Survey of India

PROFESSIONAL PAPER—No. 17

INVESTIGATIONS OF ISOSTASY IN HIMALAYAN AND NEIGHBOURING REGIONS

BY

COLONEL SIR S. G. BURRARD, K.C.S.I., R.E., F.R.S.,

SURVEYOR GENERAL OF INDIA.

PUBLISHED BY ORDER OF THE GOVERNMENT OF INDIA

Dehra Dun

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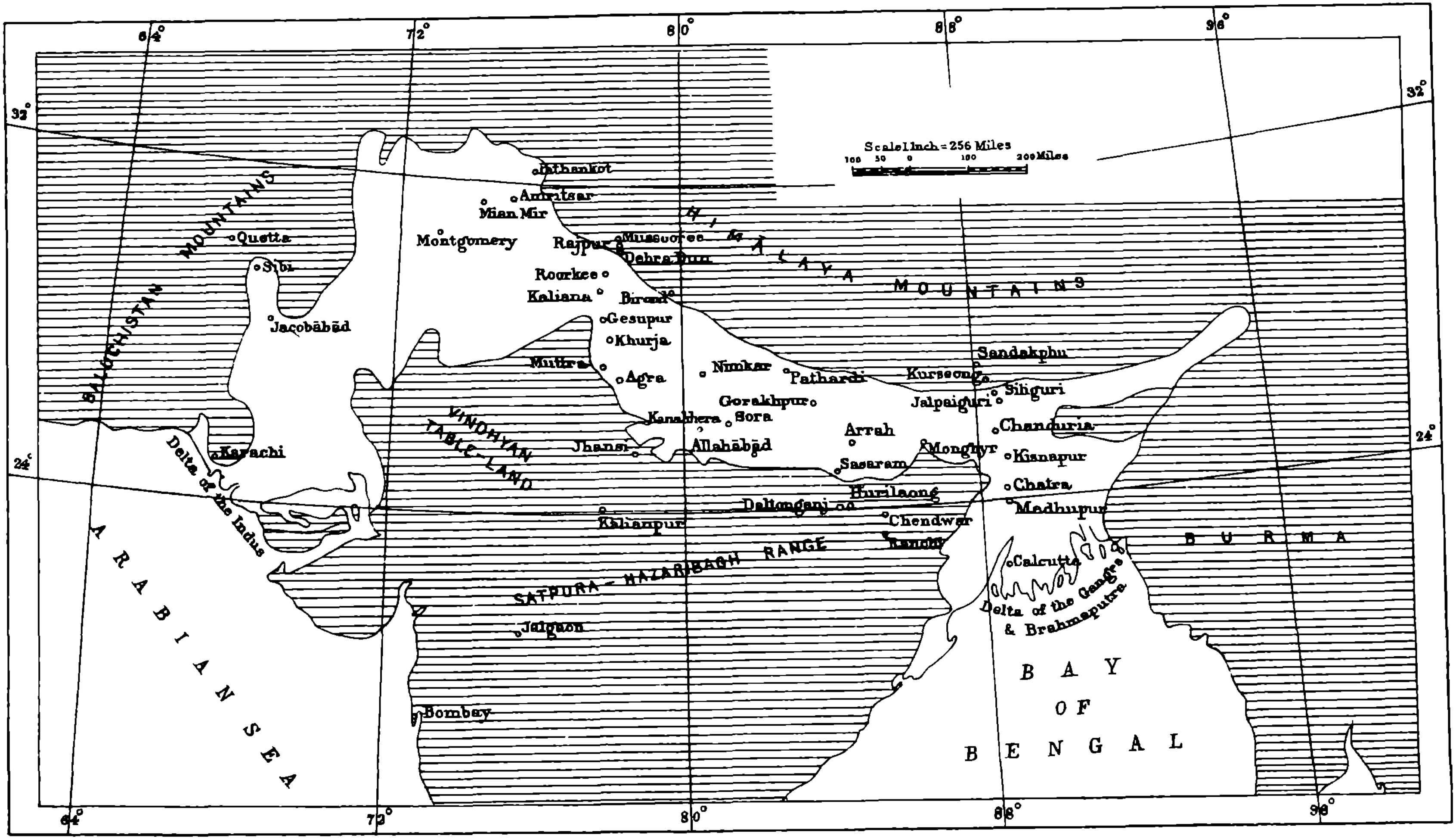

Investigations of Isostasy

in

Himalayan and neighbouring Regions.

(1) *Introduction.*

For the last ten or fifteen years the view has been generally held that the geodetic results deduced from observations in the outer Himalayas and in the plains at their foot are not in accord with the theory of Isostasy. In the last few months whilst making experimental calculations I was led to the conclusion that the evidence which we have regarded as unfavourable to the theory of Isostasy may be found to prove an unexpected support for it. As this question has received much attention from geodesists, I should like to explain how my change of view has been brought about.

In the Himalayas the problem of isostasy has been exceptionally complicated by a difficult geological problem: the effects of isostasy upon geodetic observations are so intermixed with the effects of the local geology that we were unable for many years to separate them. It was not until Hayford had shown us the isostatic effects in America that we were able to estimate the isostatic effects in India. Hayford's results constituted independent evidence from another continent, and by making use of them we have endeavoured to separate the gravity anomalies in India into two components:—(i) the isostatic and (ii) the non-isostatic.

The question I wish to discuss in this paper is whether the non-isostatic component of the Himalayan gravity anomalies cannot be explained by extending the calculations of isostatic compensation to the local geology. Under the system hitherto adopted, all heights above sea level and all depressions below sea level have been assumed to be compensated. But masses of abnormally light rock such as now occupy the Gangetic trough have not been assumed to be compensated. Compensation has in fact been confined to topography and not extended to rock-density. In this paper I propose to extend it to rock-density.

(2) *Retrospect.*

In order to explain the present position of the question under consideration I must endeavour to give a brief retrospect of our past investigations. During the greater part of the 19th century pendulum observations were reduced by the method of Bouguer, —a method which was in accord with contemporary geological opinion. Bouguer contended that, if a pendulum be observed on a mountain, the attraction of the mass of the mountain must be taken into account, because mountains are obviously solid. The gravity anomalies which resulted from the Indian pendulum observations of 1866-1870 were persistently negative at inland stations.

The following table I illustrates their negative tendency*:—

TABLE I

Stations on the central meridian of India from north to south	Height	Local Geology		Gravity anomaly (Bouguer)
		Rock-surface	Density of rock	
	feet			*dynes*
Mussooree ...	6924	Himalayan rock	2·67	– 0·154
Nojli ...	879	Alluvium	2·2 to 2·4	– 0·123
Kaliāna ...	810	Do.	2·2 to 2·4	– 0·106
Pahārgarh ...	1641	Deccan trap	3·0	– 0·088
Kaliānpur ...	1763	Do.	3·0	– 0·042
Badgāon ...	1120	Do.	3·0	– 0·048
Somtana ...	1714	Do.	3·0	– 0·053
Damargida ...	1946	Do.	3·0	– 0·103
Namthābād ...	1173	Gneiss	2·67	– 0·077
Bangalore ...	3118	Do.	2·67	– 0·084

The general opinion was that these persistent negative anomalies indicated some form of mountain compensation, such as had been originally suggested by Pratt. The influence of the local geology could not be detected.

In the years 1900-1901 by introducing isostatic compensation into the calculations, I made several endeavours to explain the gravity anomalies and the deflections of the plumb-line. I tested the effects of compensation with the aid of different assumptions of depth, namely that compensation extended uniformly downwards to depths of 10 miles, 100 miles, 500 miles, and 1000 miles†. My conclusions were summed up as follows:—

1. No hypothesis of mountain compensation will suffice to explain the co-existence of the northerly deflections observed at the foot of the Himalayas and the southerly deflections observed at distances of 50 miles.

2. The effects of Himalayan compensation are masked by subterranean variations of density south of the Himalayas.

This investigation of the available data showed the necessity of increasing the number of pendulum stations in India and of reopening pendulum observations with a new apparatus of the most recent pattern.

In 1902 Professor Helmert explained to me at Potsdam that he was unable to reconcile the negative gravity anomalies of India with the positive anomalies of northern Europe. From the observations of Austrian observers in India Helmert had arrived at the conclusion that the Indian pendulum results of 1866-70 required a correction for the flexure of the stand, but he could not estimate such a correction with any degree of confidence.‡

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* Helmert's report, International Conference, Paris, 1900.

† *Vide* pages 45-47, Professional paper No. 5, Survey of India, 1901: *The Attraction of the Himalaya Mountains upon the Plumb-line in India.*

‡ *Vide* pages 294 and 295, Philosophical Transactions, Royal Society, 1905: *On the Intensity and Direction of the Force of Gravity in India.*

In 1903 Lenox Conyngham initiated the new series of pendulum observations in India, which were continued until 1914, when they were stopped on account of the war. These recent observations are more accurate and more reliable than those of 1866-1870, and the number of stations that has been visited is considerably greater. The results obtained at certain typical inland stations are given in the following table in order to illustrate the negative tendency of the gravity anomalies (deduced by the method of Bouguer)*.

TABLE II

Station		Height	Local Geology		Gravity anomaly (Bouguer)
			Rock-surface	Density of rock	
		feet			*dynes*
Mussooree	...	6924	Himalayan rock	2·67	−0·123
Sandakphu	...	11766	Do.	2·67	−0·155
Dehra Dūn	...	2239	Alluvium	2·2 to 2·4	−0·145
Siliguri	...	387	Do.	2·2 to 2·4	−0·160
Jacobābād	...	183	Do.	2·2 to 2·4	+0 008
Nojli	...	879	Do.	2·2 to 2·4	−0·117
Kaliāna	...	810	Do.	2·2 to 2·4	−0·081
Kaliānpur	...	1763	Deccan trap	3·0	−0·009
Ujjain	...	1612	Do.	3·0	−0·056
Mhow	...	1903	Do.	3·0	−0·055
Khandwa	...	1014	Do.	3·0	+0·010
Rānchi	...	2167	Gneiss	2·67	−0·022
Daltonganj	...	707	Alluvium	2·2 to 2·4	−0·017
Bangalore	...	3118	Gneiss	2·67	−0·080

These results seemed to indicate a certain degree of isostatic compensation, but the compensation did not appear to be either uniform or complete. We were in fact not able to suggest any comprehensive explanation of the anomalies.

(3) *The introduction of isostatic compensation into the computations.*

In 1909 Hayford published his now famous work:— *The Figure of the Earth and Isostasy from Measurements in the United States.* In this work Hayford showed how different hypotheses of isostatic compensation can be practically tested by calculations. The conclusions which he reached were:—

1. Isostatic compensation is generally complete.
2. It extends to a uniform depth of about 113·7 kilometres.
3. It is uniformly distributed in depth.

* *Vide* page 188, Professional paper No 10, Survey of India, 1908: *The Pendulum Operations in India, 1903-1907* by Lenox Conyngham. Professional paper No. 15, 1915: *The Pendulum Operations in India and Burma, 1908-1913* by Couchman.

The importance of these conclusions was realised in India and steps were then taken without delay to calculate the effects of isostasy by Hayford's methods.

In 1910-11 Major Crosthwait computed for 120 stations the deflections of the plumb-line that would exist if Hayford's conclusions, derived from America, were accepted for India*; and subsequently Majors Cowie and Couchman computed for 73 Indian pendulum stations the gravity anomalies that would result if Hayford's hypotheses were accepted.†

Crosthwait did not find that the residual-deflections of the plumb-line in India were diminished to the same extent by the adoption of isostatic compensation as Hayford had found in America: Crosthwait wrote:— "Speaking generally it would appear that isostatic conditions "are much more nearly realized 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 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? The earth's crust in "India is in a process of settling down and may be, comparatively speaking, in a state of strain."

In 1912 I published a paper in which I investigated Crosthwait's results, and derived from them the following conclusions ‡:—

1. The presence of the Gangetic trough renders the consideration of Himalayan compensation difficult, but it seems clear that a considerable amount of compensation does exist.

2. The effects of the trough are so great that they mask over an extensive region the effects of isostasy.

In 1914 in discussing the effects (computed by Hayford's method) of isostatic compensation upon the gravity anomalies, derived from pendulum observations, Couchman wrote§:—

"We have the two main facts, *viz*:—

"(1) At Himalayan stations compensation is not complete, *i.e.* the underground "deficiencies of density are less than the isostatic theory requires.

"(2) At sub-Himalayan stations the compensation is more than complete, *i.e.* the "underground deficiencies of density are greater than the theory requires."

In his consideration of these departures from isostasy, Couchman made the interesting suggestion that in addition to the great trough at the foot of the Himalayas a minor trough of deficient density was lying hidden under the Gangetic alluvium along the *southern* edge of the great plains, where the latter abut against the Central India plateau.

In his introduction to Couchman's book,|| Lenox Conyngham referred to the two main conclusions of Couchman, namely, that compensation was not complete at Himalayan stations, and was more than complete at stations on the alluvial plains: he pointed out that in a region subject to rapid erosion, one would expect the force of gravity to be deficient in intensity, matter being carried off more rapidly than the restorative forces could replace it. The outer slopes of the Himalayas are subject to considerable erosion, and thus Lenox Conyngham contended it would be reasonable to find that the mountain masses were unduly light, and that gravity was in defect. Observations, however,

* Professional paper No. 13, Survey of India, 1912: *Investigation of the Theory of Isostasy in India*, by Crosthwait.

† Professional paper No. 15, Survey of India, 1915: *The Pendulum Operations in India and Burma, 1908-1913* by Couchman.

‡ *Vide* page 20, Professional paper No. 12, 1912: *On the Origin of the Himalaya Mountains.*

§ *Vide* page 179, Professional paper No. 15: *Pendulum Operations* by Couchman.

|| Professional paper No. 15.

show that gravity is in excess at Himalayan stations. "Since the undertow", Lenox Conyngham wrote, "which restores the equilibrium is set in motion by the overloading of the areas of deposition "and by the lightening of those of erosion, it is not conceivable that it should ever be in advance of "the erosion, therefore the theory of isostasy is not competent to explain" an observed excess of gravity in an area of erosion.

For the Gangetic trough, an area of deposition, Conyngham's argument was similar. In a region of deposition, he wrote, one would expect the intensity of gravity to be slightly in excess of the normal value, since alluvium is being superposed upon a crust that is already in isostatic equilibrium.

"It is not conceivable that the increase of pressure due to deposits should produce a compen-"sation corresponding to a larger mass than that which has actually been deposited."

The two questions raised by Lenox Conyngham may be stated as follows :—

(1) What is the explanation of the observed excesses of gravity at Himalayan stations, that is, of the positive anomalies discovered in a mountain region suffering from continued erosion?

