The East African Rift, Magma Genesis and Astheno-Lithospheric Dynamics

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The complexity of magmas associated with intracontinental rifts is typified by the volcanic rocks of the Great Rift Valley of East Africa. The magmas evolved from continental tholeiites, rich in incompatible elements, through alkalic products to transitional magmas relatively low in incompatible elements, which characterize a proto-oceanic stage. This evolutionary sequence requires modifications to the accepted model for generating continental intraplate magmas in terms of astheno-lithospheric dynamics.

Introduction

Since the advent of plate tectonics, magmatism has moved from the category of related geological phenomena to that of a fundamental component in the evolutionary process of our planet. Indeed, our understanding of volcanism has substantially increased with the realization that 97% of active volcanoes are oceanic. Research in the ocean basins has identified many tectonic and morphological similarities between terrestrial and submarine (mid-ocean) rifts.

This work has stimulated a renewal of interest in the study of continental rifts (partly within the framework of IGCP Project 227 - Magmatism and Evolution of Extensional Regions of the African Plate. Ed.). Of special importance is the rift system of East Africa, which provides an ideal location for the study of continental intraplate volcanism. The East African Rift is far from the edges of plates, and no orogenic phenomenon has affected this part of Africa for the past 520 Ma or so. Moreover, its northern end is a three-way junction with two oceanic ridges: the Red Sea and the Gulf of Aden.

This junction occurs in Afar (Fig. 1) which, like Iceland, is one of two regions on earth where the rocks of the present-day ocean rifts are exposed above sea level. This observation establishes unequivocally that some continental rifts were "parents" of mid-oceanic ridges (e.g. Tazieff, Varet and Barberi, 1972; Tazieff et al., 1972; Marinelli and Varet, 1973; ; Stieltjes et al., 1976).

In particular, according to Treuil and Varet (1973), there was a gradual change in magmatism, characterized by a continuous evolution from ultra-alkalic lavas in the early stages of intracontinental distension, through alkalic products (rifting) and transitional basalts (proto-oceanic stage, e.g. in Afar) to mid-ocean ridge basalts (MORBs) such as the Red Sea. This evolution is marked by a depletion in the magmas of incompatible elements, which in turn is correlated with an increase in the degree of partial melting and with the formation of successive magmas from an increasingly "depressed" mantle. For instance, for the Kivu volcanic provinces Auchapt (1985) reports a 16% partial melting for tholeiites, 5% for transitional basalts and 2.5% for basanites.

These results appear to be supported by data from geophysics and experimental petrology. In fact, Girdler and others (1969) established that the African Rift Valley overlies a layer characterized by low velocity seismic wave propagation (the Low Velocity-High Attenuation Zone, or LVHAZ) which becomes deeper from north to south in the megastructure (see also Girdler, 1983). Moreover, these data were incorporated in the experimental model for the production of magmas by diapiric upward movement of the mantle, accompanied by partial melting triggered by pressure reduction (Green and Ringwood, 1967). This model, applied to all continental rifts, is outlined in Figure 2.

This conventional scenario that assumes a gradual upward movement in the asthenosphere has recently been criticized (Lameyre et al., 1983, 1985; Giret and Lameyre, 1985).

Figure 1: Tectonic diagram of Afar (after Treuil and Varet, 1973). Black - oceanic crust; vertical lines - sialic crust.

These authors attribute the drop in pressure within the mantle to releases produced by the opening of tension cracks or "pull-aparts." Unlike the conventional model of diapirs, this hypothesis assigns an important role to translithospheric fractures and lithosphere thickness. The variation in magma type is here attributed to the thinning of the lithosphere following rifting. It would be the reverse situation of that in oceanic islands, where crust thickness increases with time.

In both interpretations, the continental tholeiitic provinces are dissociated from the magmatic history of the continental rifts because they are assumed to be related only to the opening of oceanic domains. Thus, the tholeiitic volcanism of the Ethiopian and Yemen plateaus has been linked solely to the opening of the Red Sea (Gass, 1972; Jones, 1976), in contradiction to field and geochronological data (Zanettin et al., 1974). The limitations of these models can be determined by comparing them with the appropriate geological, chronological, petrological and geochemical data, taking into account the role of continental tholeiites in the evolution of intracontinental rifts.

