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Crustal Warping—A Possible Tectonic Control of Alkaline Magmatism

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Abstract. Alkaline and peralkaline magmatism is peculiar to the epeirogenic continental environment; it is characterized by unusual concentration of alkalis, volatiles, and rare elements, the large volumes of alkaline rock contrasting with the small amounts of such rocks in alkali basalt provinces. Probably the most outstanding region of alkaline and related carbonatite activity is in east and central Africa, where localization of the activity along the rift valleys has long been recognized. Recent discoveries tend to establish this relationship. The restriction of major alkaline provinces to the stable continents has led to the suggestion that long undisturbed periods must be necessary for slow accretion beneath the crust; the implications are that the continental plate has a passive role and that any association of alkaline magmatism with rifting is fortuitous. It is here argued that the regional tectonics control the generation of alkaline magmas and their localization along the rift zones. The African shield shows a distinct 'basin and swell' pattern, and many of the rifts occupy the axial zones of the long, narrow upwarps, separating the basins. A series of erosion surfaces, dating at least as far back as the Jurassic, shows increasing elevation and separation toward the crests of the swells and indicates uplift of these zones in several distinct stages: the continuity of such erosion surfaces shows that the continental plate behaved competently during these uplifts. Upwarping of a rigid continental plate would relieve the pressure lower in the crust, allowing partial melting and the concentration of fugitive constituents from the underlying mantle. In east and central Africa, similar alkaline magmas of salic differentiate character, rich in volatiles, and often with associated carbonatites, were produced in different regions during different periods of rifting; the unusual volume of such rocks can more reasonably be explained by partial melting of crystalline source rocks and collection of juvenile fugitive constituents than by the usually favored process of fractional crystallization, which would require a vastly greater volume of parent magma.

Introduction. Many petrologists have noted that the major alkaline and peralkaline igneous complexes appear to be restricted to the stable continental or shield areas of the crust, an arrangement succinctly described by *Backlund* [1932] as the epeirodiatresis relationship, and one which has given rise to the view that the special tectonic conditions of these regions are necessary to the formation of such magmas. There is no general agreement as to the precise role of the tectonics in this magma generation; it has frequently been suggested that the long periods of quiescence have favored the accumulation of alkali-rich magma by such means as extensive gas transfer in a magma such as alkali basalt. If lack of disturbance were the criterion, however, the continental association of these magmas would still need explanation, for presumably this tectonic requirement could be met in the ocean basins. Also, if some process other than crystal–liquid equilibrium were required for the formation of alkaline rocks, it is difficult to reconcile their concordance with the low-temperature compositions of 'petrogeny's residua system' [*Bowen*, 1937]. The central question remains, therefore: Why should these rocks of distinct salic differentiate character show a marked development on the continents?

Probably the most spectacular array of alkaline igneous rocks and associated carbonatites is in Africa, particularly in the eastern and central parts of the continent, an excellent summary of the information on the activity being provided by *King and Sutherland* [1960]. That this alkaline magmatism shows a general coincidence with the rift pattern in this part of Africa has been noted by many writers, including King and Sutherland (p. 299), but there has been considerable divergence of opinion as to the relationship be-

