

The change in deflection between Birond (Table I) and Nimkar (Table V) is—

31″ according to topographic features,
13″ according to Hayford,
43″ according to observation.

* *Sketch of Himalayan Geography and Geology, 1907, page 52.*

Here we witness again in another part of the Himalayas the same phenomenon,—an observed change immensely larger than the theoretical.

In the western Himalayas we again come across the same phenomenon.

The change in deflection between Dehra Dún and Kaliana is—

29″ according to topographic features,

15″ according to Hayford,

30″ according to observation.

I take these figures to mean that between Dehra Dún and Kaliana, between Birond and Nimkar, between Kurseong and Jalpaiguri, we have crossed a rift of great depth in the sub-crust. This rift skirts the foot of the Himalayas: it is filled up with alluvium and quite hidden from view. This rift is sufficiently large to disturb the isostatic equilibrium of the crust over a vast area in Southern Asia.

Summary of observations.

TABLE VI.

Himalayan region.	Stations.	Distance in miles.		Difference of deflection.	
		Meridional.	Total.	According to Hayford.	Observed.
Eastern -	Kurseong to Jalpaiguri ...	25	38	15″	45″
Central -	Birond to Nimkar ...	112	135	13″	43″
Western -	Dehra Dún to Kaliana ...	56	64	15″	30″

Here are sudden and unexplained changes in deflection across a line skirting the Himalayan foot: we have already shown that in the interior of the mountains north of the line of rift the change is extraordinarily small. Across the rift it is extraordinarily large.

TABLE VII.

	Distance.	Difference of deflection.	
		Hayford.	Observed.
Dehra Dún northwards to Lambatach ...	52 miles north	8″	3″
Dehra Dún southwards to Kaliana ...	56 miles south	15″	30″

Over the plains south of the line of rift the change is small, and the deflections are persistently south in opposition to the hypothesis of isostasy.

If geologists will now consider the attractive forces acting north and south of the supposed rift, they will see that they are very large; the observed deflection throughout an immense area to the north is (*e.g.* Birond) 38″ north and throughout an equally large area to the immediate south it is (*e.g.* Nimkar) 5″ south.

Second Region.

TABLE VIII.

Alluvial plains of the Punjab.

Station.	Latitude.		Longitude.		Height.	Computed deflection in meridian.		Observed deflection in meridian.
						Topographic.	Hayford.	
	°	′	°	′	Feet	″	″	″
Akbar ...	30	51	73	20	641	+1	−1	+2
Isanpur ...	30	38	76	9	874	−3	−1	+3
Khimuana ...	30	22	75	3	731	−1	0	+3
Multan ...	30	11	71	29	420	−3	−1	+4
Ramthal ...	28	30	75	3	951	+6	+1	+4
Sawaipur ...	29	39	75	6	666	+2	0	+6
Telu ...	28	56	72	17	470	+3	0	+7

All over the plains of the Punjab we find a persistent deflection towards the south, which the hypotheses of Hayford do not explain.

TABLE IX.

Region of the Indo-Gangetic alluvium.

Southern portion.

Station.	Latitude.		Longitude.		Height.	Computed deflection in meridian.		Observed deflection in merdian.
						Topographic.	Hayford.	
	°	′	°	′	feet	″	″	″
Alam Khan ...	24	5	68	46	67	− 4	−1	+ 3
Calcutta ...	22	33	88	24	17	−19	0	+ 4
Kanakhera ...	25	51	80	28	416	− 6	0	+10
Madhupur ...	23	57	88	32	92	−15	−1	+ 8
Sora ...	26	17	81	12	400	−11	0	+11

Throughout the immense alluvial area of Northern India southerly deflections prevail. The hypothesis of isostasy offers no solution.

The great deflection at Lambatach, mentioned on page 11, is difficult to explain; but it is in harmony with the southerly deflections observed south of the rift. The Lambatach observation means that deflections in the heart of the Himalayas are more northerly than was anticipated, just as the deflections south of the rift are more southerly.

TABLE X.

Northern portion of the Peninsula.

