SURVEY OF INDIA

PROFESSIONAL PAPER No. 27.

# GRAVITY ANOMALIES
# AND
# THE STRUCTURE OF THE EARTH'S CRUST

BY

MAJOR E. A. GLENNIE, D.S.O., R.E.

---

PUBLISHED BY ORDER OF
BRIGADIER R. H. THOMAS, D.S.O.,
SURVEYOR GENERAL OF INDIA

PRINTED AT THE GEODETIC BRANCH OFFICE,
SURVEY OF INDIA, DEHRA DUN, 1932.

*Price one rupee and eight annas or two shillings and six pence.*

# CONTENTS

Page

Preface ... ... ... ... v

Para

1. Foreword ... ... ... ... 1
2. The existence of Burrard's Hidden Range ... 1
3. Extension of the Hidden Range ... ... 2
4. Features associated with the Hidden Range ... 2
5. The form of the Hidden Range and associated features ... ... ... 3
6. Elimination of the effect of the Hidden Range 4
7. Elimination of the topographical effects ... 4
8. Standard gravity formulæ ... ... 7
9. Explanation of the topographical correction ... 8
10. Comparison of $g-\gamma_F$ and Geology ... ... 9
11. Gravity anomalies and geology in Middle Asia .. 10
12. Gravity anomalies and rock density ... 10
13. A suggested explanation ... ... 11
14. Densities of the Crustal layers ... ... 11
15. Depth of the Hidden Range ... ... 12
16. Numerical test of $g-\gamma_F$ ... ... 12
17. The Tethys and the evolution of the Himālayas... 20
18. Further consideration of the $g-\gamma_F$ anomaly ... 21
19. Gravity anomalies at sea ... ... 23
20. Depth of the tachylytic layer under the ocean ... 25
21. The Crustal warp hypothesis and isostasy ... 26
22. Conclusion ... ... ... 27

## Charts and Figures

Facing page

Fig. 1. Geoidal Rise and Gravity Anomaly on section AA due to Burrard's Hidden Range ... ... 4
Fig. 2. Burrard's Hidden Range on section AA ... 4
Fig. 3. Crustal section on AA ... ... ... 18
Fig. 4. Crustal section on BB ... ... ... 18

Chart I. Geological sketch map of India ... 10
Chart II. Gravity anomalies. Contours $g-\gamma_F$. Survey of India Spheroid II ... ... 10
Chart III. Gravity anomalies (Hayford). Contours showing $g-\gamma_C$ from data up to Sept. 1931 (Helmert's formula of 1901). ... 10
Chart IV. The Crests of the Hidden Range ... 20
Chart V. The Geoid ... ... ...at the end
Chart VI. Compensated Geoid ... ... „
Chart VII. The Isostatic Geoid ... ... „

# PREFACE

Gravity observations with modern apparatus commenced in India in 1904 and have continued ever since, except for an eight years' break owing to the War. A shortened programme due to improved apparatus and the use of wireless time signals has led to a greatly increased rate of out-turn in recent years.

By the summer of 1929 sufficient gravity data had accumulated in India to make detailed investigation of the results worth while. This work is the outcome of investigations made during the recess seasons from 1929 to 1931. The investigation was at first very baffling, and seemed unlikely to be useful. It would not have reached the present stage but for the encouragement given by Dr. J. de Graaff Hunter, sc. d., to whom my grateful acknowledgments are due. I am also much indebted to Capt. G. Bomford, r.e., for careful criticism of the results at various stages, and to B. Mukhtar Ahmad for much laborious and monotonous computation.

The views expressed in this paper are mine and do not necessarily represent the accepted opinion of the Survey of India.

# GRAVITY ANOMALIES AND THE STRUCTURE OF THE EARTH'S CRUST

**1. Foreword.**—During the past three years* an attempt has been made to derive a gravity anomaly which would show a satisfactory correlation with superficial geological conditions, a correlation which the usual Hayford gravity anomalies had almost entirely failed to show.

As the results appeared promising, a theoretical explanation has been sought. This is set down in the present paper. It is believed that the solution is at least plausible and gives results which are numerically of the right order.

The conclusions reached are completely opposed to the Pratt system of isostasy and only to a very limited extent favourable to isostasy on the Airy system. Indeed the general appearance of isostatic conditions, which has so captivated the scientific world, appears to be mainly due to a somewhat fortuitous concomitance of circumstances.

It is desirable to emphasize this point strongly since India is the birthplace of the theory of isostasy and it is widely believed that the theory of isostasy is supported by gravity and deflection results in India. This is not the case†.

**2. The existence of Burrard's Hidden Range.**—Sir Sidney Burrard, from a consideration of deflections in the Gangetic Plain postulated the existence of a Hidden Range to the south crossing India‡. Subsequent work has abundantly confirmed the existence of this Hidden Range.

An examination of the various geoids brings this out well. *The Geoid* based on uncorrected deflections shows a broad area with an average elevation of over 25 ft., running roughly ENE. across the whole breadth of peninsular India through Jubbulpore. The average breadth of this band is over 350 miles so that covering an area of about 400,000 square miles the geoid is raised in excess of 25 ft.

The *Compensated Geoid* derived from deflections corrected for topography and its compensation according to the theory of isostasy as developed by Hayford shows precisely the same feature, only slightly reduced. Its average height over the same area is about 20 ft. Corrections based on isostasy, therefore, have not removed this anomalous rise in *the geoid*. Nor can the Hidden Range be ascribed to a merely partial defect of isostasy. If this were so the *Compensated Geoid* would show some correlation with the *Isostatic Geoid*, which is the geoid derived according to isostatic theory from

---

* Survey of India, Geodetic Reports, Vols. V & VI.

† Dr. J. de Graaff Hunter, Nature Vol. 127, p. 593-594.

‡ Burrard. The Attraction of the Himālaya Mountains upon the Plumb-line in India, 1901.

a purely theoretical consideration of topographical features. There is no correlation.

Dr. Bowie has suggested that isostasy is so well proved that the theoretical calculation of deflections from topographical data will give results which are approximately correct, and can be used in the absence of observational data. Such a method would lead to profound errors in India.

In the isostatic computations a uniform crust density of 2·67 is assumed. If the whole of the raised area of the geoid were an area of unusually dense rocks such as the Deccan trap reaching down to a great depth (about 20,000 ft.) the anomaly could be explained. This is not the case. The greatest extent and greatest thickness of the Deccan trap lies further south where the geoid is lower. The Hidden Range traverses an area of diverse geological formations with an average density not greatly different from 2·67. The chart of Hayford gravity anomalies shows a very close correlation with the compensated geoid. All over the raised part of the geoid, gravity anomalies tend to be high. It is reasonable to suppose that minor irregularities in the anomaly contours are due to local causes, but the general run of the anomaly contours forces one to the conclusion that the Hidden Range has a real existence, and that it is a very deep-seated feature. It has a dominating influence on geodetic conditions in India. If the influence of the Hidden Range can be removed the remaining anomalies should show some correlation with topography and geology*.

**3. Extension of the Hidden Range.**—It seems most unlikely that a wide-spread structure such as the Hidden Range, should end abruptly. Beyond the east coast of India it evidently extends for some distance under the sea. To the west the + 20 contour bending round just east of Sukkur gives the impression that the range is coming to an end, but the form of the geoid on the north-west near the Hidden Range is based on rather scanty data. Recent deflection observations near Sukkur and in Baluchistān show that some modification of the geoid contours is required here and that in all probability the Hidden Range extends westwards under Baluchistān.

**4. Features associated with the Hidden Range.**—There is a deep depression of the geoid south of the Hidden Range. Low gravity anomalies prevail over the same area. As in the case of the Hidden Range this depression appears to be due to a deep-seated cause.

In the extreme south there is a disparity between gravity and geoidal anomalies. Data are somewhat deficient but for the time being it is assumed that the rise of the geoid in the extreme south of India is due to excess mass under the sea and under Ceylon. Vening Meinesz's sea observations in the Indian Ocean lend support to this assumption. (See also para 16 *h*).

---

* For further consideration of the Geoids reference should be made to S. of I. Geodetic Report, Vol. V.

To the north of the Range another depression, less well-defined, runs parallel to it. Most of this area is overlaid by recent alluvium, so the arguments employed to establish the Hidden Range as a deep-seated feature cannot be applied here.

It is evident that the depression of the geoid over the Gangetic Alluvium could be adequately explained by a great depth of light sediments. Sir Sidney Burrard visualised a depth of about 50,000 ft. of alluvium over a great rift in the earth's crust*. This rift theory has not received general acceptance by geophysicists. Dr. Harold Jeffreys characterises such a depth as 50,000 ft. as "very improbable "†.

It seems more likely that we have under the Gangetic Plain the commencement of the great geosyncline which formed the basin of the Tethys. The assumption is made that this is a deep-seated warping of the Earth's crust and that the Hidden Range is intimately associated with it.

**5. The form of the Hidden Range and associated features.**—The general run of the geoidal contours indicates a marked uniformity in outline and direction of the Hidden Range. Further it is a matter of common experience that superficial irregularities in geological strata tend to become more and more smoothed out as one goes deeper down into the crust‡. The argument therefore that the Hidden Range is a deep-seated feature is also an argument in favour of its uniformity. In order to obtain a cross section of the Hidden Range and its flanking troughs India was divided into narrow strips parallel to the crest of the Hidden Range and the height of the compensated geoid, and the Hayford gravity anomalies were averaged along each strip.

Since each strip ( except the Gangetic Plain ) ran over a diversity of geological and topographical features, superficial effects are considered to have balanced out, and the curve of the effects of the Hidden Range and the trough to the south is considered to be well established from Delhi to south of Madras.

Further south where the disparity between the geoidal and gravity anomalies occurs, the trough is assumed to rise uniformly to a zero line south of Ceylon.

North of Delhi a trough roughly symmetrical with that South of the Hidden Range and equally deep is assumed. This northern trough underlies the former basin of the Tethys. The deepest part underlies the basins of the Indus and Brahmaputra Rivers between the Kailās and Himālaya ranges.

The geoidal rise and gravity anomaly due to the Hidden Range are shown on Fig. 1, and the crest and trough lines etc., are shown on Chart I. It is assumed that the curve of the Himālaya mountains portrays roughly the trend of the underlying trough, and that the crest line of the Hidden Range conforms to this. In Peninsular

---

* S. of I. Professional Papers No 12 of 1912, and No 17 of 1918.

† H. Jeffreys. The Earth, 2nd Edition, 1929, p. 201.

‡ H. G. Busk. Earth flexures, pp. 10 and 12.

India the straightness of the crest line is scarcely affected by this assumption.

**6. Elimination of the effect of the Hidden Range.**— In the summer of 1929 a correlation was found between the height of the compensated geoid ($H$ feet) and Hayford gravity anomalies ($g-\gamma_C$)*. There was a simple linear relation, so that removing it a new anomaly ($g-\gamma_D$) was obtained from the simple formula,

$$g-\gamma_D = g-\gamma_C - KH$$

where $K$ is a constant depending on the spheroid of reference, and $H$ the height of the geoid at the gravity station.

The immediate purpose for deriving this anomaly was to obtain the equatorial value of gravity for the selected spheroid of reference. For this purpose it was satisfactory since the $KH$ correction not only eliminated the effect of deep-seated masses of abnormal density but also to some extent that due to more superficial masses. If the intention is to obtain an anomaly from which deep-seated effects only have been removed Fig. 1 and Chart I can be used to obtain the required correction to the Hayford anomalies.

In this way the anomaly $g-\gamma_E$ was obtained†, which is the gravity anomaly remaining after the effect of the Hidden Range and its associated troughs has been removed.

**7. Elimination of the topographical effects.**—The anomaly $g-\gamma_E$ is only a step towards an anomaly which would show the effects due to superficial geological features.

If isostasy is not perfect, that is, if topography is under or over compensated, $g-\gamma_E$ will contain both topographical and geological effects, the topographical effect being rather more strongly marked than in the $g-\gamma_D$ anomaly. In Geodetic Report, Vol. VI, the relation between $g-\gamma_D$ and the average height of the station was shown. The average height was taken from "The average height map of India" and represents roughly the average height of the country over an area of twenty miles radius round the gravity station.

In the following table the relation between $g-\gamma_E$ and the average height is shown.

TABLE I

| Group | Number of Stations | Range of average height | Mean average height | $g-\gamma_E$ | |
|---|---|---|---|---|---|
| | | | | S. of I. Spheroid II | International Spheroid |
| | | | | $cm/sec^2$ | $cm/sec^2$ |
| I | 9 | 2,000 ft. & over | 2222 feet | + ·0123 | + ·0128 |
| II | 23 | 1,500 ft. to 1,999 ft. | 1657 feet | + ·0053 | + ·0011 |
| III | 27 | 1,000 ft. to 1,499 ft. | 1259 feet | + ·0014 | − ·0041 |
| IV | 17 | under 1,000 ft. | 709 feet | − ·0026 | − ·0045 |

---

* S. of I. Geodetic Report, Vol. V, Chapter IV.

† S. of I. Geodetic Report, Vol. VI, 1931.

Fig. 1

Geoidal Rise and Gravity Anomaly on Section AA due to Burrard's Hidden Range

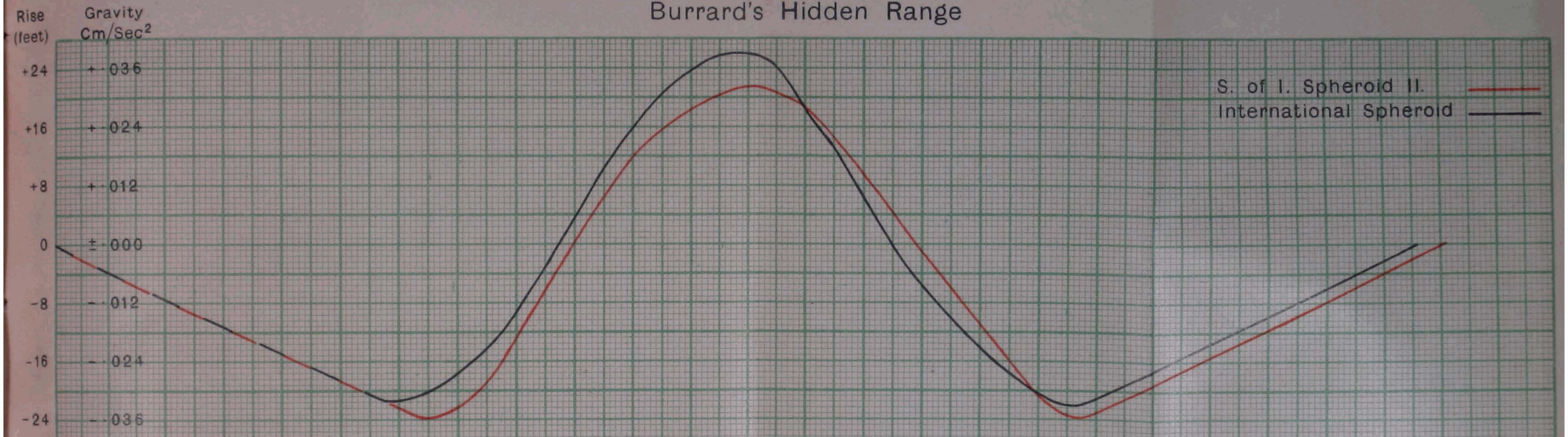
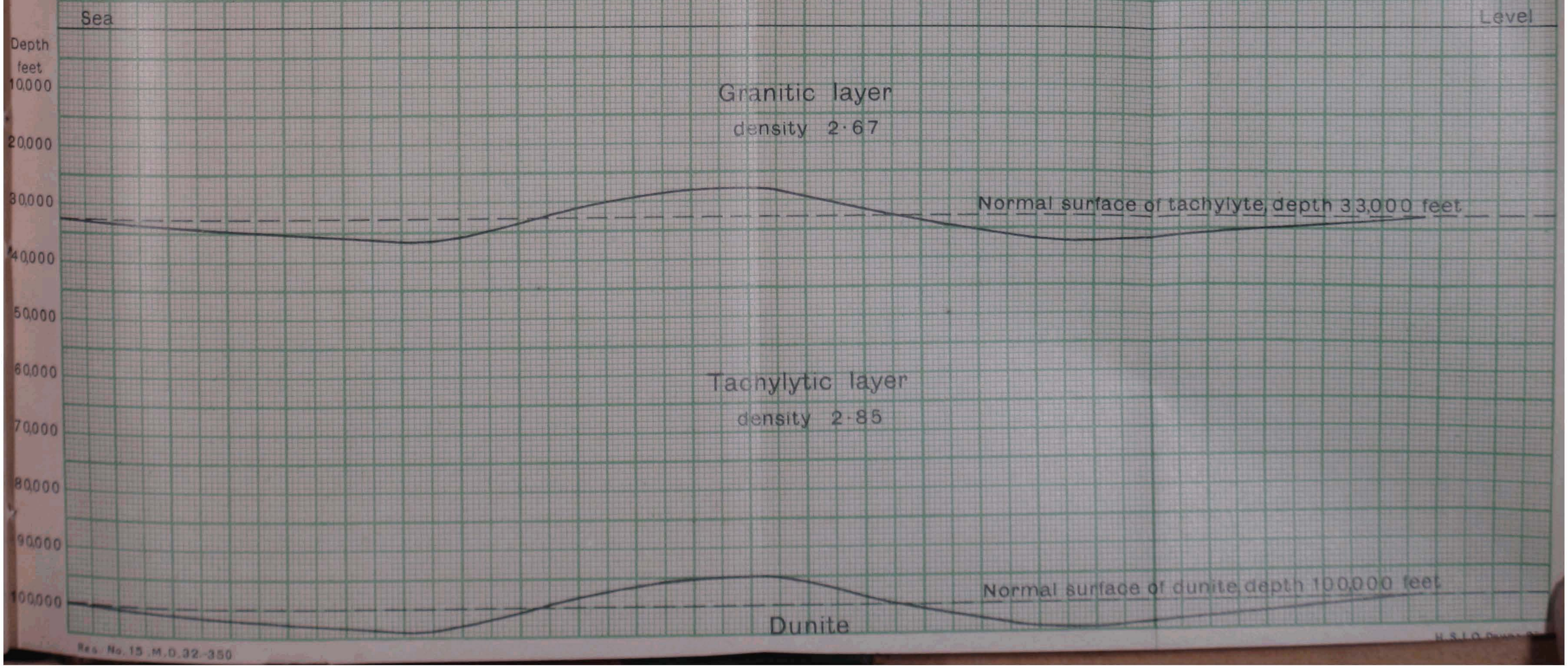


Fig. 2

Burrard's Hidden Range on Section AA

Horizontal scale 1 inch=250 miles

Vertical scale about 50 times horizontal scale



Reg. No. 15 M.D. 32-350

H. S. I. O. [illegible]

The investigation is restricted to 76 stations situated in or near the Central-Indian Highlands for the following reasons :—

( *i* ) The form of the Hidden Range under this area is well established.

( *ii* ) There is a good variety of geological features.