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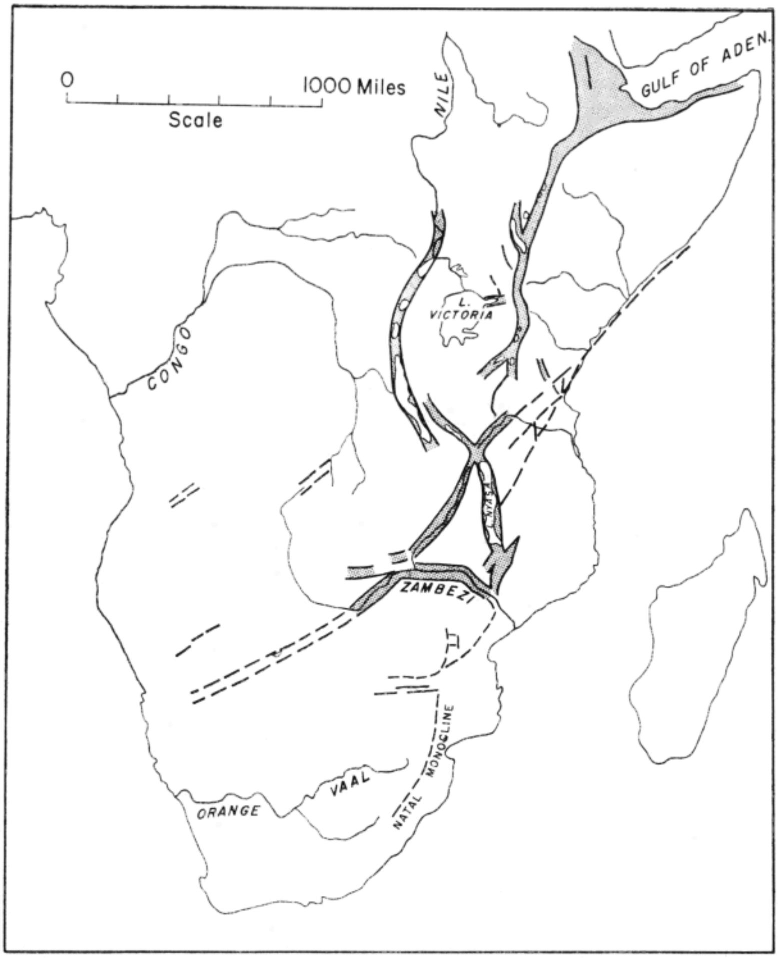

Fig. 1. The East and Central African rift zone.

tween the two, if any exists; King and Sutherland, for instance, were clearly perturbed by the lack of detailed correlation between the igneous centers and the rift faults. But the African rift zones are one of the world's major tectonic features and if they are in any way a locus of alkaline magmatism they undoubtedly hold the key to the relationship of such magmatism with epeirogenic earth movements. The following discussion will be confined to this one region, but it is felt that the basic relationship that is deduced, namely, partial melting by relief of lithostatic load, may have a more general application to the problem of the alkaline rocks.

The rift zones. The impressive topographic expression of the Tertiary rifts in east and northeast Africa, commonly known as the East African Rift zone, has focused attention on them and made them a subject of controversy since the time of the classic description by *Gregory* [1921]. But, as clearly shown by *Dixey* [1956] in his survey of the East African Rift, much of the Tertiary movement was on the site of late- or post-Karroo (Jurassic) movements, and as the Western Rift is traced from Lake Rukwa into the Nyasa trough, and farther south, the age of the major movement is predominantly post-Karroo. New work is showing that south of Lakes Tanganyika and Rukwa a pattern of post-Karroo rifting emerges that is comparable in extent and scale with the Tertiary rifting to the north, and only less striking because its topographic expression has been subdued by longer erosion: the mid-Zambezi-Luangwa rift, for in-