Station.	Latitude.		Longitude.		Height.	Computed deflection in meridian. Topographic.	Computed deflection in meridian. Hayford.	Observed deflection in meridian.
	°	′	°	′	Feet.	″	″	″
Bithnok	27	53	72	42	774	+ 6	+ 1	+ 8
Chendwar	23	57	85	29	2,817	−11	0	+ 7
Daiadhari	24	38	77	42	1,867	+ 2	0	+ 5
Gurwani	24	1	82	20	2,083	− 3	+ 1	+ 7
Hurilaong	24	2	84	24	1,378	− 4	+ 2	+15
Kankra	25	38	76	10	1,652	− 2	− 1	+ 4
Khankaria	24	37	70	56	362	− 5	0	+ 6
Kesri	25	47	77	43	1,487	+ 2	+ 1	+10
Pahargarh	24	56	77	44	1,641	+ 3	+ 1	+ 4
Rewat	26	54	74	19	1,542	+ 4	0	+ 6
Saugor	23	50	78	49	2,033	+ 4	+ 1	+ 4
Thob	26	3	72	25	856	0	− 1	+ 3

The southerly deflection which has persisted throughout the great alluvial area is still found to persist throughout the northern zone of the Peninsula. It then changes; the next table illustrates the change.

This change is due, as was pointed out in my paper on *the Attraction of the Himalaya Mountains, 1901,* to a line of high density in the crust or sub-crust. The line of high density crosses India between the parallels of 22° and 24°, and a branch from it extends northwards through the centre of the Punjab. The line of high density is parallel to the rift, the existence of which is being suggested in this paper; both the line and the rift seem to be features of a denser sub-crust rather than of the superficial topography.

TABLE XI.

Belt of negative deflections across the central portion of the Peninsula.

Station.	Latitude.		Longitude.		Height.	Computed deflection in meridian.		Observed deflection in meridian.
						Topographic.	Hayford.	
	°	′	°	′	Feet	″	″	″
Badgaon ...	20	44	77	39	1,128	− 1	0	−5
Bolarum ...	17	30	78	34	1,971	− 6	−1	−5
Chaniana ...	24	7	72	35	953	− 4	−3	−8
Colaba ...	18	54	72	51	75	− 4	0	−9
Cuttack ...	20	29	85	54	133	−23*	−3	−7
Deesa ...	24	15	72	14	443	− 6	−1	−4
Kem ...	18	11	75	21	1,951	− 3	0	−2
Khanpisura ...	18	46	74	49	2,751	− 5	−3	−7
Ladi ...	23	9	77	45	1,875	+ 1	−1	−2
Valvadi ...	20	44	75	14	1,125	+ 4	+1	−4
Lingmara ...	21	43	80	11	1,400	− 6	−1	−5
Voi ...	19	7	77	37	1,439	− 2	−1	−4
Mal ...	18	47	84	33	483	−25*	−6	−9
Mandvi ...	18	38	73	35	4,121	− 5	−1	−2
Nialamari ...	17	2	79	46	1,144	−10	−1	−7
Nitali ...	18	17	76	19	2,289	0	0	−3
Parampudi ...	17	13	81	15	684	−16	−2	−5
Rawal ...	18	32	83	36	874	−24*	−3	−3
Sanjib ...	17	31	82	44	2,142	−34*	−9	−6
Vanakonda ...	17	36	79	25	1,664	− 9	−1	−6
Vizagapatam ...	18	1	83	16	181	−28*	−5	−5
Waltair ...	17	43	83	22	200	−30*	−6	−8

Here we see from West to East northerly deflections prevailing throughout a whole belt of the Peninsula. When we were examining the results of the alluvial plains, we wished we could diminish their positive tendency by doing away with the assumed deflection of +4″ at Kalianpur. But if we do away with it in order to decrease the anomalies of the alluvial plains we shall have to add 4″ to every observed deflection in the belt of negative maxima. Any improvement in the one anomaly must intensify the other.

* Station situated on the east coast of India.

TABLE XII.

Southern portion of the Peninsula.

