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Author(s): Sidney Burrard

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ON THE ORIGIN OF MOUNTAIN RANGES

Colonel Sir Sidney Burrard, K.C.S.I., F.R.S.

Read at the Afternoon Meeting of the Society, 9 May 1921.

THE origin of mountains is a wide topic ; its study requires the co-operation of different students of science, geologists and mathematicians, seismologists and engineers, geographers, physicists and chemists. In a brief paper I can only attempt to refer to a few salient points that require discussion and help.

Mountains are the elevated portions of the Earth's crust, and in these discussions it is necessary to consider at the outset the structure of the Earth itself. The old theory of a liquid interior and of a crust supported by flotation has been abandoned. Modern astronomical, seismological, and mathematical investigations have all combined to show that the Earth is solid throughout and that its crust possesses the rigidity of steel ; the evidence in favour of solidity is now very great, and upon this fundamental fact we ought constantly to insist.

When we come to think out how mountains have arisen, the primary question at issue appears to be this—Have they been elevated by horizontal compression of the surface or by vertical uplift from below ?

One of the most conspicuous features on the flanks of the larger ranges is the compression which strata have undergone : strata which were originally horizontal have been squeezed into folds. It was the compressions of strata that gave rise to the well-known Contraction Theory.

According to this theory the Earth's crust was wrinkled into mountains by horizontal compression ; the Earth's interior was supposed to be cooling and contracting, and the outer crust was thus becoming too large for the shrinking core and was wrinkling into folds. The chief objection to this theory has been that the contraction by cooling is inadequate to account for the amount of elevation which mountains have undergone.* Osmond Fisher showed that the radial shrinkage of the Earth due to loss of heat had not been sufficient to produce mountains of even 100 feet in height.

Other objections have been raised : it has been pointed out that the principal mountain ranges were elevated in one geological age and that they are confined to certain narrow zones. If a core is slowly shrinking away from its outer shell, the latter will wrinkle in all ages and in all parts of its surface. To ascribe the rock-folds that have been concentrated in Central Asia to a general shrinkage of the Earth's core is tantamount to assuming that the crust is loose from its core.

If moreover ranges were surface folds we should expect to see the horizontal strata, in which the rocks were originally laid down, lifted up

* Osmond Fisher, " Physics of the Earth's Crust." Dutton, *Phil. Soc. Washington Bull.*, vol. 2, 1889.

and arched over the ranges. The Himalaya ranges are composed of granite, which has been uplifted from below, and although the stratified rocks on the south side of the granite have been compressed, the crumpling which they have suffered seems to be local.* There do not seem to exist any relics of great arches of strata, such as might be expected, if the ranges were folds of the Earth's crust.

In face of these objections it is difficult to be satisfied with the theory that mountains have arisen from horizontal compression. And we have to face the question—What is the force that has raised mountains? The force of gravity acts vertically downwards; what is the force that is able to lift rock-masses to great heights in opposition to gravity? This force is to be sought for in the physical and chemical changes that rocks undergo. The rocks composing the crust are heterogeneous mixtures, and they are continually undergoing changes. Sir Hubert Hayden told me that the gneiss of the Neilgherri mountains varies in density from 2·67 to 3·03, that is 14 per cent., and that the rock of the Hazaribagh plateau varies from 2·5 to 3·1, or 24 per cent. Dr. Fermor (*Records Geolog. Surv. of India*, vols. 33 and 34) has closely studied the lavas of Western India; he estimates the density of eclogite at 3·3: under a decrease of pressure the eclogite will pass into gabbro of density 3·05 and into basalt of density 2·95. The increase of volume involved in the passage of eclogite into gabbro is 8·2 per cent. An elevation of 2000 feet will be caused by the passage of a column of eclogite, 25,000 feet deep, into gabbro.

As conditions of pressure and temperature vary, rocks undergo changes of volume and density. It is to these changes that we have to attribute the elevations at the Earth's surface. The highest summits are generally composed of granite, and the granite masses are believed to have risen out of the crust.†

The range of mountains known as the Western Ghats skirts the west coast of India, and it traverses two different portions of the crust. South of latitude 16° it crosses an area of gneissic rock, and is itself composed of gneiss, its peaks rising to 6000 feet: north of lat. 16° it crosses an area of volcanic rock, and here the mountains are built up of numerous horizontal strata. It has been thought that the horizontal strata of lava may have been originally laid down at their present high altitudes; but this line of elevation continues beyond the volcanic area into the area of the gneiss; it is evident that there has been a line of upheaval across both areas. The horizontality of the strata and the absence of compression on the volcanic section show that the upheaval has been vertical and that the range has been elevated to 5000 feet without any disturbance or tilt.‡

* Hayden's sections, plate xxxviii. part iv., "Sketch of the Geography and Geology of the Himalayas." Also sections by Middlemiss, *Mem. Geol. Survey of India*, xxiv.