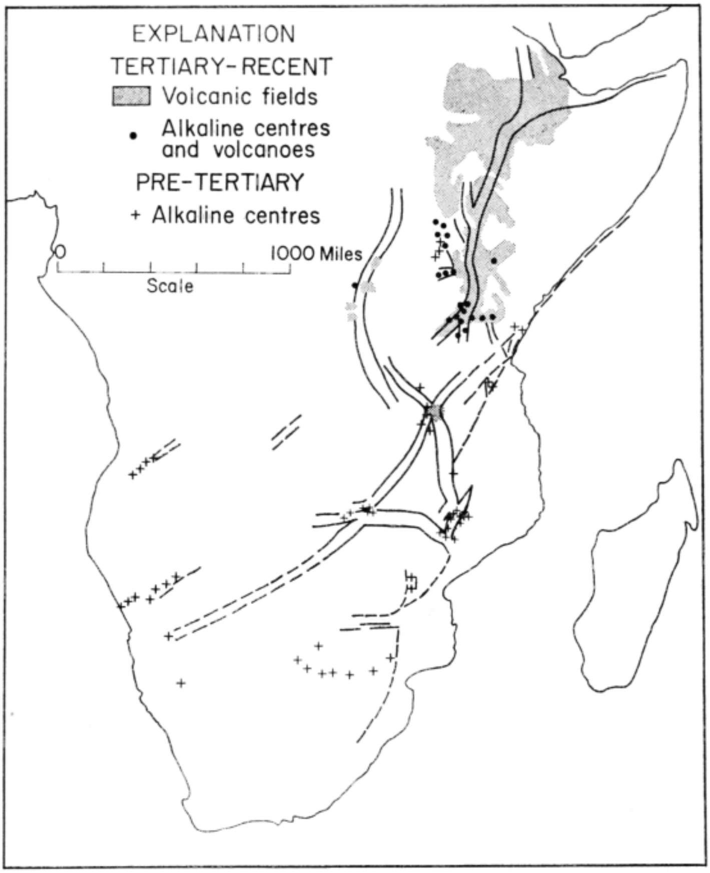

Fig. 2. Distribution of alkaline centers and volcanic fields.

stance, is merely a part of a much longer rift zone of post-Karroo age [*Bailey,* 1961]. Almost certainly there was pre-Karroo rifting too, and *Dixey* [1956] has also stressed the tendency of the rift zones to parallel the major structural trends in the Precambrian rocks; the latter are largely orogenic structures, however, and, as hinted by *Shackleton* [1956], this may be essentially accommodation of the rift pattern to a previously established 'grain' in the crust. The presently known pattern of rifting in eastern and southern Africa is shown in Figure 1.

The alkaline magmatism. When the distribution of alkaline igneous activity is superimposed on the rift pattern, as shown in Figure 2, there is a remarkable correspondence. Certainly the activity is not solely confined to the actual rift faults; it would seem naive to expect this, but the general concurrence of the two patterns, especially noticeable in the concentration of activity around rift intersections [*Dixey,* 1955, p. 28; *Bailey,* 1961] and in the strong correlation of Tertiary and post-Karroo activities with those sections of the rift in which movements of these periods respectively predominate, makes it hard to avoid the conclusion that the magmatism and the rifting are both expressions of the same major process.

The type and character of the alkaline igneous activity have already been reviewed by *King and Sutherland* [1960], with a comprehensive bibliography, so that only a brief survey is in order here. The extensive Tertiary to Recent lava fields in Ethiopia are generally recorded as being predominantly basaltic, but this may well be a convenient generalization because to the south, in Kenya, although basalts (often basanites according to *Kent* [1944]) are widespread, phonolite is very common and is perhaps the predominant lava throughout the Eastern Rift and in adjacent areas such as the Uasin Gishu plateau, the Aberdare Mountains and Mount Kenya. Trachytes, nephelinites, and alkali rhyolites are also well represented in these fields. Farther south, in Tanganyika, the lava fields give way to central volcanoes built largely of fragmental materials, mainly nephelinites and phonolites along the Eastern Rift and trachytes and phonolites to the east in the Kilimanjaro range. In eastern Uganda a chain of Tertiary volcanoes, largely composed of fragmental nephelinites, stretches northward from Mount Elgon [*Davies*, 1952], one of these, Napak [*King*, 1949], having an exposed ijolite-carbonatite core. Farther to the south and west lie the pre-Tertiary carbonatite centers of Tororo, Sekulu, and Bukusu.[2]

The potash-rich lavas of Toro-Ankole and Birunga in the Western Rift are well known [*Holmes and Harwood*, 1932; *Combe and Holmes*, 1945], but not all the volcanicity of this rift is strongly potassic, as indicated by *Bowen* [1938], although it is characteristically alkaline, basalts being well represented only in South Kivu.

