African lithospheric structure, volcanism, and topography

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In Africa volumetrically minor, mid-plate volcanic rocks of Cenozoic age are concentrated in areas affected by Pan-African (500 ± 150 Ma) crustal reactivation, and are virtually absent from cratonic areas. We interpret this as indicating that Pan-African areas are underlain by fertile lithospheric mantle and cratons by depleted lithospheric mantle, and propose a model to explain both the distribution of volcanism and the two kinds of African mantle lithosphere: (1) Cratons were formed by the assembly of collided island arcs, and for this reason are underlain by depleted, sub-oceanic-type mantle lithosphere. (2) Comparable depleted mantle lithosphere has been delaminated from beneath areas thickened during Tibetan-style continental collision (especially in Pan-African times) and replaced by fertile material which now forms the lithospheric mantle below the Pan-African reactivated crust. (3) When the African plate came to rest with respect to sub-lithospheric mantle circulation patterns at about 30 Ma, heating from below extracted magmas from the fertile but not from the depleted mantle lithosphere. (4) As a result of interaction with an underlying convective pattern for the last 30 Ma, Pan-African reactivated areas display both Neogene elevations and volcanism but cratonic areas display only elevations.

1. Introduction

A quarter century ago Kennedy [1] and Rocci [2] drew attention to differences between ancient African cratonic areas and those involved in “Pan-African thermo-tectonic events” at about the beginning of Phanerozoic times (500 ± 150 Ma). This seminal distinction has proved remarkably stimulating both in promoting understanding of African tectonics and in studies of continental evolution in general. Kennedy [1] recognized Pan-African areas as characterized by the resetting of isotopic systems in pre-existing continental crust. He chose to call the isotopic resetting a “thermo-tectonic event” because he was uncertain as to how much this kind of areally extensive reactivation resembled the processes that occur in mountain building episodes. Later workers have emphasized distinctive features of both the cratons and the reactivated areas (which have come to be called the products of the “Pan-African Orogeny”). For example, Black and Girod [3] pointed out that Cenozoic volcanic rocks are restricted to reactivated Pan-African and younger orogenic belts around the West African craton and do not occur on that craton. Thorpe and Smith [4] extended this observation to the whole continent showing that although Cenozoic volcanism has been widespread in Africa, there is very little Cenozoic volcanic rock on any of the cratons (Fig. 1).

Burke and Dewey [5] and Dewey and Burke [6], in attempting to apply uniformitarian principles to the Pan-African events, emphasized that these terranes resembled, in their vast areal extent, the kind of orogenic environments presently resulting from continental collision in the Himalaya and Tibet. They suggested, therefore, that Pan-African reactivation might have resulted from continental collision. About the same time, Briden and Gass [7], using paleomagnetic data, suggested that the Pan-African represented one of 3 intervals when Africa came to rest with respect to the Earth’s magnetic dipole-field and (by inference) the Earth’s spin-axis (the other suggested intervals were during the break-up of Gondwana and during the Neogene). They further proposed that these stationary periods might be episodes of magmatic activity. Numerous authors inferred that the Pan-African might have been an “ensialic” orogeny, several comparing it with the Hercynian Orogeny of Europe (e.g. [8]). Most early discussions of Pan-African tectonics concentrated on the
properties of the continental crust, although a few (e.g. [9]) extended consideration to the underlying mantle lithosphere. In recent years much interest has developed in the African mantle lithosphere particularly in cratonic areas where the diamondiferous kimberlites have come to be recognized as powerful probes.

2. Two kinds of mantle lithosphere?

The sub-cratonic lithosphere of Africa is becoming well-characterized. Studies of diamond inclusions, xenocrysts and xenoliths in kimberlites suggest that the cratons have deep lithospheric roots composed mainly of peridotites that have been strongly depleted in basaltic (and probably also komatiitic) components [10]. Jordan [11] suggested that the root of mantle lithosphere beneath cratonic areas was likely to extend to depths of 200–400 km. Isotopic work on garnet inclusions in diamonds has yielded Sm-Nd model ages of 3.2–3.3 Ga, indicating that these lithospheric roots are about as ancient as the crustal rocks of the overlying cratons [12]. De Wit [13], elaborating earlier ideas [14], has described how the cratons, like the greenstone belt terranes of North America (e.g. [15]) can be regarded as having been assembled by repeated and complex collisions of ancient island arcs, a process leading to formation of a deep keel of sub-oceanic depleted lithospheric
mantle beneath the cratons. Haggerty [16] has summarized the later history of the cratonic mantle lithosphere suggesting that episodic, locally hydrous metasomatism has contributed to limited further lithospheric evolution.