( *iii* ) The region is geologically old and stable, so that any isostatic adjustment should be complete.

( *iv* ) In the low lying coastal regions and the alluvial plains of Northern India the small topographical effect is likely to be entirely swamped by geological effects, which will spoil the result unless they balance out.

The table shows a fairly definite relation between $g-\gamma_E$ and the average height. It is best for the S. of I. spheroid II and better for $g-\gamma_E$ than for $g-\gamma_D$. This is as it should be, since the S. of I. spheroid II gives the best fit to the *compensated geoid,* and the process of deriving $g-\gamma_D$ directly from the *compensated geoid* has eliminated some of the topographical effect.

The figures in Table I give the following relation :

S. of I. Spheroid II ... $g-\gamma_{E_a}=g-\gamma_E-0{\cdot}000\ 0084a+0{\cdot}0086$

International Spheroid $g-\gamma_{E_a}=g-\gamma_E-0{\cdot}000\ 0104a+0{\cdot}0148$

where $a$ is the average height in feet.

In these expressions the second term is the height or topographical correction, and the constant third term represents a correction to be applied to the equatorial value of gravity employed in the standard gravity formula. These corrections should be independent of the spheroid of reference. The mean of the two values will therefore be adopted for both spheroids.

Hence in each case :—

$$g-\gamma_{E_a}=g-\gamma_E-0{\cdot}000\ 0094a+0{\cdot}012.$$

This agrees closely with the results obtained for $g-\gamma_D$* which were :—

S. of I. Spheroid II. ... $g-\gamma_{D_a}=g-\gamma_D-0{\cdot}000\ 0094a+0{\cdot}008$

International Spheroid $g-\gamma_{D_a}=g-\gamma_D-0{\cdot}000\ 0087a+0{\cdot}008$

The greatest change is in the constant term; error in this term does not materially affect the results.

It has been suggested † that the relation between $g-\gamma_C$ ($g-\gamma_D$ etc.) and height is due to the fact that the stations at high elevations are mountain stations above the general surrounding level, where compensation would be likely to be less complete than at the lower stations, and also that the lower stations are mainly on alluvium where gravity would tend to be in defect.

---

* S. of I. Geodetic Report, Vol. VI.

† de Graaff Hunter. The Hypothesis of Isostasy ( Geophysical Meeting of the Royal Astronomical Society, October 1931 ).

This is not the case; such stations have almost entirely been excluded, and those that do occur, do not support the objection as the following details will show.

Referring to Table I on page 4, out of the nine stations in Group I, one only is a mountain station markedly above the general level of the surrounding country. This station is No. 220 Pachmarhi. The $g-\gamma_E$ anomaly is strongly negative viz. $-{\cdot}036$ cm/sec$^2$ (S. of I. II), $-{\cdot}044$ cm/sec$^2$ (International). Pachmarhi stands over a deep trough of Gondwāna sediments. Groups II and III are all stations in the table-land and tend to be at a lower elevation than the surrounding country.

In Group IV out of the seventeen stations, seven only are on alluvium. Values of $g-\gamma_E$ for these stations are as follows:—

| No. | Name | $g-\gamma_E$ | |
|---|---|---|---|
| | | S. of I. II | International |
| | | *cm/sec²* | *cm/sec²* |
| 83 | Japla | + ·006 | + ·008 |
| 86 | Gaya | + ·012 | + 020 |
| 89 | Sasarām | + ·019 | + ·024 |
| 101 | Gwalior | – ·007 | – ·009 |
| 114 | Deesa | + ·033 | + ·023 |
| 118 | Pāli Mārwār | + 008 | + ·004 |
| 199 | Renigunta | – ·029 | – ·026 |
| | Mean | + ·0060 | + ·0063 |

The negative value of Group IV is therefore not due to the effect of alluvium.

Data in extra peninsular areas must now be examined to see whether it is justifiable to extrapolate the results obtained from Peninsular India.

Outside the Peninsula apart from a small section in Kashmīr, little is known about the form of the geoid. Use must, therefore, be made of uncorrected Hayford anomalies when searching for a correlation with height.

(*a*) Outer Himālayas (including Kashmīr).

Twenty-four gravity stations yield a height correlation factor of $11{\cdot}7 \times 10^{-6}$.

Application of a geoid correction to the seventeen stations in Kashmīr reduces the factor derived from these stations to $6{\cdot}5 \times 10^{-6}$.

The geoid correction applied gives the relation

$$g-\gamma_D = g-\gamma_C - KH$$

where $H$ is the height of the compensated geoid in feet
and $K = 0{\cdot}0015$ *.

It has already been pointed out that some of the topographical effect has been eliminated in the process of obtaining $g-\gamma_D$. The height correlation factor obtained from $g-\gamma_D$, therefore, is likely to be too low.

(*b*) Middle Asia.

Gravity data over the plains east of the Caspian Sea, in the Pāmirs and in Ferghana have been examined by P. Savitsky †. He finds that Hayford gravity anomalies at stations in the plains and in the mountains require correction if correlation with geological formations is to be found.

The corrections are :—

Stations in plains ... 0·005 cm/sec$^2$
Stations in mountains ... 0·113 cm/sec$^2$.

Stations on the high plateaux are further stated to give characteristically positive results.

Obviously there is here evidence of a correlation with height. No details of the heights of the stations are given, but applying a height factor of $9{\cdot}4 \times 10^{-6}$ the mountain correction of 0·113 cm/sec$^2$ implies an average height for the mountain stations of 12,000 ft. This is a very likely figure in the Pāmirs.

(*c*) The Caucasus.

Heiskanen has examined the Hayford gravity anomalies of sixty-three stations in the Caucasus and finds correlation with height; the factor is about $7 \times 10^{-6}$ (p. e. $\pm\ 2 \times 10^{-6}$).

(*d*) The Harz Mountains.

Heiskanen found that the Hayford anomalies of eleven stations gave a height factor of about $8 \times 10^{-6}$ (p. e. $\pm\ 3 \times 10^{-6}$).

The very striking agreement between the height factors obtained above from widely separated areas is remarkable.

The investigation shows plainly that extrapolation of the height correlation factor found from data in Peninsular India is fully justified.

**8. Standard gravity formulæ.**—The standard gravity formulæ employed are ‡

S. of I. Spheroid II ... $\gamma_0 = 978{\cdot}025\ (1 + {\cdot}005\,234 \sin^2\phi - {\cdot}000\,006 \sin^2 2\phi)$
International Spheroid $\gamma_0 = 978\ 017\ (1 + {\cdot}005\,287 \sin^2\phi - {\cdot}000\,006 \sin^2 2\phi)$

---

* S. of I. Geodetic Report, Vol. VI p. 54.
† P. Savitsky. Gerland's Beitrage Zur Geophysics Vol. 30, No. 3. 1931, p. 277.
‡ S. of I. Geodetic Report, Vol. V.

Hence correcting for the constant terms found above the equatorial value of gravity becomes:—

S. of I. Spheroid II ... $G' = 978{\cdot}013$ cm/sec$^2$
International Spheroid ... $G' = 978{\cdot}005$ cm sec$^2$

These values are much lower than other recently obtained values. Indian gravity results are referred to Dehra Dūn where the adopted value of gravity is 979·063 cm/sec$^2$. This value is not well established, and it is likely that it should be increased to 979·070 cm/sec$^2$ *. If this were done $G'$ would also be increased by 0·007 cm/sec$^2$. There would, however, be no corresponding change in the gravity anomalies, so it is unnecessary to consider this point further.

**9. Explanation of the topographical correction.**—As stated above a topographical correction would be required if there were over or under compensation. The negative sign of the correction indicates under compensation. Now we have already applied a large correction on account of the Hidden Range which is assumed to be uncompensated. The topographical correction now to be applied is on the average less than half the Hidden Range correction, so it is reasonable to assume that it also is due to a complete lack of compensation over a given area round the station. An area with a radius of about 120,000 ft. would give a compensation anomaly of $-{\cdot}0094$ cm/sec$^2$ per 1,000 ft. of height above mean sea-level.

On this assumption a more accurate anomaly should be obtained as follows:—

$$g-\gamma_F = g-\gamma_E - E + {\cdot}012$$

Here $E$ is the sum of the compensation corrections applied when obtaining the Hayford anomaly, $g-\gamma_C$, up to a radius of 120,000 ft. round the station. In practice this is the sum of the compensation corrections for zones A to M plus one-third of zone N, the zones being those employed in S. of I. Professional Paper No. 15.

It will be seen therefore that the correlation of $g-\gamma_E$ with height is assumed to be due to a defect in the Hayford method of computing topographical effects. The Hayford hypothesis assumes compensation of local topography. This is believed to be erroneous and the height correction removes the error due to it approximately, but the method employed to obtain $g-\gamma_F$ is the more accurate means of correcting this error.

Beyond a radius of 120,000 ft. computation of topographical corrections by the Hayford method must be suitable if $g-\gamma_F$ is to be satisfactory.

In spite of this, the conclusions, to which examination of the $g-\gamma_F$ anomalies leads, imply non-compensation of topographical features at any distance. A reason for the success of the Hayford method beyond a radius of about 23 miles from the gravity station

---

* S. of I. Geodetic Report Vol. VI.

is suggested later. It must be admitted, however, that such a small radius is surprising, and appears unsatisfactory. An extension of this radius, however, has been found to lead to unsatisfactory results, since the distinction between sedimentary and igneous areas disappears.

Values of $g-\gamma_F$ on the International and S. of I. II are given in Table II, and contours of $g-\gamma_F$ on S. of I. spheroid II are shown in Chart II. It will be seen that the difference between $g-\gamma_F$ on the two spheroids is small.

In the numerical calculations which follow, values of $g-\gamma_F$ on the S. of I. spheroid II will be employed. Contours of $g-\gamma_C$ following Helmert's 1901 formula are shown on Chart III.

**10. Comparison of $g-\gamma_F$ and Geology.**—Chart I is a geological sketch map of India *. Comparing Charts II and III with this, and ignoring areas covered by recent alluvium and Deccan trap, the comparison is at once found to be favourable to the $g-\gamma_F$ anomaly, since this anomaly does show a fairly sharp distinction between the larger areas of igneous and sedimentary rocks. The anomalies are positive over igneous rocks and negative over sedimentary formations.

North-west of Madras in the Penner Basin are the wide spread Cuddapah sediments flanked by heavy igneous rocks on the east and south, and by lighter igneous rocks on the north and west. Large negative $g-\gamma_C$ anomalies are found all over these igneous areas, but they are well defined by $g-\gamma_F$. Quantitatively $g-\gamma_C$ anomalies are at fault. The Vindhyan and Cuddapah sediments are comparable in thickness and density. The Cuddapahs are probably slightly thicker, but this is counterbalanced by slightly greater density. Similar anomalies therefore should be found over these formations. The contrast between the $g-\gamma_C$ and $g-\gamma_F$ anomalies is well shown if the anomalies at Sawai Mādhopur (Vindhyan) and Cumbum (Cuddapah) are compared.

| | Helmert 1901<br>$g-\gamma_C$ | S. of I. II<br>$g-\gamma_F$ |
|---|---|---|
| | $cm/sec^2$ | $cm/sec^2$ |
| Sawai Mādhopur .. | $-\cdot021$ | $-\cdot025$ |
| Cumbum ... | $-\cdot077$ | $-\cdot034$ |

Confronted by $g-\gamma_C$ anomalies, one would say that the thickness of the Vindhyan sediments at Kotah are less than one-third that of the Cuddapah rocks at Cumbum. The $g-\gamma_F$ anomalies give a picture which must be near the truth.

Going now to Baluchistān, positive $g-\gamma_C$ anomalies are found in the sedimentary area at Quetta but $g-\gamma_F$ is negative. $g-\gamma_F$ becomes positive only as it nears the igneous region near the

---

* Adapted from Reid's Geology of the British Empire.

Koh-i-Taftān Volcano. $g-\gamma_C$ remains positive over much of the deep sediments of the Hāmūn-i-Mashkel area. There are of course areas where $g-\gamma_F$ is apparently at fault, but in nearly all cases comparison with $g-\gamma_C$ will show that the latter fails still more.

These cases will be examined in detail later and reasons of the apparent failure of $g-\gamma_F$ given. The examples just given are sufficient to show that in well-defined geological areas the $g-\gamma_F$ anomalies show a promising correlation with the formation.

**11. Gravity anomalies and geology in Middle Asia.**—Reference has already been made (see para 7) to P. Savitsky's investigation of gravity anomalies in Middle Asia. Here is to be found valuable confirmation of the fact that Hayford anomalies require correction to obtain satisfactory correlation with geology.

Having applied a correction, Savitsky arrives at the following conclusions:—

(1) Positive anomalies are associated with ancient geological formations and massive crystalline and intrusive rocks.

(2) Negative anomalies are associated with recent formations.

(3) The extensive negative anomalies of Ferghana are associated with a down-warping of the Sial into the denser underlying matter.

(4) The very large negative anomaly at Kalan Wamar must also be attributed to movements of the crust.

These results agree well with those obtained in India and suggest that in Middle Asia there is not the added complication of a "Hidden Range".

**12. Gravity anomalies and rock density.**—In gravity calculations the normal density of the crust is assumed to be 2·67. Samples of the igneous rocks flanking the west and north side of the Cuddapah formation give densities varying from 2·65 to 2·70. An average density of 2·67 is probably very closely correct. On the other hand the well-known Cuddapah slabs have a density of 2·72 and the slates at Cumbum are equally dense. It is unlikely that the average density of the Cuddapah sediments is less than normal and it may be greater.

The average density of the Vindhyan rocks is estimated to be 2·66, that is only just below normal. If the negative anomalies over this formation were due to this, an altogether improbable thickness of the formation would have to be assumed.

The density of the surface rocks therefore does not provide an adequate explanation for the negative anomalies found over large sedimentary formations. An explanation could be furnished if the normal crustal density were assumed to be greater than 2·67. But

Chart I

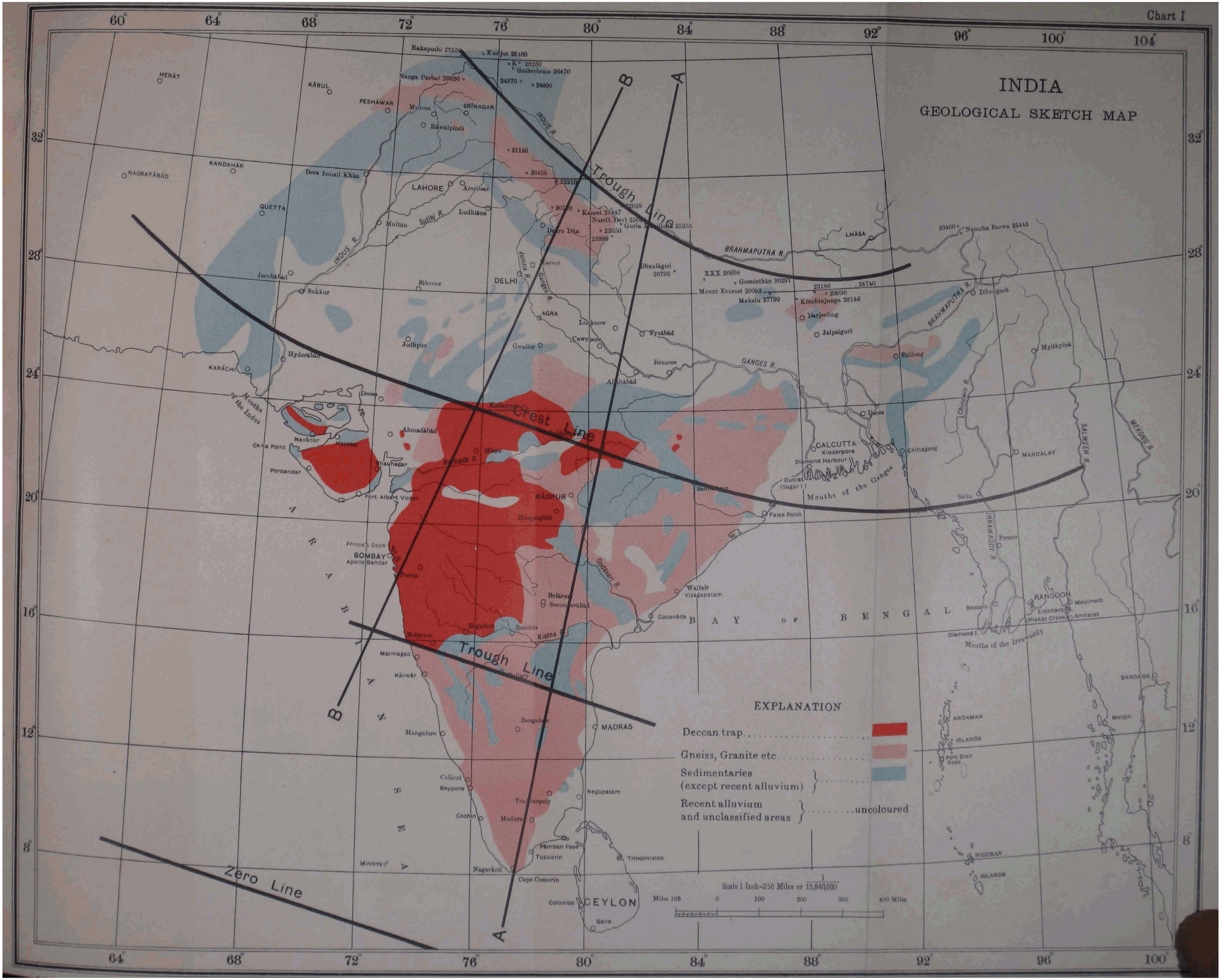
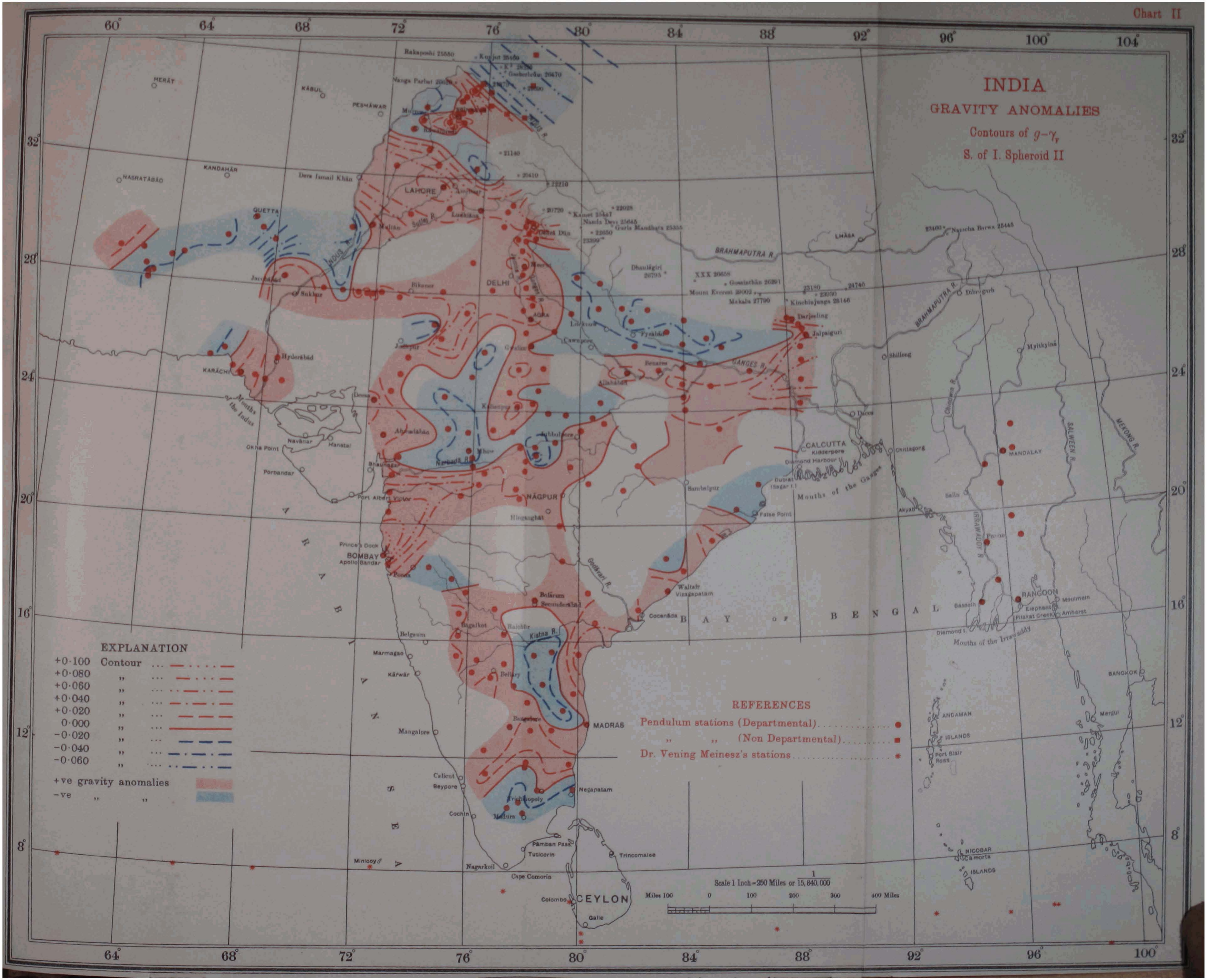