Farther south, where the Eastern and Western rifts intersect, is the more isolated Tertiary-Recent volcanic field of Rungwe, which has been studied in detail by *Harkin* [1960]. Alkali basalt is the predominant lava, and in degree of alkalinity and scope of differentiation the magma series is compared by Harkin to that of Tahiti; but the volume of salic lavas, mainly trachytes and phonolites, with some nephelinites, is about half the total eruptive material, and Harkin is forced to conclude that the alkali basalt has been contaminated by carbonatite and alkaline material, such as forms the neighboring but distinctly older complex of Panda Hill. Essentially, this problem is the same as that of the whole of the volcanism of the East African Rift—a preponderance of alkaline salic rocks, in many cases fragmental, indicating volatile-rich explosive activity, and frequently showing signs of assocated carbonatite with its attendant enrichment in rare elements. Implicit in nearly all discussions of such alkaline rocks is the view that they are differentiates of a primary magma, such as alkali basalt: Harkin, however, clearly recognizes that vast quantities of basalt would be required to yield the observed volumes of salic rocks.

In addition to the Panda Hill carbonatite in the Rungwe vicinity there are other old carbonatite and alkaline complexes such as the Nkumbwa Hill carbonatite and the Mivula nepheline syenite in Northern Rhodesia and the Ilomba nepheline syenite and another group of carbonatites in Nyasaland. A most impressive concentration of pre-Tertiary carbonatites, nepheline syenites, and syenites is found in southern Nyasaland and adjacent parts of Mozambique. The majority of these are of Chilwa age, i.e., immediate post-Karroo, but some, such as those of Port Herald, are pre-Karroo. All these are deep-seated complexes, and the large masses of nepheline syenite, and especially syenite (or perthosite), such as Zomba and Mlange, which distinguish this region, are especially significant. Such rocks are older, plutonic equivalents of the widespread phonolites and trachytes of the Tertiary rifts to the north, and they indicate that the same type of magmatism characterized the post-Karroo rifts. These plutons also tend to negate any suggestion that the Tertiary volcanics are products of differentiation in intracrustal magma chambers.

Similar considerations apply to the more scattered groups of post-Karroo and pre-Karroo complexes to the south and west of Nyasaland (Figure 2). The only exception would seem to be the group of pre-Karroo carbonatites and alkaline complexes falling in a roughly E-W zone in the Transvaal, South Africa. These are not related to any well-defined rift, but when it is remembered that even the post-Karroo rift pattern is blurred by erosion this is perhaps not surprising; they may be related to Precambrian rifting which is now almost undecipherable.

The large-scale correlation of the rifting and igneous activity in time and space, as indicated above, seems indisputable. Divergence of opinion seems to arise when the picture is examined in detail; e.g., the nephelinite volcanoes of eastern Uganda are not on a recognizable rift line [*King and Sutherland*, 1960], the volcanic phases of

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[2] In a summary of the igneous activity in Kenya, just published, ***Wright*** [1963] has drawn the additional distinction that *within* the rift valley the younger lavas (post-Miocene) are largely nepheline-free. This may have important implications in the sequence and level of magma generation, but it does not greatly modify the outline given here.

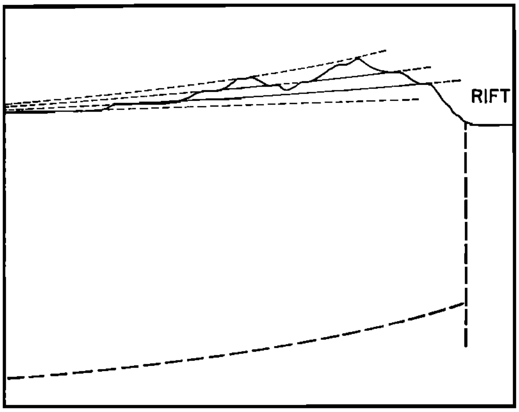

Fig. 3. Vertical section illustrating the 'rise to the rift' with increasing separation of several erosion surfaces; the upper surface may be taken to represent a Jurassic peneplane, the lowest an end-Tertiary peneplane. The heavy broken line marks a Jurassic datum plane within the crust, at an arbitrary depth. The vertical attitude of the rift fracture is diagrammatic.

