*To* ..............................................

*With the Author's compliments.*



# THE SUPPORT OF THE MOUNTAINS OF CENTRAL ASIA (BEING AN APPENDIX TO THE MEMOIR ON THE STRUCTURE OF THE HIMALAYAS, AND OF THE GANGETIC PLAIN, AS ELUCIDATED BY GEODETIC OBSERVATIONS IN INDIA).

BY

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(With Plate 3.)

[ From the Records, Geological Survey of India, Vol. XLIX, Part 2, 1918. ]

# The Support of the Mountains of Central Asia (Being an Appendix to the Memoir on the Structure of the Himalayas, and of the Gangetic Plain, as elucidated by Geodetic Observations in India). By R. D. Oldham, F.R.S. (With Plate 3).

In the memoir on "The Structure of the Himalayas and of the Gangetic Plain, as elucidated by Geodetic Observations in India,"[1] it was shown that the outer zone of the hills was a region of partial defect of compensation, or, in other words, of super-elevation of the surface, which increased in amount from the outer edge of the hills to as far in as definite observations have been made. This being only about 40 miles, the ultimate course of the discrepancy between topography and compensation cannot be traced, but less certain observations, and other considerations, indicate that the defect of compensation disappears at greater distances from the edge of the hills and may even be replaced by an excess. The conclusion, being an important one in view of its bearing on theories of the origin of mountains, requires confirmation and, in the absence of observations in the Himalayan region, this had to be looked for elsewhere. In the search for such information I came across a series of gravity measurements, made by the Russian Government, in the region of the Pamirs and neighbouring parts of Central Asia, which are of special interest as giving a complete section across a group of mountains not only comparable in elevation with the Himalayas but also, in other ways, of importance in the discussion of theories of mountain origin.

The geology of this region is still imperfectly known, but this is of no very great importance as the present investigation is not concerned with details of stratigraphy. Enough is known to show that the general strike of the strata, and of the axes of the folds, is about east and west right across the northern part of the district. In the southern part, the same strike is found towards the centre, but on the east it bends round to south-eastwards, and westwards

[1] *Mem., Geol. Surv. Ind.*, XLII, pt. 2. 1917.

to the south-west. The topography shows a general agreement with the geological structure; on the north the upper waters of the Sir Daria, or Jaxartes, flow through the valley plain of Fergana, in what is evidently a structural depression between the mountains to the north and south. South of the Fergana valley come the parallel ranges of the Alai and Trans-Alai, separated by the Alai plain, near the head of the valley of the Kizil Su. These ranges are continued, further west, by others named on maps as the Peter the Great, Hissar, and Zerafshan, which together with the Alai ranges, may be regarded as the westerly continuation and termination of the Tian Shan mountains, now separated by the erosion of valleys, cut more or less along the strike of the rocks. To the south of these high ranges a number of minor ridges stretch in a more or less south-westerly direction towards the valley of the Oxus, following, in a general way, the strike of the rocks. The valley of the Oxus, or Amu Daria, occupies a structural depression to the westwards of the junction of the Kunduz river, but the upper reaches occupy what has all the characters of a valley of erosion, cut through the mountains, at times along, and at others across, the strike. Further still to the south comes the range of the Hindu Kush and its western continuation.

Throughout this region there is, as has been indicated, a general agreement between the geological structure of the rocks exposed at the surface and the geographical aspect of the country, but upon this general agreement of what may be called the minor topography, the course of crest and valley, there is superimposed a major relief, which is quite independent of the structure of the surface rocks and arranged along an axis transverse to the strike. This is very well seen in the hills of the drainage area of the Amu Daria, where we have the lowlands of Bokhara, on the west, eastwards comes a series of low hills which do not rise above 5,000 feet, followed by the high plateau of the Pamirs, and, still further east, by the mountains of Kungur and Mustagh Ata, which rise to heights of over 25,000 feet and form the highest summits of the region. The same feature may be recognised in the increase in average height from east to west of the series of ranges which form the backbone of the region and is also, and perhaps most conspicuously marked by the feature known to geographers as the Mustagh Ata range, which lies outside the region covered by the gravity observations, but must be considered, as it will be shown to have an important bearing on the interpretation of them, and as its character is generally misunderstood.

Maps show a series of high mountains ranged along the border of the plains of Kashgaria, which are separated from the Pamir plateau by deep valleys, and are so conspicuously arranged along a nearly meridional line that, in spite of the interruption by two deeply cut valleys, it is natural to look upon them as forming a distinct and definite mountain range, which is variously designated as the Kashgar, Tagharma, or Mustagh Ata, range; the appearance is, in fact, so striking that it has even misled some geologists into regarding it as a true tectonic range, and accepting a system of disturbance of the strata which would cut right across the trend of the structure of the region immediately to the west, and of which no trace can be found in observation in the field. The Mustagh Ata and Kungur are composed of granite, and doubtless owe their preservation as the highest summits of the region to this, but to the north Dr. H. H. Hayden found that an easterly strike continued right across the line of the supposed range, up to the margin of the Kashgar plain,[1] and to the south Dr. F. Stoliczka found a south-easterly strike continued, with only a brief local occurrence of northerly strike from the edge of the plain till it bent round into the east-south-easterly strike of the Pamirs.[2] The similitude to a mountain range is largely due to the valleys which separate the summits from the Pamir plateau, and even if these valleys are not wholly due to erosion, there remains the fact that the greatest actual elevations lie in the extreme east of the region, and the common geographical interpretation has this much genetic justification, that the axis of the greatest uplift lies on the eastern edge of the hills, whence there is a rapid descent to the plains of Kashgar.

