

THE RIFT VALLEYS OF AFRICA

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ABSTRACT. The plateaus of East Africa in which the rift valleys are cut are regarded as the remains of a sunken mountain range. The granitic rocks comprising a range are much thicker than those of a continent and having the same quantity of radioactive elements in a unit volume, the base of a range gradually rises to a much higher temperature, possibly four times, than the base of the continent; the range therefore rises after being folded. Tension in the crust develops and fissures may open. The base of the range softens under the temperature and much later, for reasons given, it is gradually dispersed and mingles with the underlying basaltic substratum. The whole range then sinks and compression replaces the previous tension. The rift valleys would be the fissures which filled with basaltic lava from below as they opened. The granitic material at the base of the range and the basaltic material at the base of the fissures would be dispersed away to the same extent as the range sank. The basaltic material, however, being more dense than the granitic material, a greater weight of material would be lost beneath the fissures as compared with that lost beneath the plateaus. In consequence a deficiency of gravity would be found over the rift valleys.

IN this paper a new theory of the gravity deficiency of the rift valleys of East Africa is described. Suess, who drew attention to them as a tectonic feature of the earth, regarded them as the primary geological feature of Africa. More recently they have been regarded as an integral part of the elevated plateau there some 3,000 to 6,000 feet in height. Bailey Willis¹ has said "thus the problem shifted to the query: Why plateaus? And to the related question: Why rift valleys in plateaus?" In this paper the plateaus are regarded as the worn down peneplains of a *sunken* range of mountains, not mountains like the Himalayas or the Alps which border a continent and have an alien foreland of sediments, but like the Altai mountains of Asia which occur within a continent and have a foreland similar to the backland.

A very brief sketch of the African rifts is all that is necessary here; they have been described in many books and papers, in particular in Bailey Willis' "East African Plateaus and Rift Valleys" 1936. The series of deep trenches, or rift valleys as they are usually called, are cut in a high plateau 3,000-6,000 feet above sea level. They are occupied in places by long, narrow and deep lakes; Lake Nyassa and Lake Tan-

¹The East African Plateaus and Rift Valleys (1936), p. 1.

ganyika, the two longest, are each about 400 miles long and on the average about 30 miles wide. The western rift valley runs from the Zambesi to the upper waters of the Nile and is slightly concave to the east. It begins near the Zambesi with the Loangwa trench, and somewhat east of that trench and in about the same latitudes is the trench containing Lake Nyassa. There follows northward, after a stretch of high plateau, another trench containing Lake Tanganyika, then, with further interruptions, Lake Kivu, Edward and Albert. Lake Kivu drains into Lake Tanganyika and the latter drains west into the Congo. Another series of trenches in a roughly northerly direction, known as the eastern rift valley, is less well marked; it contains the Lake Rudolph 200 miles long, and can be traced eventually to the Red Sea. Between these two main valleys lies the roughly circular and shallow Lake Victoria, about 200 miles in diameter.

Of the longer rift valley lakes, Lake Tanganyika may be taken as typical. According to Bailey Willis (p. 52) the plateau in which it is cut varies from 4,000 to 6,000 feet above the sea, and the bottom of the trench over large areas is more than 1,400 feet below sea level. The level of the water in the lake is now about 2,000 feet above sea level. The eastern valley is evidently continued through the Red Sea, which is a rift sea, into the valley of the Jordan. The Dead Sea, 20 miles wide in the latter valley, is cut in a plateau 2,500 feet above sea level and the floor of that Sea is 2,000 feet below sea level. The Red Sea is on an altogether different scale from the African rifts, being about 1,200 miles long to Jibuti and on the average about 150 miles wide. It reaches a depth of more than 6,000 feet in places and it is bounded by steep escarpments usually 5,000 to 8,000 feet high. While it presents many of the features of a rift valley, into which the ocean has flowed, it differs in that gravity is practically normal over it according to the free air hypothesis, while according to the Heiskanen hypothesis the mean of four stations is +50 m-gals.^{2a}

J. W. Gregory (1921) regarded the valleys of Africa as a tectonic feature due to tension of the crust. Between two parallel faults, produced in this way, a part of the crust, a keystone, was let down, forming the rift. How a block of

^{2a} Vening Meinesz, Gravity Expeditions at Sea. Vol. II, p. 109.

granite can be let down and kept down in the heavier substratum beneath is not explained.