INDIA
GEOLOGICAL SKETCH MAP
EXPLANATION
Deccan trap
Gneiss, Granite etc
Sedimentaries (except recent alluvium)
Recent alluvium and unclassified areas ........uncoloured
Scale 1 Inch=250 Miles or 1/15,840,000
Miles 100 0 100 200 300 400 Miles
Trough Line
Crest Line
Trough Line
Zero Line
A
A
B
B
60°
64°
68°
72°
76°
80°
84°
88°
92°
96°
100°
104°
32°
28°
24°
20°
16°
12°
8°
HERĀT
KĀBUL
PESHĀWAR
Murree
SRĪNAGAR
Rāwalpindi
Rakaposhi 25550
Kunjut 25460
K² 28250
Gasherbrum 26470
Nanga Parbat 26620
24370
24600
INDUS R.
NASRATĀBĀD
KANDAHĀR
Dera Ismail Khān
LAHORE
Amritsar
QUETTA
Multān
Sutlej R.
Ludhiāna
21140
20410
22210
20720
Kamet 25447
Nandā Devī 25645
Gurla Māndhāta 25355
22028
22050
23399
Dehra Dūn
INDUS R.
Jacobābād
Sukkur
Bikaner
DELHI
Meerut
Jumna R.
Ganges R.
Dhaulāgiri 26795
XXX 26658
Gossinthān 26291
Mount Everest 29002
Makalu 27790
23180
23930
24740
Kinchinjunga 28146
Darjeeling
Jalpaiguri
BRAHMAPUTRA R.
LHĀSA
23460
Namcha Barwa 25445
Dibrugarh
BRAHMAPUTRA R.
AGRA
Lucknow
Fyzābād
Cawnpore
Gwalior
Jodhpur
Hyderābād
KARĀCHI
Benares
GANGES R.
Allahābād
Shillong
Myitkyina
Mouths of the Indus
Deesa
Kallanpur
Ahmadābād
Navānar
Hanstal
Okha Point
Porbandar
Bhaunagar
Mhow
Narbada R.
Jubbulpore
Dacca
CALCUTTA
Kidderpore
Diamond Harbour
Dublat (Sagar I.)
Mouths of the Ganges
Chittagong
Chindwin R.
MANDALAY
SALWEEN R.
MEKONG R.
Port Albert Victor
NĀGPUR
Sambalpur
False Point
Hinganghat
Salin
IRRAWADDY R.
Prome
Prince's Dock
BOMBAY
Apollo Bandar
Poona
Godāvari R.
Waltair
Vizagapatam
Bolārum
Secunderābād
Cocanāda
ARABIAN SEA
BAY OF BENGAL
Bassein
RANGOON
Elephant Pt.
Pilakat Creek
Moulmein
Amherst
Diamond I.
Mouths of the Irrawaddy
Belgaum
Bagalkot
Raichūr
Kistna R.
Marmagao
Kārwār
Bellary
BANGKOK
Bangalore
MADRAS
Mangalore
ANDAMAN ISLANDS
Port Blair
Ross
Mergui
Calicut
Beypore
Trichinopoly
Negapatam
Cochin
Madura
Pāmban Pass
Tuticorin
Trincomalee
Minicoy
Nagarkoil
Cape Comorin
Colombo
CEYLON
Galle
NICOBAR ISLANDS

Chart II



INDIA
GRAVITY ANOMALIES
Contours of $g-\gamma_r$
S. of I. Spheroid II

EXPLANATION

| | | |
|---|---|---|
| +0·100 | Contour | ... |
| +0·080 | " | ... |
| +0·060 | " | ... |
| +0·040 | " | ... |
| +0·020 | " | ... |
| 0·000 | " | ... |
| −0·020 | " | ... |
| −0·040 | " | ... |
| −0·060 | " | ... |
| +ve gravity anomalies | | 🟥 |
| −ve " " | | 🟦 |

REFERENCES

Pendulum stations (Departmental) .............. ●
" " (Non Departmental) .......... ■
Dr. Vening Meinesz's stations .................. *

Scale 1 Inch=250 Miles or $\frac{1}{15,840,000}$
Miles 100 0 100 200 300 400 Miles

# INDIA
## GRAVITY ANOMALIES
## (Hayford)

Contours showing $g-\gamma_c$
from data up to Sept. 1931
(Helmert's formula of 1901)

EXPLANATION

+0·080 Contour ...
+0·060 " ...
+0·040 " ...
+0·020 " ...
0·000 " ...
−0·020 " ...
−0·040 " ...
−0·060 " ...
−0·080 " ...
+ve gravity anomalies
−ve " "

REFERENCES

Pendulum stations (Departmental) ....... ●
Pendulum stations (Non Departmental) .. ■
Dr. Vening Meinesz's stations ........... ✱

Scale 1 Inch = 250 Miles or $\frac{1}{15,840,000}$

this is not permissible: seismological data show that the granitic layer with an average density not exceeding 2·67 extends to a depth of about 10 kilometres and below this comes a tachylytic layer, about 20 kilometres thick and below this again is a layer of dunite. *

When considering the theory of isostasy Jeffreys concluded that compensation must actually be concentrated near the bases of the granitic and intermediate layers †. A search is not now being made for compensation,—rather the opposite ; but the same conclusion may be adopted viz. that the cause of the anomalies will be found at the interfaces of the three crustal layers.

**13. A suggested explanation.**—The following process is therefore suggested to explain the gravity anomalies found over sedimentary formations. A warping or down-faulting of the earth's crust has occurred, the base of the tachylytic layer descending below the normal level of the top of the dunite layer and the bottom of the granitic layer descending to an equal depth below the normal surface of the tachylytic layer. The top of the granitic layer will be equally depressed below sea-level. A large negative anomaly will be found above this depression due to the departure from normal density where the granitic layer has sunk into the tachylytic and where the latter has sunk into the dunite.

The granitic and tachylytic layers are assumed to go down without change of thickness. The dunite is considered plastic and is pressed aside; hence the down-warping is compensated by a rising up of the dunite layer in an adjacent area pushing up with it the upper layers.

Over this raised area positive anomalies will occur balancing the negative anomalies over the depressed area.

Denudation of the raised area will expose the lower igneous rocks, or ancient sedimentary formations, and provide sediments to fill the depressed area.

**14. Densities of the Crustal layers.**—The hypothesis can be easily applied to obtain values for the thickness of the major sedimentary formations and the results appear to accord with geological data where this is available.

Before proceeding to numerical calculations a knowledge of the average densities of the three crustal layers is required.

(*a*) *Granitic layer.*—Jeffreys gives the density of the granitic layer as 2·61 to 2·66 ‡. Since however in most gravity computations in India and elsewhere a density of 2·67 has been assumed, it will be adopted. An average density of 2·67 agrees well with densities obtained from rock samples in India.

(*b*) *Tachylytic layer.*—The same authority gives 2·851 as the density of tachylyte.

(*c*) *Dunite.*—From the same source the density of dunite is 3·29 to 3·32.

---

* H. Jeffreys. The Earth, 2nd Edn., p. 116.

† H. Jeffreys. The Earth, 2nd Edn., p. 195.

‡ H. Jeffreys. The Earth, 2nd Edn., p. 102.

The value adopted is 3·30.

It is the difference between these densities that will be used in numerical calculations, i.e.

at the granite-tachylyte interface 0·18,
at the tachylyte-dunite interface 0·45.

**15. Depth of the Hidden Range.**—On the same hypothesis the Hidden Range is assumed to be a major warping of the earth's crust affecting both the tachylytic and granitic layers. Denudation, deposition of sediments, and subsequent earth movements have removed all obvious surface indications of this warping.

It is a broad sweeping feature so that at the crest and at the lowest part of the trough the simple formula for the attraction of a disc of infinite radius at a point on its axis may be used without serious error.

Here

$$A = 2\pi\kappa\rho t.$$

where $A = \pm$ 0·036 cm/sec². (maximum effect of the Hidden Range and its associated troughs).

$\kappa$ = the gravitational constant $= 657 \times 10^{-10}$ c.g.s.

$\rho$ = the density $= 0{\cdot}45 + 0{\cdot}18 = 0{\cdot}63$

$t$ = the rise and fall of the dunite and tachylytic layers above their normal levels.

Whence $t =$ 4,500 feet approximately.

Fig. 2 shows the Hidden Range.

### 16. Numerical test of $g - \gamma_F$.—

(*a*) *Method of Computing.*—The normal level of the top surface of the crustal layers is assumed as follows:—

| | |
|---|---|
| Granitic layer ... ... ... | sea-level. |
| Tachylyte ... | 33,000 feet below sea-level. |
| Dunite ... | 100,000 feet below sea-level. |

If sedimentary deposits extend to a depth of 40,000 ft. below sea-level, the theory put forward implies a sinking of the tachylyte surface to 73,000 ft. below sea-level and of the dunite surface to 140,000 ft. below sea-level.

If the deposits have a density 2·67 the gravity anomaly above them is solely due to the sinking of the tachylyte and dunite surfaces.

The $g - \gamma_F$ anomaly is therefore due to two cylinders of 120,000 ft. radius, and thickness 40,000 ft. with their top surfaces at 33,000 ft.

and 100,000 ft. below sea-level and densities −0·18 and −0·45 respectively. The effects of these two cylinders are :—

| | | |
|---|---|---|
| Upper or granite cylinder | ... | −0·054 cm/sec$^2$ |
| Lower or tachylyte cylinder | ... | −0·067 cm/sec$^2$ |
| Total | ... | −0·121 cm/sec$^2$ |

It will be seen that the lower cylinder has a rather greater effect than the upper as a result of the greater difference in density. This is important. If it were assumed that only the tachylyte layer was effected by the sinking of the granite, numerical calculations would yield depths of deposits more than twice as great.

Since the effect of the Hidden Range has been removed, its height or depth below the normal surface levels of the tachylyte and dunite layers must be taken into consideration when calculating the effect of deposits.

In this way Table III has been prepared showing the anomaly due to various depressions and elevations of the crustal layers when situated above the crest, zero line, or trough of the Hidden Range. The depression at the top of the granitic layer is assumed to have been filled in by material of normal density. The amount of depression or elevation corresponding to any anomaly can be obtained from this table at a glance.

Of course if surface rocks are above or below normal density, allowance should be made for these, but usually the anomaly due to this cause is trivial compared with that due to changes in the dunite and tachylyte surfaces.

It has already been pointed out that the widespread, but comparatively gentle, undulation of the crust which forms the Hidden Range, underlies all kinds of geological formations.

Other more local elevations and depressions of the crust are more abrupt in character. Here we may expect to find sedimentary formations occupying the depressions and igneous rocks exposed in the elevated areas. The elevation of the crust will often have raised up ancient sediments but denudation has largely removed these, leaving the lower igneous rocks exposed. If the elevation has been too abrupt or too great, fracture of the granitic layer is to be expected with resulting outpourings of effusive rocks derived mainly from the tachylytic layer.

The above furnishes an adequate explanation of all the main features of Chart II, when compared with Chart I.

(*b*) *Cuddapah Formation.*—In the geological sketch map (Chart I) the Cuddapah formation is represented by a roughly triangular patch centred over the Penner Basin, north-east of Madras. A somewhat larger blue area (negative anomalies) is found in Chart II.

The following gravity stations lie over exposures of the Cuddapah rocks.

| Station No. | Place | $g-\gamma_F$ |
|---|---|---|
| | | *cm/sec²* |
| 195 | Nandyāl ... | — ·021 |
| 196 | Cumbum ... | — ·034 |
| 200 | Cuddapah ... | — ·022 |

The area is near the lowest part of the trough of the Hidden Range. From Table III the following approximate depths for the formation below sea-level are obtained, after increasing the depth by 4,000 ft. on account of the Hidden Range, and assuming normal density for the rocks.

| Place | Depth of formation |
|---|---|
| | *feet* |
| Nandyāl ... | 11,000 |
| Cumbum ... | 14,000 |
| Cuddapah .. | 11,000 |

Wadia states that the depth of the Cuddapah sediments amounts to more than 20,000 ft. in the aggregate*, allowing for the height above sea-level, denudation and for the fact that the rocks probably average over normal density (which would lead to an increase in the calculated depth). The result is evidently of the right order. Further to the south of these three gravity stations at Renigunta, Station No. 199, the gravity anomaly ($g-\gamma_F = -·024$ cm/sec²) indicates an extension of the Cuddapah depression further south than is shown in Chart I. This is confirmed by Wadia†.

To the east of the Cuddapah formation is an area of dense igneous rocks with positive gravity anomalies. Here is to be found the effect of the raising of the crustal layers simultaneously with their depression under the Cuddapah area. It is satisfactory that the greatest positive anomaly, that at Station No. 176 Ongole ($g-\gamma_F = +·042$ cm/sec²), is adjacent to the

---

* Wadia, Geology of India.

† Wadia, Geology of India, Plate XVI.

greatest negative anomaly. The anomaly ( + ·042 ) corresponds to an elevation of the dunite and tachylyte layers of about 11,000 ft.

( *c* ) *The Vindhyan Formation.*—The type exposure of the Vindhyan formation is the great escarpment of the Vindhyan Mountains but to the north it is concealed by Deccan trap. Sawai Mādhopur may be taken as a typical station over a wide outcrop of the Vindhyan formation.

| Station No. | $g-\gamma_F$ |
|---|---|
| 223 | *cm/sec²*<br>— ·025 |

The height of the Hidden Range here is about 2,500 ft. From Table II a depth of Vindhyan sediments below sea-level of about 7,000 ft. is obtained. This should be slightly reduced since the average density is slightly below normal, viz. 2·66.

Negative anomalies are also obtained in the area covered by Deccan trap, e.g., at Mhow. Since the average density of Deccan trap is about 2·83 and its thickness is about 1,500 ft. the anomaly should be further increased by – ·002 cm/sec$^2$.

Allowing therefore for the effect of the Deccan trap the anomalies at Mhow ( Station No. 48 ) is $g-\gamma_F$ = — ·047 cm/sec$^2$. The height of the Hidden Range is about 4,500 ft. so that there is a depth of Vindhyan sediments below sea-level of about 13,000 ft.

Allowing for height above sea-level and denudation the result is again of the right order since Wadia states that the Vindhyan system is a vast stratified formation encompassing a thickness of over 14,000 ft.*

The elevation of the crust compensating for the Vindhyan depression is to be found in the original Arāvalli Hills and south of Narbada in the Sātpura Hills. The more recent rejuvenation of the Arāvallis is ascribed to the Himālayan upheaval. The positive anomalies in the Arāvallis (e.g., Station No. 215, Ajmer, $g-\gamma_F$ = + ·050) are on this account greater than the anomalies at Sawai Mādhopur etc., warrant.

The anomaly at Ajmer corresponds to an elevation of the dunite and tachylyte layers of about 15,000 ft. Sediments of the Delhi and Arāvalli series overlie part of this area and so positive gravity anomalies are found over them.

( *d* ) *The Deccan Trap.*—According to geological evidence the maximum thickness of the Deccan trap reaches nearly 10,000 ft. along the coast of Bombay, rapidly becoming less

---

* Wadia, Geology of India, p. 77.

further east*. Gravity data accord well with this. The highest anomalies are on the coast. They are :—

| | | $g-\gamma_F$ | |
|---|---|---|---|
| Station No. | Place | S. of I. II | International |
| | | cm/sec² | cm/sec² |
| 110 | Surat | + ·047 | + ·041 |
| 113 | Damān | + ·072 | + ·066 |
| 3 | Colāba (Bombay) | + ·102 | + ·097 |
| 109 | Alībāg | + ·040 | + ·037 |

A thickness of 10,000 ft. of Deccan trap (density 2·83) will yield an anomaly of + ·022 cm/sec$^2$. At Bombay therefore an anomaly of about + ·080 cm/sec$^2$ remains to be accounted for. The height of the Hidden Range at Bombay is about −1,000 ft., so an elevation of the tachylyte and dunite surfaces of about 20,000 ft. is required to explain the anomaly.

This brings the tachylyte to within a few thousand feet of the bottom of the Deccan trap. It is likely that we have here an extensive fracture of the granitic layer, which sufficiently explains the vast outpourings of lavas. The section on BB (Chart I) shown in Fig. 4 gives a good picture of the situation and indicates that the main focus of effusion of lavas was near Bombay. The dykes in Cutch and elsewhere are probably secondary phenomena.

The sudden reduction in the anomaly from + ·102 to + ·040 at Alībāg less than 30 miles away is remarkable. It seems likely that the Deccan trap south of Bombay overlies a widespread area of deep sediments, and that a rise of the crustal layers at Bombay balances the depression to the south. Gravity stations are lacking, but the negative anomalies at Dhond and Kurduvādi (Stations Nos. 185 and 186) lend support to this theory.

