The size and fate of the Pan-African Plume Mantle

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Overview

The upwelling of deep mantle material to the shallow mantle in the form of large plume-heads has been considered as a major mechanism of heat and material transfer to the Earth surface. It was suggested that the rising plume-heads were responsible for production of large igneous provinces such as the oceanic plateaus, and growth of continental crust during major orogenic events [1]. It is not clear, however, to which extent the uppermost mantle is affected by the rising plumes. Are they regional (in the sense of hot spots) or have a "global" impact? What size of the mantle is occupied by the plume material and for how long the plume survives there before being mixed and consumed by the "depleted asthenospheric mantle"?

Here, I focus on the evolution of the late Proterozoic Pan African continent (comprising the basement of several segments of the Phanerozoic Gondwana), and its parental "plume mantle". The lithospheric mantle of the Pan African continent provided the sources of alkali basalts that erupted ubiquitously over Gondwana during the Phanerozoic. I use the distribution of the alkali basalts to estimate the mass of the juvenile lithospheric mantle and the size of its parental "plume- mantle".

Juvenile Pan-African crust of Gondwana

In the early Phanerozoic time, the continental crust of the Earth was clustered in two large supercontinental masses: Gondwana and Laurentia. The early Paleozoic Gondwana (the continental masses of Africa, South America, Arabia, India, Australia, Antarctica and New Zealand) comprised Archean to late-Proterozoic crustal terrains that had been affected by the late Proterozoic orogenic processes that are loosely termed as the "Pan African orogeny" (lasted roughly between ~900-500Ma). This included mobilization of the pre-existing crust, metamorphism and generation of juvenile crustal terranes. The juvenile Pan-African crustal rocks are characterized by initial $^{87}Sr/^{86}Sr$ isotopic ratios of 0.7027±3, and eNd values of +4 to +6. The relatively low $^{87}Sr/^{86}Sr$ isotopic ratios indicate mantle-type sources for the crustal magmas, while the initial eNd values are significantly lower than those expected from late Proterozoic depleted (MORB type) mantle source (the ~800 Ma Gabal Gerf ophiolite in Sudan shows eNd = +8). Stein and Goldstein[2] suggested that the juvenile ANS magmas were derived from enriched plume-related mantle that was transformed by the subduction mechanism to new continental lithospheric. Late Proterozoic crustal magmas with Nd-Sr isotopic compositions that are similar to the ANS magmas were documented in several other late Proterozoic juvenile crustal terrains of Gondwana suggesting that the formation of enriched “plume mantle” during the Pan African orogeny was global.

Alkali basalts from the Pan African lithospheric mantle

Phanerozoic alkali basalts overlie many of the Pan African crustal terrains (Fig. 1). An important characteristic of the Phanerozoic basaltic magmatism over the Gondwana is their large spatial distribution and short contemporaneous activity. Alkali basalts with similar geochemical and isotopic characteristics erupted simultaneously over thousands of kilometers (e.g., over more than 5000 km along the Antarctica-New Zealand-Tasmania continent and along more than 3000 km in the ANS and over North Africa). This configuration cannot be easily explained by conventional plume models, but can be accommodated by models of “fossil plume” reactivation (e.g. [3-5]). Stein and Goldstein [2] linked the production of the Phanerozoic basalts in the ANS to the lithospheric mantle that was produce during the Pan African events. Extending this model, I suggest that the “fossil plumes” or the lithospheric mantle roots beneath the Gondwana fields are parts of the “Pan African” lithospheric mantle that was fossilized when subduction processes on the Pan-African continental margins stopped. The important consequence is that the basalts provide information on the distribution of the Pan African lithospheric mantle, and in turn on the properties of its parental plume mantle.