(2) What is the explanation of the observed deficiencies of gravity, *i.e.* the negative anomalies, at stations on the Gangetic alluvium, where additional deposits of sediment are continually being laid down?

The *excesses* of gravity in the outer Himalayas have been regarded by geodesists in India as indicating that isostatic compensation is not complete,—that the mass in the local crust is abnormally great. But Bowie has suggested that these observed positive anomalies may be due to the density of Himalayan rocks being higher than normal, the higher density in the upper crust being compensated by a counter-balancing change in density occurring in the lower crust*. The mean density of Himalayan rocks, however, as determined by the Geological Survey, is about 2·67 and does not differ from the adopted value of the mean density of the Earth's surface.

The *deficiencies* of gravity observed on the Gangetic alluvium were considered by Osmond Fisher in his hypothesis of a floating crust; he held that the additional loads of sediment, continually being deposited, were depressing the crust into the denser liquid substratum underlying it, and that the heavy substratum was thus being displaced by the lighter crust†.

Of geodesists in India Couchman has put forward the suggestion that the negative anomalies observed over the Gangetic plains can be explained by assuming that the deficiency of crustal density which constitutes Himalayan compensation extends for 100 miles to the south of the mountains‡.

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* *Vide* page 82, ***Investigations of Gravity and Isostasy***, by Bowie, U.S. Coast and Geodetic Survey, 1917.

† Account of the operations of the Great Trigonometrical Survey of India, Vol. XVIII, Appendix 1. In his recent book on Himalayan structure, published as a memoir by the Geological Survey of India, Vol. XLII, pt. 2, Mr. Oldham has conveyed the idea (pp. 47, 51 & 112) that Fisher's hypothesis of a floating crust is an hypothesis of isostatic compensation comparable with Hayford's. This treatment does not give a fair presentation of the case to geologists. Hayford has propounded a theory of isostatic compensation applicable to the whole surface of the Earth. Fisher on the other hand put forward an hypothesis to explain certain geological and geodetic results in India. Under any general theory of isostatic compensation an excess of surface mass like the Himalaya mountains would have to be treated in an opposite way to a deficiency of mass such as exists in the Gangetic trough. Under Hayford's theory the Himalayan excess is compensated by underlying deficiencies and the Gangetic deficiency is compensated by an underlying excess. But Fisher contended that both the Himalayan excess and the Gangetic deficiency were compensated in the same way: he explained their compensations by assuming, firstly, that the root of the mountains dipped into a dense liquid substratum, and secondly, that the weight of the deposits on the Gangetic plains was forcing the local crust to dip into the dense liquid also. He wrote, "The effect of the plain will resemble that of the mountain-roots, because "it will depress and displace the heavier substratum." Fisher had no system applicable to the whole Earth. Mr Oldham has introduced the expression "Fisher's constants", but no figures of Fisher's can be correctly called "constants," in that there is no general application. These so-called "constants" derived from the Himalayas are not even applicable to the plains at the foot of the Himalayas. Fisher's hypothesis of a floating crust, amplified by Oldham in the 1893 edition of the ***Manual of Geology for India***, was not a theory of isostatic compensation, and was not in any way comparable with Hayford's theory. It was however tested both in India, and America, and was not found to be true in either country. In his recent book, 1917, page 124, Mr. Oldham following Fisher suggests that certain negative anomalies on the Gangetic plains may be due to the 'depression of the crust into the denser material below." Such a suggestion is not in accord with Hayford's theory of compensation.

‡ *Vide* page 180, Professional paper No. 15: ***Pendulum Operations*** by Couchman.

Professor J. Barrell when discussing the deposits brought down by the Niger and the Nile, assumes that these loads on the crust are additional, and that they are not isostatically compensated *; if this assumption is correct, the gravity anomalies in the deltas of the Niger and Nile will be positive, and not negative, as they have been observed to be over the deposits of the Ganges. Barrell's assumption is thus opposed to the observed facts of Northern India.

Bowie has recently dealt with the problem of the gravity anomalies on the Gangetic alluvium, and he contends that the negative anomalies are evidence of isostatic compensation †.
He writes :—" In India there is a broad belt of recent geologic material running approximately east " and west at the foot of the Himalaya Mountains. The stations on the recent formation which no " doubt is largely due to the deposition of materials eroded from the mountains, have in general " negative anomalies. It is impossible that the addition of materials could make the pressure " less than normal on the surface at the depth of compensation. We may therefore conclude that " isostatic adjustment probably follows the deposition of materials and that the negative anomaly is " probably due to the lighter materials in the upper crust".

In consequence of Bowie's contention that the negative anomalies are evidence of the isostatic compensation of the Gangetic trough, I have lately made a series of calculations to test the correctness of this view. Although in the past I had never been able to perceive any strong geodetic evidence either for or against the isostatic compensation of the trough, I am now of opinion that Bowie's contention is probably correct; for reasons which I will subsequently explain, I consider that the evidence available favours the view that the Gangetic deposits are compensated.

In 1912 I put forward for the consideration of geologists the suggestion that a rift has opened in the crust at the foot of the Himalayas and has formed the Gangetic trough, and that it has been filled by abnormally light rock. ‡

Bowie referring to this hypothesis writes ‡‡ :—

" It has been held by some geodesists in India that there is probably a rift in the earth's crust " where the large negative anomalies exist. The evidence at hand makes it possible to account for " the anomalies by the Cenozoic formation in the affected area".

I agree that it may be possible to ascribe the anomalies to the cenozoic formation, but this possibility does not touch the geophysical question as to how the trough has been formed in which the cenozoic rocks are lying. The evidence does support the view that the negative anomalies are mainly due to the comparative lightness of the rock materials underlying the Gangetic plains, but the acceptance of this view does not help to solve the higher problem that these lighter materials have displaced in the crust an equivalent volume of normal rock§.

This question of the origin of the crustal hollow in which the light cenozoic rocks have been deposited is therefore independent of the purely geodetic questions, concerning the negative anomalies and the possibility of the trough being isostatically compensated.

(4) *Summary of the position in 1918.*

The following table gives the observed geodetic results of North India, corrected for isostatic compensation according to Hayford's methods. The unexplained residual deflections of the plumb-line have been taken from Crosthwait's Professional paper No. 13 of 1912, pages 9 to 13, and the unexplained gravity anomalies have been taken from chart V of Couchman's Professional paper No. 15 of 1915.

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* Journal of Geology, Vol. XXII, 1914.

† *Vide* page 84. *Investigations of Gravity and Isostasy*, U. S. C. and G. Survey, 1917.

‡ Professional paper No. 12 : *On the Origin of the Himalaya Mountains*. Proceedings of the Royal Society, A, Vol. 90, pages 32-40.

Proceedings of the Royal Society, A, Vol. 91, pages 230 and 233.

‡‡ *Vide* page 82, *Investigations of Gravity and Isostasy, 1917.*

§ The geology of the northern margin of the Gangetic trough is explained in H. H. Hayden's part IV of *A Sketch of the Geography and Geology of the Himalaya Mountains and Tibet*, pages 209-215.

TABLE III—Observed results corrected for isostatic compensation.

Geodetic station		Latitude		Longitude		Height	Distance from foot of the Himalayas :— N=in the mountains, S=in the plains south of the mountains	Region	Residual deflection of the plumb-line (Hayford)	Gravity anomaly (Hayford)
		°	′	°	′	*feet*	*miles*			*dynes*
Agra	...	27	10	78	1	535	168 S	Gangetic plains	0″	+0·006
Allahābād	...	25	26	81	55	288	170 S	Gangetic plains	...	−0·002
Amritsar	...	31	38	74	52	770	85 S	Plains of the Indus	+12″	
Arrah	...	25	34	84	39	188	130 S	Gangetic plains	...	−0·039
Bansgopal	...	28	33	78	32	658	76 S	Gangetic plains	+ 2″	
Birond	...	29	15	79	43	6967	6 N	Himalayas	−24″	
Chanduria	...	25	44	88	22	160	80 S	Gangetic plains	+11″	
Chātra	...	24	13	88	23	64	180 S	Gangetic plains	...	−0·006
Chendwar	...	23	57	85	26	2817	230 S	Vindhyan tableland	+ 7″	
Daltonganj	...	24	2	84	4	707	230 S	Vindhyan tableland	..	+0·014
Datairi	...	28	44	77	39	767	92 S	Gangetic plains	+ 1″	
Debra Dūn	...	30	19	78	3	2239	5 S	Sub-Himalayas	−13″	−0·005
Gesupur	...	28	33	77	42	691	110 S	Gangetic plains	...	−0·006
Gorakhpur	...	26	45	83	23	257	60 S	Gangetic plains	...	−0·081
Gurwani	...	24	1	82	17	2083	245 S	Vindhyan tableland	+ 6″	
Hurilaong	...	24	2	84	22	1378	230 S	Vindhyan tableland	+13″	
Isānpur	...	30	38	76	7	874	60 S	Plains of the Indus	+ 4″	
Jacobābād	...	28	17	68	27	183	100 S	Plains of the Indus	...	+0·027
Jalpaiguri	...	26	31	88	44	268	30 S	Gangetic plains	+ 7″	−0·031
Jhānsi	...	25	27	78	34	858	260 S	Vindhyan tableland	...	+0·003
Kaliāna	...	29	31	77	39	810	50 S	Gangetic plains	+ 2″	−0·018
Kaliānpur	...	24	7	77	39	1763	380 S	Vindhyan tableland	+ 4″	+0·028
Kanakhera	...	25	51	80	26	416	164 S	Gangetic plains	+10″	
Kesri	...	25	47	77	41	1487	270 S	Vindhyan tableland	+ 9″	
Khurja	...	28	14	77	52	649	120 S	Gangetic plains	...	−0·030
Kisnapur	...	25	2	88	28	113	130 S	Gangetic plains	...	+0·028
Kurseong	...	26	52	88	16	4428	4 N	Himalayas	−23″	
Madhupur	...	23	57	88	29	92	190 S	Gangetic plains	+ 9″	
Majhauli Rāj	...	26	18	83	58	219	70 S	Gangetic plains	...	−0·068
Mīān Mīr	...	31	32	74	23	708	90 S	Plains of the Indus	...	+0·029
Monghyr	...	25	23	86	28	154	100 S	Gangetic plains	...	−0·036
Mussooree	..	30	28	78	5	6924	3 N	Himalayas	−13″	+0·042
Muttra	...	27	28	77	42	562	190 S	Gangetic plains	...	+0·004
Muzaffarpur	...	26	7	85	25	179	70 S	Gangetic plains	...	−0·053
Nimkar	...	27	21	80	29	486	80 S	Gangetic plains	+ 6″	
Noh	...	27	51	77	39	710	144 S	Gangetic plains	+ 6″	
Pathānkot	...	32	17	75	39	1088	20 S	Plains of the Indus	...	−0·087
Pathārdi	...	27	26	82	45	320	14 S	Gangetic plains	−11″	
Quetta	...	30	12	67	1	5520	60 N	Baluchistān mountains	...	−0·004
Rājpur	...	30	24	78	6	3321	0	Sub-Himalayas	...	+0·015
Rānchi	...	23	23	85	19	2167	250 S	Vindhyan tableland	...	+0·019
Ranjitgarh	...	32	35	74	37	900	40 S	Plains of the Indus	+ 7″	
Roorkee	...	29	52	77	54	867	25 S	Gangetic plains	...	−0·055
Sandakphu	...	27	6	88	0	11766	26 N	Himalayas	...	+0·037
Sasarām	...	24	57	83	59	340	180 S	Gangetic plains	...	−0·002
Sibi	...	29	33	67	53	434	12 S	Plains of the Indus	...	−0·070
Siliguri	...	26	42	88	25	387	12 S	Gangetic plains	− 7″	−0·050
Sora	...	26	17	81	12	400	115 S	Gangetic plains	+11″	
Tasing	...	27	53	76	12	2050	200 S	Vindhyan tableland	+ 5″	
Usira	...	26	57	77	38	810	200 S	Vindhyan tableland	− 1″	

In the table III the deflections and the gravity anomalies are the unexplained residuals, which have not been eliminated by the application of the corrections for isostasy.

Although for years it has been recognised that the light rock deposits in the Gangetic trough must be exercising some effects upon both deflections of the plumb-line and gravity anomalies, we have not been able to make any scientific calculation of those effects. We have made rough estimates, but we have not placed much reliance upon them.

There is, however, one step that has not yet been taken: we have never yet systematically investigated the observed gravity anomalies from the point of view, that the light Gangetic deposits may be isostatically compensated. We have, it is true, by the aid of Bowie's useful tables, endeavoured to ascertain the depths of Gangetic deposits from individual anomalies, assuming isostatic compensation, but no systematic investigation has been made.

The theory of isostatic compensation has hitherto been limited to the excesses and deficiencies of mass, visible as mountains and oceans at the surface of the earth. It has not been applied to the excesses and deficiencies of density that occur in different geological formations.

The reason for this omission has been that, whilst we can measure the heights of mountains and depths of oceans we cannot determine the depth to which any particular geological rock extends downwards into the crust, and we are therefore ignorant of its total volume and mass.

I propose now to assume that the light rock deposits of the Gangetic trough are isostatically compensated and to examine whether the observed geodetic results support this assumption or not.

The Gangetic trough is the "fore-deep" of the Himalaya mountains, and geodetic observers have generally selected their stations along lines perpendicular to the mountains and the "fore-deep". The geodetic data can thus be most readily discussed if they are grouped along sections drawn across the mountains and trough from north to south.

So I will take the data of table III, and group them into the six separate cross-sections, described in table IV: the small map, plate I, illustrates generally the positions of the six cross-sections.

TABLE IV—Six sections across the Himalayas and Gangetic trough.

Section	Longitude	Principal stations
(1) The North-Eastern	88°	Darjeeling-Jalpaiguri
(2) The Eastern	84°	Gorakhpur
(3) The Eastern-Central	82°	Allahābād
(4) The Central	78°	Dehra Dūn-Agra
(5) The Western	75°	Pathānkot-Miān Mīr
(6) The North-Western	68°	Quetta-Jacobābād

The names of the stations of the North-Eastern Section and the observed results are shown in table V. This section is illustrated in plate II.

TABLE V—Stations on North-Eastern Section.

Station	Height	Distance from foot of hills	Ground surface	Deflection of the plumb-line (Hayford)	Gravity anomaly (Hayford)
	feet	*miles*			*dynes*
Sandakphu ...	11766	26 N	Himalayan rock	...	+0·037
Kurseong ...	4428	4 N	Do.	−23″	...
Siliguri ...	387	12 S	Gangetic plains	− 7″	−0·050
Jalpaiguri ...	268	30 S	Do.	+ 7″	−0·031
Chanduria ...	160	80 S	Do.	+11″	...
Kisnapur ...	113	130 S	Do.	...	+0·028
Chātra ...	64	180 S	Do.	...	−0·006
Madhupur ...	92	190 S	Do.	+ 9″	...