Geophysical studies (e.g. [9,17]) indicate that the mantle lithosphere beneath Pan-African reactivated areas is thinner, generally contributes more to surface heat flow, and is of lower seismic velocity than the mantle beneath the cratons. These properties suggest to us that there may be two different kinds of mantle lithosphere beneath Africa, and that the mantle lithosphere under the reactivated areas may be less depleted in basaltic components than that below the cratons.

It seems likely that a more depleted, thicker mantle lithosphere was generally produced during the Archean because, to quote Hoffman [18, p. 586]: “...secular decline in mean temperature of the asthenosphere implies a greater depth and volume of melting accompanying mantle upwelling in the Archean, and consequently a thicker, more depleted mantle lithosphere (see also [19,20]).” We suggest that the tectonics involved in generating the Pan-African reactivated crust and the Archean crust differed greatly, so that dif-
ferences in the underlying lithosphere may be relatable to specific processes rather than attributed to the valid (but vague) general idea of secular variation in “mantle upwelling.”

3. Contrasting history of cratons and reactivated areas

The laterally heterogeneous sub-crustal lithosphere of the African continent can be interpreted as a product of plate tectonic processes operative over almost the entire span of geologic history. A possible sequence of events is illustrated in Fig. 2. Studies of Archean cratons combined with inferences from modern tectonic environments are consistent with the hypothesis that ancient continents formed by repeated collisions of island arcs (Fig. 2a) [13,21]. Continents assembled in this way are expected to be underlain by lithospheric mantle depleted in crustal components and similar to modern sub-oceanic lithospheric mantle. This has been borne out by isotopic measurements on igneous rocks that have penetrated the cratons (as well as on their contained xenoliths). For example, igneous rocks represented by mantle-derived melting products of a variety of ages in the Archean Superior Province of the Canadian Shield consistently show depleted signatures in the Rb-Sr, Sm-Nd and Pb-Pb isotopic systems, indicating the integrity of underlying depleted mantle lithosphere there since about 2.7 Ga [22–25].

We suggest that during collisions of continental masses in Tibetan-style convergence zones, underlying depleted mantle lithosphere is detached from overlying crust, and is replaced by comparatively “fertile” asthenospheric mantle which has not been subjected to intense previous depletion in crustal components (Fig. 2d). This process is called lithospheric “delamination” [26] and has been suggested to be an important element in both mantle and crustal evolution (e.g. [27,28]). The geometry we suggest in Fig. 2d differs from that originally suggested by Bird [26], but it is close to that envisaged by later workers. Although the density of depleted mantle is likely to be less than that of fertile mantle (because of a lower content of Fe) the difference is small and buoyancy can be overcome so that sinking will occur if, for example, a small amount of garnet-bearing lower crustal mafic rock is delaminated along with the mantle lithosphere.

Fig. 2e shows a post-collisional configuration. After thickened crust returns to normal thickness by erosion, rifting and isostatic uplift, those continental areas that have experienced Tibetan-style collision and associated Pan-African-type crustal magmatism with widespread resetting of isotopic clocks overlie fertile mantle lithosphere, but unreactivated cratons overlie depleted mantle lithosphere.

We suggest that Cenozoic volcanic rocks were generally extracted only from fertile mantle lithosphere underlying areas of Pan-African reactivation (Fig. 2f). The predominantly alkaline character of these volcanic rocks may be taken as evidence for their derivation from undepleted mantle sources, although we recognize the possible roles played by fractionation and crustal contamination in producing similar effects. Under cratonic crust, the depleted mantle was generally unable to yield magma, and these lithospheric regions responded to heating from below only by lithospheric thinning and elevation increases.

The stationary behavior of the African continent over the convecting mantle since about 30 Ma ago [29] may have been an important factor in concentrating sub-lithospheric heat sources (cf. [7,30]). Although a stationary continental mass (such as Africa has been for the past few tens of millions of years) may not be necessary for eruption of continental volcanics on top of reactivated terranes, it probably helps this process. A stationary plate can be expected to be easier to burn through than a moving one [31].

The lateral distribution of African lithospheric types may also control relative elevation. Depleted mantle can be expected to be less dense than fertile mantle [32] and cratonic areas underlain predominantly by depleted mantle are therefore expected to stand higher than reactivated terranes. This accounts for the restriction of Mesozoic and Cenozoic marine deposits to Pan-African reactivated areas, a phenomenon noted by Kennedy [1]. In a similar way Phanerozoic flooding of Proterozoic North America has been more frequent than that of Archean North America (e.g. [18, p. 586]).