It is highly probable that the Deccan trap conceals several sedimentary areas, and gravity work should successfully delineate these areas. Such work may well prove economically most valuable. The sediments may contain coal fields, or failing that water, a valuable commodity in the Peninsula. Some borings have been made in the Deccan trap in hopes of finding coal: notably a boring at Bhusāwal Lat. 21° 02′ N. Long. 75° 47′ E. which went down over 1,400 ft. without reaching the bottom of the trap. Reference to Chart II shows that Bhusāwal lies well in the centre of an area of positive anomalies where boring for coal is likely to be an unprofitable speculation.

---

* Wadia, Geology of India.

There are large areas of Deccan trap untouched by gravity work. The most promising region for coal or water found up to date appears to be in the neighbourhood of Dhond or Kurduvādi: so far only comparatively shallow borings have been made here ( 250 ft. ).

(*e*) *Depsang and Himālayan Regions.*—The gravity station at Depsang established by the de Filippi Kara-koram Expedition in 1914 gave an apparently remarkable result. The Hayford anomaly following Helmert's 1901 formula is – ·064 cm/sec$^2$. The result is, however, quite in accord with the theories put forward in this paper. The table below shows results at a few mountain stations.

| Station No. | Place | Height Feet | $g-\gamma_C$ Helmert | $g-\gamma_F$ S. of I. II | $g-\gamma_F$ International |
|---|---|---|---|---|---|
| | | | *cm/sec$^2$* | *cm/sec$^2$* | *cm/sec$^2$* |
| 143 | Deosai III ... | 12,391 | + ·095 | + ·054 | + ·043 |
| F 8 | Wozul Hadur ... | 13,921 | + ·036 | + ·002 | – ·011 |
| F 10 | Skārdu ... | 7,326 | + ·015 | – ·015 | – ·029 |
| F 9 | Depsang ... | 17,589 | – ·064 | – ·075 | – ·089 |

These stations are progressing from the outer ( southern ) slope of the trough of the Hidden Range towards its deepest part. Depsang is very close to the deepest part of the trough. The $g-\gamma_F$ anomalies show that there has been an additional deepening of the trough near its axis accompanied by the formation of the mountains. The reason for positive anomalies in the outer Himālayas will appear shortly. The depth of the assumed trough at Depsang is about – 4,000 ft. ; referring to Table III we find that the $g-\gamma_F$ anomalies imply a further deepening of about 25,000 ft. ( S. of I. II ) or 31,000 ft. ( International ) that is the crustal layers have been bent down here about 29,000 ft. or 35,000 ft. below their normal level. This great depth below high mountains provides the "roots of the mountains" in the Airy theory of isostasy, but according to the theory advanced herein this deep down-warping must be accompained by a balancing uprise.

Gravity anomalies show that the whole width of the northern trough of the Hidden Range did not take part in the additional down-warping, but that there was a buckling down of the deepest part of the trough accompanied by compression of the sediments in it.

Such a violent buckling was not unnaturally accompanied by failure near by, so we find a compensating uplift of the crust in the igneous ranges of the Outer Himālaya. Here the granitic layer reinforced by a thick load of sediments did not fail sufficiently to allow effusion of basalt from the tachylytic layer on a large scale as in the Deccan. The igneous rocks exposed are mainly the lower rocks of the granitic layer. The anomaly at Deosai III corresponds to an uplift of about 14,000 ft. This is insufficient to balance the down-warp, so a search must be made further afield. Chart II indicates that the Gangetic trough has buckled up near Dehra Dūn. It is possible that there is a line of weakness along the line of the Arāvalli Range, and also towards the Salt Range. In this way the high positive anomalies in the alluvial plains of NW. India can be explained. The recent rejuvenation of the Arāvalli Range [*] was part of this process; on the east also south of Darjeeling, is a similar failure of the Gangetic trough. Sedimentary systems have been "Caught up" by the uprise of the crust under the outer Himālayas [†] and so positive gravity anomalies are found over them. The process appears to be still in progess, as the recent rejuvenation of Himālayan streams, and changes in the course of rivers in the Punjab show. There is evidence too of a recent rise in level in the upper part of the delta of the Ganges and Brahmaputra. It may be objected that a down-warping of the crust of as much as 35,000 ft. is improbable, but it is well to remember that loss of equilibrium due to this great depression of the lighter upper layers of the crust is partly compensated, first by the sediments filling the depression and secondly by the sedimentary mountains raised above it. Further in the ocean deeps we have depths of over 30,000 ft. with the much smaller compensatory weight of sea water above the ocean bed.

(*f*) *The Gangetic Trough.*—It has been shown in the preceding discussion of Himālayan regions that buckling up of the Gangetic trough has occurred near Dehra Dūn and Darjeeling. East of Lucknow (about Long. 82°) the trough appears to be comparatively undisturbed. It may be assumed that the trough of the Hidden Range is here covered by alluvium of less than normal density.

Oldham adopts a density of 2·16 for this alluvium [‡]. This value will be used in the calculations which follow. At Gonda and Gainsari the following anomalies occur:—

| Station No. | Place | $g-\gamma_F$ |
|---|---|---|
| | | $cm/sec^2$ |
| 126 | Gonda | $-\cdot 050$ |
| 127 | Gainsari | $-\cdot 052$ |

---

[*] Records of the Geological Survey of India, Vol. LXII, Part 4.

[†] Wadia, Geology of India, p. 85.

[‡] Oldham. The Structure of the Himālaya., p. 53. 1917 (Memoirs of the Geological Survey of India, Vol. XI-II).

Fig. 3

## Crustal Section on AA

Horizontal scale same as chart or 1 inch=250 miles
Vertical scale about 50 times horizontal scale

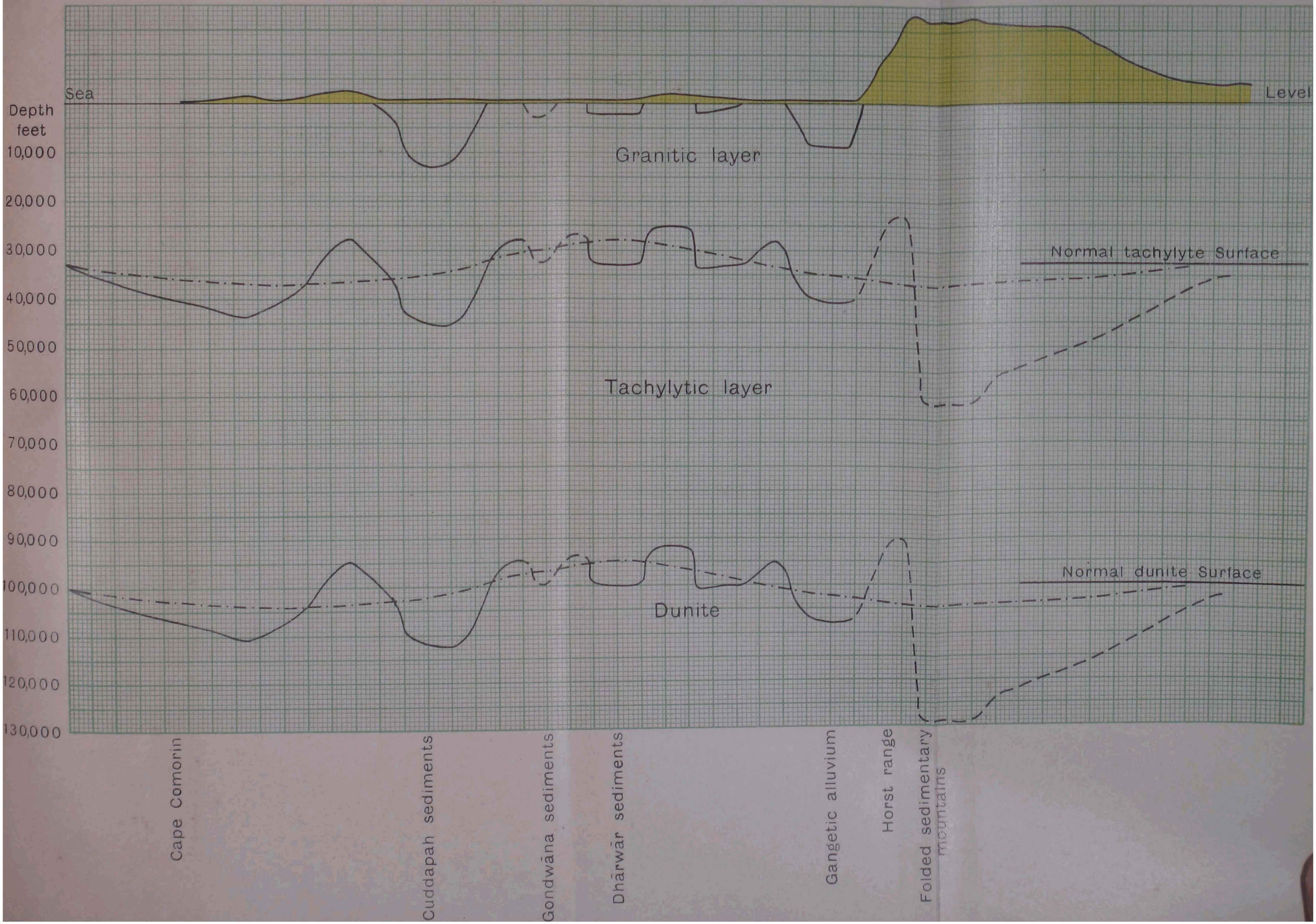
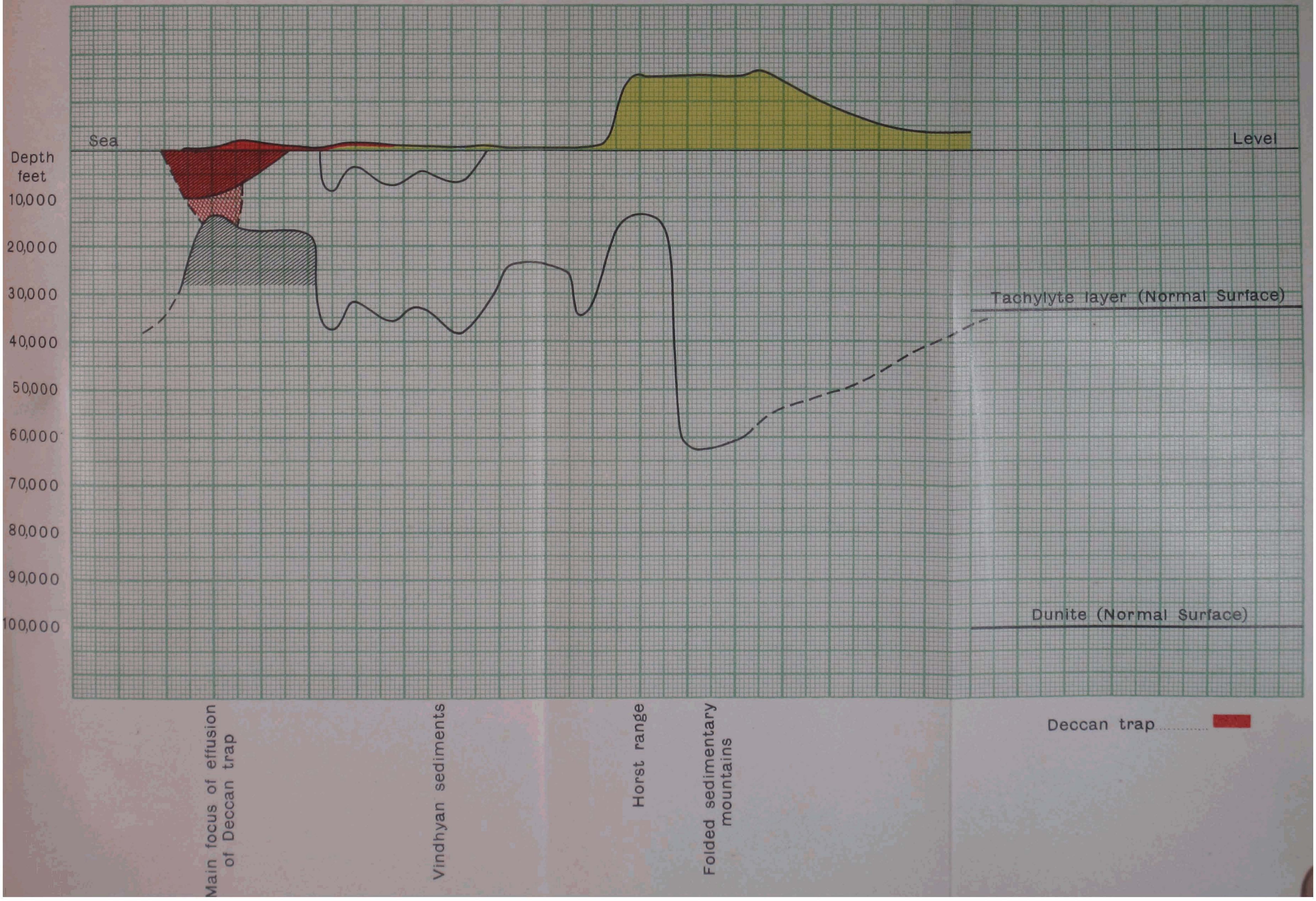


Fig. 4

Crustal Section on BB

Horizontal scale same as chart, or 1 inch = 250 miles

Vertical scale about 50 times horizontal scale



If the anomaly is due to the light alluvium only, an anomaly of $-{\cdot}050$ cm/sec$^2$ would be caused by 8,000 ft. of alluvium. But the assumed depth of the trough of the Hidden Range here is about 3,000 ft.; so there has been additional sinking of the crustal layers for which allowance must be made. This reduces the depth. A depth of about 6,500 ft. gives the required anomaly. This is of course a much smaller depth than is usually assumed for the Gangetic alluvium.

(*g*) *Baluchistān.*—The greatest negative anomaly found in this sedimentary area is at Sibi, Station No. 26.

Here a $g-\gamma_F$ anomaly of $-{\cdot}060$ cm/sec$^2$ connotes a warping down of the crust of about 17,000 ft., but this is reduced to 14,500 ft., since the height of the Hidden Range is assumed to be + 2,500 ft. at this place. Also the light density of the alluvium will lead to a further large reduction of depth. As a result of these considerations a depth of alluvium at Sibi reaching to about 6,500 ft. below sea-level is reached, that is the same figure which was found for the Gangetic alluvium, which is on the outer slopes only of the Himālayan trough. The down-warping in the Baluchistān area therefore does not extend to a great depth, and is not comparable to that under the Himālayan region. To balance this down-warping an uprising of the crust has occurred near Karāchi and Sukkur and also in the volcanic regions on the Persian boundary.

(*h*) *Southern India.*—The negative anomalies at Salem, Kodaikānal, Madura etc., are peculiar and require explanation. Although the area is not occupied by recognizably sedimentary rocks, it seems likely that a depression of the crustal layers has actually occurred in this region.

This receives corroboration from Ceylon. Adams states as follows *:—

"In structure Ceylon is a portion of a great syncline, deeply eroded, closed on the south, open to the north where it plunges beneath the Miocene Cover".

Subsequently he states † that Ceylon was "entirely submerged in pre-Cambrian times...........since then it has always been in a large part under water but throughout the long geological ages, it has been a "positive" element in the earth's crust having, with some minor oscillations, been rising out of the sea in successive stages of uplift".

Events may be pictured as follows:—

First there was a great down-warp of the earth's crust over the area now occupied by Southern India and Ceylon, possibly counter-balanced by positive areas to the north, (Nīlgiris and Eastern Ghāts to Cuddalore). Then further down-warping of this area led to a failure of the syncline with a crumpling up of

---

* Adams. The Geology of Ceylon p. 425. Canadian Journal of Research 1929.

† Adams. The Geology of Ceylon, pp. 437, 438.

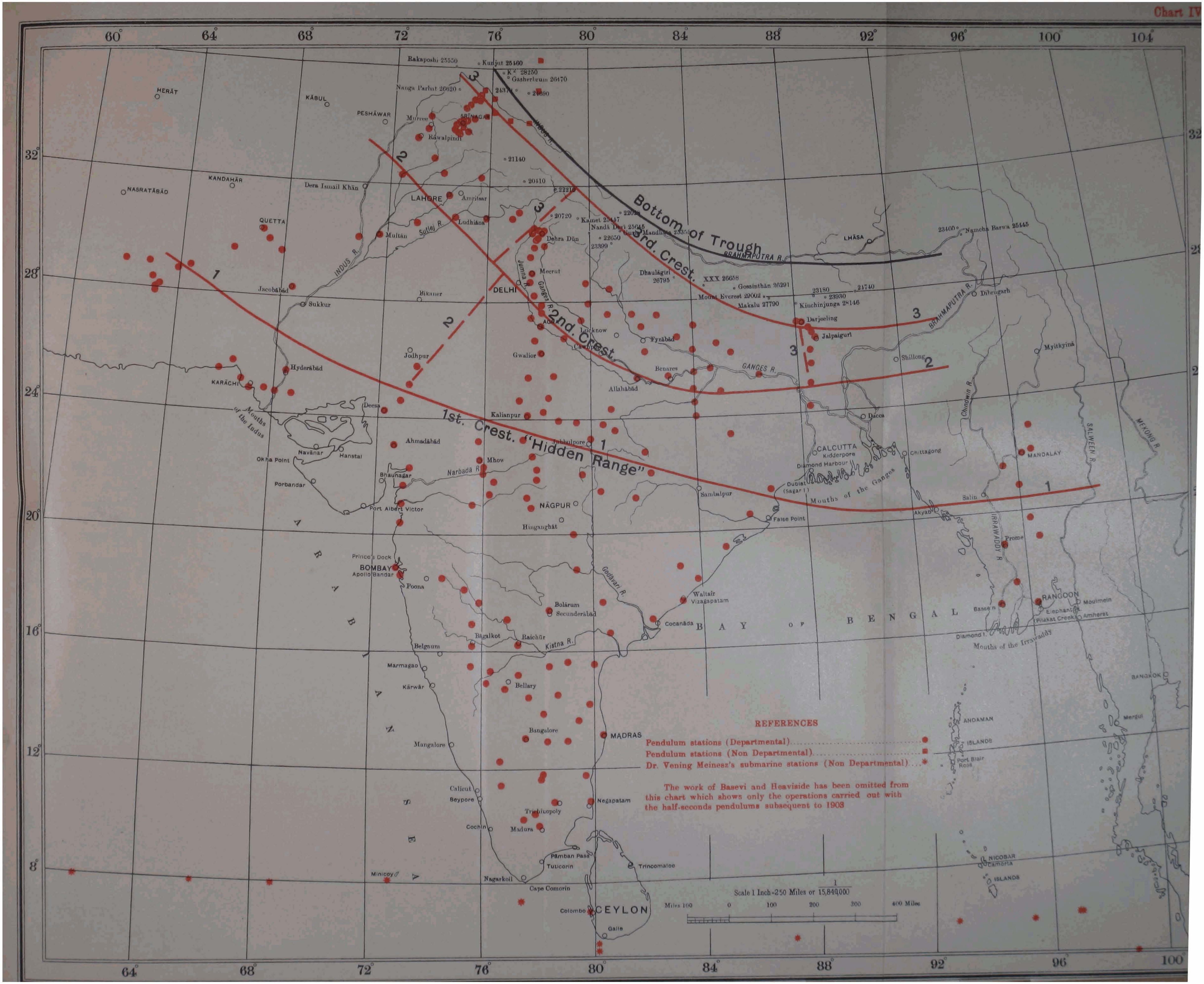
the Cardamom and Palni Hills etc., and the uprise of Ceylon to balance the deepening of the trough. Here we have an adequate explanation for the apparent discrepancy between gravity anomalies and the geoid referred to in para 4. The gravity anomalies show the down-warp of the crust in Southern India. Deflections indicate the uplift of the crust under Ceylon. This conclusion of course leads to a modification of the assumed form of the trough south of the Hidden Range. The $g-\gamma_F$ anomalies in Southern India ( Dindigul, Station No. 182 ) indicate a total down-warping of about 11,000 ft. Since Ceylon is an uprising area, positive gravity anomalies should be obtained there particularly in the south-east.