In table VI are given the stations of the Eastern Section.

TABLE VI—Stations on Eastern Section.

Station	Height	Distance from foot of hills	Ground surface	Deflection of the plumb-line (Hayford)	Gravity anomaly (Hayford)
	feet	*miles*			*dynes*
Pathardi ...	320	14 S	Gangetic plains	−11″	...
Gorakhpur ...	257	60 S	Do.	...	− 0·081
Majhauli Rāj ...	219	70 S	Do.	...	− 0·068
Muzaffarpur ...	179	70 S	Do.	...	− 0·053
Arrah ...	188	130 S	Do.	...	− 0·039
Sasarām ...	340	180 S	Do.	...	− 0·002
Daltonganj ...	707	230 S	Vindhyan table-land	...	+ 0·014
Hurilaong ...	1378	230 S	Do.	+13″	...
Chendwar ...	2817	230 S	Do.	+ 7″	...
Rānchi ...	2167	250 S	Do.	...	+ 0·019

In table VII are given the stations of the Eastern-Central Section.

TABLE VII—Stations on Eastern-Central Section.

Station	Height	Distance from foot of hills	Ground surface	Deflection of the plumb-line (Hayford)	Gravity anomaly (Hayford)
	feet	*miles*			*dynes*
Birond ...	6967	6 N	Himalayan rock	– 24″	...
Nimkar ...	486	80 S	Gangetic plains	+ 6″	...
Sora ...	400	115 S	Do.	+ 11″	...
Kanakhera ...	416	164 S	Do.	+ 10″	...
Allahābād ...	288	170 S	Do.	...	– 0·002
Gurwani ...	2083	245 S	Vindhyan table-land	+ 6″	...

In table VIII are given the stations of the Central Section.

TABLE VIII—Stations on Central Section.

Station	Height	Distance from foot of hills	Ground surface	Deflection of the plumb-line (Hayford)	Gravity anomaly (Hayford)
	feet	*miles*			*dynes*
Mussooree ...	6924	3 N	Himalayan rock	– 13″	+ 0·042
Rājpur ...	3321	0	Sub-Himalayas	...	+ 0·015
Dehra Dūn ...	2239	5 S	Do.	– 13″	– 0·005
Roorkee ...	867	25 S	Gangetic plains	...	– 0·055
Kaliāna ...	810	50 S	Do.	+ 2″	– 0·018
Bansgopal ...	658	76 S	Do.	+ 2″	...
Datairi ...	767	92 S	Do.	+ 1″	...
Gesupur ...	691	110 S	Do.	...	– 0·006
Khurja ...	649	120 S	Do.	...	– 0·030
Noh ...	710	144 S	Do.	+ 6″	...
Muttra ...	562	190 S	Do.	...	+ 0·004
Agra ...	535	168 S	Do.	0″	+ 0·006
Tasing ...	2050	200 S	Vindhyan table-land	+ 5″	...
Usira ...	810	200 S	Do.	– 1″	...
Jhānsi ...	858	260 S	Do.	...	+ 0·003
Kesri ...	1487	270 S	Do.	+ 9″	...
Kaliānpur ...	1763	380 S	Do.	+ 4″	+ 0·028

In table IX are given the stations of the Western Section.

TABLE IX—Stations on Western Section.

Station	Height	Distance from foot of hills	Ground surface	Deflection of the plumb-line (Hayford)	Gravity anomaly (Hayford)
	feet	*miles*			*dynes*
Pathānkot ...	1088	20 S	Alluvial plains of the Indus	...	− 0·087
Ranjitgarh ...	900	40 S	Do.	+ 7″	...
Isānpur ...	874	60 S	Do.	+ 4″	...
Amritsar ...	770	85 S	Do.	+ 12″	...
Miān Mīr ...	708	90 S	Do.	...	+ 0·029

In table X are given the stations of the North-Western Section.

TABLE X—Stations on North-Western Section.

Station	Height	Distance from foot of hills	Ground surface	Deflection of the plumb-line (Hayford)	Gravity anomaly (Hayford)
	feet	*miles*			*dynes*
Quetta ...	5520	60 N	Baluchistān mountains	No observations	− 0·004
Sibi ...	434	12 S	Alluvial plains of the Indus	Do.	− 0·070
Jacobābād ...	183	100 S	Do.	Do.	+ 0·027

(5) *The proposed correction of geodetic results for the isostatic compensation of the Gangetic trough.*

If the last columns of tables V to X are examined, it will be seen that the gravity anomalies tend to be positive in the Himalayas,* that they are negative over the belt of alluvium skirting the Himalayas, and that further to the south they become positive again. The southernmost stations of the Eastern and Central sections are situated on the rock of the Vindhyan table-land, and in such situations the positive gravity anomalies might have escaped attention †: but the southernmost stations of the North-Eastern, the Western, and the North-Western sections are all situated on extensive and unbroken alluvial plains, and the discovery at these places of positive gravity anomalies has for many years been regarded as important.

* At Quetta the mountain anomaly is slightly negative, − 0·004: though Quetta is in the mountains, it is unlike the other mountain stations in that it is situated on a plain of light alluvium. This alluvium gives rise to a local negative effect, which may be sufficient to obscure the main general effect of mountain and plain.

† The southernmost gravity anomaly of the Eastern-Central Section is at Allahābād, a station on the Gangetic alluvium: this anomaly is slightly negative, − 0·002; if the force of gravity were to be observed 30 miles south of Allahābād, the anomaly would probably be found to be positive.

The extraordinary agreement between these positive anomalies at stations, far distant from one another, but similarly situated with regard to the mountains, led many years ago to the idea that the anomalies were indicating a structural connection between mountains and trough*. But in our previous attempts to interpret these anomalies, we have been too much given to attributing each gravity anomaly to the abnormal densities in the rocks *vertically below* its station; we have not paid sufficient regard to the effects produced at a station by abnormal densities, situated not vertically below it, but at distances *to one side of it.* We have attributed the positive anomalies in the mountains north of the trough to one cause, namely the imperfect compensation of the Himalayas; we have attributed the negative anomalies on the trough to another cause, namely the deficient density of the deposits in the trough, and we have attributed the positive anomalies south of the trough to a third cause, namely incomplete regional compensation†. We have thus had to invoke three different causes to explain three different classes of anomalies. But if we assume the light deposits of the Gangetic trough to be isostatically compensated, we can by this one hypothesis explain to a large extent all three classes of anomalies, (*a*) the northern positives, (*b*) the central negatives (*c*) the southern positives.

The cross-section given in plate II will illustrate my meaning: the drawing in this plate represents the North-Eastern cross-section, *vide* table V, page 9. There has been no exaggeration of scale, the vertical scale being the same as the horizontal. An examination of the drawing will lead to the following conclusions :—

(*a*) If the Gangetic trough contains light deposits to a considerable depth, and if the light density of these deposits is isostatically compensated to a depth of 113 kilometres by equivalent heavy density in the crust, the gravity anomalies at stations over the trough will be negative,—because the light deposits are nearer to the surface than the deep heavy rocks, which form the compensation: the light rocks thus having a more immediate effect on the pendulum than the heavy.

(*b*) On the other hand the light deposits will have no appreciable effect at stations north and south of the trough, whilst the heavy compensation-rock will increase the intensity of gravity at these stations and will tend to make their anomalies positive. A pendulum is actuated by the vertical component of gravity: the vertical component due to surface rock deposits, situated in a horizontal direction to one side of the pendulum, will be very small, but the vertical component of the compensation rocks situated at a great depth will be considerable.

It is in this way that the hypothesis of isostatic compensation, if applied to the Gangetic trough, may explain the presence of positive anomalies north and south of the trough.

(6) *The computations of the Gangetic compensation.*

I have already referred to the difficulties experienced in deducing the depth of the Gangetic trough from the observed gravity anomalies. But such deductions are now required, for it is not enough to say that the compensation of the trough would produce positive anomalies north and south of its borders, unless it can be shown that the actual positive anomalies as observed can be quantitatively ascribed to the trough.

* The three principal positive anomalies observed on the alluvial plains are given in the following table:—

	ANOMALIES		
	by Helmert's formula of 1884	by Helmert's formula of 1901	according to Couchman in 1915
	dynes	*dynes*	*dynes*
Kisnapur …	+0·064	+0·039	+0·028
Miān Mir …	+0·065	+0·040	+0·029
Jacobābād …	+0·063	+0·038	+0·027

† Proceedings of the Royal Society, A, Vol. 91, page 237.

It is possible when observations have been multiplied that the positive anomalies, observed along the north and south borders of the trough, will come to be recognised as valuable and independent evidence of the depth of the trough. When a pendulum is observed over the trough (*see* plate II) its anomaly has to be attributed to two opposing components, the light material near the surface, and the heavy rock below compensating the lighter. But if we can attribute a positive anomaly on the margin of the trough (plate II) to the trough's compensation only, we shall obtain an independent and direct measure of the amount of compensation present; a measure of the compensation is equivalent to a measure of the surface-mass requiring compensation.

In testing the geodetic evidence I do not think that we should be justified in assuming any particular form for the trough. There are reasons for thinking that the trough is V-shaped, the V being considerably wider than it is deep, and being somewhat tilted southwards*. But in many places the southern edge of the trough is hidden by alluvium, and quite undefined, whilst the only calculations of depth that we can make are necessarily too rough to justify any assumption of exact form. All I think that we can do at the present time is to estimate the *average* depth and width of the trough on each of the six different sections.

The word "trough."—The word "trough" is somewhat misleading. It conveys the idea of a long rock hollow filled with loose alluvium: and it gives rise to the further idea that the negative gravity anomalies over the trough are due to the presence of the light alluvium. At moderate depths alluvium becomes compacted into solid rock: Middlemiss found that the Gangetic alluvium had become compacted at a depth of 3000 feet only †. The negative anomalies are due to a deep succession of light rocks, of which the alluvium is the surface covering. Whilst the word "trough" is strictly applicable to the upper Gangetic film only, geodesists are seeking for a word that will embrace the whole series of attenuated rocks that have a density lower than the normal density of the crust, and which are underlying the Gangetic alluvium to unknown depths. When therefore, for the sake of brevity, I use the expression "Gangetic trough", I mean the Gangetic zone of crustal attenuation.

It is indeed essential that we should free ourselves from the belief that the negative anomalies are due to loose alluvium. Such a view is based on misconceptions. Not only have the geologists proved that the deeper cenozoic deposits consist of consolidated rock, but the geodesists have shown at Bombay that a zone of crustal attenuation is probably bordering the Western Ghat mountains, and that this zone does not consist of alluvium or even of cenozoic deposits.

Value of density.—It is unfortunate that we have not yet been able to arrive at any general agreement as to the best mean value of density to be used for the attenuated rocks underlying the Gangetic alluvium. An increase of pressure upon any given stratum tends to produce an increase of density, and sub-surface rocks are compressible under the increases of pressure produced by deposition. Mr. Oldham has assumed the average density of the Gangetic alluvium and rocks, from the surface to a depth of 4 miles, to be 2·16. The rock-walls of the trough have a density of 2·67, and he assumes that the contents of the deep trough have a density of 20 per cent less than the rock-walls‡. Sir Thomas Holland has expressed doubts as to the possibility of so great a difference in density existing at considerable depths§. In his investigations of *the Strength of the Earth's Crust* Professor Barrell has assumed 2·5 as the density of the deposits of the Nile and the Niger‖.

* Proceedings of the Royal Society, A, Vol. 90, pages 32-40; also Vol. 91, pages 220-238.
† Memoirs, Geological Survey of India, Vol. XXIV, page 29.
‡ Memoirs, Geological Survey Vol. XLII, part 2, *Structure of the Himalayas* by R. D. Oldham, page 58.
§ B. A. A. S. Report, 1914, page 355.
‖ Journal of Geology, Vol. XXII, page 43.

General Sorsbie, author of *Geology for Engineers*, estimated that the mean density of the Gangetic deposits would not be less than 2·4. Mr. de Graaff Hunter determined the density of different specimens of exposed Gangetic strata at Hardwār and Mohan, and found that the values varied from 2·35 to 2·60. He also determined the density of *kankar* dug from the surface of the alluvial plains and found it to average 2·34. In recent borings at Agra and Muttra many strata of *kankar* have been met with, and the Sanitary Engineer of Bengal met with solid rock at a depth of only 80 feet in a boring at Azamgarh which stands on the mid-alluvium far from any rock outcrop. The boring passed through 3 feet of this rock before it struck unconsolidated material again.

A weight of 4 tons per square inch is the breaking load for good granite; and the weight of a column of granite 4 miles high is sufficient to crush its base. The cenozoic rocks underlying the Gangetic alluvium to depths exceeding 4 miles have been compacted from loose material which was derived originally from Himalayan rock of density 2·67.

The values of density accepted by different investigators have been as follows:—

2·16 by Mr. Oldham,
2·4 by General Sorsbie,
2·5 by Professor Barrell.

The effects upon geodetic results will be widely different according to which of these values is now employed. The Trigonometrical Survey of India adopts 2·67 as the mean surface density of the earth, and Mr. Oldham's value of the Gangetic density is approximately 20 per cent less than this, whilst General Sorsbie's is only 10 per cent less, and Professor Barrell's is 6½ per cent less. Any estimate of the depth of the trough based upon Oldham's value of density will be only half as great as the depth derived from Sorsbie's density, and only one-third of the depth, if Barrell's density is employed.

Having regard to the different authorities I am adopting in the calculations of this paper 2·4 as the mean density of the light and attenuated rocks underlying the Gangetic plains. But I have said enough to show that the assumption of this value is not free from uncertainty.

Methods of computation.—In deriving estimates of mass from the gravity anomalies the well-known formulæ for the attraction of a cylinder have been made use of. Round each pendulum station successive concentric circles have been drawn, and the trough has been assumed to be represented by segments of annuli.

In deriving estimates from the deflections of plumb-lines I have also drawn concentric circles round each station, and have utilised Hayford's method of rings*. The radii of the rings are those adopted by Hayford.

Hayford introduced methods of computation, that have enabled us to take account of the natural form of mountains, their ranges and their valleys. In applying his methods to the Gangetic trough I am utilising them for a hypothetical trough, bounded by assumed mathematical surfaces. It is well-known that mathematical forms depart widely from the facts, and that they ignore numerous important irregularities existing in nature. But in our present state of ignorance no other course seems feasible: mountains are visible objects and can be topographically surveyed, whilst a trough of attenuated rock is hidden from our view by alluvium. Mountains are surrounded by air, but the contents of a trough are similar to the material surrounding them, and the one may merge imperceptibly into the other.