activity in Kenya appear to be terminated by rift movements [*Kent,* 1944], and there is no correlation between the volumes of the rift troughs and the effusive materials. But these are real anomalies only if a restricted view is taken of the relationship between the magmatism and rifting; they refer to the premise that any relationship must be simply one of cause and effect, whereas it is just as likely that the rifting and magmatism are both expressions of a more fundamental process. Some such process becomes apparent as soon as the rifts themselves are looked at in a regional context.

Many people have noted that the uplift of parts of the African continent is far more impressive than the rifting, this being expressed most forcibly by *Willis* [1936], who considered that the major problem connected with the rifts was the uplift of the neighboring plateaus. Uplift of the plateaus is a misleading term, however, because it has become increasingly clear that 'the rise to the rift,' to which *Wayland* [1930] called attention, is a general feature, the rifts being essentially longitudinal fracture zones along the crests of broad geanticlines. The geomorphological evidence has been reviewed by *Dixey* [1956], and the rise of erosion surfaces of different ages (Jurassic to Quaternary) toward the rift shoulders is striking evidence of 'the arching that accompanied the rifting, involving uplifts of some thousands of feet along zones 300 to 400 miles in width and several thousand miles in length.' Such erosion surfaces have their maximum vertical separation along the flanks of the rifts (Figure 3) and converge and overlap as they are traced into the adjacent basinal areas; they give precise expression to the long-known fact that the rifts are located in the more uplifted portions of the continent (most clearly seen in the Tertiary East African Rift zone, which lies along the continental divide). This 'basin and swell' structure of Africa has been well illustrated by *Holmes* [1944], whose map is reproduced as Figure 4. Uplift of the flanks of the rifts in many places is also suggested by the increase in metamorphic grade of the Precambrian crystalline rocks as the rift is approached, but this evidence is not always unequivocal. In Rhodesia, for instance, there is an increase in metamorphic grade in the Lomagundi/Katanga rocks (625 ± 20 m.y.) as the Jurassic mid-Zambezi rift is approached [*Macgregor,* 1947]; pegmatites in this high-grade belt give ages of 430 to 460 m.y. [*Nicolaysen,* 1962], showing that this is not simply exposure by uplift of originally deeper Katanga rocks but probably also indicates localization of the rift along a distinct metamorphic belt which formed after the main Katanga orogeny.

The rise of erosion levels of different ages over the rift zones shows that the continental plate has been warped in several distinct phases, at least since the Jurassic, and that the rifts are relatively subordinate features on the crests of the crustal swells. Obviously the cause of the warping is as subject to contention as the cause of rifting, but it is possible to clarify the situation a little. *Dixey* [1956], for instance, favors the concept that the basins have sagged and that the intervening swells are largely lag areas, but, other considerations aside, the arrangement of erosion levels, with the maximum separation on the swells and the hinge lines in the basins, requires positive uplift of the swells with respect to the base levels. This observation is critical because positive uplift can be accomplished only by lateral compression or direct vertical movement below the uplifted area. Either mechanism of uplift could lead to partial melting by relief of lithostatic load, but compression will be adopted as a working hypothesis because it is more consistent with present observations.