**17. The Tethys and the evolution of the Himālayas.**—The chief tectonic features of India having been examined, the general sequence of events will now be briefly considered. The Hidden Range is ascribed to the formation of the geosyncline of the Tethys. The more ancient down-warpings filled by the Cuddapah, Dhārwār and Vindhyan sediments of Peninsular India and the Purānas of the extra-Peninsular area had reached their final stage and had become stabilized before the commencement of this later warping, and in the initial stages of the warping they were raised or lowered by it without alteration. The Tethys was well established in mid-Devonian times, and persisted until the Miocene period. It was due to a steady down-warp of the crust. The balancing uprise of the crust took place along the line of the Hidden Range. The process was extremely slow, so that denudation of the elevated area kept pace with the sinking of the geosyncline, and provided sediments always sufficient to keep the sea shallow. Chalk deposits accumulated in the central deeper area. This sequence is quite different from that usually advanced by isostasists who say that down-warping of the crust is due to isostatic adjustment of the crust under a load of sediments.

Down-warping must always be in advance of sedimentation. If the down-warp occurs in the ocean there may be no sedimentation but the down-warping frequently increases in spite of this, resulting in the formation of the great ocean deeps. In continental areas uprise of the crust adjacent to the depressed area provides material to fill up the trough. This appears to be the only essential difference between a true oceanic deep and a continental down-warp.

The gradual uprise of the Hidden Range and accompanying thinning by denudation of the upper layer of the crust brought the intermediate layer so close to the surface in upper Cretaceous times that failure of the granitic layer occurred accompanied by effusion of basalt. It is likely that the actual focus of effusion near Bombay was conditioned by a line of weakness due to an ancient down-warp to the south with an accompanying uprise of the crustal layers near Bombay.

Chart IV



The work of Basevi and Heaviside has been omitted from this chart which shows only the operations carried out with the half-seconds pendulums subsequent to 1903

Up to this stage the down-warp occupied by the Tethys had all the characteristics of a true geosyncline which is essentially a shallow feature*. The assumed form of the Hidden Range, Fig. 2 approximates to this stage.

The second stage now began; there was a rapid deepening of the Tethys, accompanied by a rise up of the crust roughly along the line Lahore, Delhi, Allahābād, Shillong, and by the rejuvenation of the Arāvalli Range. In the third stage there was an abrupt deepening and narrowing of the middle portion of the trough resulting in the crumpling up of the folded sedimentary ranges of Inner Ranges accompanied by failure and buckling up of the crustal layers of the outer slopes of the trough resulting in the horst ranges of the outer Himālayas and Siwāliks.

The second and third stages may have been nearly contemporaneous. The third stage is still in progress, witness the very recent rejuvenation of streams in the outer Himālayas, changes in the courses of the Punjab rivers and changes in level in the upper part of the Ganges and Brahmaputra delta, and frequent and severe earthquakes at the present time. Stability will not be reached until the former broad and shallow undulation of the crust has broken up into a mesh of comparatively small irregular ups and downs. The negative area of the Cuddapah region is perhaps an indication of the maximum size of the mesh consistent with stability. Chart IV shows diagrammatically how far the Hidden Range—Tethys movement has advanced towards stability. Sections through India are shown in Figs. 3 and 4.

**18. Further consideration of the $g-\gamma_F$ anomaly.**— It is claimed that the $g-\gamma_F$ anomaly represents a true picture of a cylinder of the crust centred under the station with its top surface at sea-level and with a radius of 120,000 ft., the Hidden Range and its associated troughs having been first removed. The anomaly will be nil if the tachylyte and dunite surfaces underlying the station accord with the assumptions made in Chart I and Fig. 2. The anomaly will be negative if they are depressed below the assumed levels and positive if they are elevated.

The significance of this claim must now be considered.

In effect the $g-\gamma_F$ anomaly is equivalent to the anomaly corrected for topography without compensation within a radius of 120,000 ft., and for topography and its compensation according to the Hayford hypothesis outside this area, and with the effect of the Hidden Range removed.

Neglecting the Hidden Range it appears therefore that computation of corrections according to the Hayford system are satisfactory, if the inner zones are excluded.

---

* Gregory. The Structure of Asia, Ch. V, by Prof. G. B. Barbour.

The reason for this appears to be as follows :—

The tachylyte and dunite surfaces are not smooth level surfaces. They are roughened by up and down warpings. The separate areas of depression or elevation are comparatively small when the movement which caused them has finally died out. The volume of the elevations equals the volume of the depressions, but if a point is selected equidistant from an elevation and a depression of the same size the resultant anomaly due to them will be negative, since the vertical components at the point selected are unequal and opposite in sign, and the negative attraction due to the depressed area is the greater.

In a continental area therefore this predominating effect of the crustal depressions gives the impression of compensation of the elevation of the land above sea-level. This being so, an empirical determination of the depth of compensation according to the Hayford hypothesis of isostasy will give an apparently definite solution.

Folded sedimentary mountains due to the narrowing and deepening of a geosyncline may be more than compensated by the deep crustal down-warp below them.

In oceanic areas, absence of the granitic layer, and thinning of the tachylytic layer, resulting in a great uprise of the dunite, fully compensates for the deficient density of the water, ( see para 19 ).

We may say that the oceans cover a broad up-warp of the crust. Local warpings, owing to absence of erosive agencies, are not concealed by denudation and sedimentation as in continental areas and appear as deeps and islands over which negative and positive anomalies will be found.

In the initial stages a warping movement may be a gentle undulation of great horizontal extent, raising or depressing with it the more ancient stabilized warpings. In such a case the radius of 120,000 ft. is too small, and the Hayford system fails to be a satisfactory empirical method of correcting for topographical and warping effects outside this radius.

One may extend the radius, but in this case a more generalised view of crustal conditions is obtained from the resulting anomaly and correlation with superficial geological conditions will fail.

A more satisfactory method is to determine the extent and effect of the broad crustal warping and to correct for it. If this is done the remaining anomaly will show the effect of the more ancient warpings and of any local departures from the assumptions made about the broad warping.

This is the method adopted in this paper and is the reason why the $g-\gamma_F$ anomaly contains a correction for the Hidden Range and its associated troughs.

The sum total of the warping effects from beyond a radius of 120,000 ft. from the gravity station to the antipodes should, if the hypothesis is correct, be approximately equal to the sum total of the compensation effects computed over the same area according to the Hayford hypothesis. Data is at present insufficient to determine whether this is the case. In the following Table calculations of the warping effects at four stations from beyond a radius of 120,000 ft. to 1,000,000 ft. radius have been made using Tables IV and V. The results are shown in the fourth column; the fifth column shows the remaining warping effect required if the sum of columns 4 and 5 are to equal the compensation effect beyond 120,000 ft. radius. The figures in column 5 appear reasonably small, so that the results are not unsatisfactory. Further direct proof is impracticable, but indirect proof is afforded by the satisfactory correlation of the $g-\gamma_F$ anomalies with superficial crustal phenomena.

| Station No. | Name | Height | Column 4 | Column 5 |
|---|---|---|---|---|
| | | *feet* | *cm/sec²* | *cm/sec²* |
| 196 | Cumbum | 634 | −·015 | −·059 |
| 70 | Allahābād | 288 | −·000 | −·007 |
| 143 | Deosai III | 12,391 | −·049 | −·161 |
| F9 | Depsang | 17,589 | −·087 | −·174 |

**19. Gravity anomalies at sea.**—Vening Meinesz's sea observations lend valuable support to the theory advanced. The following are Hayford anomalies over deeps and adjacent islands.

| Station No. | Sea depth metres | $g-\gamma_C$ | Remarks |
|---|---|---|---|
| | I—INTERNATIONAL DEEP | | |
| | | *cm/sec²* | |
| 26 | 8,030 | −·166 | International Deep |
| 27 | 290 | −·123 | Haiti-Port-Rice Channel |
| 28 | 4,900 | +·044 | Carribbean Sea |
| 29 | 0 | +·090 | Curacao |
| | II—WYMAN DEEP | | |
| 71 | 5,420 | −·020 | Wyman Deep |
| 73 | 0 | +·068 | Honolulu |

| Station No. | Sea depth metres | $g - \gamma_c$ | Remarks |
|---|---|---|---|
| | III—NERO DEEP | | |
| | | *cm/sec²* | |
| 92 | 8,740 | — ·072 | Nero Deep |
| 93 | 2,850 | + ·060 | Approaching Guam |
| 94 | 0 | + ·032 | Guam |
| | IV—YAP DEEP | | |
| 98 | 7,720 | — ·008 | Yap Deep |
| 99 | 0 | + ·094 | Yap |

Evidently each downfold is associated with an uprise of the crust. The small negative anomaly over the Yap Deep is explained by the fact that the submarine crossed only the extreme south-end of the deep Much larger negative anomalies would almost certainly have been found in a more central part of the deep. The absence of the granitic layer and the thinning of the tachylytic layer under the ocean with the resultant elevation of the dunite layer explains the comparatively small negative anomalies found over the deeps in the open ocean. Near the continents the tachylytic layer is thicker. This explains the much larger negative anomaly found over the International Deep, since below the deep the tachylytic layer has been folded down to a greater depth.

The same reasoning serves to explain the rather curious results obtained by Vening Meinesz in the Java Seas. A line of gravity stations across the Java deep crossing it at about longitude 106° E. may be taken as typical. Starting from the north near Java over the 2,000 metre depth contour the Hayford anomaly is + ·090 cm/sec$^2$, it then drops abruptly, before the 4,000 metre contour is reached to – ·110 cm/sec$^2$ after which there is a sharp rise to + ·050 over the centre of the Java deep followed by a more gentle rise to + ·090. Further sea-ward the anomaly drops to + ·060. Vening Meinesz explains the negative anomalies by a downward folding of the crust along the line of negative anomalies*. This is the same hypothesis as has been arrived at independently in this paper as a result of the consideration of continental conditions in India ; and is a most satisfactory corroboration from a very different area. His explanation of the positive anomalies over the deep does not, however, appear to be adequate. His explanation is as follows :—

> "A thin upper layer of a few miles' thickness does not partake of this downward fold but folds upwards forming over-thrust sheets in the way found by the geologist in all folded

---

* **Vening Meinesz. Geographical Journal, April 1931, p. 326.**

mountain systems. These formations usually cover up the effect of the deeper process and fill up the trough caused by this folding. In some parts, however, this trough is not filled up completely and part of it remains visible as an ocean deep. This supposition would make it explicable that these deeps are situated usually beside the fold and at the ocean side of them; the central part of the fold trough is the most likely to be filled up by the surface folds, and at the ocean side the upper layer will be thinnest or perhaps not be present at all, so that it seems acceptable that at this side the trough is not quite covered up."

If the trough is not filled up completely there will most certainly be a negative anomaly above it. The explanation seems to be that simultaneously with the downfold the crust has risen up, probably on both sides of the downfold. On the seaward side of the downfold owing to the uprising, the tachylytic layer, already thin, has split and though probably partly filled with dunite from below, remains a deep crack.

If this point of view is correct, then deeps around the East Indies are fundamentally different to the true ocean deeps. The latter are due to a down-warping of the ocean bed composed of basalt with no covering granitic layer. The former are due to a cracking apart or thinning of the tachylytic layer, accompanied by a rise of the dunite layer below. Hence large positive anomalies are found over the deeper parts of the Celebes and the Banda Seas ($+ \cdot 140$ cm/sec$^2$).

**20. Depth of the tachylytic layer under the ocean.**—Taking the mean depth of the ocean to be 12,500 ft., and employing the formula given on page 12, the gravity anomaly due to the defect of the density of sea water (density 1·027) from normal density, 2·67 is $A = 2\pi\kappa\rho t$

where $\rho = 2{\cdot}67 - 1{\cdot}027 = 1{\cdot}643$

whence $A = -0{\cdot}258$ cm/sec$^2$.

This has to be balanced by an equivalent positive anomaly due to the rise of the denser crustal layers. If the bed of the ocean represents the top of the normal tachylyte layer, 67,000 ft. thick, then both the tachylyte and dunite layers have risen 20,500 ft. Calculating the positive anomaly from the same formula,

$$\rho = 0{\cdot}45 + 0{\cdot}18 = 0{\cdot}63$$

whence $A = +0{\cdot}158$ cm/sec$^2$.

This is insufficient; the balance must be found by a further rise of the dunite accompanied by a thinning of the tachylyte layer.

$$\rho = 0{\cdot}45 - 0{\cdot}18 = 0{\cdot}27$$

$$A = +0{\cdot}100 \text{ cm/sec}^2$$

whence $t = 30{,}100$ ft.

Thus it appears that the tachylyte layer is only about 37,000 ft. thick under the ocean.

In exceptional "positive" areas, such as the Banda and Celebes Seas, the dunite layer directly underlies the sea.

**21. The crustal warp hypothesis and isostasy.**—The views expressed in this paper are fundamentally at variance with the hypothesis of isostasy in many important details.

A recent American paper[*] contains two chapters (Ch. VII "Isostasy" by Dr. Wm. Bowie and Ch. VIII "The influence of isostasy on geological thought" by H. F. Reid), which may be taken to represent the latest views of isostasists.

The isostatic view will be contrasted below with the views necessitated by the crustal warp hypothesis.

For the sake of brevity the quotations made are not quite literal.

| ISOSTASY | CRUSTAL WARP |
|---|---|
| Geodetic investigations show depth of crust to extend 60 miles below sea-level. | Seismological evidence is accepted, viz:—<br>Granitic layer $10^{km}$ thick: Tachylytic layer $20^{km}$ thick: below this dunite |
| In this outer shell are materials of different densities. The higher the ground the less is the density and vice versa. | The densities do not vary with elevation of the ground. |
| The cross section of a prism in independent isostatic equilibrium is 50 to 100 miles square, perhaps less. | This fails altogether in India. |
| Data secured from variation of latitude, earth and ocean tides, and transmission of seismic waves seem to indicate a contradiction between isostasy and geophysical data. This however cannot be, for isostasy certainly exists. | Geophysical data are accepted.<br>Isostasy is not accepted. |
| There is down-warping of those areas which receive great beds of sediments and upward movement of those areas from which material is removed. | It is more generally correct to say that great beds of sediments are deposited in areas which are down-warping, and that material is removed from areas which have been or are being, subjected to an upward movement. This difference is important. |
| In general for continental stations, a large positive or negative anomaly is due to very local causes. This has been definitely proved. | This is not the case in India. |
| There is only one extensive region of persistent positive anomalies in the United States. Perhaps this is merely accidental and due to the location of the gravity stations on structural anticlines, which have been found to give positive anomalies in practically every case. | This is a good argument against isostasy.<br>It is likely that there is here a crustal up-warp, probably associated with a deep down-warp further west under the Rocky Mountains.[†] |

---

[*] Bulletin of the National Research Council. Physics of the Earth—II Feb. 1931, No 78.

[†] See Journal of Geology July-Aug. 1924, Rocky Mountain Structure by E.F. Flint.

| ISOSTASY | CRUSTAL WARP |
|---|---|
| In the course of ages immense quantities of material have been eroded from the continents and deposited in the sea near the shore. Isostasy requires that an equivalent mass be abstracted from near the shore and returned to the area of erosion, and this can only be accomplished by a subterranean flow. The process is extremely slow. | This is a confusion of cause and effect.<br>There is an uplift resulting in elevated areas liable to erosion, and a down-warp adjacent providing a suitable area for the accumulation of sediments. |
| Geodetic observations in mountainous regions show that there is no defect of matter there due to erosion, and similar observations in regions of heavy deposition, such as the basin of the Ganges, show no excess of matter, so that in spite of all objections the return underground flow of rock seems pretty definitely proved. | The argument seems unsound. The process has been stated to be extremely slow and cannot be ahead of the cause. There should therefore be small positive anomalies in areas of deposition, and small negative anomalies in areas of erosion.<br>The theory of isostasy cannot account for the large negative anomalies in the Gangetic plain, nor the large positive anomalies in the outer ranges of the Himālayas, nor the large negative anomaly at Depsang, a locality subject to less rapid erosion than the outer ranges. |
| Isostasy leads to the following order in the raising of a folded mountain range:—<br>1. After accumulation of sediments to a considerable depth, they are compressed and folded leading to some elevation.<br>2. Disturbance of isostatic equilibrium leads to a further sinking of the region, but ending in more elevation.<br>3. Finally expansion of the underlying mass raises the region into a true mountain range. | The picture due to crustal warp is as follows:—<br>1. Accumulation of sediments in a continually down-warping area.<br>2. Excessive down-warping causes crustal weakness leading to a rapid deepening and narrowing of the trough. The sediments are folded as a result of this narrowing, and surplus sedimentary matter is folded up above the trough, in extreme cases failure and buckling of the crust may also lead to a folding up of the deeper crustal layers. In any case the down-warp necessitates an up-warp in some adjacent area. |
| One other hypothesis is that mountains are raised up by material forced in under them.<br>Isostasy will have none of it. It may be discarded without further consideration, for mountains are in isostatic equilibrium. | It is probable that in India the following have been raised by matter forced in under them:—<br>(*a*) The rejuvenated Arāvallis.<br>(*b*) The Siwāliks.<br>(*c*) The outer ranges of the Himālayas.<br>(*d*) Perhaps also the Salt Range.<br>Generally speaking however the up-warp is so gradual that erosion has kept pace, so mountains elevated in this way are probably exceptional. |

**22. Conclusion.**—A theory has been advanced that gravity anomalies are mainly due to density differences at the interfaces of the three crustal layers. The differences result from the down-warping (down-faulting through shear is not excluded) of the two upper layers. Accompanying the down-warp is an adjacent uprise of the crust.

