The Origin of High-Ti Picrites from the Ethiopian Flood Basalt Province

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The Ethiopian Plateau forms the larger part of an extensive continental flood basalt province, which, today, extends into Ertitrea, Djibouti, Yemen and Somalia. The province is thought to be a result of plume-head activity associated with the opening of the Red Sea and Gulf of Aden at the Afro Arabian triple junction. Tomographic images of mantle shear-wave velocities beneath Afar seem to confirm the existence of a mantle plume that extends down to the core mantle boundary (1), and elevated $^{3}He/^{4}He$ ratios for high-Ti lavas from the province support that this is sourced in an undegassed part of the mantle (2). The main phase of volcanism, which formed the traps occurred between 30 Ma and 28 Ma (3). During this period, a pile of flood basalts with an estimated thickness of up to 2000 m, covering an area of 600 000 km^2 (4) was erupted onto a basement of Pan-African arc-associated volcanics and intrusives, and Mesozoic sediments (5). 106 km^3 of this volume were emplaced within 1 myr during the peak of the activity at about 30 Ma; this indicates an average magma flux of 1 km^{3}/ yr (3). Combined fission track data and $^{40}Ar/^{39}Ar$ age-data, together with field observations, suggest that uplift preceded volcanism and that extension was synchronous with volcanism (6). Extension in the Red Sea occurred in two distinct pulses at 30 to 35 Ma and 20 to 25 Ma respectively (7) and oceanic crust appeared around 10 to 13 Ma (8), or more recently at 5 Ma (9).

The flood basalts of the Ethiopian Traps are transitional between tholeiitic and alkaline in composition. They form three distinct magma groups, which show geographical rather than temporal variation in their major and trace element composition (5). The LT basalts, which occupy the north-west part of the plateau, show consistently low TiO_2 contents and considerable heterogeneity in their trace element geochemistry. Marked troughs for Th and Ta-Nb, and variable LREE enrichment may suggest that they have undergone extensive lithospheric contamination, and that they are derived from a LREE depleted garnet free source. The HT2 basalts, which occur in the south-east part of the plateau, on the other hand, have consistently high TiO_2 contents and more homogeneous trace element signatures. Enrichment of LREE and a relative depletion of HREE suggest the presence of residual garnet in the source, and there is little evidence for contamination. The HT1 basalts display characteristics between the two other groups. Contrasting $^{3}He/^{4}He$ ratios in the HT2 and LT basalts indicate that the two types are from different parental sources (2). The HT2 basalts are typically picritic with high $^{3}He/^{4}He$ ratios and they so define a geographically localised high-Ti sub-province representative of the primary magma generated by high temperature melting possibly within the head of a plume.

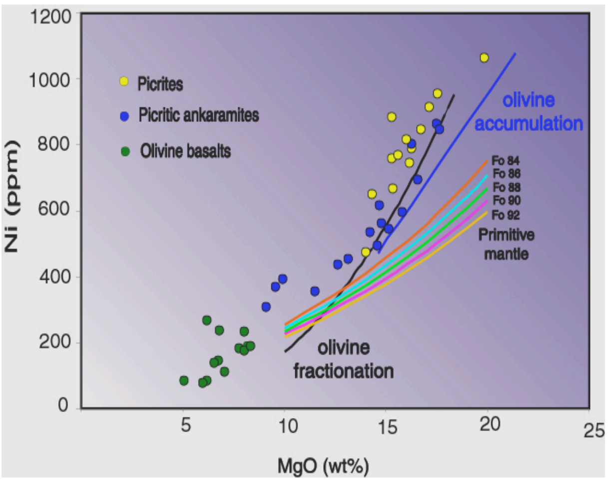

Figure 1 Plot for MgO (wt%) versus Ni (ppm) for the lavas from the high-Ti sub-province. The curves for olivine accumulation and fractionation were respectively modelled from major element data for the least and most primitive picrite. Lines for melts in equilibrium with mantle olivine of Fo84 - Fo92 were calculated using partition data from (10) and (11).

The lavas of the high Ti sub-province include pictites, ankaramites and olivine basalts, which together form a coherent suite genetically related by olivine fractionation and accumulation (Fig. 1). They have a primary melt composition of between 14 and 15 % MgO equilibrated with mantle olivine with a fosterite content of 82. This relatively low Fo content is a consequence of the high iron content of the source, which is elevated compared to normal mantle, and high Fe_{15} for the lavas compared to experimental data for KLB-1and HK-66 seem to confirm this. High iron (12 - 16 % Fe_2O_3) and titanium (3 - 7 % TiO_2) and a primary MgO of 14 – 15 % imply that the parent magma was derived from a high temperature small melt fraction. CaO/Al_2O_3 to Al_2O_3 ratios plotted against experimental data for KLB-1 (12) suggest that the melts were generated at between 4 and 5 GPa (Fig. 2).