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* *The Figure of the Earth and Isostasy* by Hayford, 1909.

(7) *Results of the computations.*

The details of computations are given in the appendix No. 1 to this paper. The following results have been obtained for the different sections of the Gangetic trough:—

TABLE XI—Results on the North-Eastern Section.

Stations	Width of trough in miles	Average depth of trough in feet deduced	
		from pendulum observations	from plumb-line observations
North of the trough ...	100	70000	50000
Over the trough ..		25000	60000
South of the trough ..		70000	
Mean between central and marginal results		47000	55000
Mean width and depth ...	100 miles	51000 feet	

A considerable discrepancy is evident in the above table between the values of depth derived from pendulum observations outside the trough and the value derived from observations taken over the trough. At stations outside the trough, namely, Sandakphu and Kisnapur, (*see* appendix No. 1) there are positive gravity anomalies : at stations over the trough there are negative gravity anomalies. It is not permissible to attach much weight to discrepancies between deductions from positive and negative anomalies, because the exact position of the zero-line from which positive anomalies are measured in one direction and negative anomalies in the other is uncertain. The position of this zero-line depends on the constants adopted in the gravity formula; of these constants the equatorial value of gravity is the most important. When we commenced pendulum observations in India in 1902, we were advised by the Potsdam Institute to accept Helmert's formula of 1884, in which the equatorial value was 978·000. Subsequently Helmert's formula of 1901 was substituted, and in this the equatorial value was 978·030. This change moved the zero-line, and thereby tended to decrease all positive anomalies and to increase negatives. The *observed* values of gravity were unaffected and remained reliable, but the theoretical values were systematically increased. The U.S.A. formula of 1916 gives 978·040 as the equatorial value, and this tends further to decrease all positive anomalies and to increase negatives. Couchman's formula of 1915 gave 978·041 as the equatorial value*. In the above tables Couchman's values of the gravity anomalies have been adopted. As pendulum observations become multiplied in the future over Africa, Asia, Australia, it is possible that the equatorial value of gravity will have to be increased further, and if this step comes to be recognised as correct, the discrepancies in the 3rd column of table XI may be eliminated. Helmert's latest value of equatorial gravity, derived from all available stations in the world, is 978·052†.

* Professional paper No. 15: *Pendulum Operations* by Couchman, page 187.

† Sitzungsberichte der Preussischen akademie der wissenschaften No. 41, page 676.

TABLE XII—Results on the Eastern Section.

Stations		Width of trough in miles	Average depth of trough in feet deduced	
			from pendulum observations	from plumb-line observations
North of the trough	...		no observations	no observations
Over the trough	...	130	55000	
South of the trough	...	180	100000 (doubtful)	67000
Mean	...	155	55000	67000
Mean width and depth	...	155 miles	61000 feet	

TABLE XIII—Results on the Eastern-Central Section.

Stations		Width of trough in miles	Average depth of trough in feet deduced	
			from pendulum observations	from plumb-line observations
North of the trough	...	200	no observations	50000
Over the trough	...		no observations	not deduced
South of the trough	...	180	no observations	
Mean width and depth	...	190 miles	50000 feet	

TABLE XIV—Results on the Central Section.

Stations		Width of trough in miles	Average depth of trough in feet deduced	
			from pendulum observations	from plumb-line observations
North of the trough	...	100	50000	35000
Over the trough	...	100	26000	35000
South of the trough	...		undetermined	undetermined
Mean	...	100	38000	35000
Mean width and depth	...	100 miles	36000 feet	

TABLE XV—Results on the Western Section.

Stations		Width of trough in miles	Average depth of trough in feet deduced	
			from pendulum observations	from plumb-line observations
North of the trough	...		no observations	no observations
Over the trough	...	{70 85	50000	75000
South of the trough	...	70	70000	
Mean	...	75	60000	75000
Mean width and depth	...	75 miles	67000 feet	

TABLE XVI—Results on the North-Western Section.

Stations		Width of trough in miles	Average depth of trough in feet deduced	
			from pendulum observations	from plumb-line observations
North of the trough	...	90	40000	no observations
Over the trough	...	...	30000	no observations
South of the trough	...	90	50000	no observations
Mean	...	90 miles	37000 feet (Mean of positive and negative values)	

In table XVII are summed up the dimensions of the trough as deduced for the several sections.

TABLE XVII—Summary of results.

Section		Width of trough in miles	Average depth of trough in feet
North-Eastern	...	100	51000
Eastern	...	155	61000
Eastern-Central	...	190	50000
Central	...	100	36000
Western	...	75	67000
North-Western	...	90	37000
Mean	...	120 miles	50000 feet

Consideration of results.—For a V-shaped trough, or for a trough of irregular shape, an attempt to deduce values of the *average* depth from stations differently situated with regard to the trough will inevitably produce discordant results. If a trough is of irregular shape its maximum depth may be twice as great as its average depth. In the tables XI to XVII the results obtained from pendulum observations accord fairly with those obtained independently from plumb-line observations and on the whole these results favour the view that the Gangetic trough is isostatically compensated. The isostatic compensation of the trough enables us to explain both the negative anomalies over the trough and the positive anomalies beyond its margins.

The question arises, whether a trough, 120 miles wide and 50000 feet deep, is out of topographical accord with other terrestrial features or with the mass of the Himalayas. The Himalaya-Tibet plateau is 600 miles wide and 15000 feet high (on the average), so that its volume exceeds the estimated volume of Gangetic rocks.

A chart of the North Pacific Ocean, made by the U. S. A. Coast Survey, shows the Tuscarora deep, in front of the Japanese islands, as being deeper than 18000 feet over a width of 400 miles, and as being deeper than 24000 feet over a width of 170 miles. The maximum depths of this trough are not known. But it seems evident that the Tuscarora deep is a larger trough than the Gangetic deep. The dimensions of the latter having been deduced from geodetic observations include all the attenuated rocks *below* the trough, whereas the observed depths of the Tuscarora deep have been derived from soundings and give the depths of the water only. If the underlying ooze, the mud, the deposits, and the light rocks were included, the depths obtained from soundings might be considerably increased.*

For geological evidence we have Middlemiss's observations in Kumaun.† Middlemiss measured between 16000 and 17000 feet of exposed strata, that had been originally deposited in the Gangetic trough and had been subsequently uplifted. Middlemiss's observations did not pretend to give the maximum depth of the trough, but they showed that the depth of the trough near its northern margin in Kumaun was not less than 16000 feet.

My conclusion is that the geodetic evidence supports the view that the Gangetic trough is isostatically compensated. If this view is eventually accepted as correct, geologists will have to recognise the probable existence of a deeper zone of crustal attenuation than they have hitherto admitted.

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* The chart of the Pacific Ocean published in 1912, by the *Institut fur Meereskunde der Universitat Berlin* shows the depth of water to exceed 21000 feet throughout a width of 250 miles, and to exceed 26000 feet throughout a width of 60 miles.

† Memoirs, Geological Survey of India, Vol. XXIV, page 29. In his recent memoir Mr. Oldham has endeavoured to show that the geodetic results can be explained by the assumption of a shallow trough, the depth of which is comparable with Middlemiss's value of depth derived from measurements of exposed strata. But this endeavour fails, unless two assumptions are made:—*Firstly*, that the rock materials of the Gangetic trough have a density 20 per cent lower than normal, and *secondly*, that the Gangetic trough is not isostatically compensated.

(8) *Possibility of obtaining evidence from other troughs.*

The difficulties of such an investigation as I have attempted are largely due to the hidden complexities and irregularities in the form of the Gangetic trough. In appendix No. 2 of this paper I have added a few notes on this subject.

In the future however some light may be thrown upon the Gangetic problems by means of investigations of other troughs which resemble the Gangetic in the age and depth of their deposits.

Two troughs occur to me, the investigation of which may lead to illuminating analogies: they are (i) the *Burma* trough, (ii) the *Sistan* trough.

The *Burma* trough separates the Shan plateau from the Arakan range, (*see* map of *Mountains of India* at end of this paper) and further south it separates the Andaman and Nicobar islands from the main-land of Lower Burma. In its northern portion it has been filled with alluvium; but in places south-east of the Andamans the depth of the sea exceeds 10,000 feet.

Sir Thomas Holland writes, "Very pertinent evidence as to the age of the Upper Siwaliks is "obtained in Burma, where the basin of the Irrawaddy contains a great system of beds chiefly com-"posed of yellow sands, which attain in some places a thickness of 20,000 feet and rest with slight "unconformity on marine beds whose miocene age is placed beyond doubt by their fossil contents"*.

The Burma trough is distinguished by the presence of the isolated volcanic cone of Popa, which rises out of the low alluvial flats to a height of 5000 feet.

Major Cowie observed the pendulum at several stations in Burma in 1910-11, and his results are most interesting†. I have however not been able to refer to them in this investigation as there have been difficulties in obtaining for them reliable corrections for isostatic compensation.

The *Sistan* trough follows the meridian of 61°. The main mountain chain of Asia changes its direction near the meridian of 61°, and at its bend a line of cleavage seems to have cut right across from north to south (*vide* map of *Mountains of India*). The line of cleavage passes through the Sistan alluvial flats, which constitute the delta of the river Helmand; and further south it separates the moribund volcanoes of Koh-i-Taftan and Koh-i-Sultan.

The basin of Sistan has been formed by successive subsidences of the Earth's surface,—due possibly to the crust below cracking under tension‡. It has been continually filled from above by wind-blown sand and fluviatile deposits. Vredenburg referring to these deposits writes of the "incredible thickness of strata"§.

Our only geodetic observations in this region are the deflections of the plumb-line at Koh-i-Malik Siah and Robat; the deflection at Koh-i-Malik Siah is 16″·4 to the west and that at Robat is 11″·4 south, both of which are too large to be attributed to the effects of topography only‖.

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* Imperial Gazetteer, India, Vol. I, page 97.

† Professional paper No. 15: *Pendulum Operations* by Couchman, page 89.

‡ An instructive discussion by Oldham of the several theories that have been put forward to account for the existence of deep troughs is included in Vol. XLII, pt. 2, Memoirs of the Geological Survey of India, pages 119-141.

§ Memoirs, Geological Survey of India, Vol. XXXI, page 203; *see* also pages 206 and 220.

‖ Professional paper No. 16, Survey of India, 1918: *The Earth's Axes and Triangulation*, by De Graaff Hunter, page 174.

(9) *The conclusions reached in this paper will influence the treatment of other geological formations.*

Explanation of the defects of gravity observed on the Deccan Trap.—Deccan Trap is the name given by geologists to the heavy volcanic rock which forms the surface of western India: this rock extends from latitude 16° to latitude 25°, and covers an area of 200, 000 square miles. The Western Ghat mountains are composed of trap from their base to their summits, which in places rise above 5000 feet* and the low-lying coastal belt at their foot is formed of this trap also. The depth of the trap is in most places unknown; Dr. Fermor has shown that it decreases from west to east.

The density of trap-rock is about 3·00, that is, 0·33 in excess of the earth's mean surface density. The existence of so extensive an area of heavy surface rock is of considerable geodetic interest. Whilst the Gangetic alluvium is an area of low surface density, the Deccan Trap is an area of high density. Owing to the uncertain compressibility of alluvium at great depths, estimates of density for the Gangetic area have varied from 1·9 to 2·5, but there are no such uncertainties in the case of the Deccan Trap: the density of the latter is generally accepted as 12 per cent above the normal surface density.

In 1909 Major Cowie observed large negative anomalies on the Deccan Trap, for example, Ujjain −0·022, Mhow −0·026, Mukhtiara −0·030†. Whilst therefore at certain stations on light alluvial plains (density 2·2 to 2·5) we had found gravity in excess (Kisnapur +0·028, Jacobabad +0·027, Mian Mir+0·029), Cowie now observed gravity in defect at places situated on heavy trap (density 3·0). If however the theory of isostatic compensation is applied to these heavy and light geological formations, the extraordinary anomalies may be explained. The presence of trap at the surface tends to produce positive gravity anomalies, but if the trap is compensated by underlying deficiencies of density there exists at all stations situated upon it a negative tendency also. If a station is situated on an *extensive* area of trap, the deep deficiencies of density in the crust are combining throughout the whole of that area to counteract the effects of the excessive density of the local rocks immediately under the station. At stations like Mhow, Ujjain, Mukhtiara and others, the negative tendency of the distant compensation has probably overcome the positive tendency of the local trap, and I regard the negative anomalies at these places on the trap as evidence in favour of isostatic compensation‡.

Geodetic observations on the Bombay coast.—From the Tapti to Cape Comorin runs the range of mountains known as the Western Ghats§. This range is parallel to the coast of India and about 40 miles inland: it rises suddenly with a steep scarp||.

The plumb-line has been observed at different points along this coast, and it is deflected strongly towards the sea. To the east of Bombay is a massive range over 4000 feet high, and to the west there is the deep sea; yet the plumb-line is deflected sea-wards. If the Western Ghats are uncompensated, in accordance with the hypothesis of Bouguer, the plumb-line at Bombay should be deflected 15″ *towards* them, *i.e.* towards the east. If on the other hand the Western Ghats are compensated by deficiencies of underlying density, then the plumb-line should hang vertically at Bombay. But the plumb-line takes neither of these courses: it hangs towards the sea. We have been puzzled for years by the plumb-line at Bombay: we used to think that the rock under the

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* *Manual of the Geology of India* by R. D. Oldham, 1893, chap. XI.

† Cowie also observed at other places, see page 68, Professional paper No. 15, *Pendulum Operations* by Couchman, chart V

‡ A well has been sunk at Mhow 130 feet below ground level; it is in trap throughout, and the trap is not pierced. The depth of the trap here is unknown.

§ See map of the *Mountains of India* at the end of this paper.

|| Records, Survey of India, Vol. IX, 1914-15, page 149.

ocean must be so heavy that it is able to pull the plumb-lines towards the sea. Major Cowie however observed on the coast of Kathiawar, north-west of Bombay, and found that the plumb-line here had a strong landward direction. The seaward deflections occur throughout the Bombay coast but not round Kathiawar. This proves that they cannot be due to submarine rocks. I am now of opinion that there must exist between Bombay and the Western Ghats a zone of subterranean deficiency, that is, a zone of rock attenuation, and of crustal tension.