The theory has been tested numerically and appears to give satisfactory results where there is sufficient geological data to provide an independent check. As a result of the circumstance that positive anomalies are due to phenomena which are less deep-seated than those which cause negative anomalies, and that ordinary downwarpings tend to reach a stable position after reaching a uniform depth—(further warping if it occurs ending in failure of the crust, buckling up of sedimentary rocks etc.,)—the illusion of compensation of topographical features down to a fixed level according to Pratt's system of isostasy is obtained.

Ranges which have been folded up over ancient geosynclines have deep roots which more than compensate them; horst ranges and other "positive" areas of the crust are not due to decreases of density below but rather to the uprising of the denser layers of the crust.

This theory appears to afford a plausible explanation for all the main tectonic features in and around India. Although isostasy as a fact is denied, as an illusion it persists; hence the presentation of gravity results in the form of Hayford anomalies still remains the best method for universal application as a first step towards the investigation of the structure of the Earth's crust.

## TABLE II

| Station No. | Latitude N. | | | Longitude E. | | | Average height | Compensation to 22·7 miles | S. of I.—II | | | INTERNATIONAL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ |
| | ° | ′ | ″ | ° | ′ | ″ | *feet* | $cm/sec^2$ | $cm/sec^2$ | $cm/sec^2$ | $cm/sec^2$ | $cm/sec^2$ | $cm/sec^2$ | $cm/sec^2$ |
| 1 | 30 | 19 | 29 | 78 | 03 | 22 | 2500 | +·028 | −·020 | +·029 | +·033 | −·026 | +·024 | +·034 |
| 2 | 13 | 04 | 08 | 80 | 14 | 54 | 20 | −·001 | −·034 | −·045 | +·002 | −·033 | −·039 | +·007 |
| 3 | 18 | 53 | 45 | 72 | 48 | 47 | 20 | +·003 | −·019 | +·072 | +·100 | −·011 | +·075 | +·095 |
| 4 | 30 | 27 | 28 | 78 | 03 | 33 | 4200 | | −·021 | | | −·026 | | |
| 5 | 30 | 27 | 35 | 78 | 04 | 32 | 4200 | +·038 | −·021 | +·077 | +·072 | −·026 | +·072 | +·072 |
| 6 | 20 | 29 | 05 | 85 | 52 | 01 | 100 | +·001 | +·031 | +·018 | −·002 | +·039 | +·019 | −·009 |
| 7 | 24 | 12 | 40 | 88 | 23 | 27 | 50 | +·001 | +·006 | +·020 | +·025 | −·002 | +·019 | +·032 |
| 8 | 25 | 02 | 26 | 88 | 28 | 29 | 80 | +·001 | −·002 | +·058 | +·071 | −·014 | +·057 | +·082 |
| 9 | 26 | 31 | 16 | 88 | 44 | 13 | 300 | +·003 | −·020 | | +·029 | −·026 | −·003 | +·032 |
| 10 | 26 | 07 | 41 | 88 | 31 | 26 | 200 | +·002 | −·016 | +·021 | +·047 | −·023 | +·019 | +·052 |
| 11 | 25 | 40 | 57 | 88 | 32 | 58 | 100 | +·001 | −·011 | +·035 | +·057 | −·020 | +·033 | +·064 |
| 12 | 26 | 41 | 47 | 88 | 24 | 50 | 1500 | +·008 | −·021 | −·023 | +·002 | −·026 | −·026 | +·004 |
| 13 | 27 | 02 | 47 | 88 | 16 | 08 | 4300 | +·044 | −·025 | +·055 | +·048 | −·028 | +·052 | +·048 |
| 14 | 26 | 52 | 51 | 88 | 16 | 45 | 3100 | +·029 | −·022 | +·030 | +·035 | −·027 | +·027 | +·037 |
| 15 | 27 | 06 | 06 | 88 | 00 | 15 | 4200 | +·056 | −·026 | +·073 | +·055 | −·028 | +·070 | +·054 |
| 16 | 31 | 06 | 19 | 77 | 09 | 50 | 5000 | +·046 | −·022 | +·062 | +·050 | −·027 | +·055 | +·048 |
| 17 | 30 | 50 | 08 | 76 | 56 | 22 | 2400 | +·025 | −·019 | +·040 | +·046 | −·025 | +·035 | +·047 |
| 18 | 30 | 55 | 25 | 75 | 51 | 09 | 900 | +·008 | −·014 | +·024 | +·042 | −·023 | +·018 | +·045 |
| 19 | 31 | 31 | 37 | 74 | 22 | 32 | 700 | +·007 | −·013 | +·063 | +·081 | −·022 | +·057 | +·084 |
| 20 | 30 | 55 | 48 | 74 | 37 | 04 | 650 | +·007 | −·011 | +·060 | +·076 | −·021 | +·054 | +·080 |
| 21 | 32 | 16 | 33 | 75 | 39 | 03 | 1500 | +·014 | −·024 | −·053 | −·031 | −·027 | −·060 | −·035 |
| 22 | 30 | 39 | 47 | 73 | 06 | 18 | 600 | +·005 | −·001 | +·041 | +·049 | −·013 | +·036 | +·056 |
| 23 | 30 | 03 | 49 | 70 | 45 | 38 | 500 | +·004 | +·011 | −·042 | −·045 | +·008 | −·047 | −·047 |
| 24 | 30 | 11 | 11 | 71 | 25 | 51 | 400 | +·004 | +·008 | −·009 | −·009 | +·002 | −·014 | −·008 |
| 25 | 28 | 16 | 34 | 68 | 27 | 05 | 200 | +·002 | +·030 | +·057 | +·037 | +·031 | +·053 | +·032 |
| 26 | 29 | 32 | 46 | 67 | 52 | 31 | 900 | +·007 | +·025 | −·040 | −·060 | +·025 | −·043 | −·063 |
| 27 | 29 | 52 | 25 | 67 | 18 | 20 | 4100 | +·044 | +·024 | +·018 | −·038 | +·024 | +·015 | −·041 |
| 28 | 30 | 12 | 15 | 67 | 00 | 41 | 6200 | +·057 | +·024 | +·030 | −·039 | +·024 | +·025 | −·044 |
| 29 | 29 | 56 | 29 | 78 | 09 | 19 | 1400 | +·014 | −·017 | +·004 | +·019 | −·024 | 000 | +·022 |
| 30 | 29 | 52 | 20 | 77 | 53 | 59 | 1050 | +·009 | −·014 | −·024 | −·007 | −·023 | −·028 | −·002 |
| 31 | 29 | 53 | 28 | 77 | 40 | 25 | 950 | +·009 | −·014 | −·008 | +·009 | −·023 | −·012 | +·014 |
| 32 | 29 | 30 | 55 | 77 | 39 | 06 | 850 | +·008 | −·014 | +·012 | +·030 | −·023 | +·008 | +·035 |
| 33 | 29 | 00 | 26 | 77 | 41 | 40 | 750 | +·007 | −·008 | +·027 | +·040 | −·018 | +·023 | +·046 |
| 34 | 28 | 33 | 02 | 77 | 42 | 03 | 700 | +·007 | −·003 | +·024 | +·032 | −·014 | +·020 | +·039 |
| 35 | 30 | 10 | 53 | 77 | 54 | 37 | 1400 | +·016 | −·018 | +·024 | +·038 | −·025 | +·019 | +·040 |
| 36 | 30 | 14 | 25 | 77 | 58 | 03 | 2500 | +·021 | −·019 | +·025 | +·035 | −·025 | +·020 | +·036 |
| 37 | 30 | 25 | 53 | 77 | 43 | 37 | 3000 | +·025 | −·019 | +·041 | +·047 | −·025 | +·036 | +·048 |
| 38 | 30 | 31 | 08 | 77 | 50 | 26 | 3500 | +·032 | −·020 | +·055 | +·055 | −·026 | +·050 | +·056 |
| 39 | 30 | 24 | 02 | 78 | 05 | 47 | 3600 | +·039 | −·021 | +·049 | +·043 | −·026 | +·044 | +·043 |
| 40 | 13 | 00 | 41 | 77 | 35 | 01 | 2900 | +·026 | −·030 | −·014 | +·002 | −·030 | −·008 | +·008 |
| 41 | 12 | 18 | 52 | 76 | 40 | 20 | 2400 | +·022 | −·026 | −·014 | +·002 | −·026 | −·008 | +·008 |
| 42 | 12 | 55 | 47 | 78 | 15 | 41 | 2200 | +·021 | −·030 | +·018 | +·039 | −·030 | +·024 | +·045 |
| 43 | 11 | 40 | 05 | 78 | 09 | 10 | 1450 | +·012 | −·026 | −·040 | −·014 | −·026 | −·034 | −·008 |
| 44 | 11 | 46 | 56 | 78 | 12 | 29 | 1500 | +·016 | −·027 | −·022 | +·001 | −·027 | −·016 | +·007 |

## TABLE II—*(Contd.)*

| Station No. | Latitude N. | Longitude E. | Average height | Compensation to 22·7 miles | S. of I.—II |  |  | International |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ |
|  | ° ′ ″ | ° ′ ″ | *feet* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* |
| 45 | 11 24 37 | 76 42 03 | 3950 | + ·042 | − ·024 | + ·024 | + ·018 | − ·024 | + ·030 | + ·024 |
| 46 | 10 13 50 | 77 27 56 | 2900 | + ·032 | − ·021 | − ·021 | − ·020 | − ·021 | − ·015 | − ·014 |
| 47 | 23 11 00 | 75 47 00 | 1600 | + ·015 | + ·030 | + ·004 | − ·029 | + ·039 | + ·004 | − ·038 |
| 48 | 22 33 10 | 75 45 40 | 1600 | + ·017 | + ·028 | − ·001 | − ·034 | + ·037 | 000 | − ·042 |
| 49 | 22 23 40 | 75 58 40 | 1100 | + ·011 | + ·027 | − ·005 | − ·031 | + ·036 | − ·004 | − ·039 |
| 50 | 22 13 20 | 76 02 50 | 1000 | + ·008 | + ·026 | + ·018 | − ·004 | + ·036 | + ·019 | − ·013 |
| 51 | 21 49 30 | 76 21 30 | 1100 | + ·008 | + ·025 | + ·060 | + ·039 | + ·034 | + ·061 | + ·031 |
| 52 | 21 28 10 | 76 17 50 | 1450 | + ·012 | + ·022 | + ·045 | + ·023 | + ·031 | + ·046 | + ·015 |
| 53 | 21 00 00 | 75 33 50 | 1100 | + ·008 | + ·017 | + ·034 | + ·021 | + ·025 | + ·036 | + ·015 |
| 54 | 20 55 50 | 77 45 40 | 1200 | + ·011 | + ·021 | + ·042 | + ·022 | + ·030 | + ·044 | + ·015 |
| 55 | 21 18 20 | 77 30 40 | 1450 | + ·016 | + ·023 | + ·045 | + ·018 | + ·033 | + ·046 | + ·009 |
| 56 | 22 45 00 | 77 43 50 | 1200 | + ·011 | + ·030 | + ·035 | + ·006 | + ·039 | + ·036 | − ·002 |
| 57 | 22 11 30 | 77 54 10 | 1800 | + ·016 | + ·029 | + ·038 | + ·005 | + ·038 | + ·039 | − ·003 |
| 58 | 21 54 10 | 77 54 10 | 2000 | + ·020 | + ·030 | + ·051 | + ·013 | + ·038 | + ·052 | + ·006 |
| 59 | 23 51 47 | 78 48 | 1600 | + ·015 | + ·032 | + ·026 | − ·009 | + ·036 | + ·026 | − ·013 |
| 60 | 23 49 54 | 79 26 | 1400 | + ·009 | + ·031 | + ·019 | − ·009 | + ·034 | + ·019 | − ·012 |
| 61 | 23 50 25 | 80 26 | 1400 | + ·013 | + ·030 | + ·022 | − ·009 | + ·031 | + ·021 | − ·011 |
| 62 | 23 31 37 | 80 54 | 1600 | + ·016 | + ·031 | + ·045 | + ·010 | + ·033 | + ·044 | + ·007 |
| 63 | 22 46 41 | 82 00 | 2300 | + ·019 | + ·032 | + ·024 | − ·015 | + ·036 | + ·024 | − ·019 |
| 64 | 22 03 53 | 82 12 | 1100 | + ·009 | + ·032 | + ·029 | 000 | + ·038 | + ·030 | − ·005 |
| 65 | 21 13 56 | 81 41 | 950 | + ·009 | + ·030 | + ·012 | − ·015 | + ·038 | + ·012 | − ·023 |
| 66 | 21 21 31 | 80 28 | 1350 | + ·011 | + ·028 | + ·011 | − ·016 | + ·038 | + ·011 | − ·026 |
| 67 | 22 05 29 | 77 29 | 1600 | + ·018 | + ·030 | + ·051 | + ·015 | + ·039 | + ·052 | + ·007 |
| 68 | 23 08 54 | 79 59 | 1550 | + ·013 | + ·032 | + ·046 | + ·013 | + ·037 | + ·046 | + ·008 |
| 69 | 24 15 38 | 80 48 | 1250 | + ·011 | + ·027 | + ·013 | − ·013 | + ·027 | + ·012 | − ·014 |
| 70 | 25 25 55 | 81 55 | 350 | + ·004 | + ·011 | + ·024 | + ·021 | + ·008 | + ·023 | + ·023 |
| 71 | 26 16 06 | 82 04 36 | 300 | + ·004 | + ·003 | − ·009 | − ·004 | − ·007 | − ·011 | + ·004 |
| 72 | 16 47 55 | 96 09 08 |  |  |  | + ·027 |  |  | + ·030 |  |
| 73 | 18 49 40 | 95 13 40 |  |  |  | + ·009 |  |  | + ·012 |  |
| 74 | 17 39 17 | 95 27 18 |  |  |  | − ·007 |  |  | − ·004 |  |
| 75 | 16 47 11 | 94 44 06 |  |  |  | + ·015 |  |  | + ·019 |  |
| 76 | 18 55 50 | 96 27 03 |  |  |  | + ·038 |  |  | + ·041 |  |
| 77 | 19 44 25 | 96 11 56 |  |  |  | + ·038 |  |  | + ·041 |  |
| 78 | 20 51 26 | 95 51 58 |  |  |  | + ·035 |  |  | + ·037 |  |
| 79 | 21 59 44 | 96 06 28 |  |  |  | + ·042 |  |  | + ·043 |  |
| 80 | 22 01 13 | 96 28 24 |  |  |  | + ·035 |  |  | + ·036 |  |
| 81 | 22 54 51 | 96 29 51 |  |  |  | + ·048 |  |  | + ·048 |  |
| 82 | 21 28 56 | 95 23 50 |  |  |  | + ·029 |  |  | + ·030 |  |
| 83 | 24 31 58 | 84 00 | 500 | + ·006 | + ·013 | + ·019 | + ·012 | + ·010 | + ·018 | + ·014 |
| 84 | 24 02 05 | 84 04 | 800 | + ·007 | + ·017 | + ·040 | + ·028 | + ·017 | + ·040 | + ·028 |
| 85 | 23 23 05 | 85 19 | 2000 | + ·019 | + ·022 | + ·045 | + ·016 | + ·022 | + ·045 | + ·016 |
| 86 | 24 47 42 | 85 00 | 350 | + ·004 | + ·006 | + ·018 | + ·020 | − ·002 | + ·018 | + ·028 |
| 87 | 25 22 53 | 86 28 | 200 | + ·002 | − ·003 | − ·005 | + ·008 | − ·014 | − ·006 | + ·018 |
| 88 | 25 34 10 | 84 39 | 200 | + ·002 | + ·001 | − ·010 | − ·001 | − ·010 | − ·012 | + ·008 |