The major relief of the country is thus seen to cut right across the minor relief, or course of ridge and valley, and for this no satisfactory explanation can be found in the visible geological structure of the country. The structure very clearly indicates that the region has undergone compression in a north and south direction, and this compression would give rise to a thickening of the crust, to which the elevation of the hills might, and very commonly is, attributed; but there is nothing in our limited knowledge of this region to suggest that the compression has been greater in the east than in the

[1] *Rec., Geol. Surv. Ind.*, XLV, 318 (1916).
[2] Scientific Results of the Second Yarkand Mission Geology, pp. 35-37 (1878).

western portion, at any rate to the extent necessary to account for the difference in the present elevation of the ground. This, however, is merely a repetition of what may be found in other parts of the world. Even in those districts where the relation between inward structure and outward form are most intimate and obvious, there is not the same apparent connection between structure and absolute elevation. The Alps and the Himalayas, for instance, have both been compressed in a direction transverse to the general course of the range, and the amount of compression seems to be of much the same order of magnitude in both cases; the geology of the Himalayas is less fully known than that of the Alps, but so far as our knowledge goes the compression seems to have been, if anything, less in amount, and certainly there is nothing like the twofold greater compression, which would be needed to account in this way for the twofold greater elevation. In both these cases, as in others of a similar character, the major relief is ranged along much the same general direction as the minor, so that it is difficult to disentangle the effects of the two and decide how far each may or may not be determined by the geological structure. In the mountains of Turkestan the opposite is the case, and here the major and the minor relief are arranged along different lines, which cross each other nearly at right angles, and, for this reason, the region seems particularly favourable for the study of those problems of mountain formation, the solution of which seems impossible by geological observation and only to be approached by the study of geodetic measurements.

The results of the observations are published in the report of the 1909 meeting of the International Geodetic Association, but in less detailed form than is customary, for only the free air correction is given. The Bouguer correction for visible mass and the Hayford correction for local topography are easily obtained, but the orographic correction for departure of the actual surface from a plateau could not be determined with accuracy from the maps accessible to me. As the stations are mostly situated in open valleys or out in the plain, this correction will in the majority of cases be less than ·01 dyne and only in a few cases, where the station is situated in a deep and narrow valley, will it exceed ·02 dyne, and is not likely to be greater than ·03 at any station of the series.

The correction for the effect of topography at a greater distance than 104 miles from the station has been determined. It was computed in detail by Messrs. Hayford and Bowie for the station of Kala Khum,[1] which is almost centrally situated in the group of stations being dealt with, and, as the amount of this correction varies comparatively slowly from station to station, the adoption of the same value at all would probably not introduce an error of more than ·02 dyne at any one. Moreover, the error would be a systematic one, changing gradually from one margin of the map towards the other, and so easily recognisable, if not obscured by other and greater irregularities. As will be seen in the sequel, the differences in the anomalies are much greater in amount and more rapid in their variation than can possibly be accounted for by the neglect of this correction. Another consideration is the fact that the correctness of the adopted value for the force of gravity at Tashkent, on which all the other values depend, is in doubt,[2] and for this reason it has seemed best to confine attention to the differences, which are most conveniently expressed as positive or negative variations from the mean value of the whole group, excluding the anomalous station of Kala Wamar. The stations are numerous enough, and the area sufficiently extensive and diversified in character, to make it probable that the mean of the anomalies will approximately represent the true zero value for the area, while the exclusion of Kala Wamar is justified by the anomalous character of the record. The negative anomaly at this station is not only abnormally high, but is nearly two-tenths of a dyne higher than at the nearest stations. There is no apparent explanation of so great an anomaly at this station, and it is difficult to avoid the conclusion that a clerical error has crept into either the calculations or their transcription, the alternative explanation being that there is some exceptional and quite local peculiarity at this station; in either case its exclusion is justified.

On the map attached to this note (Pl. 3) the relief of the surface is indicated by the contours at intervals of 5,000 feet and the positions

[1] The effect of Topography and Isostatic compensation upon the Intensity of gravity. Washington; 1912; p 84.

[2] Comptes Rendues de la seizieme Conference générale de l'Association Geodesique Internationale, Vol. III, pp. 138-141.

of the gravity stations, with the amount, expressed in hundredths of a dyne, by which the anomaly differs from the mean value. As has been mentioned, these values require a correction for irregularity of the surface, which may reach ·03 dyne and will be less at most of the stations in the mountain region; they are also subject to a correction on account of distant topography and its compensation, which will vary gradually from a positive value near one margin to a negative value at the other, or possibly may vary in either positive or negative direction from some point within the area. Another possible correction is a divergence of the actual distribution of the compensation from that assumed in the Hayford and Bowie tables, from which the figures made use of were derived; any such assumption, however, not inadmissible on other grounds, would make very small change in the amount of the anomaly, the maximum change, at the stations in the very heart of the mountains, could not exceed ·02 dyne at any individual station and would vary in amount with the altitude.

An inspection of the map shows that the actual variation in the amount of the anomaly is not susceptible of explanation in any of these ways; not only is the amount of the difference too large, reaching as it does about two-tenths of a dyne, but the distribution shows no relation to the situation of the stations, whether in deep and narrow valleys or in the open plain, nor to the elevation, nor does it vary in a manner that could be attributed to the effect of distant topography. On the other hand, the variation does show a very decided relation to the general relief of the country; in the lowlands to the west we find the anomalies all positive, and the positive values continue into the hills on the east; as the higher hills are entered the anomalies become negative, and all the eastern stations show a negative anomaly, with the exception of two groups, one in the central region of the Pamir plateau, and the other in the depression of Fergana. Expressed in general terms, it may be said that the character of the anomaly is such that where lower ground borders on higher the anomaly is positive, and negative where high ground is bordered by lower. In the case of the western plains of Bokhara, and again in the Fergana depression this relationship is obvious, but not so on the Pamir plateau, yet there, too, high as the stations lie, there is higher ground on all sides, though the barrier on the west is breached by river valleys. The station of Jekindi, which shows a small positive anomaly, isolated in a region of defect of gravity, is no exception for, though situated in a mountain region, it lies in the upper valley of the Kizil Su and not very far from the edge of the Alai plain, which, lying between the Alai and Trans Alai ranges, appears to mark a structural depression between two lines of excess of uplift.