Station.	Latitude.		Longitude.		Height.	Computed deflection in meridian.		Observed deflection in meridian.
						Topo-graphic.	Hayford.	
	°	′	°	′	Feet	″	″	″
Bangalore ...	13	1	77	37	3,126	− 5	0	−5
Bommasandra ...	14	0	77	30	2,005	+ 1	+2	+6
Danapa ...	15	56	80	0	150	−11	−1	0
Dangarvadi ...	23	43	70	59	96	−11	−2	−7
Darutippa ...	15	1	79	57	195	−13	−1	−3
Dhulipalla ...	16	26	80	8	245	−11	−1	−3
Gudali ...	14	1	80	4	292	−10	0	0
Honnavalli ...	14	17	75	13	2,775	− 5	−1	−2
Honnur ...	14	55	77	8	1,579	0	+1	+3
Kistama ...	14	27	79	48	458	− 9	0	−3
Koramur ...	14	8	75	1	2,527	− 4	+1	−6
Kundgol ...	15	15	75	17	2,147	− 3	+1	−1
Majala ...	16	47	74	29	2,613	− 3	0	−1
Madras ...	13	4	80	17	54	−10	−1	+4
Mangalore ...	12	52	74	53	186	−10	−1	+2
Namthabad ...	15	6	77	39	1,169	− 3	−1	−1
Navalur ...	15	26	75	6	2,445	− 6	−1	−3
Ongole ...	15	30	80	5	250	−12	−1	−4
Punnæ ...	8	9	77	40	48	−22	−4	−1
St. Thomas's Mount ...	13	0	80	14	250	− 8	−1	+5
Tiruvendipuram ...	11	45	79	45	30	− 7	−1	+4
Yettimalai ...	11	4	77	53	617	−10	−1	0

The southerly deflections observed at Madras and Mangalore lend support to the view that the plumb-line is deflected to the south at Kalianpur. For at Madras and Mangalore a seaward deflection is shown by the longitude observations to exist, and thus the assumption of 4″ south for the deflection at Kalianpur brings the latitude and longitude results into harmony. To give a seaward deflection to Punnæ the deflection at Kalianpur will have to be increased to 6″ south.

The line of high density crossing the northern portion of the Peninsula is well illustrated by the following *differences* of deflection. The actual deflections at the eight stations mentioned will be found in Tables X and XI.

TABLE XIII.

On the meridian of	The plumb-lines at	Are deflected	
		According to Hayford.	According to observation.
73°	Bithnok and Chaniana	4″ inwards	16″ inwards
77°	Daiadhari and Badgaon	0″	10″ inwards
81°	Gurwani and Lingmara	1″ inwards	12″ inwards
86°	Chendwar and Cuttack	3″ inwards	14″ inwards

The longitude observations over the alluvial plains of North India.

In the case of the longitude observations we are quite independent of any assumption of verticality at Kalianpúr. The longitude arc Amritsar-Multan crosses the alluvial plains of the Punjab (plate II); the Himalayas are to its immediate east, and the Baluchistan mountains to its immediate west: from Amritsar to Multan there is one long stretch of flat plains.

The combined deflections at Amritsar and at Multan should be in the aggregate

from Crosthwait's calculations of the visible topographic masses	19″	outwards,
from Hayford's hypothesis of isostasy	2″	outwards,
the observed deflections are	10″·43	inwards.

This longitude arc corroborates the latitude observations in an extraordinary way: it shows that the deflections at Amritsar and Multan are in the aggregate 10″·43 *away from the visible mountains towards the plains.* It shows that there is something hidden from us under these plains that upsets locally the effects of both topography and isostasy.*

The Agra-Multan Arc of Longitude.

The combined deflections at Agra and Multan are,—

from Crosthwait's calculations of topographic masses	5″	outwards,
from Hayford's theory of isostasy	0″·5	outwards,
as observed	9″	inwards.

It is obvious again that the Agra-Multan arc must cross something that is unexplained by the hypothesis of isostasy.

* I consider that this arc is an additional proof of the existence of a southerly deflection in the meridian at Kalianpur. This arc shows strong deflections towards the plains; in Bengal we get similar deflections in the meridian, if we assume a southerly deflection at Kalianpur.

Jalpaiguri.

The observed deflection in the prime vertical at Jalpaiguri is worthy of note:—

Topographic deflection	−8″ east.
Hayfordian deflection	0″
Observed deflection	−18″ east.

Jalpaiguri is near Siliguri (plate I). It is conceivable that the assumed rift changes direction here and passes the western edge of the Garo-Khási hills, which belong geologically to the pre-tertiary table-land.

The longitude observations across the Peninsula from coast to coast.

Waltair—Bombay Arc:—

Topographic deflections at Waltair and Bombay are	47″ inwards.
Hayfordian deflections are	9″ inwards.
Observed deflections are	4″ outwards.

Madras—Mangalore Arc:—

Topographic deflections at Madras and Mangalore are	60″ inwards.
Hayfordian deflections are	9″ inwards.
Observed deflections are	6″ outwards.

The outward deflections (*i.e.*, towards the sea) at the 4 coast stations Waltair, Bombay, Madras, Mangalore are not in accord with the theory of isostasy. It may be that the constant ebb and flow of the tides, acting like a live load twice a day for centuries, has condensed the matter in the crust along a coastal zone. It may be that the heavier basic rocks carried out to sea have formed a film of dense matter over the sea-bed* or it may be that the Indian Ocean is over-compensated.