The composition of the uppermost mantle during the plume event

The remarkable uniformity in the Nd and Sr isotope compositions of the Phanerozoic alkali basalts from various parts of the Gondwana (grand averages of available data: eNd=4.7±0.7 and ^{87}Sr/^{86}Sr=0.7028±3) is analogous to that observed in Mid-Ocean Ridge Basalts (MORB). The uniformity in MORB compositions has been used as the major argument in the widely accepted supposition that MORB represents the asthenospheric upper mantle. **It can similarly be argued that, at the time of formation of the Pan-African juvenile crustal terranes and the lithospheric sources of the Gondwana basalts, the enriched, plume type mantle material largely dominated the uppermost mantle**. This requires a substantial supply of enriched and fertile material to the uppermost mantle on a global scale. Stein and Hofmann [1] proposed that continental crust growth is associated with episodic large upwelling events in the mantle (MOMO overturn events). During these events, lower mantle material rises as large plume-heads, producing oceanic plateaus that may be later accreted to the existing continents. The rising plumes replenish the upper mantle in incompatible trace elements, and make it fertile for basalt formation. Thus, the “mid-ocean ridges” of late Proterozoic time produced oceanic crust with enriched chemical composition.

The uniformity in the Nd and Sr isotopic compositions of the Phanerozoic Gondwana basalts stands in contrast to the much larger variation in the isotopic values of the oceanic island basalts (OIB). The heterogeneity in OIB compositions has been attributed to the large variety of deep mantle sources and their different histories or to shallower mantle sources (e.g., delaminated segments of heterogeneous lithospheric mantle. However, the role of enriched-plume related oceanic lithosphere (of the Nauru basin type) as an important component in the production of OIB has been overlooked.

The size and fate of the Pan African “plume-mantle”

Considering a static model, the mass of the "plume mantle" during juvenile lithosphere formation is equivalent to the sum of the masses of juvenile lithospheric mantle + juvenile continental crust + residual depleted mantle. This simplified configuration can be described by the following mass-balance equations:

$$(1)\ M_m = M_{RDM}+M_L$$

For the total masses of the “plume mantle” , lithosphere and residual depleted mantle:

$$(2)\ M_m{*}C_m = M_{RDM}{*}C_{RDM}+ M_L{*}C_L$$

For the mass of specific elements:

By rearranging eqs. 1 and 2, one gets:

$$(3)\ M_m= M_L\ (C_L-C_{RDM})/(C_m-C_{RDM})$$

Where:

M_m is the mass of "plume mantle "
M_L is the mass of lithospheric mantle + crust
C_L is the concentration of a trace element (e.g., Nd) in the lithospheric mantle and crust
C_{RDM} is the concentration of a trace element in the residual depleted mantle
C_m is the concentration of a trace element in the "plume mantle"

The major unknown here is M_m--the mass of the “plume- mantle”. The mass of the juvenile lithospheric mantle is estimated from the distribution of the Phanerozoic basalt fields over Gondwana (Fig. 1), assuming a lithosphere thickness of ca. 100 km.

The volume of the Pan-African juvenile lithospheric mantle is estimated to be in the order of 3-4X10^9 km^3 and its parental "plume mantle" has the approximate volume of 1-2x10^{10} km^3, which is less than 10% of the volume of the upper mantle. If distributed uniformly over the globe the Pan African "plume- mantle" would occupy only the uppermost < 50 km of the mantle. If the plume material is not uniformly distributed, but rather spreads beneath “the Gondwana hemisphere”, the “plume mantle” may extend to deeper depth. In any event this estimate indicates that the upwelling of the Pan-African plume-head(s) represents a limited event that could not affect the composition of the entire uppermost mantle, and therefore cannot be described as a complete overturn of the mantle. Rather the process can be defined as a "transient intrusion event" involving large upwelling of lower mantle material to the shallower part of the mantle. This view is consistent with some geochemical constraints on the input of lower-mantle material into the upper mantle. For example, strontium isotope composition of MORB limits the total time integrated exchange between the lower and upper mantle to ca. 30% of the lower mantle mass and the ^{40}Ar budget suggesting that ~50% of the total radiogenic argon produced during Earth history is still stored in the lower mantle [6,7].