Magmatic Cycles in African Intraplate Volcanics

For the East African Rift, the nature of magmatic products in the various volcanic provinces has some obvious inconsistencies with the conventional depiction of the evolution from alkalic basalts through transitional magmas to tholeiites. The same observation also applies to other magmatic provinces of the African plate, such as the Benue Rift (Nigeria).

In eastern Zaire, three volcanic provinces (Fig. 3) have been studied in detail by scientists from the University of Lubumbashi. In the Bukavu region, three successive volcanic cycles have been defined by Kampunzu (1981) and described in detail from the petrological viewpoint (Table 1) by many workers (Kanika et al., 1981; Lubala, 1981; Lubala et al., 1982, 1984; Caron et al., 1983; Kampunzu et al., 1983a, b and c, 1984; and Kanika, 1984), and by Auchapt (1985) with regard to the geochemistry of trace and minor elements.

Although it is difficult to estimate their volumetric proportions, tholeiites appear to be the most abundant. They were also the first flows and are now partly covered by alkalic and transitional lavas. The tholeiites have quartz or olivine in the norm and, in addition to the usual minerals in basalts, they contain subcalcic augites, pigeonites and sometimes olivines with a ferri-ferous tendency (up to Fo = 36) in equilibrium in these magmas.

These doleritic basalts evolved under conditions of low oxygen fugacity, as in several continental tholeiitic provinces studied throughout the world (e.g.

Figure 2: Relationship between asthenospheric dynamics and the production of basalts that are first (A) alkalic ("virgin" mantle and bulging of the sialic crust), then (B) transitional (appearance of a rift and genesis of magmas from a depleted mantle) and finally (C) tholeiitic (oceanic stage). From Treuil and Varet (1973).

Thingmuli; Carmichael, 1967). Although the early position of this volcanism in the volcanic sequence of Bukavu is unanimously accepted, currently available radiometric data (Guibert, 1978; Bellon and Pouclet, 1980; Kampunzu, 1981; Baubron, 1983; Pasteels et al., 1985) do not agree. However, the likeliest ages are between 18 and 7 Ma.

The last effusions of this tholeiitic cycle were synchronous with the first outflows of alkalic lavas constituting the second volcanic cycle, which began around 8 Ma ago (Bellon and Pouclet, 1980; Lubala, 1981; Pasteels et al., 1985). This cycle is subdivided into two episodes, Neogene (8-3.6 Ma) and Early Pleistocene (1.9-1.6 Ma). The alkalic volcanism consists of a normal sodic sequence, with ankaratrites, basanites, hawaiites, mugearites, benmoreites, trachytes and phonolites. The co-

existence of undersaturated and oversaturated types is normal in such a setting.

The last volcanic outflows in the Bukavu region were transitional basalts or olivine tholeiites of the third cycle. Some were erupted from hyaloclastic cones built after formation of Lake Kivu during the Late Pleistocene (Kampunzu et al., 1984).

TABLE 1

Mineralogy and ages of rocks of the three volcanic cycles in the Bukavu region. Geochronological data in part from Bellon and Pouclet (1980), Pasteels et al. (1985), and Baubron (1983).

	Rock type	Mineralogy	Timing of activity
III Cycle	Transitional basalts and Ol - tholeiites	Pl (An 66-39) + Ol (Fo 88-68) + Cpx (Ca 48-37, Mg 41-35) ± Ti-Mt (Usp: 64-58) ± Ilm (Hem: 14-12) ± Cr-Sp (Cr/Cr+Al: 42-33) + glass	starting: ≥10.000 yBP
II Cycle	Na - ankaratrites and Na - basanites	Pl (up to An 73 Ab 26) + Ol (Fo 86-59) + Cpx (Ca 51-41, Mg 38-41) + Fe-Ti oxides + glass	2nd episode: 1.9 to 1.6 Ma 1st episode: 8.4 to 3.6 Ma
I Cycle	Qz or Ol - tholeiites	Pl (An 68-35) + Cpx (Ca 47, Mg 42-63) + Ol (Fo 79-36) + Ilm (Hem: 0-10) + Ti-Mt (Usp: 43-71) ± glass.	17.6 to 6.9 Ma

Figure 3: Map showing the distribution of the volcanic provinces of Mwenga-Kamituga, Bukavu, and Virunga.