A Wegener², recognizing from Kohlschütter's gravity observations (1911) that the rifts were not isostatically compensated, suggested that the rifts are clefts due to tension but are of moderate depth only, not going right through the continent. He suggested that where, as in the Red Sea, the cleft went right through the continent the underlying plastic basalt rose in the cleft and gravity was therefore normal over that sea. The moderate clefts of Wegener must run down about 5,000 feet over a width of 30 miles on the average. Besides being extremely shallow they would, if uncompensated, and Wegener provided for no compensation, show a gravity deficiency far exceeding that found. The gravity deficiency over Lake Tanganyika is represented by less than 1,500 feet of a granite layer.

If the fissures are due to tension, which have gone right through the continent, the lava would have welled up in them from below, and would have been in isostatic equilibrium with the granite plateau and when solidified would still be in isostatic equilibrium as the mass would be unaltered. Such isostatic equilibrium is contrary to the facts as gravity is in marked deficiency over the rifts. Commenting on the tension theories E. C. Bullard³ says "It is impossible to produce a gravity deficiency over the Rifts by such a process. This argument will apply to *any* tension theory of Rift formation." Whatever values the tension theory may have in other directions, and they are many, the impossibility of providing for any gravity deficiency is a serious difficulty.

E. J. Wayland has suggested that the rifts are due to compression of the crust, and has developed another theory, the ramp theory. Compression would cause two portions of the granite to approach one another, and if, in approaching, they rode up over a third portion of the crust, as on a wedge shaped ramp of granite, the latter would be forced down into the heavier plastic material beneath. As the lighter granite of the ramp displaced the heavier material it would give a deficiency of matter beneath and account for a deficiency of

² The Origin of Continents and Oceans. Eng. Tr. 1924, p. 170.

³ Gravity Measurements in East Africa. Phil. Trans. A. 1936, p. 513.

gravity. The granite ramp, being strong, is held down by the pressure of the granite loads on its two sides.

The deficiency of gravity over the rifts, which has been known for some time and was investigated by E. Kohlschütter has recently been investigated with every care on isostatic hypotheses by Bullard at 87 stations in the paper cited. In Kohlschütter's time no isostatic corrections for topography were made. Bullard finds the gravity deficiency, on the Hayford hypothesis, is 63 and 73 m-gals at two stations at Lake Albert (p. 502); the corresponding deficiencies on the Heiskanen hypotheses is practically the same. At three stations at Lake Tanganyika (based on Kohlschütter's observations) he calculates the deficiency is 34, 39 and 46 m-gals on the Hayford hypothesis, with similar values for the Heiskanen hypotheses. A deficiency of gravity of 100 m-gals corresponds approximately to a deficiency beneath of an infinite slab of granite 1 km thick.⁴

Commenting on these results Bullard says in conclusion (p. 523) "The gravity measurements therefore show that the African plateau is, on the whole, in isostatic equilibrium but that the Rift Valleys have more light matter under them than is required for isostasy. This distribution of matter under the Rift can be accounted for if they have been formed by faulting and folding under horizontal compression, but not if they have been formed by tension." On p. 516, however, he says—"On the above hypothesis (the ramp theory) the additional light matter under the Rift will be spread over a width considerably greater than the width of the Rift itself and calculation shows that the gravity anomalies produced by it would extend over about twice the distance actually observed. Further the calculated anomaly is only about half that observed. These discrepancies can only be removed by assuming that the root of light matter is narrower than the Rift and nearer the surface than the 40 km which we have provisionally assumed for the thickness of the crust. This large narrow root is somewhat difficult to account for on any view." A narrow root, it may be observed, while it might be in agreement with compression is not in agreement with a wide ramp.

If under the plateaus adjoining the rift an excess of light

⁴Jeffreys, H.: 1935, *Earthquakes and Mountains*, p. 71.

matter exists, such as a ramp would provide, one would expect, as gravity is generally normal over those plateaus, that those plateaus would be elevated into a ridge of considerable height, as an excess of light matter (granite) would float high. E. J. Wayland⁵ however says "The country as a whole has risen towards the [western] rift but the maximum rise is not as one might perhaps expect, at the escarpment but [east of it] along a line running about twenty-three miles from it . . . I shall call it the *rift crest*." There is therefore no considerable elevation in the neighbourhood of the rift such as an underlying ramp would require.