References

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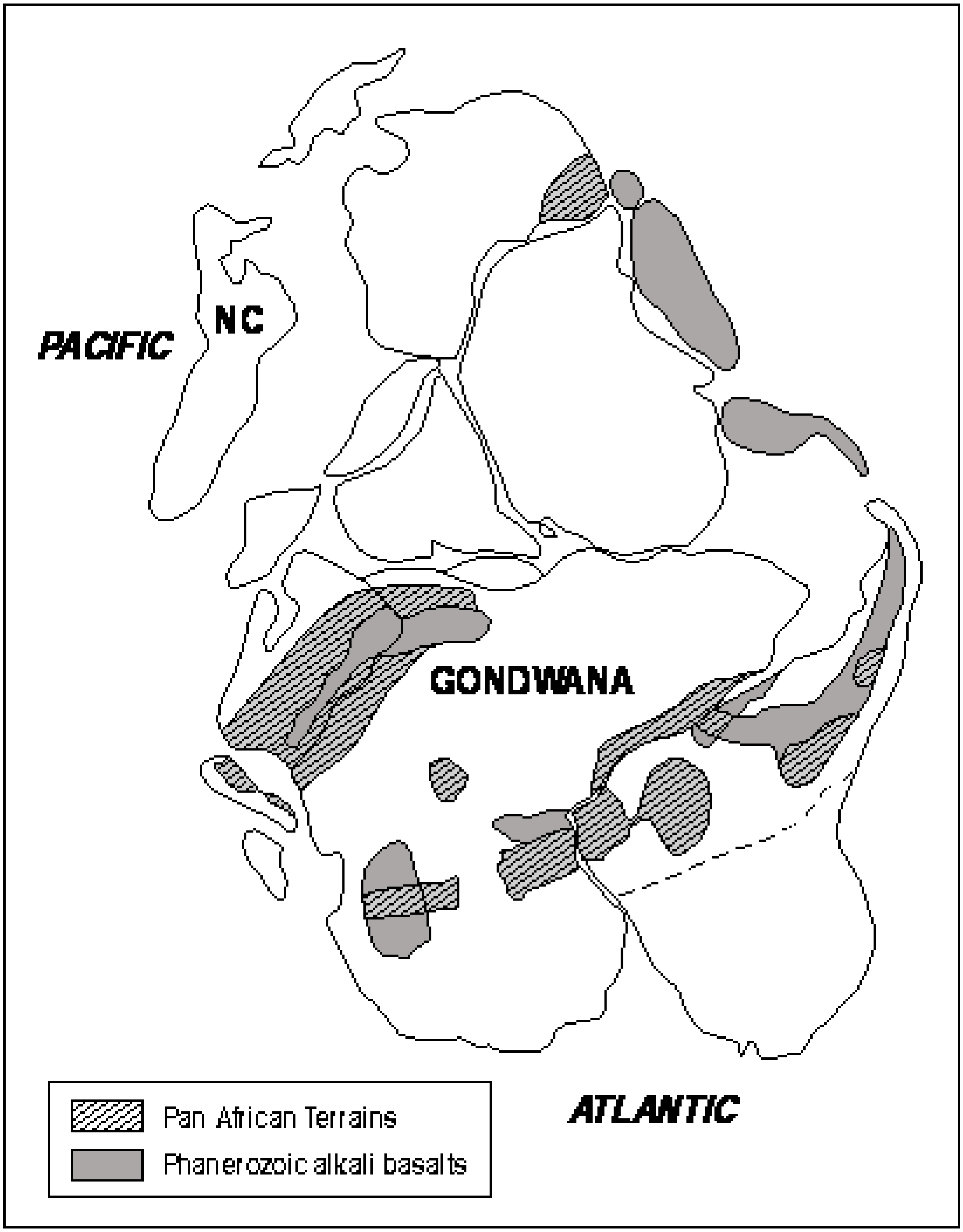

Fig. 1. Distribution of Pan African juvenile lithosphere terrains