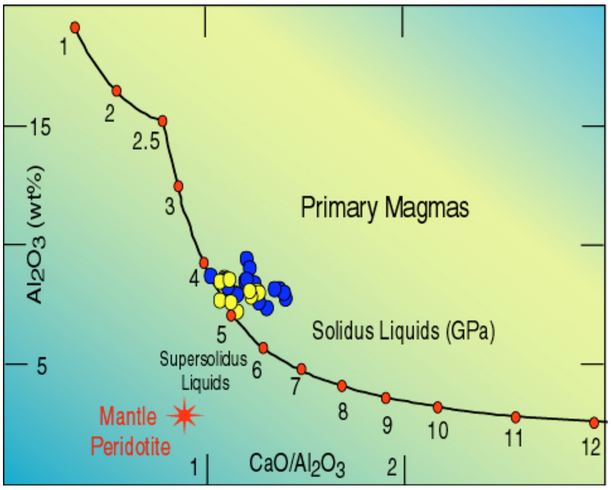

Figure 2 Plot of Al_2O_3 versus CaO/Al_2O_3 showing pressure of melting for the picrites and ankaramites from the the high-Ti sub-province. The lavas are compared to experimental data for KLB-1. Liquids formed along the solidus will have Al_2O_3 and CaO/Al_2O_3 contents indicated by the pressures in GPa (12).

These pressures are equivalent to depths of 120 - 150 km, and imply melting at temperatures between 1600 and 1700°C beneath thick lithosphere prior to extension. The random stratigraphic order of the primitive picrites and ankaramites, and the more evolved olivine basalts within the volcanic pile further implies that pulses of primary magma were released into the crust, some of which made their way directly to the surface while some were able to equilibrate in a shallow-seated reservoir before eruption.

The consistent homogeneity of the trace element patterns for the lavas of the high-Ti sub-province seems to support their common parentage, and strongly fractionated REE patterns indicate the presence of garnet in the source. Sub-parallel HREE patterns for the olivine basalts confirm that they fractionated at a shallow level compared to the picrites and ankaramites which show a distinct fanning of the REE indicative of variable degrees of partial melting within the garnet stability field. Dy/Yb and La/Yb ratios can be used to constrain the depth and degree of melting within the garnet field. Using pressure, temperature and composition dependent coefficients and phase proportions, the lavas can be modelled as 2 -3 % partial melts at pressures in excess of 3 GPa. The picrites and ankaramites define a discreet linear array for Dy/Yb versus La/Yb, and Dy/Yb versus Si_{15}; this reflects a range of melt conditions from moderate to high pressures with increasing garnet signatures.

The major and trace element data all support a model for melt generation at high temperatures and pressures. In particular the high temperature of melting, well above that expected for normal variations in the mantle, is indicative of melting within a plume.

Initial $^{187}Os/^{188}Os$ ratios for the picrites and ankaramites are all sub-chondritic with a restricted range (0.125 - 0.126). This reflects a source more like that expected for depleted mantle; in this respect they are quite different from any other reported plume-head lavas (Fig. 3). Total Os concentrations for the lavas are high (750 - 2025 ppt) compared to other continental flood basalts; they are more similar to komatiites. Since it is unlikely that the source contains no sulphide, this elevated Os concentration may be a feature of high pressure/temperature partitioning of Os.

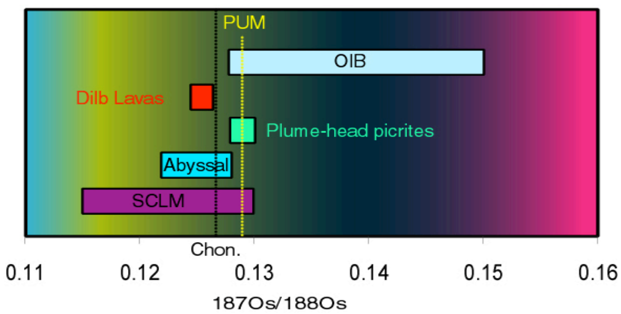

Figure 3 $^{187}Os/^{188}Os$ range for the Ethiopian picrites and ankaramites compared to selected mantle derivatives.

Sub-chondritic $^{187}Os/^{188}Os$ ratios suggest that there is no excess ^{186}Os in these high-Ti lavas; it is therefore unlikely that they have interacted with the core as is implicit in the tomographic images presented by Ritsema et al. (1). More recent tomographic images presented by Nolet et al. (13), however, affirm that the Afar upwelling is rooted in the upper mantle.

The Os isotope composition of the high -Ti lavas from the Ethiopian plateau is intriguing because they have values similar to what would be predicted for the depleted upper mantle. However, recent studies of both MORB and OIB lavas, and estimates of the Os isotope composition of the mantle, indicate that there is no simple delineation between sub-chondritic upper mantle and more primitive lower mantle. Some plumes have very low $^{187}Os/^{188}Os$ and some MORB have values within error of estimates for the primitive mantle. In conclusion then, although the Ethiopian lavas have Os isotope ratios similar to upper mantle their actual origin within the mantle is still elusive. What is clear, is that they are from a source significantly more homogeneous than that for MORB.

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