Again if one imagines that the rifts are filled with granite to the same general level as the plateaus surrounding them, then, as the rift so filled and the plateaus adjoining will be underlain by a ramp of granite, the base of which must be considerably wider than the rift, one would expect gravity to be the same over the filled in rift as over the plateaus, that is, it would be normal. In the case of Lake Tanganyika a layer of granite over 5,000 feet thick and about 30 miles wide would be necessary, but the deficiency of gravity that exists there is represented by less than $\frac{1}{2}$ km., i.e. less than 1,500 feet, of a granite layer. A discrepancy of this order can be avoided only by the hypothesis that the rift consists of basalt or some material heavier than granite so that on cooling and crystallizing it sank deep into the rift. The narrowness of the root and the granite nature of the root appear to be serious difficulties in the *granite ramp* theory. On the other hand the hypothesis that the rift is filled with basalt from below, while in harmony with narrowness of the root, leads to the equally serious difficulty of the gravity deficiency.

S. J. Shand⁶ after reviewing the two theories says: "The mind does not readily accept two contradictory explanations of what seems to be one and the same phenomenon and rather than agree easily to the conclusion that some valleys are rift troughs and others ramp troughs one would like to put the question whether rifting is not really the fundamental feature in every case and ramping a later effect superimposed in some instances only upon the rifts."

A mountain range has a deep root of granitic material

⁵ Uganda—Report Ann. Survey. 1933, pp. 72 and 73.

⁶ Earth Lore. 1937, p. 110.

which, on folding, is thrust down into the plastic substratum which lies beneath the strong continent. The substratum, which is probably basaltic, is evidently maintained in a plastic condition, partly by the water contained in it, which cannot escape except rarely when lava reaches the surface from a volcano, and partly by the relatively high temperature at which it is kept by the radio-activity in the continent above. The granitic material of the lower levels of the continent, out of which the root is fashioned, is strong; it must be strong to resist the upward hydrostatic pressure to which, as a root, it is subjected. There is, however, much evidence to indicate that the lower levels of the continent have not crystallized owing to the presence of water which could not escape. R. W. Goranssen⁷ has shown that under a pressure of 15 km of granite, a granite magma can hold more than 9% in weight of water. H. Jeffreys⁸ on this has remarked: "These facts suggest that much of the water in the upper and intermediate layers has been held in them by pressure, and that they have consequently failed to crystallize." Quartz in the intrusives has crystallized at low temperatures, 500°-700°, which indicates that the granitic material at low levels, from which the intrusives came, contains much water. There is also the fact that the velocity of the seismic waves for the continent "is below that for granite and near that for obsidian for high pressures."⁹ It will therefore be accepted that the granitic root of a mountain range, though solidified, contains much water and would soften and melt at much lower temperatures than granite.

The root, although it contains water, must be stronger than the plastic substratum in which it is immersed, as otherwise there would be no mountain range.

An hypothesis outlined by the author in the *Geological Magazine* March/April, 1944, suggests a reason for the strength of the lower aqueous levels of the continents. According to that hypothesis the continents were formed by floating crystals (the felspars) which separated out of the fluid magma. The magma was then in convective circulation rising at the equator and sinking at the colder poles. The floating crystals would be formed as the magma approached the poles

⁷ *AMER. JOUR. SCI.*: 1931, p. 481 and 1932, p. 227.

⁸ *Earthquakes and Mountains*. 1935, p. 128.

⁹ Jeffreys, H.: 1929. *The Earth*. P. 102.

and would entangle some of the magma. The whole, felspars and entangled magma, consolidated into two continents, which later floated towards the equator and became known to geology as Laurasia and Gondwanaland. In their upper levels the material of the continents crystallized into granite, but in the lower levels where the water could not escape it consolidated into a non-crystalline mass with the felspars as phenocrysts. The presence of the phenocrysts in the mountain roots would strengthen them and permit the roots to withstand the hydrostatic pressure.