In the Mwenga-Kamituga region (Fig. 3), the sequence of magmatic cycles exactly matches that found in Bukavu, with tholeiites at the base, alkalic lavas (with relatively unevolved end products, up to the hawaiites) and finally, a recurrence of saturated basalts at the top (Kanika, 1984). The difference lies in the age of the initial volcanism, which began later than 5 Ma ago.

In both Bukavu and Mwenga-Kamituga volcanic provinces, the geochemical properties of the continental tholeiites making up the first volcanic cycle are comparable and similar to the continental tholeiites associated with the Atlantic opening (Fig. 4 and Table 2).

In the volcanic district of the Virunga Mountains (Fig. 3), the first basaltic outflows are also saturated (olivine tholeiites), though of relatively minor extent (Kampunzu et al., 1983b). The same applies to the lavas constituting the alkalic second cycle, which form a sodic sequence evolving from ankaratrites to benmoreites (Kampunzu et al., 1982). The basic difference between this volcanic province and those mentioned earlier is the lack of recurring saturated basalts.

The Pliocene-Quaternary lavas of the Virunga chain (Fig. 5) are potassic to highly potassic. They are associated with eight main volcanoes, including the famous Nyiragongo and Nyamulagira, (Fig. 6), the most active "continental" volcano of the African Rift Valley (Kampunzu et al., 1985). These volcanoes are aligned along a fracture zone transverse to the rift axis, which is interpreted as a newly formed transform fault in a continental domain (Vellutini et al., 1982;). A similar continental transform fault also appears to characterize the ultra-alkalic, late Tertiary to Quaternary province of northern Tanzania, which is strongly sodic and contains carbonatites. Work under way should enable us to determine whether this relationship linking ultra-alkalic magmatism to transform faults holds true for other continental plates.

Figure 4: Chondrite-standardized multi-element spectra of continental tholeiites from the western branch of the African Rift Valley (6729 - Kamituga; 6642 - southern Idjwi Island in the Bukavu region) and from the Atlantic opening (1137 - Morocco; 5834 - Nova Scotia). Note the similarities with the basalts of the oceanic islands (H26 - Hawaii tholeiite). From Auchapt (1985).

TABLE 2

Average compositions of selected first volcanic cycle tholeiites in Zaire (new data), and representative analyses of Moroccan tholeiites associated with opening of the Atlantic Ocean (from Bertrand et al., 1982). A - 3 samples from the Mwenga-Kamituga area; B - 8 samples from Bukavu district; C - from the Anti-Atlas; D - from the High Atlas. Oxides in %, other elements in ppm.

