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RELATIVE TIMING OF RIFTING AND VOLCANISM ON EARTH AND ITS TECTONIC IMPLICATIONS

A.M. Celal Şengör and Kevin Burke

Department of Geological Sciences, State University of New York at Albany
Albany, New York 12222

Abstract. Rifts occur in diverse tectonic environments that result from the continuous two-dimensional evolution of the multi-plate mosaic of the Earth and also from the interaction between the mantle processes and the overlying lithosphere. Most rifts have associated volcanics that are mainly basaltic. In continental rifts these basalts are predominantly alkaline and the relative timing of rifting and volcanism is variable; however, despite this variation there seem to be two basic types of rifting-volcanism relative timing: in one, volcanism and usually local doming predates major rift formation whereas, in the other, rifts form first and volcanism (? and doming) follow thereafter. These two basic types of rifting-volcanism relative timing may be related to two basic modes of rifting. In the first the mantle plays an active role, convection 'plumes' dome up and crack the lithosphere, whereas, in the second, the horizontal movements of plates give rise to extension of the lithosphere and induce rifting. In this latter case, the mantle is passive. Numerous local conditions complicate this simple pattern and result in extremely complicated rifting-volcanism relationships that make geophysical/geochemical modelling difficult. Petrologic/geochemical studies of rift volcanics do not provide unique solutions for our understanding of rift environments. Detailed stratigraphic/structural analysis of individual rifts are still the best methods for rift analysis.

Introduction

Rifts, elongate depressions beneath which the entire thickness of the lithosphere has ruptured under extension, occur in diverse tectonic enviroments that result from the continuous two-dimensional evolution of the multi-plate mosaic of the Earth and also from the interaction between mantle processes and the overlying lithosphere. There is a great variation in the sizes and length-to-width ratios of individual rifts, as well as in their mode of occurrence. Some rifts are seemingly isolated such as that of Lake Baikal (*Logatchev and Florensov,* 1978), others are aligned along relatively narrow belts such as those of East Africa (*Burke and Whiteman,* 1973), and yet others are clustered together, in nearly parallel arrangement, in roughly equidimensional areas such as those of the Basin and Range Province of the western United States (*Atwater,* 1970). Although the genetic significance of this variation is far from being clearly understood, it is an empiric conclusion that rifts that occur along 'rift belts' are associated with areas of primary extension, whereas 'rift clusters' are more characteristic of wide, imperfect strike-slip regimes. Isolated rifts occur in both environments.

A feature common to most rifts is basaltic volcanism. In continental rifts, with which we are here concerned, these basalts are mainly alkaline. The relative timing of basaltic volcanism with respect to the associated rifting shows considerable variation. Currently there are two main hypotheses attempting to explain the origin of basaltic magmas beneath rifts: one favors the preliminary cracking of the lithosphere due to differential stresses resulting from two-dimensional plate evolution (e.g., membrane stresses: *Turcotte and Oxburgh,* 1973; *Turcotte,* 1974; stresses due to the collision of continents: *Molnar and Tapponnier,* 1975; Şengör, 1976; stresses resulting from the propagation of existing accreting plate margins into continents: *McKenzie and Weiss,* 1975) that upsets the T/P balance of the underlying mantle resulting in its partial melting. This results in a volume increase in the partially melted area and may induce a post-rifting uplift of the overlying lithosphere as happened in the Upper Rhine Graben (*Şengör et al.,* 1978). The other view holds a complicated convection pattern in the mantle responsible for doming and cracking the lithosphere thereby giving rise to extensional fractures and eventually to rifts (*Burke and Whiteman,* 1973; *Burke and Dewey,* 1973). In the former view, the expected sequence of events is rifting – (?uplifting) – volcanism, whereas in the latter it is doming-volcanism-rifting (Fig. 1). It is our contention that both hypotheses are compatible with the available data, but are applicable to fundamentally different tectonic environments. The first hypothesis is applicable to regions where rifting is the result of horizontal movements of plates and their interaction in which mantle plays a passive role. The second hypothesis seems to be valid where (?small scale) convection in the mantle (*McKenzie and Weiss,* 1975) directly affects the overlying lithosphere and induces rifting as a combined result of primary vertical tectonics (uplift) and (?later) horizontal motion (initial spreading). It appears that this latter mode of rifting occurs mainly on plates that are fixed with respect to the underlying mantle, as Africa has been suggested to have been since 25 m.y. ago (*Burke and Wilson,* 1972). At present, the former mode of rifting is by far the more widespread of the two.