Bearing in mind the fact that a positive anomaly, where the effect of compensation has been considered, means that the surface level stands higher than it would if a condition of complete isostatic equilibrium existed under the station, the distribution of the anomalies may be expressed in a different way, as indicating that the low ground is borne up above, and the ranges depressed below, their respective proper levels. This is the condition which was established as regards one part, and shown to be probable as regards the other, in the case of the Himalayas, and, in that connection, was shown to suggest a certain amount of residual rigidity in the crust of the earth. The way in which this would work can be illustrated by the diagram, fig. 1, where an originally level surface is supposed to have been subjected to elevatory forces such as would result in a surface as represented by the firm line between A and H, if the surface level everywhere coincided with the upward or downward forces; if, however, the crust were possessed of a degree of permanent rigidity which would not allow it to adapt itself to the flexures, the resulting surface would take some such form as that represented by the dotted line, the exact form depending on the degree of rigidity of the crust and the abruptness of the flexures.


Fig. 1.

Here we see that on either side of the central uplifted tract, the level surface is bent upwards and stands at a higher level than it otherwise would, while the outer edges of the uplift are held down below the level which they should have reached. In the centre of the plateau it might be that the surface would be forced up above its proper level by an arching upwards of the crust, as a result of the bending down on either side.

The conditions assumed in the diagram have been reduced to an extreme simplicity, but a similar result would follow in more complicated circumstances, and, further, if we suppose the elevatory force to be the result of the same changes which have given rise to the compensation, we should find an apparent excess of gravity in all those regions where the dotted line runs above the firm one, and where the actual amount of the compensation would be less than that deduced from the measured altitude; where the dotted line runs below the firm there would, similarly, be an apparent defect of gravity, the real compensation being greater in amount than was allowed for in the computation.

Before passing on to the consideration of the observations it may be well to point out that if the compensation were an indirect result of the accumulation of surface material to form the plateau, the relationship between the real surface and the surface of equilibrium would be the opposite of that shown in the diagram. In this case the ground on either side of the plateau would be borne down, and a defect of gravity would be observed, while the plateau would be supported above the level of equilibrium and show an excess of gravity.

Examining the anomalies in the light of this explanation, we find, in the first place, high positive values in the most westerly stations; then, entering the hills, this positive anomaly decreases in amount in an easterly direction, as the high plateau of the Pamirs is approached, till it disappears and is replaced by a negative anomaly both in the stations along the course of the Oxus and in the hills to the north of it.

In the upper Oxus valley, the anomaly has a negative value of about ·06 dyne at Kala Khum, of which ·01 is due to the omission of the orographic correction. At Kala Wanj, Kharuk and Ishkasham the negative anomaly amounts to ·08, of which some ·02 to ·03 may be due to the orographic correction, and at Langar Kisht, where this correction is probably larger than at any other station, the negative anomaly of ·11 would be reduced to ·07 or ·08.

Eastwards of these high negative values there are no stations till the Pamir plateau is reached, where a group of positive anomalies is met with, the greatest of which amounts to ·11 dyne, at Robat Muskol. This very high value may be attributable, in part, to a purely local variation in the density of the rocks under the station, and it may be that the lesser positive anomalies at the neighbouring stations would be made negative by a computation including the effect of more distant topography, but any such change would still leave the values positive in comparison with the anomalies at the stations round about.

Taking an anomaly of ·03 dyne as representing in round numbers the attraction of 1,000 feet thickness of average rock, we may interpret the figures as showing a superelevation of about 3,000 feet in the plain about Bokhara, a depression of rather less along the edge of the high plateau of the Pamirs, about Kala Khum or Kala Wanj, and a superelevation of about the same amount in the central part of the plateau round about Robat Muskol. The distance from Charjui to Robat Muskol is about 550 miles and the maximum difference of load equivalent to about 5,000 feet of rock, indicating a permanent strength of the crust of more than double that which, according to Prof. Barrell, is revealed by the observations in the United States, but only about one-half to three-quarters of that exhibited by part of the floor of the Pacific Ocean.[1]

On this line of section, a disturbing element may come in, of the effect of which we can form no estimate, for the line is flanked on the north by the high ranges stretching westwards between the Oxus and Jaxartes valleys, and on the south by the Hindu Kush and its westerly continuation. Nothing of the same proportionate amount needs consideration on the transverse section from north to south across the Pamirs. Beginning from the south, we find a negative anomaly at Langar Kisht which, allowing for the effect of the orographic correction, is equivalent to a depression of about 3,000 feet. This station is close to the crest of the Hindu Kush and to peaks which rise to an altitude of 22,000 to 24,000 feet. At Murghabi, the depression has sunk to –·04 dyne and, as the orographic correction would be comparatively small, the depression may be put at about 1,000 feet. At the next station, Robat Ak Baital, there is a superelevation of about the same amount, which increases to 3,000 feet or more at Robat Muskol. Lake Karakul seems to stand at about the level due to the compensation but northwards the depression at Bordaba amounts to 1,000 feet and to 3,000 feet at Ak Bossaga, diminishing again to about 1,000 feet at Sufi Kurgan and Gulcha. At Liansar and Osh, in the Fergana valley, there is a positive anomaly, indicating a superelevation of

[1] *Journ. Geol.*, XXII, 30, 37, 38 (1918).

less than 1,000 feet, surrounded on three sides by stations indicating a depression of the surface level, as the mountains are neared.

