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# Partial melting of fenitized crustal xenoliths in the Oldoinyo Lengai carbonatitic volcano, Tanzania: Reply

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## Abstract

There is perhaps no more exotic an igneous rock type than natrocarbonatite, erupted from the volcano Oldoinyo Lengai, in northern Tanzania. Its origin is still the object of debate. Gittins (1988) has proposed that the alkalic carbonatite magma is a relatively evolved derivative of a mantle-derived olivine-bearing sövite. We agree that it is geochemically an evolved magma, as are the associated silicate lavas; however, the bulk of the evidence suggests to us that the natrocarbonatitic magma has a crustal component and may well have formed within the crust. In this essay, we review the background information pertinent to this proposal, made in our paper on xenoliths of fenitized crustal material brought up in the natrocarbonatite lava (Morogan and Martin, 1985).

## Introduction

The investigation of Morogan and Martin (1985) was motivated by a natural curiosity concerning the assemblage of xenolithic materials of crustal origin brought to the Earth's surface in the highly unusual natrocarbonatite lava of Oldoinyo Lengai volcano, located in the southern part of the Gregory Rift, in northern Tanzania. The focus of our investigation was a suite of nine hand specimens of fenitized rocks, and not the host natrocarbonatite lava. We realized at the outset that as in any investigation of a suite of metasomatic rocks in which the unmetasomatized starting material is unexposed and unsampled, ours was perforce an open-ended survey of the phase assemblages developed prior to and during entrainment in the unusual lava. Clearly, therefore, we did not set out to address the evidently controversial question of the ultimate origin of the Oldoinyo Lengai natrocarbonatite. In our Discussion section, however, and specifically in the last two paragraphs of the paper, we did propose a petrogenetic scheme that could explain, at least in a qualitative way, the variety of igneous products in this sector of the rift system, as described by others, and the metasomatic phenomena that we had just documented. We welcome this unexpected opportunity to clarify our views and evaluate the background information that led to our novel proposal that the natrocarbonatite could have originated in the suite of metasomatized crustal rocks rather than deep in the upper mantle.

## Scale of the metasomatic transformations

There is obviously nothing recorded in the nine hand specimens of fenitized crustal rocks to justify a firm statement one way or the other concerning the scale of the zones of metasomatic assemblages. The width of the "metasomatic facies," characterized by high-grade, medium-grade, and low-grade fenites, could be measured in centimeters or meters, as might be expected near the outer, near-vertical contact of an intrusive alkaline complex emplaced in cold host-rocks near the Earth's surface, or on either side of a crack along which the fenitizing fluids are percolating. But the metasomatic interaction was considered to be developed on a broader scale by Morogan and Martin (1985), in part because of the anomalous thermal gradient found in this area (cf. the "alkaline province geotherm" of Jones et al., 1983).

"That fenitization might occur on a regional scale . . . is a new idea," says Gittins (1988, p. 1465). We were attracted to it because of the unusual regional geophysical characteristics of the upper mantle and lower crust along various parts of the East African Rift. An elliptical area (the Kenya dome) approximately 900 km along its short axis dominates the eastern rim of the East African plateau; the dome results from a maximum uplift of 1.5 to 2 km since mid-Tertiary time (Baker and Wohlenberg, 1971; Savage and Long, 1985). The Gregory Rift, a 70-km-wide zone of normal faults, bisects the domal feature along its crest. Regional gravity and seismic surveys show that the dome reflects the presence of a broad elliptical area of anomalous upper mantle. The mantle below the Gregory Rift has an anomalously low specific gravity of 3.2 and is characterized by attenuated P- and S-wave velocities. At the normal depth of the Moho, a 30-km-wide bulge of anomalous upper mantle crosses into the lower crust, and narrows upward (Savage and Long, 1985). This lower crust, characterized by a P-wave velocity of 7.3 km/s, presumably represents a mixture of shield-type lower-continental crust, as characterized off the rift axis (6.5 km/s), and alkaline igneous basic and ultrabasic ma-

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terial crystallized from magmas injected from the upper mantle (Maguire and Long, 1976; Mooney et al., 1983; Savage and Long, 1985). Mooney et al. (1983) considered the development of a lower crust modified in this way to be a common feature of continental rifts. The proportion of intruded material probably decreases upward; the relatively high density inferred for the upper half of the crust (3.05 g/cm$^3$) is consistent with the presence of igneous bodies there as well and with a concomitant alteration of the crust. The area is considered generally to be in isostatic equilibrium, and domal uplift is viewed as the response to the presence of a regional low-density mass in the upper mantle.