Passive Mantle Hypothesis

The horizontal movement of plates and their interaction give rise to differential stresses within the lithosphere that result in rifting. *Turcotte and Oxburgh* (1973) and *Turcotte* (1974) argued that membrane stresses can be generated within a plate moving longitudinally on the surface of the Earth, due to the ellipticity of the Earth, and result in rifting. *Burke and Dewey* (1974), however, indicated that the elastic stresses thus generated cannot be stored for long periods of time and therefore may not be as important in generating rifts as *Turcotte and Oxburgh* (1973) suggested. Moreover, the supporting evidence that *Oxburgh and Turcotte* (1974) used to apply this idea to the East African rifts consisted of incorrect K/Ar data and misinterpretation of palaeomagnetic results.

Molnar and Tapponnier (1975) and *Şengör* (1976) pointed out that continental collision, especially of irregular margins, also generates extension within continental plates resulting in rifting more or less perpendicular to the direction of convergence; if collision-induced strike-slip faulting also causes rift formation, as is the case for the Baikal rift (*Sherman,* 1978), such rifts are not likely to have any systematic orientation with respect to the convergence direction. In the foreland of the Alps in Europe, for example, rifting events are well-correlated with the Mesoalpine collision (*Trümpy,* 1973; see *Şengör,* 1976, table 1). Here rifting appears to have predated major basaltic volcanicity. In the case of the Upper Rhine Graben, rifting can be shown to have started during medial Eocene with some minor volcanicity of 42 m.y. age along the master faults (*Şengör et al.,* 1978). Major basaltic volcanic activity began at the northern end of the graben about 25 m.y. ago (*Lotze,* 1974). This volcanic center, the Vogelsberg, appears to have continued its activity until very recently. In the south, well within the major graben trough, the Kaiserstuhl volcano began its activity about 18 m.y. ago; this however, unlike that of the Vogelsberg, was a short-lived event. In the Lower Rhine Graben there are few volcanics, but the maars of Eifel appear to be related to Plio-Pleistocene NW-trending faults (*Greiner and Illes,* 1977). In Bohemia, both along the Thuringian disturbance and in the grabens between the Bohemian and the Thuringian blocks (*Schollen*) volcanicity began during the Oligocene and lasted through the Pliocene; rifting along these lines had begun at the beginning of the Tertiary and accelerated during late Eocene (*Lotze,* 1974). It appears that in Europe it is this kind of intra-plate but inter-*Scholle* activity that caused basaltic volcanism that is largely of olivine-nepheline bearing alkaline type.

Western Turkey and the Basin and Range Province of the western United States are areas of extensive rift development, characterized by numerous sub-parallel grabens in 'rift clusters'. Both areas are related to large, imperfect strike-slip plate boundary zones (western Turkey: *Dewey and Şengör,* 1978; western U.S.: *Atwater,* 1970). In western Turkey rifting began during the late Miocene and is currently active. Most rifts