	A	B	C	D
SiO ₂	51.00 ± 2.00	51.20 ± 0.70	50.97	52.96
Al ₂ O ₃	15.06 ± 0.70	15.10 ± 0.50	14.40	13.16
Fe ₂ O ₃ t	10.50 ± 1.00	11.60 ± 0.30	10.22	10.80
MnO	0.17 ± 0.01	0.18 ± 0.03	0.15	0.19
MgO	7.02 ± 0.70	6.10 ± 0.50	7.80	7.66
CaO	9.84 ± 0.20	9.40 ± 0.90	11.62	9.07
Na ₂ O	2.63 ± 0.10	2.80 ± 0.20	1.91	2.53
K ₂ O	0.33 ± 0.04	0.33 ± 0.05	0.33	0.42
TiO ₂	1.39 ± 0.02	1.66 ± 0.10	0.97	1.34
P ₂ O ₅	0.32 ± 0.02	0.28 ± 0.06	0.14	0.23
Li	3.30 ± 0.60	5.40 ± 1.50	9	11
Rb	7.30 ± 2.00	9 ± 3	12	42
Sr	298 ± 10	272 ± 46	167	200
Ba	234 ± 12	249 ± 130	92	208
V	179 ± 1	206 ± 17	285	239
Cr	197 ± 36	232 ± 20	201	206
Co	45 ± 7	53 ± 14	45	46
Ni	133 ± 44	138 ± 32	92	85
Cu	71 ± 5	70 ± 20	240	132
Zn	90 ± 5	113 ± 15	124	223
La	23.30 ± 0.50	27 ± 15	6.84	19.20
Ce	43.50 ± 2.00	49 ± 26	14.20	39.40
Sm	4.18 ± 0.20	5.45 ± 1.9	2.52	4.73
Eu	1.44 ± 0.10	1.83 ± 0.6	0.91	1.39
Tb	0.69 ± 0.05	0.98 ± 0.3	0.48	0.81
Yb	1.86 ± 0.02	2.70 ± 0.8	1.76	2.40
Lu	0.30 ± 0.01	0.43 ± 0.1	0.30	0.40
Th	3.20 ± 0.20	3.50 ± 2.0	1.20	4.30
Hf	2.00 ± 0.10	3.30 ± 1.0	1.90	4.10
Sc	24 ± 1	25 ± 2	36	32
Y	26 ± 2	35 ± 8	24	33
Zr	80 ± 3	108 ± 20	71	165
Nb	21 ± 1	24 ± 7	6.60	16.10

In southwestern Tanzania, the western branch of the Rift Valley contains alkalic lavas (Harkin, 1960). According to modern classifications, such as those using the $\text{Na}_2\text{O}-\text{K}_2\text{O}$ ratio, these lavas could be attributed to a sodic alkalic series evolving from ankaratrites to phonolites and trachytes, as in the Kivu area. The lack of transitional basalts overlying these alkalic lavas distinguishes this immature rift region from the other volcanic provinces of the African Rift Valley. On the other hand, our preliminary data on the petrological characteristics of the early basalts of this region indicate that these are also tholeiitic in nature.

In the eastern branch of the Rift Valley, which has been studied for a very long time, a link between the degree of rifting and the eruption of continental tholeiites, found particularly in Kenya, has only recently begun to be established (Bellieni et al., 1981; Watkins, 1981). Here, tholeiitic transitional basalts were emplaced between approximately 33 and 30 Ma ago (Zanettin et al., 1983), and the last outflows of this tholeiitic cycle were nearly synchronous with alkalic lavas (second cycle). The transitional Lothidok basalts have been dated at 15 Ma old, but currently available data do not allow us to determine whether they represent the end of the initial tholeiitic magmatism or the beginning of the transitional cycle marking an evolved stage of rifting.

The transitional stage (third cycle) is, however, represented by the Pliocene-Quaternary transitional magmas described in both Kenya and Ethiopia (e.g. Zanettin et al., 1974; Baker et al., 1978; Lippard and Truckle, 1978; Piccirillo et al., 1979; Barberi and Santacroce, 1980). These magmas always appear after the first cycle tholeiites and the second cycle alkalis. They are early in the evolution of continental rifts, because in Bukavu volcanic province they are directly above a zone of weak crustal extension and upward movement of the asthenosphere.

In Afar, where the conventional process of magmatic evolution from alkalic compositions through transitional to oceanic tholeiites was established (Treuil and Varet, 1973), earlier workers had totally dissociated the volcanism of the Afar depression (see cover photo) from the older basaltic series that constitutes the Ethiopian Plateau and that extends into Ethiopia and Yemen. These Ethiopian basalts are essentially continental tholeiites (Jones, 1976; Schubert, 1975; Mohr, 1983), of the same type and significance as their equivalents in the intracontinental volcanic provinces of the Rift Valley. Thus the initial magmatism of the

various volcanic provinces of the African Rift is clearly tholeiitic in nature, despite other views often expressed in the literature (e.g. references in Giret and Lameyre, 1985).