## TABLE II—*(Contd.)*

| Station No. | Latitude N. | | | Longitude E. | | | Average height | Compensation to 22·7 miles | S. of I.—II | | | INTERNATIONAL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ |
| | ° | ′ | ″ | ° | ′ | ″ | *feet* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* |
| 89 | 24 | 57 | 21 | 83 | 59 | | 400 | +·005 | +·008 | +·027 | +·026 | +·002 | +·026 | +·031 |
| 90 | 25 | 17 | 03 | 83 | 06 | | 300 | +·003 | +·006 | +·013 | +·016 | −·002 | +·012 | +·023 |
| 91 | 25 | 34 | 42 | 83 | 59 | | 200 | +·002 | +·002 | +·004 | +·012 | −·008 | +·002 | +·020 |
| 92 | 26 | 07 | 05 | 85 | 25 | | 200 | +·002 | −·009 | −·024 | −·005 | −·019 | −·026 | +·003 |
| 93 | 26 | 17 | 46 | 83 | 58 | | 200 | +·002 | −·005 | −·039 | −·024 | −·016 | −·041 | −·015 |
| 94 | 26 | 44 | 58 | 83 | 23 | | 250 | +·003 | −·011 | −·053 | −·033 | −·020 | −·055 | −·026 |
| 95 | 24 | 41 | 29 | 78 | 24 | 26 | 1400 | +·012 | +·029 | +·015 | −·014 | +·031 | +·014 | −·017 |
| 96 | 24 | 10 | 41 | 78 | 11 | 46 | 1500 | +·013 | +·032 | +·042 | +·009 | +·034 | +·041 | +·006 |
| 97 | 23 | 15 | 58 | 77 | 25 | 00 | 1600 | +·015 | +·032 | +·035 | 000 | +·039 | +·035 | −·007 |
| 98 | 24 | 38 | 48 | 77 | 19 | 13 | 1400 | +·015 | +·032 | +·039 | +·004 | +·034 | +·038 | +·001 |
| 99 | 24 | 07 | 11 | 77 | 39 | 17 | 1600 | +·015 | +·032 | +·058 | +·023 | +·036 | +·057 | +·018 |
| 100 | 25 | 27 | 02 | 78 | 33 | 43 | 800 | +·008 | +·022 | +·032 | +·014 | +·022 | +·031 | +·013 |
| 101 | 26 | 13 | 57 | 78 | 12 | 49 | 800 | +·007 | +·017 | +·010 | −·002 | +·017 | +·008 | −·004 |
| 102 | 25 | 25 | 52 | 77 | 39 | 25 | 1250 | +·013 | +·026 | +·047 | +·020 | +·026 | +·046 | +·019 |
| 103 | 26 | 42 | 01 | 77 | 54 | 47 | 700 | +·005 | +·014 | +·012 | +·005 | +·011 | +·010 | +·006 |
| 104 | 27 | 10 | 20 | 78 | 01 | 07 | 550 | +·005 | +·008 | +·036 | +·035 | +·002 | +·033 | +·038 |
| 105 | 27 | 28 | 25 | 77 | 41 | 48 | 550 | +·005 | +·007 | +·033 | +·033 | 000 | +·030 | +·037 |
| 106 | 27 | 36 | 52 | 78 | 03 | 22 | 550 | +·005 | +·004 | +·030 | +·033 | −·005 | +·027 | +·039 |
| 107 | 27 | 53 | 32 | 78 | 00 | 31 | 600 | +·006 | +·002 | +·013 | +·017 | −·009 | +·010 | +·025 |
| 108 | 28 | 14 | 19 | 77 | 51 | 53 | 650 | +·006 | 000 | 000 | +·006 | −·012 | −·004 | +·014 |
| 109 | 18 | 38 | 30 | 72 | 52 | 10 | 100 | +·001 | −·021 | +·008 | +·040 | −·015 | +·011 | +·037 |
| 110 | 21 | 10 | 05 | 72 | 48 | 05 | 20 | +·001 | +·009 | +·045 | +·047 | +·017 | +·046 | +·040 |
| 111 | 22 | 18 | 35 | 73 | 11 | 05 | 150 | +·001 | +·021 | +·006 | −·004 | +·030 | +·006 | −·013 |
| 112 | 23 | 01 | 20 | 72 | 33 | 55 | 150 | +·002 | +·025 | +·051 | +·036 | +·035 | +·051 | +·026 |
| 113 | 20 | 24 | 45 | 72 | 50 | 05 | 100 | 000 | +·001 | +·061 | +·072 | +·010 | +·064 | +·066 |
| 114 | 24 | 15 | 20 | 72 | 11 | 30 | 550 | +·005 | +·030 | +·063 | +·040 | +·039 | +·062 | +·030 |
| 115 | 24 | 35 | 40 | 72 | 43 | 00 | 1200 | +·015 | +·032 | +·047 | +·012 | +·038 | +·046 | +·005 |
| 116 | 21 | 42 | 05 | 72 | 59 | 00 | 50 | +·001 | +·016 | +·029 | +·024 | +·024 | +·030 | +·017 |
| 117 | 25 | 08 | 55 | 73 | 03 | 35 | 1200 | +·010 | +·032 | +·041 | +·011 | +·036 | +·040 | +·006 |
| 118 | 25 | 47 | 30 | 73 | 19 | 25 | 800 | +·007 | +·030 | +·038 | +·013 | +·032 | +·036 | +·009 |
| 119 | 26 | 47 | 00 | 79 | 00 | 55 | 500 | +·005 | +·008 | +·003 | +·002 | +·002 | +·001 | +·006 |
| 120 | 27 | 22 | 06 | 79 | 38 | 00 | 500 | +·005 | +·001 | −·011 | −·005 | −·010 | −·014 | +·003 |
| 121 | 28 | 39 | 05 | 79 | 49 | 31 | 650 | +·006 | −·012 | −·038 | −·020 | −·021 | −·042 | −·015 |
| 122 | 27 | 54 | 21 | 79 | 55 | 52 | 550 | +·005 | −·006 | −·020 | −·007 | −·017 | −·023 | +·001 |
| 123 | 27 | 33 | 13 | 80 | 41 | 08 | 450 | +·004 | −·005 | −·036 | −·023 | −·016 | −·039 | −·015 |
| 124 | 28 | 27 | 39 | 80 | 44 | 24 | 900 | +·006 | −·016 | −·051 | −·029 | −·023 | −·055 | −·026 |
| 125 | 27 | 34 | 02 | 81 | 35 | 41 | 400 | +·004 | −·010 | −·044 | −·026 | −·020 | −·047 | −·019 |
| 126 | 27 | 08 | 21 | 81 | 56 | 25 | 350 | +·003 | −·006 | −·065 | −·050 | −·017 | −·068 | −·042 |
| 127 | 27 | 31 | 43 | 82 | 35 | 45 | 550 | +·005 | −·013 | −·072 | −·052 | −·022 | −·075 | −·046 |
| 128 | 27 | 08 | 06 | 84 | 03 | 05 | 500 | +·003 | −·017 | −·070 | −·044 | −·024 | −·073 | −·040 |
| 129 | 26 | 39 | 10 | 84 | 54 | 35 | 200 | +·002 | −·015 | −·081 | −·056 | −·023 | −·084 | −·051 |
| 130 | 32 | 26 | 48 | 74 | 06 | 28 | 800 | +·007 | −·019 | +·021 | +·045 | −·025 | +·014 | +·044 |
| 131 | 32 | 55 | 20 | 73 | 42 | 41 | 1200 | +·009 | −·021 | 000 | +·024 | −·026 | −·008 | +·021 |
| 132 | 33 | 36 | 41 | 73 | 01 | 07 | 2100 | +·017 | −·021 | −·024 | −·008 | −·026 | −·032 | −·011 |

## TABLE II—*(Contd.)*

| Station No. | Latitude N. | | | Longitude E. | | | Average height | Compensation to 22·7 miles | S. of I.—II | | | International | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ | Hidden Range effect | $g-\gamma_C$ | $g-\gamma$ |
| | ° | ′ | ″ | ° | ′ | ″ | *feet* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* |
| 133 | 33 | 54 | 07 | 73 | 23 | 15 | 3900 | + ·036 | − ·025 | 000 | + ·001 | − ·028 | − ·008 | − ·004 |
| 134 | 34 | 21 | 08 | 73 | 28 | 07 | 6300 | + ·045 | − ·029 | − 023 | − ·027 | − ·029 | − ·031 | − ·035 |
| 135 | 34 | 11 | 14 | 74 | 41 | 00 | 7200 | + 058 | − ·033 | − ·005 | − ·018 | − ·031 | − ·013 | − ·028 |
| 136 | 34 | 12 | 48 | 74 | 46 | 09 | 7200 | + ·064 | − ·033 | + ·036 | + ·017 | − ·031 | + ·028 | + ·007 |
| 137 | 34 | 13 | 54 | 74 | 58 | 29 | 9500 | + ·088 | − ·034 | + ·045 | + ·003 | − ·031 | + ·037 | − ·008 |
| 138 | 34 | 18 | 02 | 75 | 16 | 19 | 11800 | + ·107 | − ·035 | + ·072 | + ·012 | − 032 | + ·064 | + ·001 |
| 139 | 34 | 39 | 32 | 74 | 54 | 01 | 11500 | + ·106 | − ·035 | + ·060 | + ·001 | − ·032 | + ·052 | − ·010 |
| 140 | 34 | 47 | 30 | 75 | 04 | 49 | 13000 | + ·109 | − ·036 | + ·064 | + ·003 | − ·033 | + ·056 | − ·008 |
| 141 | 34 | 57 | 21 | 75 | 14 | 41 | 12400 | + ·116 | − ·037 | + ·121 | + ·054 | − ·033 | + ·113 | + ·042 |
| 142 | 35 | 02 | 04 | 75 | 23 | 47 | 13100 | + ·118 | − ·036 | + ·093 | + ·023 | − ·033 | + ·084 | + ·011 |
| 143 | 34 | 55 | 47 | 75 | 25 | 38 | 13100 | + ·119 | − ·036 | + ·125 | + ·054 | − ·033 | + ·117 | + ·043 |
| 144 | 34 | 05 | 37 | 74 | 32 | 12 | 7500 | + ·061 | − ·032 | + ·043 | + ·026 | − ·030 | + ·035 | + ·016 |
| 145 | 34 | 04 | 36 | 74 | 49 | 27 | 7800 | + ·061 | − ·033 | + ·048 | + ·032 | − ·031 | + ·040 | + ·022 |
| 146 | 33 | 54 | 23 | 74 | 55 | 59 | 8200 | + ·060 | − ·033 | + ·034 | + ·019 | − ·031 | + ·026 | + ·009 |
| 147 | 33 | 49 | 57 | 74 | 39 | 57 | 8400 | + ·070 | − ·029 | + ·033 | + ·004 | − ·029 | + ·025 | − ·004 |
| 148 | 33 | 48 | 32 | 74 | 33 | 19 | 7800 | + ·077 | − ·029 | + ·060 | + ·024 | − ·029 | + ·052 | + ·016 |
| 149 | 33 | 55 | 18 | 74 | 29 | 58 | 7800 | + ·075 | − ·029 | + ·077 | + ·043 | − ·029 | + ·069 | + ·035 |
| 150 | 24 | 50 | 17 | 67 | 02 | 46 | 30 | + ·001 | + ·027 | + ·037 | + ·021 | + ·037 | + ·036 | + ·010 |
| 151 | 25 | 26 | 03 | 65 | 49 | 44 | 400 | + ·002 | + ·028 | − ·005 | − ·023 | + ·038 | − ·006 | − ·034 |
| 152 | 25 | 39 | 16 | 66 | 22 | 26 | 500 | + ·002 | + ·029 | 000 | − ·019 | + ·038 | − ·002 | − ·030 |
| 153 | 25 | 06 | 36 | 66 | 43 | 52 | 200 | + ·001 | + ·028 | + ·029 | + ·012 | + ·037 | + ·028 | + ·002 |
| 154 | 24 | 51 | 18 | 67 | 36 | 06 | 200 | + ·002 | + ·028 | + ·042 | + ·024 | + ·037 | + ·041 | + ·014 |
| 155 | 24 | 41 | 51 | 68 | 03 | 39 | 50 | + ·001 | + ·028 | + ·030 | + ·013 | + ·037 | + ·029 | + ·003 |
| 156 | 24 | 42 | 55 | 68 | 34 | 26 | 50 | 000 | + ·028 | + ·031 | + ·015 | + ·038 | + ·030 | + ·004 |
| 157 | 25 | 22 | 59 | 68 | 21 | 17 | 150 | + ·001 | + ·030 | + ·026 | + ·007 | + ·039 | + ·024 | − ·004 |
| 158 | 28 | 53 | 31 | 64 | 24 | 54 | 3500 | + ·029 | + ·032 | + ·029 | − ·020 | + ·037 | + ·025 | − ·029 |
| 159 | 27 | 56 | 29 | 63 | 02 | 55 | 1900 | + ·017 | + ·031 | + ·012 | − ·024 | + ·039 | + ·008 | − ·036 |
| 160 | 28 | 00 | 40 | 63 | 05 | 59 | 1800 | + ·015 | + ·031 | + ·011 | − ·023 | + ·039 | + ·007 | − ·035 |
| 161 | 28 | 07 | 18 | 63 | 14 | | 1800 | + ·015 | + ·031 | + ·013 | − ·021 | + ·039 | + ·009 | − ·033 |
| 162 | 28 | 21 | 14 | 62 | 59 | 52 | 1800 | + ·015 | + ·032 | + ·026 | − ·009 | + ·039 | + ·022 | − ·020 |
| 163 | 28 | 49 | 34 | 62 | 44 | 42 | 2400 | + ·022 | + ·032 | + ·038 | − ·004 | + ·038 | + ·034 | − ·014 |
| 164 | 28 | 51 | 57 | 61 | 54 | 26 | 2800 | + ·026 | + 031 | + ·068 | + ·023 | + ·039 | + ·064 | + ·011 |
| 165 | 28 | 44 | 39 | 63 | 50 | 52 | 2700 | + ·025 | + ·032 | + ·033 | − ·012 | + ·038 | + ·029 | − ·022 |
| 166 | 29 | 32 | 27 | 66 | 02 | 43 | 4300 | + ·038 | + ·029 | + ·037 | − ·018 | + ·031 | + ·033 | − ·024 |
| 167 | 32 | 16 | 20 | 72 | 28 | 36 | 900 | + ·006 | − ·011 | + ·059 | + ·076 | − ·021 | + ·052 | + ·079 |
| 168 | 21 | 20 | 08 | 86 | 45 | 52 | 100 | 000 | + ·032 | 000 | − ·020 | + ·036 | + ·001 | − ·023 |
| 169 | 19 | 21 | 14 | 84 | 59 | | 200 | + ·001 | + ·027 | + ·039 | + ·023 | + ·037 | + ·042 | + ·016 |
| 170 | 18 | 22 | 00 | 83 | 51 | 50 | 200 | + ·001 | + ·017 | + ·007 | + ·001 | + ·026 | + ·010 | − ·005 |
| 171 | 18 | 45 | 20 | 83 | 18 | 40 | 1000 | + ·005 | + ·019 | + ·005 | − ·007 | + ·028 | + ·008 | − ·013 |
| 172 | 17 | 34 | 30 | 83 | 16 | 50 | 100 | 000 | + ·008 | + ·031 | + ·035 | + ·016 | + ·034 | + ·030 |
| 173 | 16 | 59 | 00 | 82 | 14 | 40 | 150 | 000 | − ·004 | + ·004 | + ·020 | + ·005 | + ·008 | + ·015 |
| 174 | 16 | 30 | 19 | 80 | 37 | 46 | 150 | + ·001 | − ·019 | + 009 | + ·039 | − ·010 | + ·012 | + ·033 |
| 175 | 17 | 36 | 08 | 80 | 19 | 05 | 700 | + ·006 | − ·004 | − ·001 | + ·009 | + ·005 | + ·002 | + ·003 |
| 176 | 15 | 29 | 57 | 80 | 02 | 42 | 100 | + ·001 | − ·030 | + ·001 | + ·042 | − ·023 | + ·005 | + ·039 |

## TABLE II—(*Contd.*)

| Station No. | Latitude N. | | | Longitude E. | | | Average height | Compensation to 22·7 miles | S. of I.—II | | | INTERNATIONAL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ |
| | ° | ′ | ″ | ° | ′ | ″ | *feet* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* |
| 177 | 14 | 08 | 36 | 79 | 50 | 53 | 100 | +·001 | −·036 | −·036 | +·011 | −·030 | −·031 | +·010 |
| 178 | 12 | 54 | 51 | 79 | 07 | 45 | 500 | +·009 | −·032 | −·033 | +·002 | −·032 | −·027 | +·008 |
| 179 | 11 | 45 | 20 | 79 | 45 | 20 | 50 | −·001 | −·029 | −·018 | +·024 | −·029 | −·012 | +·030 |
| 180 | 10 | 46 | 57 | 79 | 50 | 50 | 20 | 000 | −·025 | −·058 | −·021 | −·025 | −·052 | −·015 |
| 181 | 10 | 47 | 58 | 78 | 40 | 46 | 450 | +·003 | −·024 | −·033 | 000 | −·024 | −·027 | +·006 |
| 182 | 10 | 21 | 00 | 77 | 59 | 01 | 1750 | +·011 | −·022 | −·052 | −·029 | −·022 | −·046 | −·023 |
| 183 | 9 | 55 | 34 | 78 | 08 | 24 | 900 | +·005 | −·020 | −·051 | −·024 | −·020 | −·046 | −·043 |
| 184 | 30 | 41 | 58 | 77 | 52 | 10 | 5100 | +·046 | −·022 | +·090 | +·078 | −·027 | +·085 | +·078 |
| 185 | 18 | 27 | 55 | 74 | 34 | 50 | 1850 | +·017 | −·017 | −·027 | −·015 | −·009 | +·024 | −·020 |
| 186 | 18 | 05 | 34 | 75 | 24 | 57 | 1700 | +·016 | −·020 | −·028 | −·012 | −·013 | −·025 | −·016 |
| 187 | 17 | 39 | 24 | 75 | 54 | 27 | 1600 | +·014 | −·023 | −·018 | +·003 | −·017 | −·014 | +·001 |
| 188 | 16 | 49 | 39 | 75 | 43 | 30 | 1800 | +·018 | −·031 | −·004 | +·021 | −·024 | −·001 | +·017 |
| 189 | 16 | 11 | 22 | 75 | 41 | 45 | 1850 | +·017 | −·036 | −·017 | +·014 | −·028 | −·013 | +·010 |
| 190 | 15 | 25 | 38 | 75 | 37 | 57 | 1900 | +·019 | −·036 | −·003 | +·026 | −·031 | +·001 | +·025 |
| 191 | 15 | 16 | 27 | 76 | 23 | 20 | 1700 | +·016 | −·036 | −·016 | +·016 | −·031 | −·012 | +·015 |
| 192 | 14 | 49 | 24 | 76 | 12 | 54 | 2000 | +·018 | −·035 | −·016 | +·013 | −·033 | −·012 | +·015 |
| 193 | 14 | 41 | 42 | 76 | 51 | 36 | 1800 | +·017 | −·035 | −·009 | +·021 | −·032 | −·005 | +·022 |
| 194 | 15 | 09 | 58 | 77 | 22 | 21 | 1450 | +·014 | −·036 | −·031 | +·003 | −·030 | −·027 | +·001 |
| 195 | 15 | 27 | 40 | 78 | 28 | 59 | 1000 | +·008 | −·034 | −·059 | −·021 | −·027 | −·055 | −·024 |
| 196 | 15 | 35 | 14 | 79 | 07 | 01 | 800 | +·011 | −·032 | −·067 | −·034 | −·025 | −·063 | −·037 |
| 197 | 14 | 24 | 43 | 77 | 43 | 00 | 1500 | +·014 | −·035 | −·034 | −·001 | −·032 | −·029 | +·001 |
| 198 | 13 | 48 | 01 | 78 | 15 | 58 | 2200 | +·019 | −·034 | −·018 | +·009 | −·033 | −·013 | +·013 |
| 199 | 13 | 38 | 06 | 79 | 30 | 25 | 600 | +·007 | −·035 | −·064 | −·024 | −·033 | −·059 | −·021 |
| 200 | 14 | 17 | 52 | 78 | 49 | 29 | 850 | +·008 | −·036 | −·062 | −·022 | −·031 | −·057 | −·022 |
| 201 | 16 | 11 | 23 | 77 | 20 | 43 | 1200 | +·012 | −·032 | −·030 | +·002 | −·025 | −·026 | −·001 |
| 202 | 17 | 03 | 17 | 76 | 59 | 31 | 1500 | +·013 | −·025 | −·023 | +·001 | −·020 | −·020 | −·001 |
| 203 | 17 | 26 | 40 | 78 | 28 | 30 | 1700 | +·016 | −·016 | −·011 | +·001 | −·008 | −·008 | −·004 |
| 204 | 18 | 45 | 36 | 79 | 26 | 10 | 700 | +·006 | +·005 | +·006 | +·007 | +·013 | +·009 | +·002 |
| 205 | 19 | 57 | 56 | 79 | 17 | 38 | 650 | +·006 | +·017 | +·012 | +·001 | +·026 | +·014 | −·006 |
| 206 | 28 | 02 | 05 | 70 | 00 | 28 | | +·002 | +·028 | +·035 | +·017 | +·028 | +·032 | +·014 |
| 207 | 27 | 59 | 23 | 70 | 44 | 26 | | +·003 | +·026 | −·001 | −·018 | +·026 | −·004 | −·021 |
| 208 | 27 | 57 | 12 | 71 | 25 | 24 | | +·003 | +·024 | +·042 | +·027 | +·024 | +·039 | +·024 |
| 209 | 27 | 53 | 40 | 71 | 44 | 42 | | +·004 | +·024 | +·027 | +·011 | +·020 | +·023 | +·007 |
| 210 | 27 | 53 | 37 | 71 | 57 | 17 | | +·004 | +·022 | +·035 | +·021 | +·022 | +·031 | +·017 |
| 211 | 27 | 59 | 57 | 72 | 14 | 42 | | +·004 | +·020 | +·031 | +·019 | +·020 | +·027 | +·015 |
| 212 | 27 | 50 | 05 | 72 | 57 | 20 | | +·007 | +·019 | +·027 | +·013 | +·019 | +·024 | +·010 |
| 213 | 28 | 04 | 20 | 74 | 37 | 05 | | +·010 | +·012 | +·043 | +·033 | +·010 | +·040 | +·032 |
| 214 | 26 | 53 | 59 | 74 | 19 | 25 | | +·011 | +·024 | +·002 | −·021 | +·024 | −·001 | −·024 |
| 215 | 26 | 28 | 18 | 74 | 38 | 42 | 1450 | +·015 | +·027 | +·080 | +·050 | +·027 | +·076 | +·047 |
| 216 | 24 | 27 | 50 | 74 | 50 | 48 | 1550 | +·015 | +·032 | +·011 | −·024 | +·038 | +·011 | −·030 |
| 217 | 23 | 20 | 02 | 75 | 03 | 03 | 1400 | +·015 | +·030 | +·028 | −·005 | +·039 | +·028 | −·014 |
| 218 | 23 | 22 | 46 | 76 | 43 | 32 | 1370 | +·014 | +·031 | +·042 | +·009 | +·039 | +·042 | +·001 |
| 219 | 22 | 45 | 08 | 78 | 21 | 22 | 1400 | +·012 | +·031 | −·007 | −·038 | +·039 | −·006 | −·045 |
| 220 | 22 | 28 | 23 | 78 | 25 | 42 | 2000 | +·020 | +·030 | −·006 | −·044 | +·039 | −·006 | −·053 |