The Western Ghats are very different in character from the Himalaya Mountains and it will be a matter of great geophysical interest if it can be proved that these two dissimilar ranges are both skirted by zones of crustal attenuation. The evidence, upon which the idea of a zone skirting the Western Ghats is based, is summarised in Lenox Conyngham's report to the Board of Scientific Advice*. He writes "At Colaba, Karanja, Mandvi and Dhauleshvar astronomical azimuths are "available whence the deflections in the prime vertical can be deduced. The results are very "remarkable: they are:—

Station	Height in feet	Situation	Deflection
Colaba ...	75	Coast	7″·3 west
Karanja ...	997	2 miles inland from coast	15″·2 west
Mandvi ...	4121	40 miles from coast	15″·4 east
Dhauleshvar ...	2939	80 miles from coast	9″·3 east

"These sudden changes in deflection are not susceptible of explanation on any general "hypothesis: they must be due to some local peculiarity of structure".

The section of hills and plains represented in plate II, though drawn for the Himalayas, gives a general picture of the conditions existing also at Bombay. A section drawn through Bombay from east to west will show the Ghat mountains on the east, the coastal flats in the centre and the sea on the west. On the Ghats at Mandvi and Dhauleshvar the plumb-lines are deflected eastwards, near the coast at Colaba and Karanja they are deflected westwards. They suggest the existence of a zone of attenuation along the foot of the mountains.

The results of the pendulum observations in this region confirm this view: at Alibag 30 miles from the mountains the gravity anomaly is −0·014 and at Colaba 40 miles from the mountains the anomaly is +0·052. The isostatic compensation of the Western Ghat mountains and of the Indian Ocean has been taken into the account in the deduction of these results. The following hypotheses will explain the tendency of the anomalies at Alibag and Colaba: a zone of attenuation, (such as we call a "trough" in the Gangetic area,) skirts the Western Ghats: Alibag is situated over this zone, and the lightness of the attenuated crust produces a negative anomaly there: Colaba is situated at the outer edge of this zone, and the excessive density that is underlying and compensating the zone produces a positive anomaly at its outer edge.

As the Western Ghats trend north and south, their effects upon the plumb-line have to be measured in the prime vertical. The best method of making such measurements has hitherto been by electro-telegraphic longitudes. But it has only been possible to observe such longitudes near large telegraphic offices, such as Bombay, and we have thus not been able to obtain good determinations of deflections either on the Ghats or between Bombay and the Ghats. Our deflections in the prime-vertical at several stations near the western coast of India have been deduced from azimuth observations†, and though these can be trusted to a certain extent if they are considered in groups, they

* Annual Report, Board of Scientific Advice for India, 1914-15, page 68.

† Professional paper No. 16: *The Earth's Axes and Triangulation* by De Graaff Hunter, chapter IX.

do not deserve the same confidence as longitude observations and they require confirmation. In future it will be possible to determine deflections by the method of wireless longitudes, and longitude stations will no longer be tied to telegraph offices. The deflection of the plumb-line will then be determined at many places between the Western Ghats and the coast, and it will be settled beyond doubt whether a zone of crustal attenuation exists or not.

Colaba itself is a longitude station and its large seaward deflection has been well-determined*. Mangalore is on the coast 400 miles south of Bombay: there is a seaward deflection of 4″ at Mangalore, which has also been determined from longitude observations.

The low-lying strip of land, 40 miles wide, that runs along the coast between the Ghat mountains and the sea is composed of trap-rock in the latitude of Bombay, whilst further south at Mangalore it consists of gneiss. In this region there exists no surface trough filled with alluvium, and the zone of crustal attenuation, if it is proved to exist, cannot be explained as a belt of cenozoic deposits. It will denote an expansion and a stretching of the crust.

The Eastern Ghat Mountains.—The Eastern Ghat mountains are to the eastern coast of India what the Western Ghats are to the west coast. The deflection at the coast station of Waltair (Vizagapatam) is 6″ seawards, and the coastal rock is composed of gneiss. We have therefore at Waltair a marked seaward deflection, as we have at Bombay and Mangalore.

At Madras, 400 miles south of Waltair, the seaward deflection is no less than 11″. Madras is situated on cenozoic deposits. But it is unreasonable to attribute the deflection of 11″ to the presence of very deep deposits, when similar seaward deflections are found at Waltair, Mangalore and Bombay where no deep deposits exist.

The geodetic observations on the eastern coast are too few to warrant any scientific deductions: all we can say is that so far as these observations go they support the conclusions derived from the observations on the Bombay coast.

Explanation of the high values of gravity observed at stations in the Satpura mountains.—The map of the *Mountains of India* attached to this paper shows that a range runs across India in an E. N. E. direction, immediately south of the line of the Narbada—Son rivers. The western portion of this range is known as the Satpura mountains, whilst the eastern portion is designated the Hazaribagh plateau.

The Satpura mountains are situated within the area of the Deccan trap, and to the lay observer they appear to be composed of trap-rock, but Dr. Fermor has described them as a folded crystalline range with a capping of trap†. At the peak of Amarkantak, at the source of the Narbada, Fermor found that the gneissic core attained a height of about 2660 feet and that over this there was a capping of trap, 670 feet thick.

The following gravity anomalies deduced by Hayford's method of isostatic compensation have been observed at stations in the Satpuras:—

Station	Height	Anomaly
	feet	*dynes*
Asirgarh	2077	+0·019
Khandwa	1014	+0·036
Shahpur	1286	+0·012
Badnur	2103	+0·027
Seoni	2032	+0·025
Jubbulpore	1467	+0·019
Umaria	1499	+0·018

* Professional paper No. 13: *Investigations of Isostasy* by Crosthwait, page 14.

† Records, Geological Survey of India, Vol. 47, page 133 and Vol. 45, pages 111, 128 and 129.

Chart V attached to Couchman's professional paper shows that the whole Satpura range is an area of positive anomalies, and the conclusion hitherto drawn has been that the Satpura range is not compensated. But having regard to the calculated results of the isostatic compensation in the case of the Gangetic formation, I am now of opinion that the positive values in the Satpuras may be largely due to the compensation of the "trough" of the river Narbada, for this "trough" in the Deccan trap is in close connection with the Satpura range.

The course of a river upon the Earth's surface is not often of geodetic importance, but the line of the Narbada has been recognised for years as exceptional, and as marking structural peculiarities in the crust.

At the latitude stations* immediately north of the Narbada, the deflections of the plumb-line are northerly:—

Station		Residual deflection (Hayford)
Deo Dongri	...	− 1″
Kundgol	...	− 2″
Naharmau	...	− 2″

These results are not sufficiently striking in themselves to gain attention, but immediately south of the Narbada the deflection at Thikri is southerly and + 4″. The suddenness of the change in crossing the Narbada was considered significant. The easterly deflection of 7″ at Jubbulpore confirms the view that a zone of crustal attenuation underlies the valley of the Narbada.

In 1908-10 Major Cowie observed the pendulum at stations near the meridian of 76°, and he noted a marked change in the anomaly as he passed the Narbada†. North of the Narbada his observed anomalies were negative, south of the Narbada they were positive.

Station		Situation		Gravity anomaly (Hayford)
				dynes
Ujjain	...	North of the river	...	− 0·022
Mhow	...	North of the river	...	− 0·026
Mukhtiara	...	Near north bank	...	− 0·030
Mortakka	...	Near south bank	...	+ 0·005
Khandwa	...	South of the river	...	+ 0·047
Asirgarh	...	South of the river	...	+ 0·030

Further east where the river Son continues the alignment of the Narbada a similar change in the gravity anomalies occurs at the river:—

Station		Situation		Gravity anomaly (Hayford)
				dynes
Maihar	...	North of the river	...	− 0·003
Katni	...	On the river	...	+ 0·007
Umaria	...	South of the river	...	+ 0·029
Jubbulpore	...	South of the river	...	+ 0·030
Seoni	...	South of the river	...	+ 0·036

* Professional paper No. 13: *Investigations of Isostasy* by Crosthwait.

† Narrative Reports, Survey of India, 1908-09, page 108. Records, Survey of India, Vol. I, 1909-10, page 61.

Extensive alluvial plains exist in the valleys of the Narbada and Tapti*. In the Narbada valley the principal plain extends for 200 miles, and varies in breadth from 12 miles to 35. The alluvial deposits of the upper basin of the Narbada extend to a considerable depth beneath the level of the rock bed at the point of the river's exit, so that the plain lies in a great rock basin. It is probable that the floor of the basin extends below the trap rock. In a boring at Sukakheri a depth of 491 feet was attained without the base of the alluvial deposits being reached. Throughout the thickness of 491 feet no change of importance was detected in the alluvial formations.

Vredenburg writes :—"The enormous depth of the ancient alluvium of the Narbada was never "suspected before it was revealed by boring"†.

If these deep Narbada deposits of light density are isostatically compensated, the excessive density underlying them to depths of 70 miles will be affecting gravity in the Satpuras, and will be producing positive anomalies at Satpura stations. Having regard therefore to the geographical and geological conditions of the region I am of opinion that the positive anomalies in the Satpuras support the hypothesis of isostatic compensation.

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* *Geology of India* by R. D. Oldham, 1893, pages 396, 398 and 495.

† The Geological problems of the Narbada are discussed by Vredenburg, Records, Geological Survey of India, Vol. XXIII, 1906, pages 33-45.

APPENDIX No. 1

CALCULATIONS OF THE GRAVITATIONAL EFFECTS OF A TROUGH, CONTAINING LIGHT ROCK (DENSITY 2·4) AND ISOSTATICALLY COMPENSATED.

APPENDIX No. 2

NOTES ON THE FORM OF THE GANGETIC TROUGH.

Appendix No. 1.

CALCULATIONS OF THE GRAVITATIONAL EFFECTS OF A TROUGH, CONTAINING LIGHT ROCK (DENSITY 2·4) AND ISOSTATICALLY COMPENSATED.

For the following table I am indebted to the U. S. Coast and Geodetic Survey: they first published such a table, which I have ventured to copy and to expand*.

Table of attractions for various masses.

Each value is the vertical attraction in dynes produced by a mass equivalent to a stratum 100 feet thick, of density 2·67, if that mass is uniformly distributed to the depth indicated in the top argument and in all directions horizontally to the distance indicated in the left-hand argument.

Radius in miles	DEPTH IN FEET											
	1000	5000	10000	15000	20000	25000	30000	40000	50000	60000	70000	113·7 kilo-metres
0·8	0·0030	0·0018	0·0011	0·0008	0·0006	0·0005	0·0004	0·0003	0·0003	0 0002	0·0002	0·0000
1·5	·0031	·0024	·0017	·0013	·0012	·0010	·0009	·0008	·0007	·0006	·0005	·0001
2·0	·0032	·0027	·0020	·0017	·0016	·0015	·0014	·0012	·0011	·0011	·0010	·0001
3·1	·0033	·0029	·0025	·0021	·0021	·0020	·0019	·0019	·0018	·0017	·0016	·0001
5·0	·0033	·0031	·0028	·0025	·0025	·0023	·0022	·0022	·0021	·0020	·0019	·0002
6·25	·0034	·0032	·0029	·0027	·0026	·0025	·0025	·0023	·0023	·0023	·0022	·0003
7·5	·0034	·0032	·0030	·0028	·0028	·0027	·0027	·0026	·0026	·0025	·0024	·0004
12·0	·0035	·0033	·0031	·0030	·0029	·0029	·0029	·0028	·0028	·0027	·0026	·0006
20·0	·0035	·0033	·0032	·0032	·0031	·0031	·0031	·0030	·0030	·0030	·0029	·0008
40·0	·0036	·0034	·0033	·0033	·0032	·0032	·0032	·0031	·0031	·0031	·0030	·0013
60·0	·0036	·0034	·0034	·0033	·0038	·0033	·0033	·0032	·0031	·0031	·0031	·0018
104·0	·0037	·0034	·0034	·0034	·0034	·0034	·0034	·0033	·0033	·0033	·0033	·0024
750·0	·0040	·0037	·0037	·0037	·0037	·0037	·0037	·0037	·0037	·0037	·0037	·0036

GRAVITY ANOMALIES.

I. NORTH-EASTERN SECTION, (table V, plate II).

(*a*) SANDAKPHU.—Gravity anomaly $+0\cdot037$.

Situated 26 miles north of the northern border of the trough: if trough is assumed 100 miles wide, its southern edge, which is not visible nor defined in nature, is 126 miles from Sandakphu.

For purposes of computation the Gangetic trough, as viewed from Sandakphu, is taken to be the southern half of an annulus, (outer radius 126 miles, inner radius 26 miles).

The problem is to find the *average* depth of a semi-annular trough (outer radius 126 miles, inner radius 26 miles) which will produce a gravity anomaly of $+0\cdot037$ at Sandakphu.

The method of calculation is to deduce the effect of the annulus by subtracting the effect of the 26-mile inner cylinder from the 126-mile cylinder, and then to divide by 2 to obtain the effect of the half-annulus.

* *Investigations of Gravity and Isostasy* by Bowie, 1917.

It can be found by successive trials that 70000 feet is the depth for the trough that satisfies the conditions of the problem: thus—

Effect of compensated disc, 126^m rad.

$$= -(0 \cdot 0033 - 0 \cdot 0025) \times 70 = -0 \cdot 056$$

Effect of disc, 26^m rad.

$$= -(0 \cdot 0029 - 0 \cdot 0010) \times 70 = -0 \cdot 133$$

Therefore, effect of outer annulus ($126^m - 26^m$)

$$= -(0 \cdot 056 - 0 \cdot 133) = +0 \cdot 077$$

Effect of half this annulus $= +0 \cdot 038$

The observed gravity anomaly $+0 \cdot 037$ can thus be accounted for by a compensated trough, 100 miles wide, *averaging* 70000 feet deep.

(*b*) SILIGURI.—Gravity anomaly $-0 \cdot 050$.

Siliguri stands over the trough, 12 miles from its visible northern edge, 88 miles from its supposed southern edge. The trough, as viewed from Siliguri, may be represented, ***firstly***, by a complete disc of 12 miles radius, and, ***secondly, in addition*** by a half-annulus (outer radius 88 miles, inner 12 miles). 30000 feet is found by trial to satisfy the problem.

Firstly,

Effect of compensated disc, 12^m rad.

$$= -(0 \cdot 0029 - 0 \cdot 0006) \times 30 = -0 \cdot 069$$

Secondly,

Effect of annulus, ($88^m - 12^m$)

$$= -(0 \cdot 0032 - 0 \cdot 0022) \times 30 + (0 \cdot 0029 - 0 \cdot 0006) \times 30$$

$$= (-0 \cdot 0010 + 0 \cdot 0023) \times 30 = +0 \cdot 039$$

Effect of half-annulus $= +0 \cdot 020$

Sum of the two effects at Siliguri—

12-mile disc		$-0 \cdot 069$
Half-annulus ($88^m - 12^m$)		$+0 \cdot 020$
Total computed effect	=	$-0 \cdot 049$
Observed anomaly	=	$-0 \cdot 050$

(*c*) JALPAIGURI.—Gravity anomaly $-0 \cdot 031$.