On this section the bearing up of the low ground, and the bearing down of the high, is very clearly exhibited. In the case of the Fergana valley it is obvious enough, and, as has been pointed out, the central region of the Pamir plateau is in much the same case, in spite of its altitude, but here another cause may co-operate in producing superelevation. The observations indicate a bending down of the crust towards the north and south, and towards the west; on the east no observations exist but we may infer that a similar condition would be found towards the plains of Kashgar.

Granted the correctness of this interpretation, the strength and rigidity of the crust implied by it might well give rise to an upward bending of the portion of the crust lying between and so to an uplift, reaching its maximum in the centre and dying out on either side, as was suggested in dealing with the suppositious case illustrated in fig. 1.

However this may be, we have a section which may be regarded as something over a complete wave, having a length of about 150 miles from crest to crest or trough to trough, and a height of about 7,000 feet from trough to crest. This last figure may be excessive, and partly due to this increase of the maximum anomalies by purely local causes, but the general average of the observations shows that the difference is at least equivalent to some 5,000 feet or 2,500 above and below the mean level of equilibrium.

Westwards from Fergana the stations in the drainage area of the Sir Daria, or Jaxartes, show the same features, of negative anomalies on the east giving place to positive anomalies to the westwards, as was found further south. It is not possible to recognise any influence of the high mountains which lie between the two rivers, as there are no stations within the ranges or close to them, and the elevated mass is so insignificant in volume, as compared with the Pamir plateau, that the effect of the latter would be predominant, and any influence exerted by the former only recognisable by a larger number of more closely set stations than are available.

Taken as a whole, the results agree in a remarkable manner with those obtained from the study of the geodetic observations in the Himalayas, indicating that a condition of general isostatic equilibrium, of the mountains as a whole, is subject to considerable local departures from this condition. In both cases these departures from complete equilibrium are distributed with a marked relation to the greater relief of the surface and are just such as would result from the uplift being due to some deep-seated cause, acting mainly in a vertical direction, combined with some considerable strength and permanent rigidity of the overlying crust, which is, consequently, prevented from adapting itself completely to the bending, and so may hold the surface level down below or upraised above that at which it would otherwise stand. The limit to the amount of the departure from the level of equilibrium is about the same in both regions and reaches a maximum of some 3,000 feet; the observations which have been made in the Andes suggest a similar departure from complete equilibrium and to about the same amount. We find, then, that three great mountain ranges, each of about the same magnitude, and the three greatest in the world, agree in showing the same phenomenon and to the same degree. This would in itself give great support to the supposition that there is a real connection and a cause common to all. There are, besides, within the limits of the region now under consideration, two groups of facts, wholly independent of each other, and each in its way giving support to the deduction that the greater relief of the surface is independent of the superficial geological structure, but is directly due to the same processes as have given rise to the compensation.

The first of these is the fact that the course and distribution of the principal mountain ranges and the larger features of the relief of the ground are not directly determined by the geological structure. The point is very clearly brought out in a paper by Dr. Ellsworth Huntington, on the Mountains of Turkestan, and can hardly be more graphically and succinctly expressed than by three brief extracts from his account, in which he consistently writes of the Tian Shan Mountains as a plateau and never as a range.[1]

"In physiographic terms, the Tian Shan plateau may be described as a peneplain which has been highly uplifted and warped, and is now in a state of extreme youth". * * * "The result of these geological changes is that, although the *internal structure* of the Tian Shan region is highly mountainous, its *external appearance*, or, in other words, its geographical aspect, is that of a plateau" * * * "The ridges rise by long gentle slopes to flat summits,

[1] *Geog. Journ.*, XXV, pp. 22-40, 139-158 (1905).

where often for many miles the sky-line is an almost straight crest from which the rounded slopes of pure white snowfields descend gradually toward the basins. Here and there the crest line is notched by high passes, the lowest of which are but 1,000 or 2,000 feet below the top of the ridge. Oftener the summit of the ridge is broken into individual mountains, broadly flat topped and of nearly equal height."

The description of this author is borne out by that of every other traveller, and the region appears as one which has undergone a very considerable amount of disturbance, accompanied by a general compression of the strata, which may have given rise to true tectonic irregularities in the form of the surface. These original features had been worn down and the country reduced to a lowland type of gentle relief, such as it is the fashion to describe as a peneplain, when, at a later date, the country was uplifted and, by the opportunity so given to the action of denudation, the surface carved into steep slopes, and deep-cut valleys, converting a downland plateau into the aspect of a series of mountain ranges. The uplift was not uniform, but greater along certain lines than elsewhere, and in some cases these lines of greater elevation followed the general course of the earlier axes of disturbance of the strata, so that the present range of high crests has the appearance of being a true tectonic range, but even in these cases the amount of the later elevation varies along the length of the range, and the variation has no relation to the geological structure. More generally, however, there seems no direct connection, and the most conspicuous geographical feature of the region, the line of mountains running north and south, between the Pamirs and the Plains of Yarkand and Kashgar, runs right across the trend of the geological structure. This series of mountains is so distinctly ranged along a definite axis that it may naturally be regarded as a definite range, and the study of the topographical map has even led geologists to infer the existence of a meridional range of true tectonic character. As has already been mentioned, the surface observations are opposed to this conclusion, and show that, if the range is in any sense of the word a tectonic one the tectonics are more deeply seated than those of the disturbance of the rocks near the surface.