† "Interior of the Earth," by Chamberlin, *Proc. Americ. Phil. Soc.*, Sept. 1915.

‡ The isolated peak of Guru Sikkar (Mount Abu) standing up out of the desert, 5650 feet high, may be a northern outburst of the Western Ghat range: compare deflections at Deesa and Chaniana with Colaba, *Phil. Trans. Roy. Soc., A*, vol. 205, p. 310.

The largest protuberance at the Earth's surface is the plateau of Tibet. In 1851 Richard Strachey found the bones of elephant and rhinoceros at a height of 15,000 feet in Tibet, in deposits of silt which are as horizontal now as when they were first laid down (*Journal Geolog. Soc.*, 7, 306).

At its present altitude Tibet is almost arctic in its climate, whilst the elephant and rhinoceros are tropical animals. Strachey explained the presence of these animals in Tibet by assuming that the horizontal strata had been elevated from sea-level to their present height since the time when the animals had lived; he suggested that these strata had been raised vertically without any tilt, compression, or disturbance.

It may be asked if the evidence in favour of vertical uplift be so strong, why has this solution not been accepted? The answer is that vertical uplift does not explain the horizontal compression of strata. In the Western Ghats there is no horizontal compression, but the flanks of the Himalayas and of the Alps furnish evidence of compression. Some writers have tried to divide mountains into two classes, the vertical and the horizontal; but there is no justification for such a step; in one Himalayan area the bones of elephants have been raised vertically, and in another Himalayan area there are signs of horizontal compression.

In this difficulty let me turn to geodesy to consider the evidence it furnishes. Its principal contribution has been the discovery of Isostasy, which has taught us lessons concerning the structure of the crust, and concerning the behaviour of rock masses under varying conditions of pressure. According to the theory of Isostasy, all elevations are compensated by deficiencies of density underneath them, and all oceanic depressions are compensated by excesses of density underneath.

In the diagram (Fig. 1) I have drawn a section of the crust from mountains to sea, and the vertical lines descending from the surface to a depth of 70 miles show the vertical columns of Isostasy. In each of these columns there is the same amount of matter per unit of area: the high columns have no more mass per unit than the low. The high columns are of low density, and the low columns are of high density.

The horizontal lines show how the isostatic crust is divided by geologists into three shells—the sedimentary, the granite, and the basaltic. The basaltic shell is the principal seat of isostatic compensation.

In 1860 Pratt contended that mountains had risen up out of the crust by vertical expansion, and that their extra mass above sea-level was compensated, because its own rise by expansion had created the deficiency below. This explanation is no longer considered complete. Mountains that were elevated many ages ago and that have been suffering losses of rock from the unceasing destruction wrought by weather are found in this our own time to be accurately compensated by deficiencies of matter below. So we have to explain how the compensation of the mountain is being accurately adjusted underneath when its weight is obviously being reduced above by wear and tear.

If a mountain is always being worn away, it must be gradually losing its weight, and if its streams are carrying away its lost material to the nearest basin, the basin must be gaining in weight. Geodesy has proved that the mountain's loss of weight is being corrected by additions underground, and that the gains by the basin are being corrected by withdrawals of matter underground. Mr. Hayford has suggested that there is a subterranean transfer of matter through the crust from below the basin to below the mountain; and he has called this transfer the "undertow." In March last Colonel Tandy read a paper before this Society on "The Circulation of the Earth's Crust," and he gave an explanation of the "undertow." Colonel Tandy expressed the opinion

Fig. 1.—Section from mountains to sea.

that the rock-material, eroded from mountain sides, fell down into the valleys, and that it there sank into the crust and flowed back underground to the mountains; by its return flow it raised the mountains in height and restored to them the rock of which they had been denuded above. Colonel Tandy's description of the "undertow" is that of a liquid stream flowing horizontally through the solid crust—from under every valley to under every hill.

Colonel Tandy contends that the falling stones sink by their weight into the crust as though the latter were molten. I have not time in this short paper to review the evidence collected by different branches of science concerning the strength and rigidity of the Earth's crust. But

I may point out that the crust has for ages supported the plateau of Tibet. The isostatic compensation of this plateau does not alter the fact that at sea-level its immense weight is supported by the rocks below it. These rocks show no signs of being crushed, their surface is not yielding. In certain European mines the solid rock has been observed slowly to creep, a phenomenon known as rock-flow ; but rock-flow only occurs when man is interfering with nature. No rock-flow has been detected at the base of the Tibet plateau. In my opinion Colonel Tandy's assumption that stones falling from the Tibet mountains sink by their own weight into the crust is not in keeping with the observed fact that the Tibet mass itself stands without sinking.