Situated on the trough, 30 miles distant from northern edge, 70 miles from supposed southern edge. We must sum the effects of a 30-mile disc and of ¾ ths. of the annulus (70 miles − 30 miles).

Firstly,

Effect of compensated disc, 30-mile radius, 20000 feet deep

$$= -(0 \cdot 0031 - 0 \cdot 0011) \times 20 = -0 \cdot 040$$

Secondly,

Effect of annulus ($70^m - 30^m$)

$$= -(0 \cdot 0033 - 0 \cdot 0019) \times 20 + 0 \cdot 040 = -0 \cdot 028 + 0 \cdot 040 = +0 \cdot 012$$

Three-fourths of annulus	$= +0 \cdot 009$
Combined effects of 30-mile disc and of ¾ ths annulus	$= -0 \cdot 031$
Observed anomaly	$= -0 \cdot 031$

(*d*) KISNAPUR.—Gravity anomaly $+0 \cdot 028$.

Situated on the alluvium, 30 miles south of the assumed southern edge of the trough*. Effect of annulus ($130^m - 30^m$) 70 000 feet deep

$$= -(0 \cdot 0033 - 0 \cdot 0025) \times 70 + (0 \cdot 0030 - 0 \cdot 0012) \times 70$$

$$= (-0 \cdot 0008 + 0 \cdot 0018) \times 70 = +0 \cdot 0010 \times 70 = +0 \cdot 070$$

* Position of southern edge of trough cannot be estimated with accuracy. It is probably not a definite edge at all.

The trough as measured geometrically from Kisnapur is slightly less than half the annulus: it may be taken at $\frac{4}{9}$ ths $= +0\cdot032$.

We have so far assumed that Kisnapur is 30 miles south of the trough, and that the trough is a segment of an annulus (130—30 miles) north of Kisnapur.

But Kisnapur, though assumed outside the trough, is itself standing on alluvium, of unknown depth, and the effect of this alluvium (compensated) may be estimated for a 30-mile disc as follows :—

if 1000 feet deep	...	...	$-0\cdot002$
if 2000 feet deep	...	...	$-0\cdot005$
if 3000 feet deep	...	...	$-0\cdot008$

The effect at Kisnapur of the trough, 70000 feet deep, has been estimated above at $+0\cdot032$. If the alluvium be assumed to be 3000 feet deep below Kisnapur, the gravity anomaly may be estimated at $+0\cdot032-0\cdot008 = +0\cdot024$. Observed anomaly $= +0\cdot028$.

(*e*) CHATRA.—Gravity anomaly $-0\cdot006$.

Chatra is 50 miles south of Kisnapur. The positive effect produced at Chatra by the excess of density compensating the trough is smaller than the effect at Kisnapur, and is apparently insufficient to counteract the purely local negative effect of the Chatra alluvium. The result is that at Chatra the observed anomaly is slightly negative.

II. EASTERN SECTION, (table VI).

(*a*) GORAKHPUR.—Gravity anomaly $-0\cdot081$.

Situated near the centre of the trough, 60 miles distant from northern edge and 100 miles from southern. If Gorakhpur is assumed to be at the centre of a trough, 120 miles wide, then a rock-disc of average depth 60000 feet, of radius 60 miles, density 2·4, isostatically compensated, will produce a gravity anomaly of $-(0\cdot0032-0\cdot0018)\times 60$

$$= -0\cdot0014\times 60$$
$$= -0\cdot084$$

Observed anomaly $= -0\cdot081$.

The assumption, that the anomaly at Gorakhpur is produced by the attraction of a circular disc, will probably tend to give the depth of the assumed disc smaller than the true depth of the trough in nature: the trough is probably much wider than 120 miles on this section and it extends for great distances to the east and west of our assumed circular disc, and if we were to include these distant portions of the trough, our estimate of its depth would be increased from 60000 feet to 70000 feet or more. Gorakhpur is near the centre of the trough, and it is most interesting to find at such a situation so large a negative anomaly and so large a corresponding value of depth.

(*b*) MAJHAULI RAJ.—Gravity anomaly $-0\cdot068$.

Situated 70 miles from northern edge of trough. It will be 50 miles from southern, if trough is assumed to be 120 miles wide. We have then to sum the effects of a disc of 50-mile radius and of the segment of an annulus (70 miles — 50 miles).

Effect of disc 50000 feet deep, 50-mile radius, $= -(0\cdot0032-0\cdot0016)\times 50 = -0\cdot080$

Effect of annulus (70^m-50^m)

$$= -(0\cdot0032-0\cdot0019)\times 50+(0\cdot0032-0\cdot0016)\times 50$$
$$= (-0\cdot0013+0\cdot0016)\times 50 = +0\cdot015$$

The annulus encircles Majhauli Raj from W.S.W. through N. to E.S.E.: we can take $\frac{2}{3}$ rds of its effect $= +0\cdot010$.

Effect of disc	$= -0\cdot080$
Effect of annular segment	$= +0\cdot010$
Computed anomaly	$= -0\cdot070$
Observed anomaly	$= -0\cdot068$

If for purposes of estimation we had assumed Majhauli Raj to be standing at the centre of a disc of 70-mile radius, we should have computed the anomaly at $-(0\cdot0032-0\cdot0019)\times50 = -0\cdot065$, instead of $-0\cdot070$.

(*c*) MUZAFFARPUR.—Gravity anomaly $-0\cdot053$.

Situated on the trough 70 miles south of the northern edge, and 70 to 90 miles south of supposed southern edge. Procedure will be the same as at Majhauli Raj.

Effect of disc 40000 feet deep, 50-mile radius $= -(0\cdot0032-0\cdot0016)\times40 = -0\cdot064$.

Effect of annulus $(70^m - 50^m) = -(0\cdot0032-0\cdot0019)\times40 + (0\cdot0032-0\cdot0016)\times40$

$= (-0\cdot0013+0\cdot0016)\times40 = +0\cdot012$.

Two thirds of annulus $= +0\cdot008$.

Computed anomaly for a depth of 40000 feet $= -0\cdot064+0\cdot008$

$= -0\cdot056$

Observed anomaly $= -0\cdot053$

As in the case of Majhauli Raj it would perhaps have been simpler to assume Muzaffarpur at the centre of a disc of 70 miles radius. The depth would then have been estimated at about 40000 feet, thus $-(0\cdot0032-0\cdot0019)\times40 = -0\cdot052$ = computed anomaly. Observed anomaly $= -0\cdot053$.

(*d*) ARRAH.—Gravity anomaly $-0\cdot039$.

Situated 130 miles from northern edge of trough and 30 miles from southern edge of alluvial plains. If Arrah were situated at the centre of a disc, 130 miles radius, 70000 feet deep, this disc would produce an anomaly of $-0\cdot056$. The computation would be $-(0\cdot0033-0\cdot0025)\times70 = -0\cdot056$.

As Arrah is on the edge of a semi-circular disc, the computed effect will be only half that of the complete disc, namely $-0\cdot028$.

We have also to allow for the local surface alluvium immediately underlying Arrah. Assuming that Arrah is standing over alluvium, 5000 feet deep, we must allow for the effect of this (for a radius, say, of 20 miles) *viz*, $-(0\cdot0035-0\cdot0009)\times5 = -0\cdot013$

Effect of a semi-disc $= -0\cdot028$

Effect of purely local alluvium $= -0\cdot013$

Computed anomaly $= -0\cdot041$

Observed anomaly $= -0\cdot039$

(*e*) SASARAM.—Gravity anomaly $-0\cdot002$.

Sasaram is on the Gangetic alluvium, depth of which is unknown. It is 180 miles south of the northern edge of the trough. The positive effect of the distant trough seems to be counterbalanced by the negative effect of the local alluvium.

(*f*) RANCHI.—Gravity anomaly $+0\cdot019$.

Situated on the gneiss table-land 100 miles south of the southern edge of the Gangetic alluvium. It is 250 miles south of the northern edge of the trough. Ranchi is too far south of the Gangetic trough to be included in this investigation with any confidence. A station in its position is open to external influences from the south, which have no connection with Himalayan-Gangetic attractions. If, however, the positive anomaly is to be ascribed to the effects of the Gangetic trough, a depth for the latter of 100000 feet would have to be assumed.

The attraction of a disc, 100 miles radius, 100000 feet depth
$= -(0\cdot0033 - 0\cdot0024) \times 100 = -0\cdot090$

The attraction of a disc, 250 miles radius, 100000 feet depth
$= -(0\cdot0034 - 0\cdot0028) \times 100 = -0\cdot060$

Subtracting the effect of the smaller disc (100 miles) from that of the larger (250 miles) we get $+0\cdot030$ as the effect of the annulus ($250^m - 100^m$). We take half this annulus to represent the Gangetic trough, as viewed from Ranchi, and computed anomaly becomes $+0\cdot015$. Observed anomaly $+0\cdot019$.

III. EASTERN-CENTRAL SECTION, (table VII).

ALLAHABAD.—Gravity anomaly $-0\cdot002$.

Allahabad is on the Gangetic alluvium, being 20 miles north of the southern limit of the alluvium. It is 170 miles south of the northern edge of the Gangetic trough. The depth of the alluvium at Allahabad is quite unknown. The positive effect of the distant trough appears to be counterbalanced by the negative effect of the local alluvium.

IV. CENTRAL SECTION, (table VIII).

(*a*) MUSSOOREE.—Gravity anomaly $+0\cdot042$.

Mussooree is situated in the mountains 3 miles from their foot, 20 miles from the foot of the Siwalik hills, 100 miles from the southern edge of the trough. In this case our estimates require three discs of respective radii, 3 miles, 20 miles, 100 miles. I assume the depth of the light strata in the ($20^m - 3^m$) annulus to be 10000 feet*.

(i) *Effect of the annulus* ($20^m - 3^m$)—
Attraction of 3-mile disc $= -(0\cdot0025 - 0\cdot0001) \times 10 = -0\cdot024$
Attraction of 20-mile disc $= -(0\cdot0032 - 0\cdot0008) \times 10 = -0\cdot024$
Effect of annulus $(20^m - 3^m) = 0\cdot000$

(ii) *Effect of the annulus* ($100^m - 20^m$)—
In order to obtain an anomaly of $+0\cdot042$, we must adopt for this annulus an assumed *average* depth of 60000 feet.

Attraction of 20-mile disc $= -(0\cdot0032 - 0\cdot0008) \times 60 = -0\cdot144$
Attraction of 100-mile disc $= -(0\cdot0034 - 0\cdot0024) \times 60 = -0\cdot060$
Effect of annulus $(100^m - 20^m) = +0\cdot084$
Computed anomaly = half the effect of the annulus $= +0\cdot042$. Observed anomaly $= +0\cdot042$.

(*b*) RAJPUR.—Gravity anomaly $+0\cdot015$.

Situated at the foot of the Himalayas, 17 miles from edge of Siwaliks, 100 miles from southern edge of trough.

(i) Effect of disc, 17 miles radius, 10000 feet deep,
$= -(0\cdot0032 - 0\cdot0008) \times 10 = -0\cdot024$
Effect of half this disc at Rajpur $= -0\cdot012$

* Memoirs Geological Survey of India. Vol. XLII, part 2, *Structure of the Himalayas* by R.D. Oldham, page 107.

(ii) Effect of annulus $(100^m - 17^m)$ 40000 feet average depth—

17-mile disc,	$-0\cdot0022 \times 40$	=	$-0\cdot088$
100-mile disc,	$-0\cdot009 \times 40$	=	$-0\cdot036$
	Effect of annulus	=	$+0\cdot052$
	Half this effect	=	$+0\cdot026$
Subtract half effect of 17-mile disc (p. 29)			$-0\cdot012$
	Computed anomaly	=	$+0\cdot014$
	Observed anomaly	=	$+0\cdot015$.

(*c*) Dehra Dun.—Gravity anomaly $-0\cdot005$.

Situated 5 miles south of Himalayan foot, 12 miles north of Siwalik edge and 95 miles from southern edge of trough.

Effect of 5-mile disc, 10000 feet deep $= (-0\cdot0028+0\cdot0002)\times10 = -0\cdot026$
Effect of annulus $(12^m - 5^m)$ 10000 feet deep $= 0\cdot000$.
Effect of annulus $(95^m - 12^m)$ 40000 feet average depth may be computed as follows :—

12-mile disc,	$-0\cdot0022 \times 40$	=	$-0\cdot088$
100-mile disc,	$-0\cdot0009 \times 40$	=	$-0\cdot036$
Effect of annulus $(100^m - 12^m)$		=	$+0\cdot052$
Half this annulus		=	$+0\cdot026$
Subtract effect of local alluvium, (5-mile disc)			$-0\cdot026$
Computed anomaly		=	$0\cdot000$
Observed anomaly		=	$-0\cdot005$

(*d*) Roorkee.—Gravity anomaly $-0\cdot055$.

Situated on the Gangetic plains 25 miles south of the Himalayan foot, and 75 miles from southern edge of the trough.

We must sum the effects of a 25-mile disc and of a half annulus (outer radius 75 miles, inner radius 25 miles).

(i) Effect of compensated disc, 25-mile radius, depth 35000 feet,

$$= -(0\cdot0030 - 0\cdot0010) \times 35$$
$$= -0\cdot070$$

(ii) Effect of outer disc, 75-mile radius

$= -(0\cdot0032 - 0\cdot0020) \times 35$	...	=	$-0\cdot042$
Deduct effect of 25-mile disc ...	...		$-0\cdot070$
Effect of annulus	...	=	$+0\cdot028$
Effect of half the annulus ...	...	=	$+0\cdot014$
Sum of the two effects, *viz.* that of disc and that of half annulus		=	$-0\cdot056$
Observed anomaly ...	...	=	$-0\cdot055$

(*e*) Kaliana.—Gravity anomaly $-0\cdot018$

Kaliana is on the plains 50 miles from the hills. The effect of a disc of 50-mile radius 12000 feet deep, would be $-(0\cdot0031 - 0\cdot0016) \times 12$

$$= -0\cdot0015 \times 12 = -0\cdot018$$

Observed anomaly ... ... $= -0\cdot018$

It should be noted that the estimate does not imply that the depth of the lighter rock immediately under Kaliana is 12000 feet. The meaning conveyed is that a trough, 100 miles wide, of the ***average*** depth of 12000 feet, would explain the anomaly at Kaliana.