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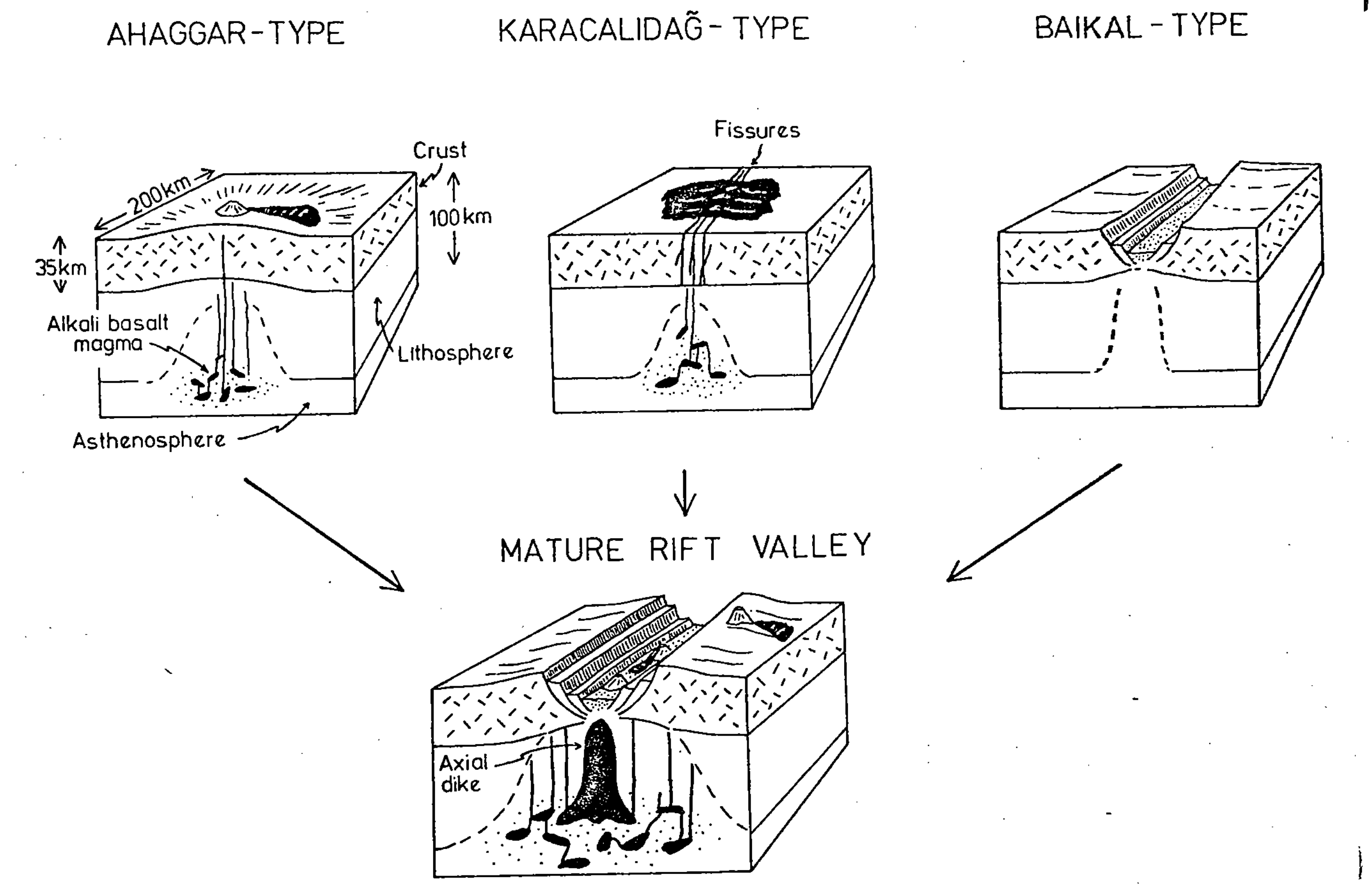

Fig. 1. Idealized and simplified block diagrams showing the evolution of a 'mature rift valley' from three different initial configurations. In Ahaggar-type rift valley evolution mantle is active and induces uplift and subsequent rifting. In this case volcanism is likely to predate rifting. In the Baikal-type mantle is passive and there is no pre-rifting doming or volcanism. Karacalidag-type was added to the diagram to illustrate a complexity: horizontal extension forms fissures through which magma wells up prior to major downfaulting and rift formation. Hence, in the geological record the sequence of events in the formation of a Karacalidag-type rift will look like those of an Ahaggar-type rift, although the mode of rifting was that of a Baikal-type rift. The end products of all rift processes are likely to look very similar.