The consideration of this range, which is seen to be probably a true range, genetically as well as in superficial appearance, merely emphasises the conclusion drawn from the general study of the region, that the broad features of the major relief, as well as the determination of the more restricted zones of greater uplift, are not the result of processes apparent in the structures visible at the surface, but of more deeply seated, and possibly quite independent, processes, which are not accessible to surface observations, and are, presumably, connected with the cause of compensation.

The second group of facts has a more direct bearing on the particular nature of the changes, or processes, which produce the compensation. It is known that great earthquakes send out two sets of waves, which are transmitted through the interior of the earth and recorded at distant stations. In addition to the record of the waves which have travelled by direct courses, there are subsidiary records which are attributed to those which have been one or more times reflected; though the interpretation of the records has been questioned, and is certainly doubtful as to some of the supposed twice or more times reflected waves, the concordance of a very large proportion of the records seems to have established the presence of the two types of singly reflected waves, the condensational and the distortional, each reflected from a midway point as the same form of wave. In the mathematical treatment of this question it is usual to assume a reflection from the surface of a solid sphere, and this is too often taken to mean that it takes place at the surface of the earth; this, however, is impossible, in the case of the actual records, for the rocks of which the outer shell of the earth is composed are too heterogeneous to transmit a simple form of wave-motion without repeated breaking up into waves of more than one form, and the constituent rocks have, almost without exception, so different a degree of elasticity in different directions that they are incapable of transmitting either of the simple forms of wave-motion. The result is, that the simple waves, on entering the outer crust, become broken up into more complex forms and lost; consequently, it is not at the surface of the earth that we must look for the surface of reflection, but at the under surface of the heterogeneous crust, and it is reasonable to find an explanation, of the greater or less conspicuousness of the record of the reflected waves, in the varying degree of abruptness of transition to the more uniform material below. Now it has been observed that, of all the earthquakes registered at European observatories, those originating in the neighbourhood of the Philippines, that is, those which have the central point of reflection under the region of high mountains of Kashmir and the Pamirs, give the most conspicuous record of the reflected waves, usually even larger than that of the distant ones.

The obvious interpretation of this is that the transition from the outer crust to the underlying material is more than usually rapid and sharply defined in the region under the Pamirs, and it is natural to associate this with the changes which have given rise to the compensation of this group of mountain ranges, the largest and loftiest in the world. And so we reach the same conclusion as was drawn from the gravity observations, that the processes and changes, to which the effect is due, are localised, or at least concentrated, in the lower part of the crust, or in the layer immediately beneath it.

The conclusion reached in the course of this investigation may not be without importance on the geodetic side, as a guide in the determination of the nature, and distribution in depth, of the compensation. On the geological side it is of great interest as showing that two distinct causes and actions have been at work and must be taken into account in any attempt to elucidate the origin of mountain ranges. On the one hand, we have the actions which have given rise to the disturbance of sedimentary rocks from their originally horizontal position, and to the intrusion of igneous rocks among them. The well-established importance of trend-lines of structure is unimpaired, and to the structure set up in this way, combined with the effects of surface denudation, the details of surface form and the course of ridge and valley are due. The boundary between hill and plain is often determined by the same cause, and to it ranges of hills may sometimes be due, but there is a distinct limit to the amount of the difference of elevation which can be produced in this way. No exact figure can be given for these limits; they are probably incapable of precise numerical definition, but the limit of height must be somewhere about 2,000, or possibly, 3,000 feet, and the limit of breadth 150 to 200 miles. Where the difference becomes greater than this, we must look to some other cause than compression of the rocks, for the load imposed on the crust becomes too great for it to bear, and so the conclusion is reached that the larger differences in elevation, and the more extensive areas of uplift, are due to some cause which is independent of that which has given rise to the structures revealed by the geological examination of surface rocks.

As a speculation this is not new, but the present investigation has given clearer indication of its truth than had previously been published, within my knowledge, and more especially has shown, in the first place, that the uplift of the higher mountain ranges is directly connected with those changes which have given rise to the defect of density under the ranges, known as their compensation, and, in the second place, that these changes are deep-seated and take place at the lower limit of the outer crust. Of the nature of these changes, or the way in which they are brought about, the investigation gives no direct indication, but, from the intimate connection between the uplift and the compensation, it follows that the centre of gravity of the two is probably at the same average depth, and this, according to Mr. Hayford's investigation, is somewhere about 35 miles below the surface. Further, the distribution of the departures from complete local equilibrium are such as to show that the compensation is not the indirect effect of the formation of the mountain ranges, but that it is the primary phenomenon and the originating cause of the uplift, of which the mountains are the indirect result and to which they owe their present altitude.

### LIST OF STATIONS AND DETAILS OF OBSERVATIONS UTILISED.

[NOTE.—The Stations in this list belong to two series of observations, one based on Tashkent, the other on Tiflis. As the value adopted for the base station in the former differs from that determined for the same place in the latter, and earlier in point of date, by ·015 dyne, a correction of this amount has been made at the other stations in order to bring the two series into uniformity. Stations of the series based on Tiflis, to which the correction has been applied, are distinguished by an asterisk. Spelling of place names follows the Survey of India, or a similar system where the name is not to be found on published maps.]