(*f*) GESUPUR.—Gravity anomaly $-$ 0·006.

Gesupur is situated near the southern edge of the trough, depth of alluvium unknown.

If a trough 100 miles wide, 12000 feet deep, (as estimated from Kaliana) existed 10 miles from Gesupur, its effect at Gesupur would be

$$\begin{aligned}
\text{Effect of 110-mile disc} &= -(0\cdot0034 - 0\cdot0024) \times 12 \\
\text{Effect of 10-mile disc} &= -(0\cdot0031 - 0\cdot0006) \times 12 \\
\text{Effect of half the annulus} &= \tfrac{1}{2}(-0\cdot0010 + 0\cdot0025) \times 12 \\
&= +\ 0\cdot009
\end{aligned}$$

As the observed anomaly is $-0\cdot006$, we must assume the existence of sufficient light deposits under Gesupur to account for $-0\cdot009 - 0\cdot006 = -0\cdot015$. A disc of radius 10 miles, depth 5000 feet, would produce an effect of $-0\cdot014$.

(*g*) KHURJA.—Gravity anomaly $-0\cdot030$.

Khurja is a station, which, like Monghyr further east, is situated on the southern edge of the trough and which nevertheless exhibits a ***large negative anomaly***. Gesupur and Khurja are in similar situations: whereas the anomaly at Gesupur is only $-0\cdot006$, that at Khurja is $-0\cdot030$ which is considerably larger than at Kaliana, a station on the mid-alluvium. This is a proof that the form of the trough is complex and varied, and that it cannot be represented geometrically.

(*h*) MUTTRA.—Gravity anomaly $+0\cdot004$.
AGRA. —Gravity anomaly $+0\cdot006$.
JHANSI. —Gravity anomaly $+0\cdot003$.

The compensation underlying the Gangetic trough would tend to produce positive anomalies at these stations.

(*i*) KALIANPUR.—Gravity anomaly $+0\cdot028$.

It is 380 miles from the foot of the Himalayas, and more than 100 miles south of the Gangetic alluvium. It will be interesting to test whether the compensating excess under the Gangetic trough can be exercising any appreciable influence at so great a distance. We will imagine 2 discs, one of 380 miles radius, the other of 150 miles radius, and we will subtract the effect of the latter from that of the former in order to obtain an idea of the effect of the annulus: we will assume that half the annulus will represent approximately the Indo-Gangetic trough as viewed from Kalianpur.

Assuming an average depth for the trough of 20000 feet, we obtain

$$\begin{aligned}
\text{Effect of larger disc} &= -\ 0\cdot010 \\
\text{Effect of smaller disc} &= -\ 0\cdot020 \\
\text{Effect of annulus} &= +\ 0\cdot010 \\
\text{and of half-annulus} &= +\ 0\cdot005
\end{aligned}$$

The conclusion is that the gravity anomaly at Kalianpur cannot be wholly ascribed to the presence of Gangetic compensation.

V. WESTERN SECTION, (table IX).

(*a*) PATHANKOT.—Gravity anomaly $-$ 0·087.

Situated on the alluvium 20 miles from the foot of the mountains.

The effect of a disc, radius 20 miles, depth 50000 feet,

$$= -(0 \cdot 0030 - 0 \cdot 0009) \times 50 = -0 \cdot 105$$

Effect of the more distant portions of the trough may be estimated as follows :—

Effect of 50-mile disc, 50000 feet deep,

$$= -(0 \cdot 0031 - 0 \cdot 0016) \times 50 = -0 \cdot 075$$

Effect of 20-mile disc ... ... $= -0 \cdot 105$

Therefore effect of half-annulus ... ... $= +0 \cdot 015$

Effect of 20-mile disc $= -0 \cdot 105$
Effect of half-annulus $= +0 \cdot 015$

Computed anomaly $= -0 \cdot 090$
Observed anomaly $= -0 \cdot 087$

(*b*) MIAN MIR.—Gravity anomaly $+$ 0·029.

Situated on the alluvium 20 miles south of the assumed southern edge of the trough.* Effect of the local alluvium at Mian Mir, which may be assumed 3000 feet deep = $-$ 0·007.

Then we have to calculate the effect of a half-annulus ($90^m - 20^m$).

Effect of 20-mile disc $= -(0 \cdot 0030 - 0 \cdot 0009) \times 70 = -0 \cdot 147$
Effect of 90-mile disc $= -(0 \cdot 0033 - 0 \cdot 0022) \times 70 = -0 \cdot 077$
Effect of annulus ... ... $= +0 \cdot 070$
Effect of half-annulus ... ... $= +0 \cdot 035$
Effect of local alluvium ... ... $= -0 \cdot 007$

Computed anomaly $= +0 \cdot 028$
Observed anomaly $= +0 \cdot 029$

VI. NORTH-WESTERN SECTION, (table X).

(*a*) QUETTA.—Gravity anomaly $-$0·004.

Quetta is situated on a small alluvial basin in the Baluchistan mountains, 60 miles from the great plains of the Indus.

Effect of 150-mile disc 40000 feet in depth $= -(0 \cdot 0034 - 0 \cdot 0026) \times 40 = -0 \cdot 032$
Effect of 60-mile disc $= -(0 \cdot 0032 - 0 \cdot 0018) \times 40 = -0 \cdot 056$
Effect of annulus $= -(0 \cdot 032 - 0 \cdot 056) = +0 \cdot 024$
Take $\frac{1}{6}$ th of this annulus, $= +0 \cdot 004$

Observed anomaly ... ... $= -0 \cdot 004$
Discrepancy ... ... $= -0 \cdot 008$

This discrepancy can be accounted for if we assume that Quetta is standing near the centre, of a circular alluvial basin, 2 miles radius, 3000 feet deep.

(*b*) SIBI.—Gravity anomaly $-$0·070.

Sibi is situated in a bay 12 miles from the foot of the mountains. A disc of 12 miles radius and 30000 feet deep would produce an effect of

$$-(0 \cdot 0029 - 0 \cdot 0006) \times 30 = -0 \cdot 0023 \times 30 = -0 \cdot 069$$

Observed gravity anomaly ... $= -0 \cdot 070$

* Position of southern edge is unknown : it has to be assumed for purposes of computation.

As the outer portion of the trough towards Jacobabad would have a positive effect at Sibi, and as this positive effect has been left out of the estimate, we may conclude that 30000 feet is too small a value for the depth of the trough at Sibi.

(*c*) JACOBABAD.—Gravity anomaly $+0 \cdot 027$.

Jacobabad is situated on the wide alluvial plains of Sind, 40 miles from the hills at their nearest point, 100 miles from the hills towards Quetta. It is apparently outside the trough but is standing on alluvium, which in the absence of any near outcrops of rock cannot be assumed to be shallow.

Let us assume 3 discs, one of 10-mile radius, one of 40, one of 100.

(i)	Effect of 40-mile disc, 50000 feet deep	$= -(0 \cdot 0031 - 0 \cdot 0014) \times 50$	$= -0 \cdot 085$
	Effect of 10-mile disc, 50000 feet deep	$= -(0 \cdot 0028 - 0 \cdot 0005) \times 50$	$= -0 \cdot 115$
	Effect of the annulus ($40^m - 10^m$)		$= +0 \cdot 030$
	and of the half annulus		$= +0 \cdot 015$
(ii)	Effect of 100-mile disc, 50000 feet deep	$= -(0 \cdot 0033 - 0 \cdot 0024) \times 50$	$= -0 \cdot 045$
	Effect of 40-mile disc ...	... ...	$= -0 \cdot 085$
	Effect of the annulus ($100^m - 40^m$)	... ...	$= +0 \cdot 040$
	and of ¼th of the annulus ...	... ...	$= +0 \cdot 010$
	Effect of half the ($40^m - 10^m$) annulus	... ...	$= +0 \cdot 015$
	Effect of one quarter the ($100^m - 40^m$) annulus	... ..	$= +0 \cdot 010$
		Computed anomaly	$= +0 \cdot 025$
		Observed anomaly	$= +0 \cdot 027$

DEFLECTIONS OF THE PLUMB-LINE.

I. NORTH-EASTERN SECTION, (table V, plate II).

(*a*) KURSEONG.—Deflection 23″ north.

Kurseong is situated 4 miles north of the foot of the Himalayas, and about 104 miles north of the supposed southern edge of the trough. To estimate the effect of the trough upon the plumb-line at Kurseong, we must assume 2 semi-circles drawn round Kurseong to the south, one of radius 4 miles, the other of radius 104 miles. Then if we compute the effects of the trough by Hayford's method*, we find that there are 9 annuli, and $9 \times 8 (= 72)$ compartments. To produce a deflection of 23″ there must be in the several compartments an average deficiency of normal rock $(2 \cdot 67)$ equalling $\frac{23}{72} \times 10000 \times F$, where F is the factor for isostatic compensation†. The same result may be stated as follows: at the distances of the annuli an isostatic deflection of 23″ denotes a topographical deflection of 38″, due to the uncompensated trough, and the average deficiency of rock is $\frac{38}{72} \times 10000$ feet.

If the deficiency of density is assumed to be 10 per cent below the normal, the average depth of the trough will be $\frac{23}{72} \times 100000 \times 1 \cdot 7$. Depth of trough $= 50000$ feet.

(*b*) SILIGURI.—12 miles south of the mountains; deflection 7″ north.

JALPAIGURI.—30 miles south; deflection 7″ south.

In the 18 miles between Siliguri and Jalpaiguri the deflection of the plumb-line has changed from 7″ N. to 7″ S.: the plumb-line will hang vertically midway between these two stations at a point A situated about 20 miles distant from the mountains. If, therefore, the trough is assumed to be 100 miles wide, the deficiency of mass in the northern 20 miles will in its effect at the point A exactly counterbalance the deficiency in the southern 80 miles. This is a proof that the northern portion of the Gangetic trough is somewhat deeper than the southern.

* *The Figure of the Earth and Isostasy* by Hayford, 1909.

† Professional paper No. 13: *Investigations of Isostasy* by Crosthwait. Every 100 feet of rock in any compartment produces a deflection of 0·″01. Every 10000 feet produces a deflection of 1″·0.

It is difficult to make any estimates of the depth of the trough from the deflections at stations situated like those of Siliguri and Jalpaiguri. It is possible to devise many forms of trough of different depths that will suit these two deflections. These different forms of trough are based on different initial assumptions, each of which is as deserving of weight as the others. Without some initial assumption I do not think that the deflections at Siliguri and Jalpaiguri can be used to determine the absolute deficiency of mass in the trough. They might, however, be used in conjunction with other data for a determination of the most probable form of the trough.

(*c*) CHANDURIA.—Deflection 11″ south.

Situated 80 miles south of the hills. From this deflection it may be estimated that the average depth of the trough in the 60 miles immediately south of the mountains is 60000 feet.

(4 rings, 32 compartments, F = 0·54). The large southerly deflection at Chanduria, +11″, and that further south at Madhupur +9″ deserve the consideration of all geodesists, who are endeavouring to learn the physical meanings of gravity anomalies.

II. EASTERN SECTION, (table VI).

(*a*) PATHARDI.—Deflection 11″ north.

Situated on the alluvium 14 miles from the mountains. As in the cases of Siliguri and Jalpaiguri it is difficult to make any reliable estimate of depth from a deflection on the alluvium. We can devise several forms of trough that will produce a deflection of 11″ north at Pathardi. The large northerly deflection at Pathardi teaches the lesson that the aggregate effects of the light rock lying south of Pathardi are considerably greater than the effects of the mass-deficiency lying north.

(*b*) HURILAONG.—The southerly deflection of 13″ at Hurilaong has attracted attention for many years. Hurilaong is situated in the Hazaribagh range south of the Gangetic plains. The deflection can not be attributed to the attraction of the range, because this value of the deflection is the residual obtained by Crosthwait after he had corrected the original observation for the effect of the range.

The average density of the rocks of the Hazaribagh range is believed to be between 2·65 and 2·70*.

If we decide to utilise the deflection at Hurilaong as a measure of the mass-deficiency in the Gangetic trough, we can estimate the amount of that deficiency by drawing over the Gangetic trough two semi-circles round Hurilaong as a centre, one with a radius of 24 miles, which is the distance of Hurilaong from the southern edge of the alluvium, and the other with a radius of 205 miles, which is the distance of Hurilaong from the northern edge of the alluvium. Then by Hayford's method we have over the alluvium 6 half-rings of 8 compartments each = 48 compartments. For every 100 feet of mass-deficiency in the trough, there will be a corresponding topographical deflection of 0″·48, and if the isostatic deflection is 13″, (topographical deflection = 34″) it will require an average mass-deficiency in the trough of 7500 feet (equivalent to a depth 75000 feet, if the deficiency of density is taken as 10 per cent of normal rock). We thus find ourselves in a dilemma; we must either abandon the idea of ascribing the Hurilaong deflection to the effects of the trough, or we must be prepared to accept for the trough a depth larger than has been previously imagined.

(*c*) CHENDWAR.—Situated in the Hazaribagh range, but is slightly more distant from the southern edge of the Gangetic alluvium than Hurilaong is, (that is, 40 miles instead of 24). Its southerly deflection is 7″ (compared with 13″ at Hurilaong) and if this deflection is to be regarded as the effect of the Gangetic trough (compensated) it gives 60000 feet as the average depth of the trough, 180 miles wide.

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* From values supplied by the Director, Geological Survey of India.

III. EASTERN-CENTRAL SECTION, (table VII).

(*a*) BIROND.—Northerly deflection 24″. The width of the alluvial plains in this section is 200 miles. There will be 10 semi-annuli and 80 compartments. If 24″ is the isostatic deflection, the topographical deflection at the distances involved will be 42″.

The average mass-deficiency throughout the compartments will be $\frac{42}{80}$ × 10000 feet = 5000 feet, and the average depth of the trough, 200 miles wide, density of deposits = 2·4, will be 50000 feet.

(*b*)	NIMKAR.—	Deflection	6″ south, distance from hills	80	miles
	SORA.—	„	11″ south, „	115	„
	KANAKHERA.—	„	10″ south, „	160	„

It is very difficult to deduce values for the depth of the trough from these three deflections. The increased deflections at the two southern stations lead to the idea that on this section the trough immediately south of the Himalayas becomes shallower from north to south but under the mid-alluvium it again becomes deeper.

(*c*) GURWANI.—Deflection 6″ south.

Situated 70 miles from southern edge of alluvium, 250 miles from northern edge. If the Gangetic trough, compensated, can produce an isostatic deflection of 6″ at Gurwani, the topographical deflection due to the uncompensated trough must be about 50″.