Summary of conclusions.

Himalaya Mountains.

The extraordinary rift in the deflections all along the foot of the Himalayas renders the consideration of Himalayan compensation very difficult, but it seems clear from table I that a considerable amount of compensation does exist.

The effects of the rift are so great that they obliterate over an extensive region the effects of topography and of isostasy.

The alluvial plains of North India.

Throughout these immense alluvial plains the plumb-line is deflected everywhere away from the mountains. The observed deflections throughout this area are in opposition both to the topography and to the theory of isostasy.

Mean observed deflection	5″ south.
Mean topographic deflection	10″ north.
Mean Hayfordian deflection on the hypothesis of isostasy	1″ north.

* Murray's Pres. Add. B.A.A.S. Geograph. Section, Dover. 1899. Sir J. Murray showed that in the processes of weathering the light siliceous constituents were left on continents and the basic removed to the Oceans.

Pre-tertiary Peninsula.

Throughout the northern portion of the Peninsula southerly deflections prevail; these cannot be accounted for by the hypothesis of isostasy, nor can they be attributed to the topography.

Mean observed deflection	6″ south.
Mean topographic deflection	1″ north.
Mean Hayfordian deflection	0″

Across the northern portion of the Peninsula there is a long line of excessive density; iti would appear that the Vindhya Mountains overlie this line in places: this result is of great importance, as it seems to show that the earth's crust is rigid enough to support a large mountainous area 2,000 feet high.

Throughout the central portion of the Peninsula northerly deflections are met with; this is in accordance with the topography, although the observed values of deflections are not so large as the topographic deflections :—

Mean observed deflection	6″ north.
Mean topographic deflection	10″ north.

Throughout the central portion of the Peninsula the Hayford corrections tend to diminish the observed deflections :—

Mean observed deflection (uncorrected)	6″	north.
Mean Hayfordian deflection (= correction for isostasy)	2″	,,
Mean resulting deflection (corrected for isostasy)	4″	,,

The direction of the plumb-line appears to be normal along the following line across the Peninsula :—

Points on the line of high density.	Lat.		Long.	
	°	′	°	′
Between Deesa and Chamu ...	25	30	72	30
Between Ahmadpur and Ladi ...	23	20	77	44
Between Naharmau and Saugor ...	23	40	78	50
Between Sareykhan and Karaundi ...	22	40	80	4
Near Dalea ...	22	20	82	4
Near Chandipur ...	21	27	87	5

At stations round the southern coast the plumb-line is deflected sea-wards.

Appendix No. II.

THE RESULTS OF THE PENDULUM OBSERVATIONS.

It is with some hesitation that I am referring to the results of the pendulum observations. These results have not as yet received corrections for isostasy, and cannot therefore be accepted as absolute. Nevertheless they are, I think, deserving of consideration,—*firstly*, because they illustrate the difficulty of obtaining reliable corrections for isostasy, and *secondly*, because valuable information may be gained from studying *differences* of results; *differences* may in fact be accepted, although the *absolute* values may be doubtful.

In 1910, Captain Cowie commenced the determination of "Hayford" corrections for isostasy for the Indian pendulum results. The labour of these computations cannot be realised by anyone who has not had actual experience. The effects of all topographic features and of their Hayfordian compensation have to be calculated for each station. Captain Cowie has now obtained Hayfordian corrections for the topography within 100 miles of each of 42 pendulum stations.* Major E. A. Tandy has extended the investigation for each station from the antipodes to within 350 miles.

The difficulties of obtaining corrections for isostasy for pendulum results.

In former days a pendulum observer believed that he could, by means of his pendulum, ascertain the density of the *local* crust. He now learns that the results, which he has been attributing to local conditions, may possibly be due to distant continents and oceans. In order now to obtain a corrected result, he has to estimate the effects of distant topography. The labour of calculation is excessive, and no final corrections are forthcoming for years. This postponement is serious; an observer learns much from studying and watching his results. His results are an encouragement and an interest to him.

The absolute values of gravity in India are based on the value for Kew of g=281·200.†
But this value for Kew was obtained without any consideration of the correction for isostasy.