The well known seismologists B. Gutenberg, L. H. Adams and H. Jeffreys have expressed the view that the continents are about 15 km thick and that the intermediate layer (the plastic basaltic layer) is about 25 km thick,¹⁰ while below that there is a deep crystalline layer, probably of olivine. The mechanism which formed the folded mountains was probably the slow horizontal creep of the plastic basaltic layer, which threw into wrinkles the strong continent it carried on its back, as Ampferer had (1906) previously suggested. A lava flow throws into wrinkles the crust which forms on its surface. The horizontal creep of the plastic layer was from the high levels, at which it stood under the centre of the continents, to the margins where deep sediments had forced it down; the high levels being probably caused by the expansive effects of radioactive heat in the continent on the deep portions of the crystalline olivine layer below. That differential expansion would occur between the centres of the continent and the floor of the oceans, due to the excess radioactivity in the continent, was pointed out by H. Jeffreys.¹¹ The piling up of granite in the form of wrinkles would require a root of the continental material to be formed in the plastic layer beneath in order that isostasy may be preserved. The root having room to spread in the plastic substratum would be unlikely to penetrate the strong crystalline olivine layer.

The root being formed of continental material would contain radioactivity to the same amount as the continent. If the root and the range above it were *double* the thickness of

¹⁰ Adams, L. H. Internal Constitution of the Earth. Ed. Gutenberg, 1939, pp. 86 and 87, and H. Jeffreys, AMER. JOUR. SCI., Nov. 1941, p. 833.

¹¹ The Deformation of the Earth Due to Unsymmetrical Cooling. M.N.R.A.S. Geoph. Suppl.: May 1932.

the continent, i.e. 30 km, the temperature created at its base by radioactivity would be *four* times that created at the base of the continent 15 km thick; while if the root and the range were 40 km thick the temperature at its base would be seven times that at the base of the continent. The radioactive temperature varies as the square of the thickness. In addition at the base of a deep root the temperature due to the internal heat of the earth would be higher than at the base of the continent. A consequence would be that during a period, probably of the order of 10 to 20 million years,^{11a} from the folding of the mountains, the range and the root would expand and the range would "float" higher in the basaltic layer. Calculations on certain reasonable assumptions indicate that it might rise above its initial folded position by about 2 km. The range being bound down to the undisturbed continent at its margins would, in the process of folding and rising, show signs of tension between the margins and the top of the range, and fissures would develop along its length.

The high temperature attained by the granitic root would be expected to liquefy a pocket of the basaltic layer (which contains water) adjacent to the root and the basaltic lava would quietly emerge from the fissures; this quiet flow would continue so long as the fissures remained freely open, that is so long as the range was rising. The lava being liquid would be in isostatic equilibrium with the granite plateaus. With increasing temperature the granitic root, which contains water, would probably also soften, though not so readily as the plastic basaltic layer which also contains water. The granitic root contains less water and also contains, as suggested, strengthening phenocrysts. The root would then by friction of the movement of the basaltic layer gradually disintegrate and be rubbed off and mingle with the surrounding layer. The immense quantity of lava erupted from around the root must play a significant part in shaping it so that the undersurface might well be worn away.

Owing to the loss of part of the root the range would cease to rise and would begin to sink. It would sink partly because of the loss of hydrostatic support and partly to the falling temperature in the range through the loss of the dis-

^{11a} See Jeffrey, H.: 1941. *AMER. JOUR. SCI.*, Nov., p. 826.

persed radioactive material in the root. The tension which occurred when it was rising would change to compression when it was falling. The fissures would, under the compression, cease to be freely open to the uprising lava which would crystallize into basalt. The crystalline basalt, having a density 3.00, and the underlying basaltic material in the fissure, having probably a density 2.85, if seismic evidence is accepted, would stand in the fissure at a lower level than the surrounding granite plateaus, density 2.65, the whole being in isostatic equilibrium. The contraction and sinking of basalt in the necks of extinct volcanoes has been suggested as the cause of the falling in of the tops and the formation of great caldera often filled with lakes.¹² The deep floors of the rifts of Africa and the subsequent filling of them with water can be visualized as having been similarly caused.