Also I cannot follow him when he presses the view that the "undertow" is a stream flowing horizontally through the crust. What is the force that produces a horizontal flow? Gravity acts vertically, and gravity is the force that maintains Isostasy. If the Earth were in a fluid state it would have the form of a spheroid. The strength of rocks is, however, sufficient to maintain mountains at great heights, and thus the figure of the solid Earth is irregular. But gravity is able to correct for these irregularities and to keep the Earth's mean figure the same as it would be if the Earth were liquid ; in other words, the geoid conforms to the spheroid. Under the action of gravity deep-seated rocks change their density ; when a basin is overloaded by silt, gravity decreases the density underneath, and if a mountain becomes too light, gravity corrects the error by increasing the density underneath. If we insist upon the fact that gravity acts vertically, we are forced to the conclusion that a horizontal "undertow" through the crust cannot be justified. Our ignorance of the conditions in the Earth's core debars us from speculating how gravity, acting always in a vertical direction, can balance the horizontal transfers of mass at the surface.

One of the lessons learnt from the researches of Hayford and Bowie is that the rock of the crust is composed of a vast number of vertical columns, some 70 miles in depth, and that these various columns differ from one another in density. The different densities are existing and persisting side by side. The structure of the crust is vertical in character, and its vertical arrangement lends support to the view that mountains have been vertical in their origin.

I have already explained that the chief evidence against this view is the compression of the strata. As I have worked in the area of Himalayan compression for many years, perhaps you will allow me to express the opinions that I have formed.

There have been discovered under the sea several long deep hollows, known as "deeps," very long in proportion to their width. There is one off the coast of Java, another off Japan, and four in the Pacific. There are also similar "deeps" existing on land ; there is a great deep extending along the foot of the Himalayas ; it is in our time filled up with sand and

silt, and its surface forms the plains of India. Professor Suess, the Austrian geologist, was the first writer to suggest that a deep must be related to the range that stands beside it. The Indian deep is bordered by the Himalayas, the Chili deep by the Andes, the Tuscarora deep by the Japanese and the Kurile and the Aleutian islands, which are the peaks of a submerged range.

Suess called these deeps "foredeeps," because he thought that the ranges were moving forward and that the foredeeps were subsidences in front of the advancing earth-waves. Most writers have admitted that there are objections to the old idea of the Earth's crust being wrinkled into folds; Suess not only upholds this idea, but he assumes that his folds are

Fig. 2.—Diagram of Alps and Himalaya.

moving across the Earth's surface. He holds that this Indian deep is a subsidence which has left Asia laterally unsupported, and that therefore Asia is slipping southwards.* But he produces no evidence to upset the accepted view that Asia is firmly supported by the rock foundations underneath it. The weight of Asia acts vertically, not laterally, and Asia does not depend upon any lateral support.

Professor Suess is so widely read that I have to ask you to consider another of his conclusions. This long zone of mountains extends from France to China, and it has been shown by geologists to have been elevated in the Tertiary age. We call its western portion the Alps and its eastern portion the Himalayas because the human race is divided into

* "Face of the Earth," I, 596, Sollas's translation; also *Geographical Journal*, July 1920, pp. 37, 38, "The African Rift Valleys," by Professor Gregory.

different peoples speaking different languages; but to the geographer this is one long zone of mountains. Suess contends that Asia has moved southwards because the southern subsidence has removed its lateral support; but he thinks that Europe has lost its northern support in the Arctic regions and that the loss of this lateral support has caused Africa to move northwards and to fold up the surface in front of it into the Alps. So we have the Himalayas created by the moving of Asia southwards, and the Alps created by the moving of Africa northwards; and yet these two independent and opposite movements are supposed to have elevated the crust along the same alignment and to have produced one line of mountains. The geological deductions upon which Suess was building are not in accord with the mechanical or the geographical evidence.

The existence of a deep at the foot of the Himalayas has been proved by both geologists and geodesists. There are other submontane regions where geodetic evidence is forthcoming. One's natural expectation is that a plumb-line suspended within sight of mountains will be slightly deflected towards them by their attraction. Isostasy will decrease the amount of the attraction, but will still leave a deflection towards the mountains. At 60 miles, however, from the Himalayas all the plumb-lines are strongly deflected in the opposite direction; and the only explanation of this curious repulsion is that there exists a hidden deep skirting the hills, and that this deep is filled up with light rock.