The same applies to the Benue Rift of West Africa, where basalts show a chemical evolution from Jurassic olivine tholeiites to Cretaceous alkalic compositions (Popoff et al., 1982). Certain magmatic provinces of the Cameroon Line have been relatively well studied, and their alkaline nature has been emphasized; they are interpreted in terms of the classic model of intracontinental rifting. In fact, in the plutonic-volcanic complex of Golda-Zuelva, at 66 Ma the oldest gabbroic intrusion of the Cameroon Line (Jacquemin et al., 1982) contains orthopyroxene in equilibrium and early plagioclase (Jacquemin, 1981), a combination difficult to conceive of in basic materials of an alkalic nature. The high content and fractionation of LREEs in these products, described by Jacquemin (1981), is not strong enough evidence of an alkalic base, because this is standard in continental tholeiites (Dupuy and Dostal, 1984).

Figure 6: Nyamulagira, the only shield volcano in the Virunga chain.

Similar observations can be made regarding several African magmatic provinces said to be alkalic (such as the Iskou massif of the Air in Niger, described by Leger, 1985). For example, among the marine volcanics of the Cameroon Line, the first flows of Principe Island (≈ 31 to 23 Ma old; Dunlop and Fitton, 1981; Dunlop, 1983) are tholeiitic. They are overlain by subaerial volcanics consisting of sodic alkalic lavas with a level of undersaturation that decreases from the "old" basalts and hawaiites (≈ 23 to 19 Ma) to recent basanites (≈ 5 to 3 Ma, Dunlop, 1983).

The volcanic succession we are proposing for these magmatic provinces of Africa is consistent with that marking the start of the Atlantic opening (e.g. Bertrand and Prioton, 1975; Bertrand and Coffrant, 1977; Bertrand et al., 1982; Bellieni et al., 1984). Indeed, though earlier work suggested that the continental rifts are the beginnings of oceanic rifts (e.g. Girdler et al., 1969; Gass, 1972; Burke and Whiteman, 1973), the sequence of magmatic cycles proposed earlier in the African Rift Valley is not consistent with this interpretation.

Contrary to what is conventionally accepted (see syntheses of Lameyre et al., 1983 and 1985; Giret and Lameyre, 1985), the magmatic succession we describe indicates that there was no reverse evolution of the magmatic sequences in the continental rifts and oceanic islands. Indeed, everything takes place as if the mechanisms were the same at the outset. The only differences occur when the development of the rifting process on the continents introduces a new

Figure 5: Distribution of Pliocene-Quaternary lavas of the Virungas (within dashed line) and location of various major volcanoes. See also cover photo.

parameter into the evolution of the magmas and leads to the recurrence of saturated basic magmas. In short, the genesis of intraplate magmas should be attributed to the same mechanisms, regardless of whether the products are continental or oceanic. This conclusion has ramifications for models of magma genesis as it relates to the dynamics of the asthenosphere and lithosphere.

Mantle Magmas and Astheno-Lithospheric Dynamics

There are conflicts between the distribution in space and time of magmatic activity and the model of gradual upward movement of asthenospheric diapirs. According to the second model, alkaline liquids are produced first at great depth (in the continental rifts), and are succeeded by relatively shallow transitional magmas (evolved continental rifts and proto-oceanic rifts of the Afar type), and finally by oceanic (MORB) tholeiitic magmas. Indeed, the tholeiitic nature of the first basalts extruded in the African rifts implies melting under low pressures that correspond in the diapiric model to shallow depths. On the other hand, the subsequent alkaline lavas would result from partial melting at greater depth, indicating a deepening of the level of magma genesis with time, contrary to the diapiric hypothesis.

It is possible, of course, that the pressure drop does not reflect a rise in the LVHAZ, but rather a release caused by lithospheric fracturing (Lameyre et al., 1983 and 1985). This, however, cannot be verified using available geophysical data on present rifts, since it assumes that the geometry of the asthenospheric "tumour," and the associated crustal bulging, are the result of a volume increase related to melting. According to this model, the inverted sequence of tholeiitic and alkaline intraplate magmas (oceanic and continental) is explained by the variation with time of lithosphere thickness. In the oceanic islands, which are being built up gradually by thickening the lithosphere beneath them, the magmas evolve from tholeiitic to alkaline.