The basalt would make a strong joint with the granite walls of the fissure so that as the range sinks both the granite and the basalt would sink with it. The cause of the sinking would be the removal from the bottom surface of the granitic root of a disintegrated layer, which would have been "planed" off by the movement of the basaltic layer and have been replaced by it as it flowed in to take the place of the lost granitic root. While therefore there would be no loss of matter over a region and gravity would therefore remain generally normal over the plateaus, a loss would occur in the basaltic material within the fissure. The "planing" action on the bottom of the root would wear away as much basaltic material as granitic material, but as the former would be the heavier, *the mass of basaltic matter lost would be greater than the mass of granitic matter*. An estimate of the difference of mass lost may be made if the thickness of the root worn away, h cm, and the densities ρ and σ of the granitic and basaltic material could be ascertained. The difference of mass lost would be $h(\sigma - \rho)$ grms per unit column. To produce a gravity deficiency of 50 m-gals, which is a little more than that over Lake Tanganyika, there should be a loss of mass nearly equal to an infinite slab of granite $\frac{1}{2}$ km thick. If the deficiency of gravity is due to the loss of mass, $h(\sigma - \rho)$ must be equal to $0.5 \times 10^5 \times 2.65$, approximately, taking the width

¹² Williams, H.: 1941. Crater Lake. The story of its origin.

of the rift 30 km as approximately equivalent to an infinite slab. The densities σ and ρ refer to the basaltic and granitic matter, which contain probably much water; if then it is assumed in the absence of accurate data that the difference $\sigma - \rho$ is about the same as the difference between the densities of crystalline basalt and granite, which have lost their contained water, then $\sigma - \rho = 3.00 - 2.65 = 0.35$

$$\text{therefore } h \times 0.35 = 0.5 \times 10^5 \times 2.65$$

$$\text{or } h = 4 \text{ km approximately.}$$

If the thickness of the range and its root was (say) 30 km originally it would become 26 km. Gravity would still be normal over the plateaus but over the basaltic rifts it would be deficient by about 50 m-gals. There would be an upward pressure per cm^2 by the plastic basalt beneath on the basalt in the fissure equal to the weight of $\frac{1}{2}$ km of granite which would be resisted by the strength of the junction between the basalt and the granite of the walls of the fissure. It will be noted that the loss of matter is concentrated in a narrow rift as was found to be necessary by Bullard. If the rift is wide the hydrostatic pressure upwards being proportional to the area, the junction would not be able to hold and isostatic equilibrium would result. The rift was wide in the case of the Red Sea. In that sea gravity is practically normal on the free air hypothesis, but is about +50 m-gals on the Heiskanen hypothesis. The latter indicates an excess of matter under that sea, if the Heiskanen hypothesis is more correct than the free air hypothesis over the ocean.

A range would when rising exhibit signs of tension and when falling it would exhibit signs of compression; both should give rise to features of geological interest, but the latter would be superimposed upon the former as suggested by Shand. Among the facts that suggest subsequent compression is the fact to which Wayland draws attention in regard to the rivers of Uganda, which previously drained west into the western rift, and now drain the other way. He says¹³ "When it is realized that the western rift valleys of Uganda and in part of Tanganyika form an arc, it is easy to picture the rift crest [23 miles east of the rifts] as the lip of a vast shallow saucer whose centre is occupied by Lake Vic-

¹³ Uganda—Report Ann. Survey. 1933, p. 73.

toria into which the reversed rivers of this Protectorate feed." Again referring to the isolated snow capped granite mountain of Ruwenzori, which interrupts the western rift between Lakes Edward and Albert, Bailey Willis (p. 46) says "We are thus led to conclude that the elevation of Ruwenzori has been due to lateral compression"

Under tension the fissures would be kept open to fissure lava flows. Under compression, however, the fissures would tend to seal up with the consolidated basalt. If later, owing to the forces of compression, deep cracks occurred in some of the rifts, the heated and confined lava would be forced up and a volcano would be formed. Extinct volcanoes and some active ones are a feature of the rift valleys around the periphery of the central plateau but not of all of them and not in the Tanganyika trench. "Some sections of the rift do not show this deficiency of gravity; these seem to be the parts in which there has been extensive volcanic action," says Bullard.¹⁴ This may be due to a free lava flow, restoring gravity to normal in the rift. The presence of volcanoes, especially extinct volcanoes, as distinct from fissure lava flows, should therefore on this hypothesis be an indication of a sinking range.

¹⁴ Bailey, Willis: 1936. *East African Plateaus and Rift Valleys*. P. 343.