Heat loss along the Gregory Rift (11–30 MW/km: Crane and O'Connell, 1983) is focused through the central part of the Kenya dome, but geothermal manifestations do occur on a regional scale. The heat flow is considered an expression of focused mantle degassing (Bailey, 1983) and the unusual intensity of injections of mantle-derived magmas into the crust. In our opinion, fenitization of crustal rocks could be effected by both agents, i.e., (1) a fluid medium released locally along an intrusive contact as a result of crystallization of an alkaline magma derived from the anomalous mantle below and (2) a fluid phase released from a leaky anomalous mantle. Is the shortest distance between two intrusive contacts in this zone measured in terms of meters or in kilometers? We believe that there is such an intense veining of the crust that a proposal of a regionally affected, metasomatically modified crust below the Oldoinyo Lengai area is not to be considered far-fetched.

What is going on *geochemically* in the anomalous upper mantle under the Kenya dome obviously is relevant to the question of the nature of the fluid leaking into the crust above. As in the case of our knowledge concerning the crust, any insight into the state of the upper mantle is based on meager samples brought to the surface in eruptions of alkali basalt and nephelinite and on geophysical modeling. Textural and mineralogical studies of ultramafic xenoliths from this and other areas along the East African Rift have revealed abundant evidence for regional metasomatic enrichment of the upper mantle via a mobile fluid, considered dominantly $CO_2$-bearing (Lloyd and Bailey, 1975; Bailey, 1980, 1982; Cohen et al., 1984; Dawson, 1987; Lloyd, 1987). There is clear evidence for regional metasomatism as long as 2 Ga ago in this area, as well as an episode just prior to the generation of the host basalt. The metasomatic reactions have consumed olivine and produced clinopyroxene and new accessory phases. They have effectively added alkalis and a variety of incompatible elements to "normal" and, in some cases, depleted mantle. The increase in volume that reflects metasomatism and ensuing partial melting is responsible for the regional uplift and the anomalies in heat flow. Morogan and Martin (1985) tacitly assumed that the fluid phase that has been focused into the anomalous zone from deeper in the mantle eventually must move on into the crust, either via the batches of partial melt that rise into the crust, which is in a state of tension because of regional doming, or very efficiently, as direct "emanations from below." There remain problems concerning the mechanisms of migration of a discrete volatile phase in the mantle, but the evidence for regional metasomatism in the mantle beneath continental rifts, in our opinion, is compelling.

## Nature of the "emanations from below"

Recent contributions on the topic of mantle metasomatism make a clear case for the introduction of a suite of incompatible elements, including the alkalis, but are less categorical concerning the respective roles of $H_2O$ and $CO_2$, which are likely to be the two dominant species in the relatively oxidized continental lithosphere (Eggler, 1987). The two species are likely to play different roles, $H_2O$ effective in complexing most major and trace elements in the solute, and $CO_2$ more effective in mobilizing the alkalis and the rare earths. The relevant experimental data are still sparse. In the opinion of Bailey (1980, 1983), the important volatile constituents to escape from the mantle into continental rift systems are $CO_2$, $H_2O$, F, and Cl.

Jones et al. (1983) have documented metasomatic reactions involving $CO_2$ in the lower crust in the Gregory Rift: relicts of olivine-normative alkali gabbros are metamorphosed into mafic granulites that contain sulfate- and carbonate-rich meionitic scapolite. These xenoliths were collected from the Lashaine tuff cone in northern Tanzania. The development of scapolite is considered mainly a result of $CO_2$ metasomatism at an unusually high regionally developed temperature (1200 K) at a pressure of 14 kbar, but $H_2O$ is likely also involved, as in the reconstructive transformation of any silicate (Donnay et al., 1959). Metasomatism involving K (and $H_2O$?) seems to have occurred later, near the surface, after the incipient decompression-related melting recorded in the xenoliths. In a companion study, an important 2.0 Ga event of chemical fractionation involving the U-Pb, Sm-Nd, and Rb-Sr systems was discovered in garnet lherzolite xenoliths from Lashaine by Cohen et al. (1984). The preferential mobilization of U, Pb, Rb, and Sr probably reflects the influence of $H_2O$ more than $CO_2$.

Morogan and Martin (1985) did not investigate the nature of trapped fluids in the metasomatic suite and so did not have direct information on the nature of the metasomatizing fluid. In view of the major reconstructive steps involved in the transformation of the pre-existing plagioclase to nepheline, and of amphibole to alkali-rich clinopyroxene, and the formation of disordered alkali feldspars, we *inferred* that the fluid phase was aqueous and peralkaline. In view of the presence of accessory calcite in most samples of the fenitized rocks, and the experimental data of Cermignani and Anderson (1983) showing that the nephelinization of plagioclase is more likely in concentrated carbonate than chloride solutions, we *inferred* that the metasomatizing fluid was $CO_2$-bearing. We also showed that in some cases, the metasomatic reactions had completely transformed the pre-existing mineral assemblages by the time incipient melting began. As in the study of Jones et al. (1983), the melting was attributed to entrainment in a rising batch of magma.