In 1871 the Russian Survey reported to the International Geodetic Association as follows (International Geod. Assoc., *Comptes Rendus*, 1871, p. 40): "At the southern foot of the Caucasus the plumb-line is apparently repelled instead of being attracted."

At Zurich the plumb-line is deflected away from the Alps (*Comptes Rendus*, 1903, p. 408). At Neuchatel it is deflected away from the Jura (*Comptes Rendus*, 1890, p. 161, Annexe B, 11). At Bombay and at Mangalore, 30 miles from the foot of the Western Ghat Range, the plumb-line is repelled from the mountains in a remarkable way.* My Himalayan experiences have led me to suspect that these repulsions may be due to hidden deeps, and that many mountain ranges may have deeps beside them, which are not visible to the geologist or to the topographer (Fig. 3).

These mountain deeps are now of primary importance; Hayford's theory of Isostasy has explained all the larger geodetic anomalies except those of one class. This class consists of the peculiar repulsions which have been observed at the foot of mountain ranges.

The error in Clarke's determination of the Figure of the Earth was due mainly to his endeavour to eliminate the seaward deflections at Bombay and at Mangalore.† Recently at the Geophysical Society Dr.

* 'Board of Scientific Advice, India,' 1914-15, p. 68. "Earth's Axes and Triangulation," by De Graaff Hunter, chap. xi.; Profess. Paper, "Survey of India," 17, p. 21.

† The Indian arcs of longitude being near the Equator had great influence in the evaluation of the major axis.

Morley Davies pointed to the seaward deflection at Bombay as evidence of the over-compensation of the ocean. So long as these repulsions are unexplained, they form an argument against Isostasy: I do not believe in this argument. I believe that the cause of these deflections is the presence of attenuated rock in the crust, of which no account has yet been taken in the calculations. We allow in the calculations for the light weight of sea-water compared with rock, and we must similarly allow for the presence of abnormally light rock. It is a difficult matter to estimate the depth to which masses of light rock descend into the crust, and for this reason it is essential that we should try and discover what these deeps are.

On both the Atlantic and Pacific coasts of America (lat. 35° to 45°) there is a tendency for the plumb-lines to be deflected away from the mountainous regions towards the sea.* Bowie has attributed these seaward deflections to the light density of the Cainozoic deposits which form the American coast. This explanation is probably correct, but we still want to know what depth of Cainozoic deposit is required to account for the actual deflections.

The American deflections resemble the seaward deflections at Bombay, and there are no light Cainozoic deposits at Bombay. The Bombay coast is composed of the same heavy volcanic rock as the Western Ghat Range: the difference between the coast and the range is that the horizontality of the strata, which is so characteristic of the mountains, has been much disturbed in the submontane zone. At Bombay the geodetic evidence leads me to believe that a deep exists, but it is not a surface feature. Some of the Pacific deeps are 28,000 feet below the level of the sea, and these deeps must be features of the granite shell which underlies the sedimentary rocks. The long deep skirting the Himalayas is completely hidden by sand; its depth cannot be estimated with confidence; from many calculations which I have made I conclude that this deep must descend below the sedimentary rocks into the granite. When I see a deep depression in the solid crust, I can imagine only two probable explanations of its origin; either it has been formed by vertical subsidence, or it has opened horizontally under tension. The elongated forms of the ocean deeps and of the land deeps do not support the view that they have originated by vertical subsidence. When a hollow in the crust takes the form of a long narrow depression with parallel margins it conveys the idea of a fracture; its form is that of a crack. I think that the deeps may have opened under tension.†

Geologists have given proofs that the beds of the Himalayan rivers have been excavated by the streams; no scientific fact has been more clearly established. But I have frequently seen it suggested that in the first instance the main course of a mountain river may have been decided

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

† "Origin of Himalayan Folding," by Sir T. Holland, *Geol. Mag.*, 10, 167-170. Presidential Address by Sir T. Holland, Section C, Brit. Ass. 1915.

by a fracture in the range. The sections drawn by the Himalayan geologists show that mountains are permeated by fractures; strata are fractured, hill-sides are fractured, boulders are fractured; and water imprisoned behind a range might in the first instance be helped to escape by a rift.