The normal value of gravity in India is obtained from Helmert's formula of 1884,

$$\gamma_0 = 978{\cdot}000\ (1 + 0{\cdot}005310\ \sin.^2\phi).$$

But this formula was derived from pendulum results that had not been corrected for isostasy,

† Lenox-Conyngham's *Pendulum Observations in India.*

I will now consider Cowie's results in the Vindhya-Satpura region of the Peninsula. Three of Cowie's stations exceed 2,000 feet in height.

Station.		Latitude.		Longitude.		Height.	$g_0'' - \gamma_0$	
							Bouguer.	Hayford.
		°	′	°	′	feet	″	″
Seoni	...	22	5	77	29	2,032	+ 0·009	+ 0·051
Asirgarh	...	21	28	76	20	2,077	+ 0·017	+ 0·046
Badnur	...	21	54	77	54	2,103	+ 0·006	+ 0·052

The Bouguer values represent the theory of crustal rigidity, the Hayford values represent the theory of isostasy.

The Bouguer correction produces a positive value of $g_0'' - \gamma_0$; the Hayford correction, deduced from a circular area of 100 miles radius, increases the positive anomaly. These stations are distant from the coast—

Seoni	400 miles.
Asirgarh	230 „
Badnur	330 „

It is difficult to believe that these positive anomalies, observed at stations above 2,000 feet high in the Vindhya-Satpura mountains, can be due to the isostatic compensation of the Indian Ocean. They seem in fact to show that the Vindhya-Satpura mountains are not compensated. If this conclusion is correct, we are faced with a new difficulty, for all Cowie's corrections for isostasy have been deduced on the assumption that the Vindhya-Satpura mass is completely compensated.

Throughout the Vindhyan region the Hayford corrections (deduced from the topography within a radius of 100 miles) tend to increase the positive anomalies ($g_0'' - \gamma_0$).

INLAND VINDHYAN STATIONS.*

Station.		Latitude.		Longitude.		Height.	$g_0'' - \gamma_0$	
							Bouguer.	Hayford.
		°	′	°	′	feet	″	″
Hoshangabad	...	22	45	77	44	1,002	+0·004	+0·039
Khandwa	...	21	49	76	22	1,014	+0·038	+0·067
Ellichpur	...	21	18	77	29	1,314	+0·009	+0·047
Jubbulpur	...	23	9	79	59	1,467	+0·003	+0·042
Umaria	...	23	32	80	54	1,499	+0 003	+0·041
Saugor	...	23	52	78	48	1,757	− 0·016	+0·022
Pendra	...	22	47	82	0	1,996	− 0·024	+0·022

* *Reports of Board of the Scientific Advice*, 1908-9 and 1909-10.
General Reports of the Survey of India, 1908-9 and 1909-10.

It remains then to be seen whether the extension of the calculations for isostasy to the antipodes, combined with the application of a correction for isostasy to our base-value of g at Kew, and with a modification of Helmert's formula for γ will decrease the Hayford anomalies in this table.

Our pendulum observations have led us hitherto to believe that the archæan Peninsula of India is under different conditions of compensation from those of the Himalayas, where the value of $(g_0''-\gamma_0)$ is always negative. It remains now to be seen whether the application of systematic corrections for isostasy will show that this conclusion has been erroneous.

Lessons to be learnt from differences of results.

I have explained in this appendix the doubts which I feel concerning the absolute values of our pendulum results. But those doubts arise from the theoretical corrections; I have no doubts about the observations themselves.

If then I take stations situated near together on flat open plains, and discuss not the values of g, but the *differences* between the values of g, I feel I am on safe ground.

In the first place I will take a line of pendulum stations across the flat plains of the Punjab from west to east.

Station.	Latitude.		Longitude.		Height.	$g_0''-\gamma_0$	
						Bouguer.	Hayford.
	°	′	°	′	feet		
Dera Ghazi Khan ...	30	4	70	46	397	−0·088	−0·064
Multan ...	30	11	71	26	404	−0·045	−0·031
Montgomery ...	30	40	73	6	557	+0·003	+0·016
Ferozepore ...	30	56	74	37	647	+0·006	+0·022
Mian Mir ...	31	32	74	23	708	+0·004	+0·022
Ludhiana ...	30	55	75	51	835	−0·048	−0·024

The Bouguer values of $(g_0''-\gamma_0)$ are given in Lenox-Conyngham's *Pendulum Operations in India*. The Hayford values of $(g_0''-\gamma_0)$ are given in Cowie's report for 1909-10.

The Bouguer values are based on an assumption of no compensation; the Hayford values are based on an assumption of complete compensation within a depth of 113·7 kilometers. (Hayfordian corrections have as yet been calculated up to a distance of 100 miles only from each station.)