## Evidence for a crustal component in the natrocarbonatite

Isotopic systems constitute the most sensitive tool to evaluate the question of ultimate derivation of the natrocarbonatite and associated rocks. The Oldoinyo Lengai natrocarbonatite is so unusual that it has been investigated by a number of sophisticated techniques. Bell et al. (1973) found an unusually large spread of initial $^{87}Sr/^{86}Sr$ values (between 0.7034 and 0.7096; $\epsilon_{Sr}$ between $-18$ and $+70$) in the various products of igneous activity at Oldoinyo Lengai. Values at the low end of this range refer to xenoliths of plutonic aspect (melteigite, ijolite), but other samples of similar aspect have a value closer to 0.707. Two values are reported for modern carbonatite flow rocks: 0.7059 and 0.7061. Finally, phonolite and nephelinite are typically higher than 0.705 (maximum 0.7096), although one sample of nephelinite has a value of 0.7034. The suite is anomalous in its scatter of values; compared to carbonatites elsewhere, which are more depleted in $^{87}Sr$ than the bulk Earth at the time of formation (e.g., Andersen, 1987, Fig. 9), the Oldoinyo Lengai natrocarbonatite clearly is anomalous.

The $\epsilon_{Nd}$ value of $+0.1 \pm 0.9$ determined for the natrocarbonatite (DePaolo and Wasserburg, 1976) is similar to that of silicic rocks in many continental massifs. In light of the enrichment in $^{87}Sr$, an $\epsilon_{Nd}$ value close to zero may simply imply that the Nd-Sm system remained virtually unaffected in the crustal reservoir. The single determination is inconsistent with the signature expected for the geochemically enriched upper mantle that underlies the area. An integrated investigation of the isotopic composition of Sr, Nd, and Pb will be required to assess properly the respective roles of crust and upper mantle in the volcanic products of Oldoinyo Lengai and the stage (prior to melting, during or after crystallization?) at which interaction with crustal materials occurred.

Peterson and Marsh (1986) and Donaldson et al. (1987) found it impossible to explain the interrelationships among silicate members of the Oldoinyo Lengai suite using closed-system crystal-liquid processes. Peterson and Marsh (1986) interpreted the presence of combeite ($Na_2Ca_2Si_3O_9$) phenocrysts and pseudomorphs of wollastonite phenocrysts in the nephelinites (which are unusually peralkaline and highly evolved: Donaldson et al., 1987) as a product of sodium carbonate addition to the nephelinitic magma. They proposed that the natrocarbonatite exsolved from carbonated nephelinite in the course of its crystallization and that troniferous sedimentary rocks are the probable crustal contaminant; however, the $^{230}Th/^{232}Th$ value (Williams et al., 1986), like the $\delta^{18}O$ values (O'Neil and Hay, 1973), precludes the possibility that the carbonatite is simply a remobilized trona-rich evaporite deposit, such as are found in lake basins in the area. Additional problems with contamination by addition of trona were mentioned by Donaldson et al. (1987). The approach of Williams et al. (1986), based on Ra-Th disequilibria, indicates that the carbonate magma formed and erupted within 7 to 18 yr and that it probably exsolved from nephelinite that was itself Ra-enriched. If the assumption of Williams et al. concerning the geochemical coherence between Ra and Ba holds, one could propose that enrichment of nephelinite in Ra (and, by extension, $^{87}Sr$ and Ba) reflects the incorporation of a crustal component, possibly variably fenitized and thus difficult to characterize as an "end member" in a mixing process.

## Concluding remarks

The ultimate origin of alkali carbonatite magma evidently remains one of the controversial topics of igneous petrology. Twyman and Gittins (1987) cogently argued in favor of an origin by fractional crystallization of a relatively dry, mildly alkalic olivine sövite magma, which in turn probably separated as an immiscible melt from olivine nephelinite magma "deep within the mantle," at a confining pressure of approximately 27 kbar. The proposed site of immiscible separation is thus in the anomalous, geochemically "fertilized" upper mantle. The carbonatitic melt must rise 40 km through anomalous upper mantle to reach the Moho, further through 25 km of anomalous, altered lower crust, then through 15 km of fractured upper crust before making it to the surface. During this trajectory, the sövitic magma is said to fractionate anhydrous and alkali-poor minerals, which sink efficiently, making the derivative carbonatite magma alkaline and, where the fugacity of water is low, strongly peralkaline and enriched in the halogens. However, Twyman and Gittins (1987) and Gittins (1988) have made no reference to the likelihood that such a melt will interact with (and become contaminated by) its surroundings at any stage. In view of the reactivity of a natrocarbonatitic melt in contact with silicate materials that are not equilibrated with it, closed-system fractional crystallization is considered a highly unlikely possibility. We do agree with Twyman and Gittins that alkalic carbonatite magmas are highly evolved, and not to be construed as primary magmas. However, we consider the bulk of the evidence, which is admittedly largely circumstantial at this point, to favor an origin that involves a component of metasomatically modified crust. Like King (1965), we contend that the rheomorphism of fenites can account for the more evolved members of the magmatic associations along the East African Rift.

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