## TABLE II—*(Concld.)*

| Station No. | Latitude N. | | | Longitude E. | | | Average height | Compensation to 22·7 miles | S. of I.—II | | | INTERNATIONAL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ | Hidden Range effect | $g-\gamma_C$ | $g-\gamma_F$ |
| | ° | ′ | ″ | ° | ′ | ″ | *feet* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* |
| 221 | 22 | 56 | 37 | 79 | 12 | 40 | 1600 | + ·012 | + ·032 | + ·020 | − ·012 | + ·038 | + ·020 | − ·018 |
| 222 | 25 | 12 | 09 | 75 | 53 | 15 | | + ·008 | + ·030 | + ·019 | − ·007 | + ·032 | + ·018 | − ·010 |
| 223 | 26 | 01 | 05 | 76 | 21 | 36 | | + ·009 | + ·025 | − ·003 | − ·025 | + ·025 | − ·005 | − ·027 |
| 224 | 27 | 22 | 07 | 75 | 33 | 47 | | + ·015 | + ·015 | + ·063 | + ·044 | + ·014 | + ·059 | + ·042 |
| 225 | 28 | 11 | 56 | 76 | 36 | 30 | | + ·008 | + ·004 | + ·031 | + ·031 | − ·005 | + ·027 | + ·036 |
| 226 | 29 | 09 | 14 | 75 | 43 | 18 | | + ·007 | 000 | + ·028 | + ·033 | − ·012 | + ·024 | + ·041 |
| 227 | 30 | 20 | 13 | 76 | 50 | 00 | | + ·009 | − ·016 | + ·013 | + ·031 | − ·023 | + ·006 | + ·032 |
| *Wozul Hadur* | 35 | 11 | 56 | 75 | 32 | 19 | 12100 | + ·116 | − ·037 | + ·069 | + ·002 | − ·033 | + ·060 | − ·011 |
| *Skārdu* | 35 | 17 | 50 | 75 | 38 | 32 | 12100 | + ·108 | − ·037 | + ·044 | − ·015 | − ·033 | + ·034 | − ·029 |
| *Depsang* | 35 | 17 | 24 | 77 | 58 | 24 | 18200 | + ·134 | − ·034 | + ·013 | − ·075 | − ·030 | + ·003 | − ·089 |
| *Yār-kand* | 38 | 24 | 22 | 77 | 15 | 46 | 3990 | + ·039 | − ·027 | − ·025 | − ·025 | − ·023 | − ·036 | − ·040 |

## TABLE III

*Sea-level anomalies due to elevation or depression of crustal layers*

| Elevation or Depression | ELEVATION | | | DEPRESSION | | |
|---|---|---|---|---|---|---|
| | Level of Hidden Range | | | Level of Hidden Range | | |
| | + 5000 *feet* | Zero | − 5000 *feet* | + 5000 *feet* | Zero | − 5000 *feet* |
| | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* | *cm/sec²* |
| 5000 *feet* | + ·0205 | + ·0194 | + ·0185 | − ·0185 | − ·0174 | − ·0167 |
| 10000 *feet* | + ·0410 | + ·0388 | + ·0370 | − ·0370 | − ·0347 | − ·0333 |
| 20000 *feet* | + ·0864 | + ·0819 | + ·0780 | − ·0703 | − ·0669 | − ·0634 |
| 30000 *feet* | ... | ... | ... | − ·0997 | − ·0937 | − ·0871 |
| 40000 *feet* | ... | ... | ... | − ·1275 | − ·1183 | − ·1086 |

## TABLE IV

*Effects of outer Zones in cm/sec²*

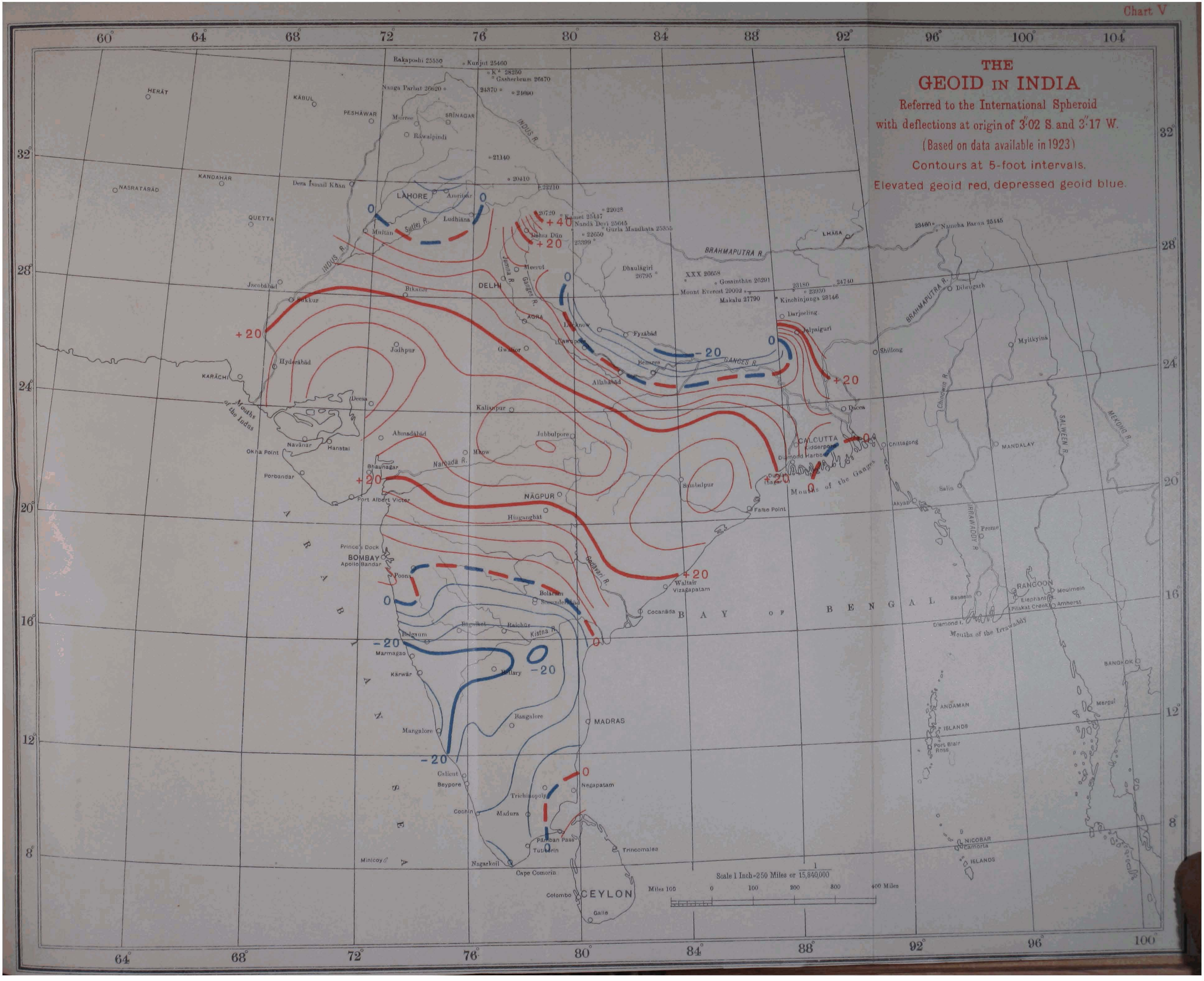
| Zone | Crustal layers Elevated | | Crustal layers Depressed | | | |
|---|---|---|---|---|---|---|
| | 10000 *feet* | 20000 *feet* | 10000 *feet* | 20000 *feet* | 30000 *feet* | 40000 *feet* |
| A | + ·0130 | + ·0249 | − ·0132 | − ·0276 | − ·0446 | − ·0593 |
| B | + ·0075 | + ·0161 | − ·0097 | − ·0190 | − ·0282 | − ·0370 |
| C | + ·0053 | + ·0088 | − ·0051 | − ·0101 | − ·0175 | − ·0253 |
| D | + ·0096 | + ·0180 | − ·0055 | − ·0110 | − ·0168 | − ·0225 |
| E | + ·0028 | + ·0052 | − ·0026 | − ·0055 | − ·0086 | − ·0117 |
| F | + ·0018 | + ·0033 | − ·0019 | − ·0041 | − ·0065 | − ·0089 |

## TABLE V

*Radii of Zones*

| Zone | Radii in feet | | Radii in miles | |
|---|---|---|---|---|
| | Inner | Outer | Inner | Outer |
| A | 120000 | 200000 | 22·7 | 37·9 |
| B | 200000 | 300000 | 37·9 | 56·8 |
| C | 300000 | 400000 | 56·8 | 75·8 |
| D | 400000 | 600000 | 75·8 | 112·6 |
| E | 600000 | 800000 | 112·6 | 151·5 |
| F | 800000 | 1000000 | 151·5 | 189·4 |

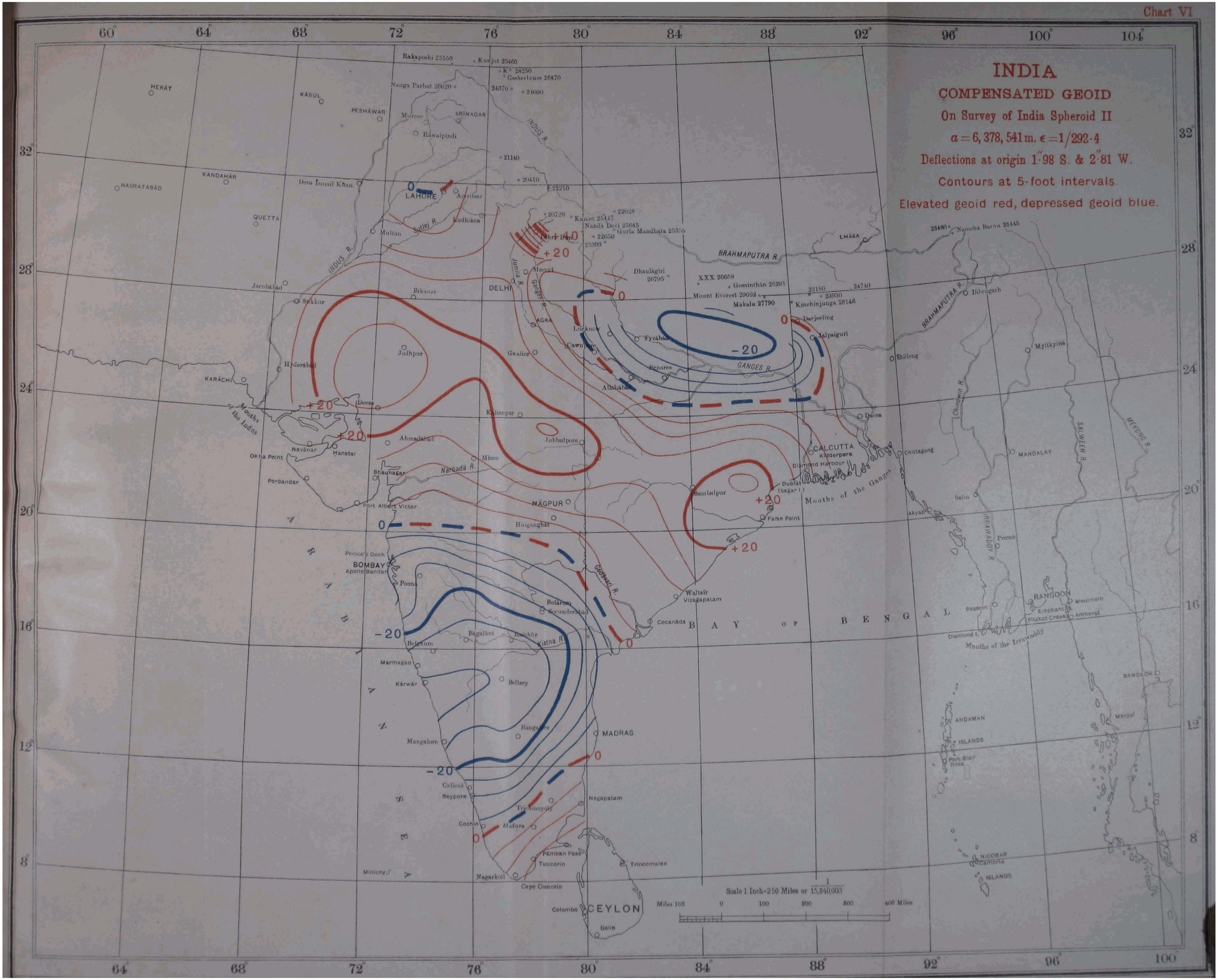
Chart V



# THE GEOID IN INDIA

Referred to the International Spheroid
with deflections at origin of 3".02 S. and 3".17 W.
(Based on data available in 1923)
Contours at 5-foot intervals.
Elevated geoid red, depressed geoid blue.

Scale 1 Inch = 250 Miles or $\frac{1}{15,840,000}$



# INDIA

## COMPENSATED GEOID

On Survey of India Spheroid II

$a = 6{,}378{,}541\text{m.}\ \epsilon = 1/292{\cdot}4$

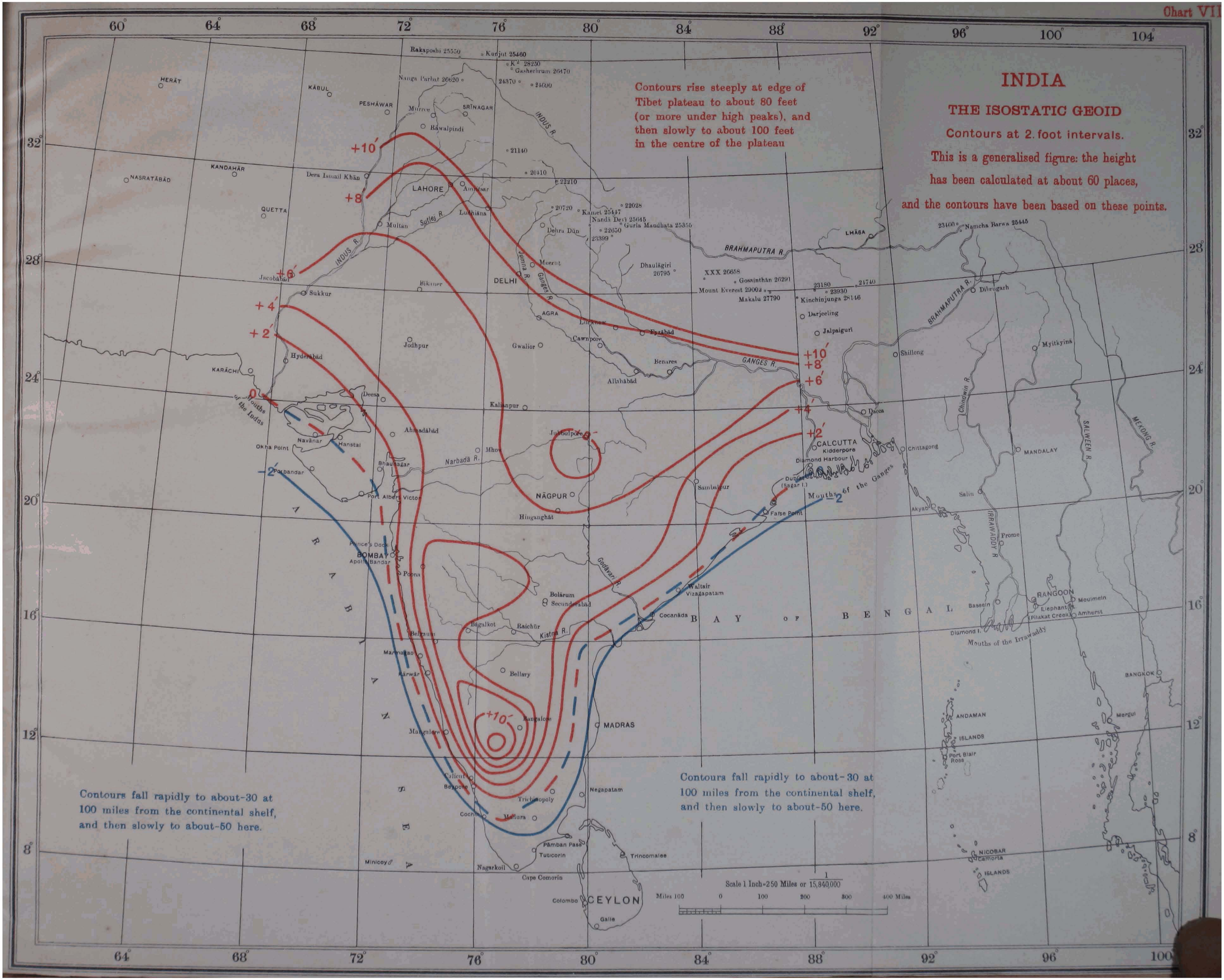
Deflections at origin 1″98 S. & 2″81 W.

Contours at 5-foot intervals.

Elevated geoid red, depressed geoid blue.

Scale 1 Inch=250 Miles or $\frac{1}{15{,}840{,}000}$

Chart VII



# INDIA

## THE ISOSTATIC GEOID

Contours at 2. foot intervals.

This is a generalised figure: the height has been calculated at about 60 places, and the contours have been based on these points.

Contours rise steeply at edge of Tibet plateau to about 80 feet (or more under high peaks), and then slowly to about 100 feet in the centre of the plateau

Contours fall rapidly to about -30 at 100 miles from the continental shelf, and then slowly to about -50 here.

Contours fall rapidly to about -30 at 100 miles from the continental shelf, and then slowly to about -50 here.

Scale 1 Inch=250 Miles or $\frac{1}{15,840,000}$