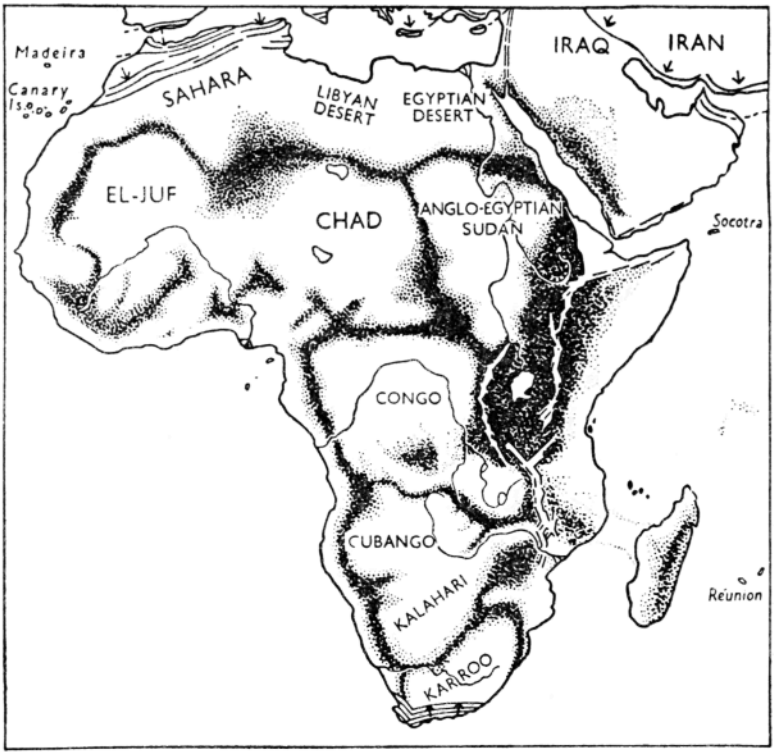

Fig. 4. Generalized map of tectonic basins, plateaus, and swells of Africa. (Reproduced from *Principles of Physical Geology* by Arthur Holmes, 1944, with the author's permission.)

Compression, uplift, and melting. Lateral compression on a large scale is suggested even in the simple basin and swell structure of Africa, which has a tessellated pattern such as might be expected from compression of a rigid but anisotropic plate that has tended to yield along 'grains' established by earlier metamorphic belts.

In an isotropic plate of uniform thickness the compression required for initial warping would be much greater than that necessary to increase the flexure, and it is to be expected, therefore, that in a continental plate the initial flexures would appear where the plate was already thickened or already uplifted. Such conditions would obtain in old orogenic belts, especially if in a state of over-recovery from previous isostatic imbalance, which would accord with the tendency of swells and rifts to parallel earlier orogenic trends. Present lack of knowledge of the mechanism of major earth processes makes it fruitless to dwell long on the possible cause of this compression, but if the southern continents were once welded together and have since been driven apart, then Africa, the Gondwana nucleus, has presumably been under compression from all sides.

Upwarping of the rigid continental plate would produce relief of lithostatic load below the crest of the flexure. Where the bulk composition and temperature lower in the crust were favorable, this would lead to partial melting [*Yoder*, 1952],[3] and the zone of pressure relief would act also as a trap for volatiles and fugitive constituents from the underlying mantle even if melting in the mantle were not possible. It was noted before that the alkaline rocks were

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[3] Since the original presentation of this paper (*Trans. Am. Geophys. Union, 44,* 115, 1963) my attention has been directed to a lecture, 'The Tectonic Significance of Alkaline Igneous Activity,' by R. M. Shackleton, at the first (British) Inter-University Geological Congress, 1953. In the printed summary he states, 'Subcrustal melting was due to the lifting of part of the load on the layers under the swells, and eruption was facilitated by the fractures.' This is an essential part of the process elaborated in this paper.

generally regarded as derivative magmas, but if it is possible for them to form as residual liquids from the crystallization of a magma such as alkali basalt, then before any *crystalline* basalt above the eclogite-basalt transition zone can be rendered completely molten it should partly melt to yield alkaline liquids. This mechanism produces 'derivative' magmas without requiring the vast quantities of heat necessary to completely melt all the parent material, and at the same time it disposes of the volume problem whereby the volume of 'derivative' magma is far too large in comparison with that of the 'parent.' It may be that only below the cover of the continents are all the conditions appropriate for partial melting of basaltic materials at the base of the crust, hence the restriction of major alkaline magmatism to this environment.