A remarkable feature of the mountains of Asia is that several of the principal river gorges cut across the main ranges at points where the ranges are highest.* The Sutlej escaping from Tibet makes straight for the peak of Leo Porgial, the highest point of the border range. The Indus rushes for 600 miles across the Tibet plateau before it can escape, and where does it eventually find a gateway? At the very foot of Nanga Parbat, the highest peak of the Western Himalayas. The other great river of southern Tibet is the Brahmaputra, and up to 1914 it was not exactly known where this river had effected its escape. But when its course came to be explored by Bailey and Morshead, it was found to have a passage through the mountains at the very foot of Namcha Barwa, the highest peak of the Eastern Himalayas. I have no time to refer to the other instances of rivers crossing mountains near points of maximum altitude, but I have to say that I think we should be wrong in dismissing these phenomena as mere coincidences. I have been gradually led to believe that these main rivers are crossing the mountains on the lines of ancient fractures. I have had the advantage of discussing fractures with a most able physicist in Mr. De Graaff Hunter, and I think that relief of pressure, generation of heat and elastic rebound are among the probable consequences of crustal fracture (*Proceedings Royal Society, A*, vol. 91, 1915, p. 234). I venture to submit the following explanation of the proximity of a river gorge to a high peak—a fracture occurred relieving the pressure in the crust, the granite expanded upwards and formed a peak, the imprisoned water found a passage through the rift.

If this explanation is regarded as worthy of attention in the case of a mountain gorge, it deserves to be considered in the case of the great deep. What the lesser fracture is to the solitary peak, the main deep is to the range. As the peak arose from a relief of pressure in the crust, so has the range arisen from the opening of the deep.

The lower diagram of Fig. 3 is a section across the Himalayas; the dotted portions show the protrusions of granite; the horizontal compression is shown; the plumb-line is repelled from the mountains; the hidden deep skirts the hills. I cannot draw the deep. The Himalayan geologists place its northern edge near the margin of the hills; geodesists would place it a little further north and inside the hills; seismologists would say that the disastrous earthquakes of Kashmir, Dharmasala, Katmandu, struck the mountains with greatest force within the zone of compression; the geological maps that illustrate the forms of the continents

* 'Sketch of Geography and Geology of the Himalaya Mountains and Tibet,' 1907, part iii. p. 185.

before the rise of the Himalayas show a long narrow channel of sea crossing Asia along the line of this deep, but the ancient Mesozoic channel embraced both the deep and the range, and it conveys the idea that the present granite ranges may have arisen vertically out of the original deep.

The question still remains—How has this discussion of the Indian deep assisted the problem of the horizontal compression of mountains? In this way: the main Himalayan range runs parallel to the deep; the

Fig. 3.—Sections showing the "Deeps" of the Western Ghats and the Himalayas.

distance of the main granite outburst from the edge of the deep averages 40 miles; and it is within this zone between the range and the deep that the horizontal compression has been observed. Here we have a zone 40 miles wide, and its surface is one vast rock-ruin: its rocks have been compressed and stretched, depressed and elevated, tilted and cracked: in 19 miles of this zone Middlemiss found a contraction of 8 miles (*Mem. Geolog. Surv. India*, xxiv. 2, p. 77). Is all this rock-ruin due to the shrinkage of the Earth's core away from its outer shell? I have closely analyzed the geological sections by Oldham, Middlemiss,

Hayden, and Vredenburg, and the rock-ruin seems to me to be due to a local cause acting within the zone. The foldings are on so small a scale that I find difficulty in attributing them to a world-wide cause or to Suess's southward advance of the mountains of Asia. It seems to me as if the subterranean rocks in the crust between the deep and the range have been undergoing constant chemical changes. It seems as if the foundations of this zone had been expanding and contracting, and as if their contortions had crumpled the rocks above them. Even within this zone the granite has protruded in many places from below, and the zone itself is one of the principal seismic regions of the Earth.

DIAGRAMMATIC SECTIONS ACROSS THE HIMALAYA (AFTER HAYDEN)

Fig. 4.

Whilst therefore there is evidence of compression in the Himalayas, I do not think that there is any evidence that the Himalayas have been elevated by compression.

My experiences have been confined to one region, and it is possible that they may not accord with the views of those who have studied mountains elsewhere. The problems involved will not be solved by one branch of science or in one locality. I hope that by expressing my own opinions I may induce others to express theirs.

Before the paper the President said : There is no need for me to introduce to you Sir Sidney Burrard, the late Surveyor-General in India, because he has already been before us this session. We are very glad to welcome him here again this afternoon, and I will now ask him to read his address.

Colonel Sir Sidney Burrard then read the paper printed above, and a discussion followed.

Dr. MORLEY DAVIES : The subject which Sir Sidney Burrard has introduced is one of very great difficulty and complexity, upon which the opinions of geologists have changed so much from time to time that it would be very unwise to be at all dogmatic. But there were certain views expressed by Sir Sidney Burrard on which I should like to comment. He refers to the rigidity of the Earth, and, pointing out that gravity acts in a purely vertical direction,

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