The average deficiency of rock throughout the 4 half-annuli, which represent the trough as viewed from Gurwani, will be $\frac{50}{32}$ × 10000 = 15000 feet. The *average* depth of the trough, 180 miles wide, density 2·4, will thus be 150000 feet, if the deflection at Gurwani is assumed to be due to its effects.

IV. CENTRAL SECTION, (table VIII).

When we come to the Central Section we meet with the difficulty that the Himalayan range and trough are trending to the north-west, and that meridional deflections are no longer complete measures of attractive effects.

The meridional deflection at Dehra Dun is 13″ north, but there is at this place a deflection also in the prime vertical of 9″ east*. The resultant deflection at Dehra Dun is consequently 15″·5 towards the N.N.E.

(*a*) MUSSOOREE.—Meridional deflection 13″ north.

Situated in the mountains 3 miles from the foot of the Himalayas. It is difficult to decide how to treat this station as it is separated from the Gangetic plains by 20 miles of Siwalik foot-hills. We will assume † the depth of the tertiary deposits in this Siwalik zone to be 10000 feet, density 2·4, and this assumption will account for 3″ isostatic deflection at Mussooree. There remains a deflection of 10″ to be ascribed to the trough : at the distances of the several annuli from Mussooree 10″ isostatic deflection denotes a topographical deflection of 25″. The width of the Gangetic alluvium outside the Siwalik belt is on this section 90 miles : it may be represented from Mussooree by the Hayford rings (half-annuli) 10 to 13. A trough 76 miles wide, of an average depth of 80000 feet, will produce a topographical deflection of 25″ at Mussooree.

If we regard the Siwalik belt as an undisturbed part of the Gangetic trough we obtain for the average depth of the whole trough 25000 feet, and width 100 miles.

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* Professional paper No. 13 : *Investigations of Isostasy* by Crosthwait, page 14.

† Memoirs, Geological Survey of India, Vol. XLII, part 2, *Structure of the Himalayas* by R.D. Oldham, page 107.

(*b*) DEHRA DUN.—Meridional deflection 13″ north. Regarding the Siwalik belt as part of the trough, we represent the latter as viewed from Dehra Dun by rings (half-annuli) 17 to 10. An isostatic deflection of 13″ denotes at the distances of the rings a topographical deflection of 22″: and to produce this latter value an average depth of 35000 feet for the whole trough, 100 miles, is required.

(*c*) KALIANA } Deflections 2″ south. These stations are situated near the middle of the BANSGOPAL } alluvial plains. The smallness of the deflections at these central points of the trough lead to the conclusion that on this section the depth of the trough does not decrease regularly from north to south.

(*d*) NOH.— Deflection 6″ south } These two stations are similarly situated near the southern AGRA.—Deflection 0″. } edge of the Gangetic plains. The difference in their deflections is a reminder that the form of the trough is complex and varied, and that the geometrical forms used in computations can never be more than inadequate approximations.

(*e*) AGRA.—Deflection 0″. USIRA.—Deflection 1″ north. KESRI.—Deflection 9″ south. } These deflections lead one to suspect the existence of a zone of attenuated rock between Usira and Kesri: the zone is traversed by the river Chambal.

V. WESTERN SECTION, (table IX).

(*a*) RANJITGARH.—Deflection 7″ south.

Situated on the alluvium 40 miles south of the mountains. This deflection furnishes evidence that the hidden trough is strongly developed on this section, but being centrally placed with regard to the trough it cannot easily be utilised to obtain a measure of the depth.

(*b*) AMRITSAR.—Deflection 12″ south.

Situated over the trough and on the alluvium 85 miles south of the mountains. If we assume that the effect of the trough for 20 miles north of Amritsar is balanced by the effects of the trough and alluvium south of Amritsar, we arrive at the result that a trough 65 miles wide produces a deflection of 12″. There will be 4 rings and 32 compartments: an isostatic deflection of 12″ implies at the distances involved a topographical deflection of 24″. And to produce a topographical deflection of 24″, an *average* depth of 75000 feet (density 2·4) is required for the trough, 65 miles wide.

VI. NORTH-WESTERN SECTION, (table X).

No deflections have been observed on this section.

Appendix No. 2.

NOTES ON THE FORM OF THE GANGETIC TROUGH.

The western termination of the Gangetic trough.

The Gangetic trough has been traced geodetically from longitude 74° to longitude 89°. In longitude 74° it is still strongly marked in front of the Himalayas between Pathankot and Mian Mir. On the west of the Punjab a considerable trough has been discovered skirting the Sulaiman mountains, and probably extending to the sea. The existence of the Sulaiman trough has been placed beyond doubt by the pendulum observations at Sibi, Jacobabad, Dera Ghazi Khan and Multan*, by the longitude observations at Multan†, and by several observed azimuths.

Whether the Gangetic and Sulaiman troughs are connected, either in the angle north of the Salt range or by a trough south of the Salt range, are questions upon which there is no geodetic evidence at present available‡.

The eastern termination of the Gangetic trough.

In longitude 89° the Gangetic trough is still strongly marked in front of the Himalayas at Siliguri and Jalpaiguri. Whether it continues eastwards up the valley of Assam, or whether it bends southwards towards Calcutta, or whether it bifurcates into both directions are questions that await future observations.

At Jalpaiguri the plumb-line is deflected no less than 13″ towards the east, and this shows that an important subterranean change is taking place in the vicinity. The rivers Ganges and Brahmaputra obtain an exit to the sea through a gap in the mountains, 150 miles wide, the Assam plateau being on the east of the gap, the Rajmahal hills on the west. The Himalaya mountains throughout their length of 150 miles, where they face this Ganges-Brahmaputra gap, have no Siwalik hills at their foot. This is the only place in which the Himalayas are not bordered by Siwalik hills.

The Siwalik hills form part of the Gangetic trough, in that the materials of which they are composed were originally deposits in the trough. It is a reasonable hypothesis that the elevation of the Siwalik hills and the opening of the Gangetic trough were due to one and the same force.

The Siwalik foot hills reappear further east in the Assam valley skirting the Himalayas; there is however no geodetic evidence yet available from the Assam valley.

With regard to the 150-mile gap in the mountains, the observed azimuths (Ataro Banki 22″ east, Alangjani 20″ east, Halkachar 20″ east, Aloakandi 10″ east, Daulatpur 8″ west, Lakhinagar 15″ west, Gangapur 3″ west) show deflections of the plumb-line that cannot be ascribed to the topography only§: they justify the belief that there must be an extraordinary amount of light rock-material underlying the alluvium of the gap on its eastern side. On the western side of the gap, the azimuth observations also give indications that there exists some hidden cause, from which the plumb-lines are deflected away, (Madhpur 11″ west, Kalsibhanga 8″ west). If the azimuth observations are to be trusted the deflection of the plumb-line must be undergoing a change of 16″ within the 30 miles of flat alluvial plains west of Calcutta‖. Azimuth observations can only be accepted as preliminary determinations; they require to be confirmed by longitude results.

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* Professional paper No. 15: *Pendulum Operations* by Couchman, page 4.

† Professional paper No. 13: *Investigations of Isostasy* by Crosthwait, page 120.

‡ Map of *Mountains of India* at end of this paper.

§ Professional paper No. 16: *The Earth's axes and Triangulation* by De Graaff Hunter, page 202.

‖ Professional paper No. 16, pages 201 and 202.

The Vindhyan trough.—Couchman has put forward the suggestion that the Vindhyan plateau is bounded on the north by a trough, which is hidden under the southern portion of the Gangetic alluvium. He refers to the possible "existence of a continuous line of deficient density "running more or less along the northern edge of the Central Indian plateau"*.

An immense trough, like that of the Ganges, cannot escape the attention of geodesists, but minor troughs may be bordering the lesser ranges of mountains, and such troughs, however deep, may be difficult to trace from geodetic observations if the density of their rock-contents is differing but slightly from the density of their rock-walls.

The form of the Gangetic trough is varied and complex. On no two sections can it be said to be identical: its varieties of form may however be broadly classified under two heads; (i) the portions of the trough where it is bordered by mountains or highlands on both sides; and (ii) the portions of the trough, where it is bordered by mountains on one side only, and where its southern edge is hidden under the alluvium. Throughout its whole length it is bounded on the north by the Himalayan mountains: it is bounded also on the south by mountains for many hundreds of miles, but on the east in Bengal and on the west in the Punjab there are no mountains to the south, and the southern border of the trough is hidden under alluvial plains. The form of the trough seems to vary with the character of its southern boundary: where the Himalaya mountains are opposed by the southern mountains of Rajmahal, Hazaribagh, Kaimur, Aravalli, positive values of gravity anomalies are rarely found along the southern border and when observed they are small (Muttra $+0 \cdot 004$, Agra $+0 \cdot 006$, Allahabad $-0 \cdot 002$); where the Himalaya mountains face unbroken plains of alluvium, large positive values occur on the alluvium (Kisnapur $+0 \cdot 028$, Mian Mir $+0 \cdot 029$, Jacobabad $+0 \cdot 027$).

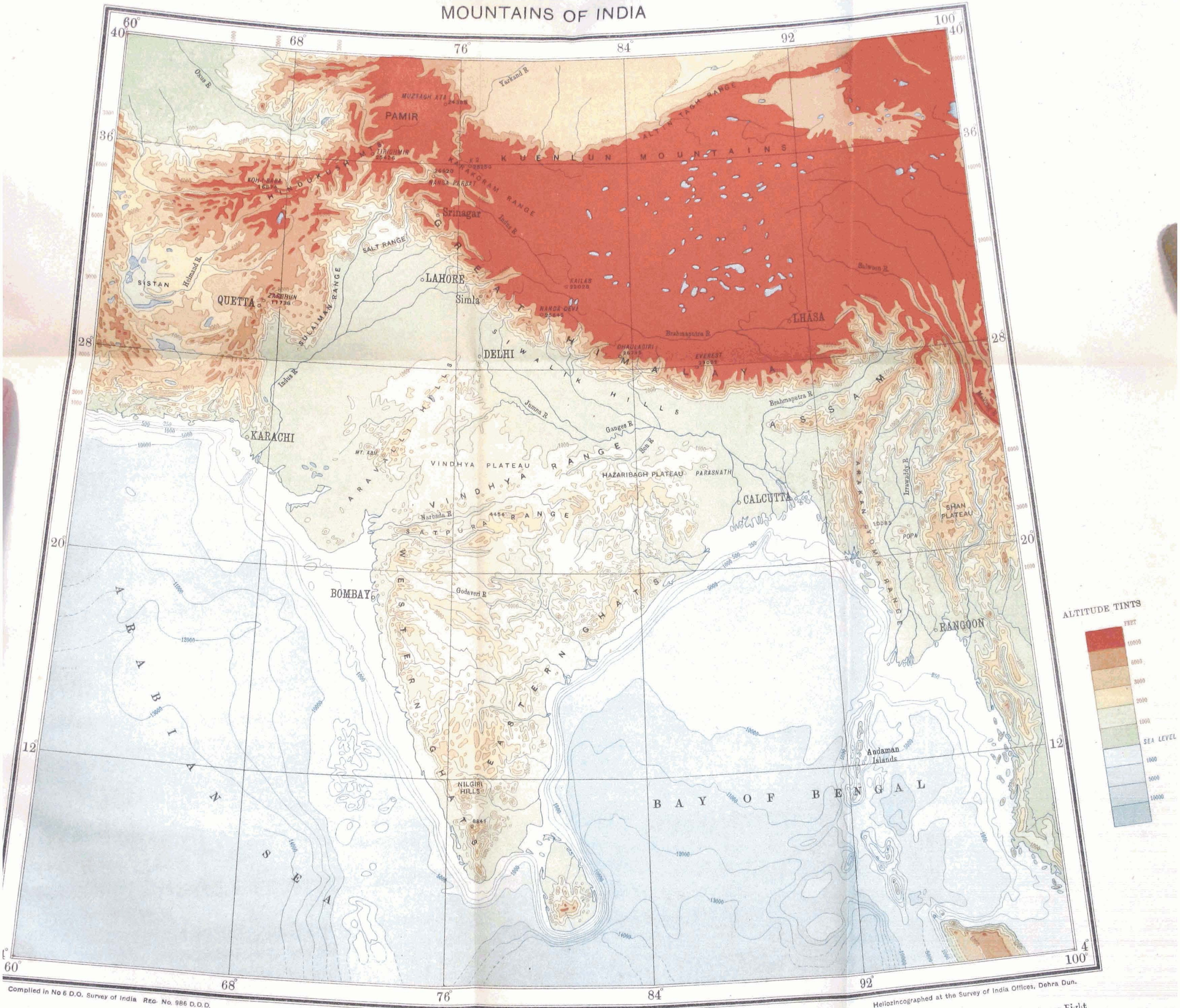
The large positive anomalies at Kisnapur, Mian Mir and Jacobabad occur about 100 miles from the Himalayas: on the Central and Eastern-Central sections, (*vide* tables VIII and VII), no positive values whatever are observed within 100 miles of the hills.

This evidence furnishes support to Couchman's suggestion that the Gangetic alluvium may be hiding two parallel troughs, a major trough on the north and a minor trough on the south skirting the Vindhyan peninsula.

Nowhere is the Gangetic trough more deeply developed than on the Eastern section (table VI, Gorakhpur $-0 \cdot 081$ at 60 miles from the hills, Majhauli Raj $-0 \cdot 068$ at 70 miles, Muzaffarpur $-0 \cdot 053$ at 80 miles), and such a trough if isostatically compensated, would be tending to produce positive values of gravity anomaly near its southern border. But along the southern border we have Moghal Sarai $-0 \cdot 016$, Sasaram $-0 \cdot 002$, Gaya $-0 \cdot 008$, Monghyr $-0 \cdot 036$, and these results lead me to think that if any general tendency towards positive values similar to that on the east at Kisnapur and to that on the west at Mian Mir and Jacobabad does exist, it is masked along the foot of the Vindhyan plateau by a local zone of crustal attenuation. The negative value of $-0 \cdot 036$ at Monghyr at the foot of the plateau in Bengal has its parallel at Khurja near Delhi, where a negative value of $-0 \cdot 030$ has been observed on the southern side of the Gangetic trough. Khurja is a station of the Central section (table VIII) and its negative value of $-0 \cdot 030$ at 120 miles from the mountains is greater than the value $-0 \cdot 018$ at Kaliana or than $-0 \cdot 006$ at Gesupur. Kaliana and Gesupur are stations on the trough north of Khurja and nearer to the hills. The inference is that the Gangetic trough becomes shallower from Roorkee to Kaliana and Gesupur, and thence becomes deeper again at Khurja.

* Professional paper No. 15: *Pendulum Operations* by Couchman, page 187.

MOUNTAINS OF INDIA



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