The cause of the rifting in the crest of the arch is, of course, a thorny subject of debate, but there is little reason to suppose that the rifts represent subsidence due to removal of underlying magma to the surface; e.g., there is no volcanism associated with the deepest rift, that of Lake Tanganyika, its floor being 2500 feet below sea level. Strong arguments have been made that the rifts are compression structures held down by the overriding flanks, but the supporting evidence of negative gravity anomalies in the rifts [*Bullard,* 1936] has been weakened by drilling evidence of a considerable thickness of light sediments in the best example, the Albert Rift [*Dixey,* 1956]. The whole subject of rifting, like most geologic problems, probably suffers from our natural tendency to fit a simple explanation to a complex phenomenon. If the swells were produced by a series of compressions, as indicated by the series of erosion surfaces, then in a period of relief of compression a rift zone might be initiated as an elastic-release fracture zone, which, once established, would be perpetuated and aggravated by subsequent compressions and releases. An explanation of this kind might resolve the conflict between the opposing tension and compression hypotheses of rifting.

Perhaps the most interesting result of *Bullard's* [1936] gravity survey of the rift zones, albeit overshadowed by the discovery of the negative anomalies of the rifts, is that the adjacent plateaus are in isostatic equilibrium. These areas have been uplifted and peneplaned several times since the Jurassic, and this implies that they were in isostatic equilibrium at the end of each erosion cycle. To achieve such a condition lighter material would have to be added at depth to compensate each succeeding uplift. The relevance of this to the present suggestion of partial melting below the rigid layer of the crust and withdrawal of light materials from the underlying mantle needs no emphasis. But this does introduce, too, the alternative that addition of lighter material at the base of the crust might, in itself, be responsible for the uplift. The main objection to such a mechanism is the difficulty in explaining the rifting in the crest of the upwarp, for this would require withdrawal of material from below the rifts and long sections of these have little or no associated volcanism. Expressed in another way, accretion of light material to produce the upwarps requires that rifting is a consequence of magmatism, whereas the alternative preferred here is that the accretion of light material, the magmatism, and the rifting are all consequences of lateral compression and upwarping of the crust.

Direct vertical movement below the swells, the alternative mechanism to lateral compression, might be supposed to result from uplift above a rising convection current. The latter possibility will undoubtedly find advocates among those who believe that such a mechanism is responsible for the midocean rises, for *Heezen* [1962] has shown that the form of the African swells and rifts is similar to that of the mid-Atlantic rise with its median 'rift valley'; he also shows the East African Rift zone as a continuation of the Indian Ocean rise, but the detailed pattern of the Gulf of Aden and Red Sea rifts requires that this be an extremely tortuous transition. If, however, the African rift zones are the continental analogs of the midocean rises, they pose difficulties for a convection origin, because it is postulated that the rising convection current causes the uplift, splits to give the median 'rift,' and then spreads, giving ocean-floor spreading and separation of the continents. There is so far no evidence of similar spreading of the African continent around the rift zones; in fact, it is held by some that the rifts are compression features, and it is difficult to see why a tensional process should have the same expression through the different thicknesses and structures of the oceanic and continental crusts (perhaps the similar wavelengths are merely a function of the physical state of the outer shells of the earth). Ocean spreading and concomitant continental drift are also supposed to have started in the Cretaceous, but there is evidence of rifting in the Jurassic, and probably much earlier, in Africa. Other difficulties are that the African rift pattern would require the operation of numerous small convection cells (one at least as small as the Lake Victoria basin!) and the situation of rifts along earlier metamorphic belts requires that there are now rising currents where previously there were descending ones. These remarks are intended chiefly as a warning against too facile an application of the convection hypothesis to all major crustal processes, for even if it could be demonstrated that the African swells were intermittently uplifted by rising convection currents the pressure would be relieved during the intervals and the main thesis of this paper would remain applicable.