here are devoid of volcanics with the exception of the Gediz and Simav grabens (*Dewey and Şengör*, 1978). On the northern shoulder of the Gediz graben, an area, 50 km. long and 20 km. wide, is covered with Pliocene to recent alkaline basalts that are nepheline, leucite, and hornblende bearing (kulaite, *Washington*, 1894; *Erinc*, 1970). These basalts emanated from fissures that can be shown to be controlled by faults related to the Gediz graben. *Zeschke* (1954) documented a similar history for the Simav basalts.

In the Basin and Range Province major rifting related to the present regime began about 18 m.y. ago (*Noble*, 1972) and was closely followed by basaltic/rhyolitic bimodal volcanism (*McKee et al.*, 1970). The geographic extent and the close temporal association with a strike-slip regime (*Hamilton*, 1970) of the western Siberian rift system of Triassic age (*Logatchev*, 1977) suggest that it might be a fossil analog of the Basin and Range-type rift regimes, where generally basaltic volcanism postdates rifting.

Active Mantle Hypothesis

Rifts active on the African Plate can be interpreted as products of relatively simple mantle-lithosphere interaction. The control appears to be the lack of relative motion between the African Plate and underlying convective circulation over the last 25 m.y. (*Burke and Wilson*, 1972). The interaction beneath the African Plate shows itself in several phenomena: the distinctive basin and swell structure; the occurrence of intraplate volcanism (largely on swell crests); the development of rifts and the evolution (in the Red Sea and in the Gulf of Aden) of rifts into oceans (see *Burke*, 1977 for a review).

Throughout southern Africa swell crests carry no volcanoes and rifts are mainly not on swells but are reactivated old structures. This indicates that a sequential development from volcanoes on swells to rifts such as *Burke and Whiteman* (1973) distinguished is not universally recognizable. Further evidence that rift development is complex can be seen in the active rifts of East Africa. Volcanism, there, is very unevenly distributed along the length of the rifts and in some areas (for example, near Addis Ababa) is dominantly tholeiitic, whereas in other areas it is dominantly alkaline (see, for example, *Baker et al.*, 1972). The implication is that the petrology of the igneous rocks is a very poor indicator of rift style compared with more direct structural/stratigraphic features such as topography, faulting, and sediment fill. The general absence of signs of interaction between magma and continental crust in the rift igneous rocks is perhaps the most significant feature and is to be expected in a regime where axial dikes and extension dominate.

Older episodes of rifting induced by similar mantle interaction are hard to identify but the lack of motion between Africa and the spin axis during the break-up of Pangaea has been taken as evidence that African rifting during that time was similarly induced (*Burke and Dewey*, 1973). The Pangaean-rupturing rifts on either side of the Atlantic formed just before that ocean opened provide further examples of the diversity of styles of volcanism. Some rifts appear to be without volcanic material as are the majority of the rifts of western Turkey; others are associated with extensive pre-rift igneous activity and yet others show igneous activity only when the rifts are well-developed. As in East Africa now, compositional diversity is the rule. In some areas carbonatites and alkaline syenites abound (e.g., Los, Bagbe, Songo), whereas in other tholeiitic basalts are the only igneous rocks.

Conclusions

Rift studies are now at a very exciting stage. Tentative classifications of rifts and rift systems based on global tectonic hypotheses such as that in this paper are being made and a major need is for comprehensive study of all aspects of selected rifts. They are exceedingly complex structures and timing of events in rifts is a difficult task (see Fig. 1 for a simplified sketch of rifting-volcanism relative timing types and a few of the involved complexities). Some rifts are particularly well-suited for the study of some properties – for example, igneous petrology in the Keweenawan – while others are better adopted for the study of the properties such as subsidence and sediment fill (e.g., the North Sea rifts). A unified approach recognizing that these phenomena are all related to similarly induced processes is likely to prove most rewarding.

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