| Station. | Longitude. | Latitude. | Elevation (in metres). | Observed value of gravity. | Theoretical value of gravity. | Apparent amount of defect. | CORRECTIONS. Height. | CORRECTIONS. Mass. | CORRECTIONS. Compensation. | Resulting anomaly. | Difference from mean. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Murghabi | 73° 58·2′ | 38° 10·0′ | 3,700 | 978·832 | 980·004 | 1·172 | 1·142 | ·407 | ·320 | —·117 | —·04 |
| 2. Irkeshtam | 55·5′ | 39° 41·9′ | 2,850 | 9·203 | 0·139 | 0·936 | 0·880 | ·313 | ·232 | —·137 | —·06 |
| 3. Robat-Ak-Baital | 51·5′ | 38° 29·7′ | 4,100 | 8·842 | 0·033 | 1·191 | 1·265 | ·451 | ·326 | —·051 | +·03 |
| 4. Robat Muskol | 31·7′ | 38° 42·0′ | 4,200 | 8·924 | 0·051 | 1·127 | 1·296 | ·462 | ·328 | +·035 | +·11 |
| 5. Lake Karakul | 31·2′ | 39° 6·4′ | 3,920 | 8·912 | 0·087 | 1·175 | 1·210 | ·431 | ·315 | —·081 | ·00 |
| 6. Sufi Kurgan | 30·0′ | 40° 1·5′ | 2,115 | 9·424 | 0·168 | 0·744 | 0·653 | ·232 | ·210 | —·113 | —·03 |
| 7. Gulcha | 25·7′ | 40° 19·0′ | 1,583 | 9·580 | 0·195 | 0·615 | 0·489 | ·174 | ·185 | —·115 | —·03 |
| 8. Bordaba | 16·2′ | 39° 30·9′ | 3,470 | 9·028 | 0·122 | 1·094 | 1·071 | ·382 | ·293 | —·112 | —·03 |
| 9. Ak Bossaga | 13·7′ | 39° 48·6′ | 2,875 | 9·134 | 0·149 | 1·015 | 0·887 | ·316 | ·259 | —·185 | —·10 |
| 10. Liansar | 5·7′ | 40° 24·′6 | 1,685 | 9·615 | 0·202 | 0·587 | 0·520 | ·185 | ·174 | —·078 | ·00 |
| 11. Osh | 72° 46·6′ | 40° 31·4′ | 1,021 | 9·791 | 0·212 | 0·421 | 0·315 | ·112 | ·156 | —·062 | +·02 |
| 12. Langar Kisht | 38·5′ | 37° 2·6′ | 2,915 | 8·847 | 979·906 | 1·059 | 0·900 | ·320 | ·289 | —·190 | —·11 |
| 13. Andijan | 20·6′ | 40° 45·8′ | 530 | 9·885 | 980·234 | 0·349 | 0·164 |  | ·111 | —·132 | —·05 |
| 14. Karaul Kishlak | 6·0′ | 40° 2·2′ | 1,300 | 9·611 | 0·169 | 0·558 | 0·401 | ·143 | ·166 | —·134 | —·05 |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| 15. Jekindi . . | 71° 54·5′ | 39° 30·0′ | 2,380 | 9·321 | 0·121 | 0·800 | 0·734 | ·262 | ·260 | —·068 | +·01 |
| 16. Margilan . . . | 46·7′ | 40° 23·7′ | 581 | 9·863 | 0·201 | 0·338 | 0·179 | ·064 | ·122 | —·101 | —·02 |
| 17. Namangan . . | 38·7′ | 40° 59·7′ | 440 | 9·941 | 0·255 | 0·314 | 0·136 | ·048 | ·098 | —·128 | —·05 |
| 18. Kharuk . . . | 32·2′ | 37° 29·5′ | 2.105 | 9·132 | 979·944 | 0·812 | 0·650 | ·231 | ·236 | —·157 | —·08 |
| 19. Kala Wamar . . | 32·0′ | 37° 56·7′ | 1,985 | 9·019 | 9·984 | 0·965 | 0·615 | ·218 | ·230 | —·340 | —·26 |
| 20. Ishkasham . . | 30·2′ | 36° 52·4′ | 2,460 | 8·967 | 9·981 | 0·924 | 0·759 | ·271 | ·277 | —·159 | —·08 |
| 21. Kala Wanj . . | 27·0′ | 38° 22·2′ | 1,795 | 9·290 | 980·021 | 0·731 | 0·554 | ·197 | ·218 | —·156 | —·08 |
| 22. Damburachi . . | 22·7′ | 39° 16·1′ | 1,795 | 9·393 | 0·101 | 0·708 | 0·554 | ·197 | ·228 | —·123 | —·04 |
| 23. Chust . . . | 13·9′ | 40° 59·3′ | 639 | 9·916 | 0·254 | 0·338 | 0·197 | ·070 | ·098 | —·113 | —·03 |
| 24. Khokand . . | 70° 57·0′ | 40° 30·5′ | 437 | 9·913 | 0·211 | 0·298 | 0·135 | ·048 | ·089 | —·122 | —·04 |
| 25. Kala Chait . . | 52·0′ | 39° 10·8′ | 1,600 | 979·443 | 0·093 | 0·650 | 0·494 | ·176 | ·209 | —·123 | —·04 |
| 26. Kala Khum . . | 46·5′ | 38° 27·3′ | 1,345 | 9·462 | 0·029 | 0·567 | 0·415 | ·148 | ·165 | —·135 | —·06 |
| 27. Tabidarreh . . | 28·2′ | 38° 41·9′ | 1,630 | 9·440 | 0·051 | 0·611 | 0·503 | ·179 | ·167 | —·120 | —·04 |
| 28. Garm . . . | 22·2′ | 39° 1·5′ | 1,370 | 9·498 | 0·079 | 0·581 | 0·423 | ·151 | ·189 | —·120 | —·04 |
| 29. Jol . . . . | 7·7′ | 37° 45·8′ | 1,380 | 9·437 | 979·968 | 0·531 | 0·426 | ·152 | ·127 | —·130 | —·05 |
| 30. Saripul . . . | 5·5′ | 38° 24·5′ | 1,500 | 9·462 | 980·025 | 0·563 | 0·463 | ·165 | ·150 | —·115 | —·04 |
| 31. Muminabad . . | 1·7′ | 38° 6·5′ | 1,280 | 9·491 | 979·999 | 0·508 | 0·395 | ·141 | ·130 | —·124 | —·04 |
| 32. Bogarak . . . | 69° 50·2′ | 37° 37·0′ | 610 | 9·609 | 9·956 | 0·347 | 0·188 | ·067 | ·160 | —·120 | —·04 |
| 33. Baljuan . . . | 39·2′ | 38° 18·2′ | 890 | 9·591 | 0·015 | 0·424 | 0·275 | ·098 | ·113 | —·134 | —·05 |