Conclusion. The position of the East African Tertiary Rift zone along the continental divide, the general off-lap of younger formations away from the rifts, and the rise of the series of old erosion bevels to the rift shoulders indicate the position of the rifts as median fracture zones in the crests of broad crustal arches. There is a close spatial and temporal relationship between the rifting and alkaline, peralkaline, and carbonatitic magmatism, characterized by abundant volatiles, both in the Tertiary rifts and the older rifts such as those of the post-Karroo. Essentially the question is, can the generation of these vast quantities of uncommon rocks be related to the warping and rifting of the crust? The continuity of the various erosion surfaces across the upwarps indicates that the crust has behaved competently, and present evidence favors the view that it has warped in response to lateral compression. Regardless of the cause, however, it is to be expected that there would be relief of lithostatic load below the crest of a rigid arch due to support in the limbs, giving rise, under favorable conditions, to partial melting lower in the crust and perhaps in the upper mantle and withdrawal of fugitive constituents from the upper mantle. The bulk of the magmas in the rift zones are of salic differentiate type, e.g. phonolites, trachytes, and nephelinites; to call them products of fractional crystallization is to say that vast quantities of parent *magma*, such as alkaline olivine basalt magma, were available but only a fraction of this reached the surface or even the plutonic levels that are exposed today in the post-Karroo rifts; moreover, such a state of affairs must have prevailed in many different places and in several geological periods. It would seem more logical to regard these salic rocks as products of partial melting of parent crystalline materials, such as alkali basalt, in the lower crustal region, with contributions of juvenile material from the upper mantle, and relief of pressure would be a suitable mechanism for this.

Any discussion involving the origin of carbonatite must touch on the origin of kimberlite, for rocks of kimberlitic composition are associated with carbonatites, and vice versa, and some people [e.g., *von Eckermann*, 1961] hold that carbonatite is derived from a magma of kimberlite composition. But while the distribution of carbonatite centers shows a strong correlation with the rift pattern, the major kimberlite provinces do not, although they do appear in uplifted areas; the associated alkaline igneous activity of carbonatites and their unusual suite of trace elements also set them apart from kimberlite activity, which is typically expressed as breccia pipes and intrusions with little or no associated magmatism. Apparently the two kinds of activity, in their typical development, reflect differing tectonic conditions, as inferred by *James* [1956], and there is a vital need for more information on the regional tectonics of the major kimberlite provinces as well as gravity and seismic data from both tectonic environments. It seems likely that both kimberlite and carbonatite are derived from the upper mantle, though not necessarily related through some simple process such as fractionation from a common parent. The difference in the expressions of the two activities may lie in the fact that below the rift zones the *PT* conditions are such as to produce melting in the lower crust, as indicated by the igneous activity; therefore, any kimberlitic material from the mantle would generally have to be erupted through a crustal zone of melting and magma generation and would thus be expected to reach the surface only in such form as melilite basalts and kindred lavas such as those of Toro-Ankole, which show affinities with both kimberlite

[*Holmes and Harwood,* 1932] and carbonatite [*Holmes,* 1956; *von Knorring and Du Bois,* 1961]. Away from the rifts the conditions in the crust are not suitable for extensive melting, and kimberlite is allowed to pass from the mantle to the surface in its typical form of a gas-transported breccia.

Bowen, in 1937, used the compositions of the rift valley lavas to test 'petrogeny's residua system,' showing that they were almost certainly the products of crystal–liquid equilibrium, which for him, it seems, was most often synonymous with fractional crystallization. But the same consideration would apply to the products of partial melting, and, when the volumes of such rocks in the rift valleys are taken into account, partial melting seems more feasible. Such a thought is at the root of the present suggestion of tectonic control of the alkaline magmatism in eastern and central Africa. Obviously in other regions different conditions may determine the generation of alkaline magmas, but wherever such magmas are developed in unusual amounts the possibility of some control mechanism for relief of pressure should be examined.

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