According to Lameyre and others, the progressive lithospheric thinning that characterizes the rifting process will be marked by a sequence the reverse of that observed in oceanic islands, i.e. from alkaline to transitional basalts. Such an explanation may apply to the passage from alkaline to transitional volcanics, but it cannot explain the passage from tholeiites to alkaline compositions observed in the African Rift.

The advantage of this model lies in the fact that it attributes an important role to lithospheric dynamics in the formation of intraplate volcanic provinces. In fact, certain parts of the African Rift Valley (such as the Tanganyika and Mobutu Lakes regions in Central Africa), are characterized by similar gravimetric anomalies, although not everywhere are volcanic provinces found directly above them. The volcanic regions are generally located at the junction of two or more major fracture zones.

Another aspect is the link that seems to exist between per-alkaline magmatism and continental transverse fractures (Vellutini et al., 1982). However, models that take into account only lithospheric dynamics are, like the diapiric hypothesis, unsatisfactory. Indeed, highly potassic volcanic provinces such as the Toro-Ankole in Uganda, are related to active faults that are interpreted as trans-lithospheric fractures that triggered melting by lowering the pressure. Such fractures should at the same time have caused a release in pressure in the upper zones of the mantle. The lack of saturated and moderately alkaline basalts in this region is not entirely consistent with this hypothesis.

A New Model

To reconcile all available data, we propose a model involving the combined dynamics of the asthenosphere and lithosphere, in which the evolution of the rifting process is correlated to the nature of the magmas emplaced. This

involves consideration of the upward movement of the asthenospheric "cushion" whose existence beneath the continental rifts has been established by geophysical data. We feel that, at the start of a distension event, there is an almost instantaneous (geologically speaking) asthenospheric rise throughout the whole solid mantle. This upward movement is blocked at the base of the crust, at depths that obviously vary with crustal thickness in each region considered.

Depending on this depth, the first magmas produced at the top of the rising asthenosphere would be more or less saturated basalts (e.g. Kivu) and even, exceptionally, alkaline magmas, such as at Toro-Ankole. The whole of the rising asthenosphere is in disequilibrium because of the fall of pressure, and partial melting takes place simultaneously at all levels in the ascending diapir. The liquids produced are tholeiites at shallow levels, transitional at intermediate levels and alkaline at greater depths. The time of arrival of these magmas at the surface is determined by their level of formation, with tholeiites and transitional types at the base (first cycle) followed by alkaline basalts of the second cycle.

This mechanism explains the decrease in magma saturation with time observed in the oceanic islands and in the first evolutionary stages of the continental rifts. It also allows for the overlap in age between alkaline and tholeiitic magmas in different volcanic provinces of the East African Rift Valley (Kampunzu et al., 1985). It could even explain the simultaneous outflowing of LIL-rich and LIL-poor basalts in the oceanic domain (e.g. Iceland, Sigvaldason et al., 1974 and 1976).

The recurrence of saturated basalts of the third cycle, characteristic of several volcanic provinces in the Rift Valley but not of the oceanic islands, seems to indicate a difference in the energies of the diapiric systems of these two different settings. Indeed, this recurrence seems to characterize continental rifts with a potential of becoming oceanic, and it reflects a high-energy diapir. This situation occurs only where there is asthenospheric rise of large proportions with regard to mass, speed and, probably, temperature.

A Final Comment

It should be pointed out that this improvement in our understanding of the Rift Valley volcanism has been made possible only by the use of detailed mapping and structural analysis. Unfortunately, this approach is being abandoned more and more by geologists, especially as field work conditions in Africa are not as comfortable as in the developed countries. On the other hand, field work cannot be fully utilized in preparing models unless it is backed up by exacting laboratory analysis.

These two aspects could form a good basis for North-South cooperation, but African researchers usually do not have the funds to finance research work, especially when such work does not have short-term economic applications. International agencies and the wealthier countries should thus encourage the geological sciences by granting research funds to experienced African teams who are able to collaborate on an equal footing with their colleagues from the developed countries.

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