| Station. | Longitude. | Latitude. | Elevation (in metres). | Observed value of gravity. | Theoretical value of gravity. | Apparent amount of defect. | CORRECTIONS. | | | Resulting anomaly. | Difference from mean. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Height. | Mass. | Compensation. | | |
| 34. Khodjend . . | 34·7′ | 40° 17·1′ | 320 | 9·953 | 0·192 | 0·239 | 0·099 | ·035 | ·076 | —·099 | —·02 |
| 35. Parkhar . . . | 23·7′ | 37° 29·9′ | 475 | 9·659 | 9·945 | 0·286 | 0·147 | ·052 | ·078 | —·113 | —·03 |
| 36. Nau . . . | 22·4′ | 40° 9·2′ | 415 | 9·951 | 0·180 | 0·229 | 0·128 | ·045 | ·074 | —·072 | +·01 |
| 37. Faizabad . . | 18·7′ | 38° 30·9′ | 1,210 | 9·581 | 0·034 | 0·453 | 0·373 | ·133 | ·122 | —·091 | —·01 |
| 38. Sarai . . . | 5·0′ | 37° 13·9′ | 405 | 9·661 | 979·922 | 0·261 | 0·125 | ·045 | ·061 | —·120 | —·03 |
| 39. Ura Tyube . . | 0·7′ | 39° 55·3′ | 1,025 | 9·814 | 980·159 | 0·345 | 0·316 | ·113 | ·095 | —·047 | +·03 |
| 40. Dushambe . . | 68° 46·7′ | 38° 34·5′ | 835 | 9·673 | 0·040 | 0·367 | 0·258 | ·092 | ·109 | —·092 | —·01 |
| 41. Chernajajewo . . | 43·6′ | 40° 13·0′ | 360 | 980·003 | 0·186 | 0·183 | 0·111 | ·040 | ·065 | —·047 | +·03 |
| 42. Nishne Panj . . | 31·7′ | 37° 11·5′ | 355 | 979·699 | 779·918 | 0·219 | 0·110 | ·039 | ·051 | —·097 | —·02 |
| 43. Zamin . . . | 23·5′ | 39° 58·2′ | 650 | 9·896 | 980·163 | 0·267 | 0·201 | ·071 | ·074 | —·063 | +·02 |
| 44. Karatagh . . | 20·0′ | 38° 36·7′ | 905 | 9·684 | 0·043 | 0·359 | 0·279 | ·099 | ·114 | —·065 | +·02 |
| 45. Aivanj . . . | 1·7′ | 36° 56·9′ | 340 | 9·693 | 979·897 | 0·204 | 0·105 | ·037 | ·052 | —·084 | 00 |
| 46. Deh Nau . . . | 67° 53·7′ | 38° 16·3′ | 550 | 9·751 | 980·013 | 0·262 | 0·170 | ·060 | ·089 | —·063 | +·02 |
| 47. Jisak* . . . | 48·7′ | 40° 6·8′ | 386 | 980·018 | 0·176 | 0·158 | 0·119 | ·043 | ·052 | —·030 | +·05 |