Dera Ghazi Khan is near the mountains on the west of the Punjab, and Ludhiana is near the mountains on the east; Montgomery and Ferozepore are centrally situated (see plate II.)

Although the Punjab plains are flat, the Bouguer values bring to light a curious fact, namely that g is greater in the Central Punjab than it is near the mountains on either side. It was at first expected that the Hayford corrections for isostasy would explain the anomaly, but this they have not done.

The Bouguer system showed $(g_0''-\gamma_0)$ at Ferozepore to be 0·094 in excess of $(g_0''-\gamma_0)$ at Dera Ghazi Khan, and 0·054 in excess of $(g_0''-\gamma_0)$ at Ludhiana.

The correction for isostasy, calculated up to 100 miles, has only accounted for a small fraction of the differential anomaly; the differential anomaly remains unexplained.

The Hayford system shows the Ferozepore excess over Dera Ghazi Khan to be 0·086, and over Ludhiana to be 0·046.

These Punjab stations are all near together, and no modification of the constants in Helmert's formula for γ will affect the differential results. No change in the base value at Kew will have any effect.

If the Hayford correction be now extended to the antipodes, as it will be, the negative values of $(g_0'' - \gamma_0)$ at Dera Ghazi Khan and Ludhiana will be decreased, or perhaps even eliminated, but the positive values at Ferozepore and Mian Mir will be increased. The *differences* of results may be slightly reduced, but they will not disappear. No hypothesis of compensation will explain both a negative anomaly at Ludhiana and a positive anomaly at Ferozepore. The *difference* between these two stations is probably a real difference,—a local difference.

We arrive then at the conclusion, that on the plains of Northern India the pendulum observations confirm the results of the plumb-line observations, which have been discussed in Appendix No. I of this paper.

Now let us consider four pendulum stations, situated close together, on the plains between the Himalayas and Delhi (plate I). Of these stations Roorkee is nearest to the mountains, Meerut is the most distant.

Station.	Latitude.	Longitude.	Height.	$g_0'' - \gamma_0$	
				Bouguer.	Hayford.
	° ′	° ′	feet		
Roorkee ...	29 52	77 54	867	−0·107	−0·070
Nojli ...	29 53	77 40	879	−0·095	−0·059
Kaliana ...	29 31	77 39	810	−0·058	−0·028
Meerut ...	29 0	77 42	734	−0·027	−0·008

We cannot obtain any reliable absolute values of g, but we can again consider the *differences* between different stations. Here the steady decrease in the value of $(g_0'' - \gamma_0)$ is the significant fact.

According to the Bouguer system the negative value of $(g_0'' - \gamma_0)$ is decreased between Roorkee and Meerut by 0·080. According to the Hayford system the decrease is 0·062. The correction for isostasy within 100 miles has accounted for one-fifth of the anomaly: the extension of the correction to the antipodes will probably account for a further small fraction; almost four-fifths of the anomaly remain unexplained.

It is possible when the deduction of the Hayford corrections has been extended to the antipodes, the large negative values of $(g_0'' - \gamma_0)$ observed at Roorkee and other places near the foot of the Himalayas will be explained and eliminated. But this elimination will necessarily be accompanied by an increase in the positive values of $(g_0'' - \gamma_0)$ at stations more distant from the mountains. If the application of corrections for isostasy renders values of g normal along the foot of the hills, it will show values of g to be in excess of normal all over the Indo-Gangetic plains.

The pendulum station of Pathankot is situated at the foot of the Himalayas in the Eastern Punjab and 90 miles from Mian Mir, (page 24).

Lenox-Conyngham found gravity here in great defect, $(g_0'' - \gamma_0) = -0{\cdot}179$.

By Helmert's method of "*die Ideelle Störende Schicht*" this value of 0·179 is equivalent to a deficiency of rock in the crust of 5,114 feet.* At Mian Mir gravity is in excess.

The value of $(g_0'' - \gamma_0) = -0{\cdot}179$ for Pathankot has not been corrected for isostasy, and so I am not justified in assuming any *absolute* result. But I am justified in adopting the view that $(g_0'' - \gamma_0)$ at Pathankot is considerably less than $(g_0'' - \gamma_0)$ at Mian Mir. The correction for isostasy may get rid of the absolute negative value at Pathankot, but it cannot get rid of the differential anomaly between Pathankot and Mian Mir.

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* *Pendulum Operations in India, page 189.*