4. Rift-related volcanism

We consider it useful to distinguish minor mid-plate volcanic activity from that associated
with intracontinental rifting. Development of rifts appears to involve upwelling of fertile, asthenospheric mantle, and concomitant thinning of the lithosphere in response to deeper mantle convective patterns. Wendlandt and Morgan [33] have documented and theoretically modelled progressive lithospheric thinning for the East African rift system, and Phipps [34] argued that “melt-generating mantle material” had been emplaced beneath the ancient continental rifts of North America while they were active, serving to localize later episodic igneous activity. This mechanism is distinct from the collision-related delamination and asthenospheric replacement process we discuss above. Both processes facilitate volcanism, although much larger volumes of magma are often associated with rifting, particularly in areas of substantial extension, and rifts may indeed develop over and propagate from the localized intracontinental volcanic areas [35, table 3; 36, fig. 1].

Rift-related processes can explain the existence of two areas in Africa and neighboring Arabia where Cenozoic volcanic rocks overlie crust unaffected by Pan-African reactivation. The first is associated with the Western Rift of the East African rift system which cuts across the eastern corner of the Congo craton (Fig. 1). Volcanic rocks in this area forming the Virunga Mountains and Rungwe volcanics are extremely alkaline and indicate great depths of equilibration, we suggest below the base of the thick, depleted cratonic mantle lithosphere. We interpret the Virunga and Rungwe volcanics (which are no older than 5 Ma) to be related to horizontal propagation of the Western Rift system into the Congo craton since the end of the Miocene. Prior to that time, the thick, depleted mantle lithosphere of the Congo craton proved resistant (as elsewhere) to igneous penetration. By analogy with the Eastern Rift, as interpreted by Wendlandt and Morgan [33], and with the ancient rifts of North America, as interpreted by Phipps [34], we would expect volcanic rocks erupted in the future to indicate progressively shallower levels of equilibration as the Western Rift evolves, cutting across the Congo craton.

The second area of Cenozoic volcanism not underlain by Pan-African reactivated crust lies on either side of the Red Sea in Arabia, Egypt and Sudan (Fig. 1). Here the crust is composed of material accreted to the continent during Pan-African times in the form of oceanic island-arc rocks and ophiolitic suture zones [37]. Our interpretation predicts this crust to be underlain by depleted mantle lithosphere of the kind that underlies the ocean floor. We would not expect volcanics to be erupted through this crust. On the African side of the Red Sea, there is indeed very little Cenozoic volcanism in the area east of the Bayuda (15 in Fig. 1), which lies west of the limit of Pan-African arc assembly. What volcanism there is of Cenozoic age overlying the Pan-African accreted material is close to the Red Sea and is small in volume. We relate it to the Red Sea rifting (cf. [33,34]), recalling that the rifting process brings fertile mantle close to the surface.

On the Arabian side of the Red Sea, Cenozoic volcanism is more abundant in an area overlying Pan-African accreted material. Here the relationship to extension is shown by the occurrence of volcanic centers on north–south trends parallel to the fissures of Karacalidag immediately south of the Bitlis suture [38–40]. These features may have formed in response to collisional rifting related to the Bitlis suturing event at about 12–15 Ma [40]. Mantle xenoliths may provide a test of our hypothesis. Xenoliths from Pan-African reactivated areas are predicted to be typical of fertile mantle whereas those brought to the surface by rift-related volcanics which cut through arc-accreted terranes or cratonic areas may include representatives of depleted mantle lithosphere.

5. A memory of times lost?

A possible consequence of the process we envisage is that isotopic compositions of continental extrusives and intrusives might be usable, in some cases, as indicators of the prior history of crust that has passed through a later collisional experience. For example, the depleted isotopic signature of pre-collisional mantle-derived magmatic products in continental crust, such as the Mid-Proterozoic anorthosite massifs of the Grenville Province [41] may indicate that the continental crust into which they were intruded had not experienced collisional events before the Grenvillian event at about 1 Ga. Unfortunately, isotopic compositions other than those indicative of derivation
from depleted mantle will in many cases be ambiguous because of the difficulties in distinguishing fertile or enriched mantle signatures from the effects of crustal assimilation. It is intriguing, however, to consider that although the depleted mantle lithosphere that underlay much of the Grenville Province from 2.0 to 1.2 Ga was possibly removed by delamination during the Grenville collisional orogeny, an indirect record of its character is preserved in the anorthosites (“geological madeleines?” [42]) emplaced into the continent before collision.

6. Summary and conclusions

Cenozoic volcanism on the African continent is strongly concentrated in areas of Pan-African reactivated crust. What little other volcanism occurs is rift-related. We attribute this concentration to the establishment of fertile and depleted mantle lithosphere types during crustal assembly and subsequent modification. Cratonic areas formed by assembly of collided island arcs, and are underlain by depleted, oceanic-type mantle lithosphere from which magmas are unable to be extracted subsequently. During Tibetan-style collision in Pan-African times, depleted mantle lithosphere was delaminated, and replaced by comparatively fertile, asthenospheric material. This material was able to yield alkalic basalt when Africa came to rest with respect to mantle circulation patterns at about 30 Ma.

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