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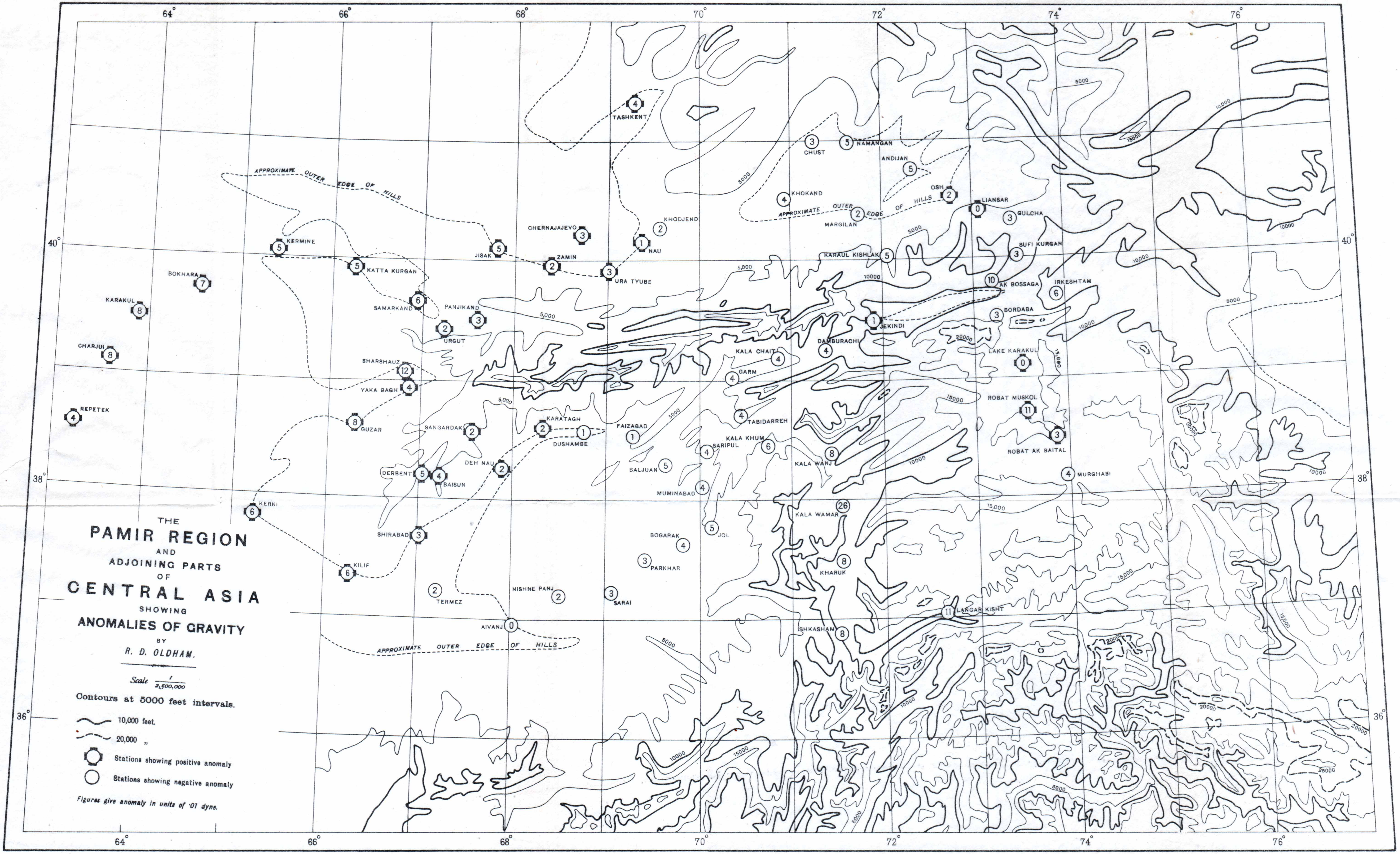
|---|---|---|---|---|---|---|---|---|---|---|---|
| 48. Panjikand . . | 36·2′ | 39° 29·8′ | 980 | 997·768 | 0·121 | 0·353 | 0·302 | ·108 | ·108 | —·051 | +·03 |
| 49. Sangardak . . | 33·0′ | 38° 32·8′ | 1,330 | 9·600 | 0·037 | 0·437 | 0·410 | ·146 | ·115 | —·058 | +·02 |
| 50. Urgut . . . | 15·2′ | 39° 24·6′ | 995 | 9·755 | 0·113 | 0·358 | 0·307 | ·109 | ·095 | —·065 | —·02 |
| 51. Termez . . . | 13·6′ | 37° 13·7′ | 346 | 9·711 | 979·922 | 0·211 | 0·107 | 0·38 | ·041 | —·101 | —·02 |
| 52. Baisun . . . | 12·5′ | 38° 12·0′ | 1,230 | 9·624 | 980·007 | 0·383 | 0·380 | ·135 | ·096 | —·042 | +·04 |
| 53. Derbent* . . | 3·2′ | 38° 12·0′ | 1,012 | 9·687 | 0·007 | 0·320 | 0·312 | ·111 | ·089 | —·030 | +·05 |
| 54. Shirabad* . . | 2·6′ | 37° 40·9′ | 479 | 9·756 | 979·961 | 0·205 | 0·148 | ·053 | ·063 | —·047 | +·03 |
| 55. Samarkand* . . | 66° 58·7′ | 39° 39·1′ | 719 | 9·898 | 980·135 | 0·237 | 0·222 | ·079 | ·074 | —·020 | +·06 |
| 56. Yaka Bagh . . . | 52·0′ | 38° 55·4′ | 700 | 9·802 | 0·070 | 0·268 | 0·216 | ·077 | ·092 | —·037 | +·04 |
| 57. Sharshauz* . . | 50·2′ | 39° 3·4′ | 646 | 9·907 | 0·082 | 0·175 | 0·199 | ·071 | ·086 | +·039 | +·12 |
| 58. Guzar* . . . | 17·0′ | 38° 36·6′ | 555 | 9·861 | 0·043 | 0·182 | 0·171 | ·061 | ·071 | —·001 | +·08 |
| 59. Kilif* . . . | 15·7′ | 37° 20·7′ | 290 | 9·821 | 979·932 | 0·111 | 0·089 | 0·32 | ·038 | —·016 | +·06 |
| 60. Katta Kurgan* . | 15·5′ | 39° 54·2′ | 477 | 9·994 | 980·157 | 0·163 | 0·147 | ·053 | ·041 | —·028 | +·05 |
| 61. Kermine* . . | 65° 23·1′ | 40° 4·4′ | 398 | 980·038 | 0·173 | 0·135 | 0·123 | ·044 | ·030 | —·026 | +·05 |
| 62. Kerki* . . . | 13·8′ | 37° 50·1′ | 262 | 979·884 | 979·974 | 0·090 | 0·081 | ·020 | ·019 | —·019 | +·06 |
| 63. Bokhara*. . . | 64° 34·7′ | 39° 43·0′ | 225 | 980·091 | 980·141 | 0·050 | 0·069 | 0·25 | ·017 | —·011 | +·09 |
| 64. Karakul . . . | 63° 52·7′ | 39° 29·9′ | 198 | 0·062 | 0·121 | 0·059 | 0·061 | ·022 | ·015 | —·005 | +·08 |
| 65. Charjui* . . . | 36·1′ | 39° 6·2′ | 192 | 0·029 | 0·086 | 0·057 | 0·059 | ·021 | ·015 | —·004 | +·08 |
| 66. Repetek* . . | 14·1′ | 38° 33·7′ | 188 | 979·946 | 0·039 | 0·093 | 0·058 | ·021 | ·015 | —·041 | +·04 |




Litho G. S. I Calcutta.