PETROGENESIS AND GEODYNAMIC SIGNIFICANCE OF THE VOLCANISM OF THE NORTHERN ETHIOPIAN PLATEAU

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INTRODUCTION

After the pioneering works of Morgan during the Seventies (Morgan, 1971) a renewed interest on mantle plumes has arisen in the last decades with controversial hypotheses on depths of plume provenance, triggering mechanisms, shape and size of the convective mantle, as well as relationships with hot spots, Large Igneous Province (LIP), and rift volcanism (Ernst & Buchan, 2001; Foulger *et al.*, 2005; Foulger & Jurdy, 2007).

In this regard, the Ethiopian-Yemen basaltic plateau represents a very convenient natural laboratory to study Continental Flood Basalts (CFB) and the tectonomagmatic processes that led to the formation of the Red Sea, Gulf of Aden and East African rift system, from Oligocene to Present. This area is centred on the Afar hot spot which appears unequivocally related to a deep plume originating in the lower mantle (Courtillot *et al.*, 2003, Davaille *et al.*, 2005). A multidisciplinary study has been developed on the Ethiopian Oligocene Plateau, integrating field data with detailed sampling of selected basaltic sections, geochemical and petrological results, as well as GIS processing, in order to provide new insights on the mantle plume region from which plateau basalts were generated.

The integrated approach includes:

1. Digitalization, georeferentiation and projection in the UTM system WGS-84 Datum of the geological map 1:2.000.000 by Merla *et al.* (1973), and subsequent creation shapefiles for each geological formations related to the Oligocene CFB and a shapefile containing the UTM coordinates of the studied samples. The topographic values (z) were obtained by NASA Shuttle Radar Tomography Mission (SRTM) rasters.

2. Petrochemical analyses of samples collected along selected plateau sections and petrological classification allowed definition of a zonal arrangement of volcanics with Low-Ti tholeiites in the NW part and High-Ti transitional basalts (and picrites) in the SE sector of the Ethiopian plateau. Calculation of the erupted volumes of each magma-type was carried out.

3. Thermobarometric methods and the Niu & Batiza (1991) empirical model were applied to the various magmatypes in order to constrain their degree of partial melting (F), temperature (T), as well as initial (P_o) and final (P_f) pressures of melt generation in a mantle upwelling region. Calculations were carried out on selected representative near-primary magmas, *i.e.* in equilibrium with peridotite mantle sources. Petrogenetic modelling is also used to figure out the plume influenced mantle region from which northern Ethiopia CFB were generated.

VOLCANOTECTONIC FRAMEWORK

The northern Ethiopian plateau (Fig. 1) mainly consists of tholeiitic to transitional basaltic lavas (up to 2 km thick; Mohr & Zanettin, 1988) erupted in 1-2 Ma (between 31 and 29 Ma) over an area of about 210.000 km^2, in concomitance with similar flood volcanism in the Yemen conjugate margin (Baker *et al.*, 1996; Ukstins *et al.*, 2002).

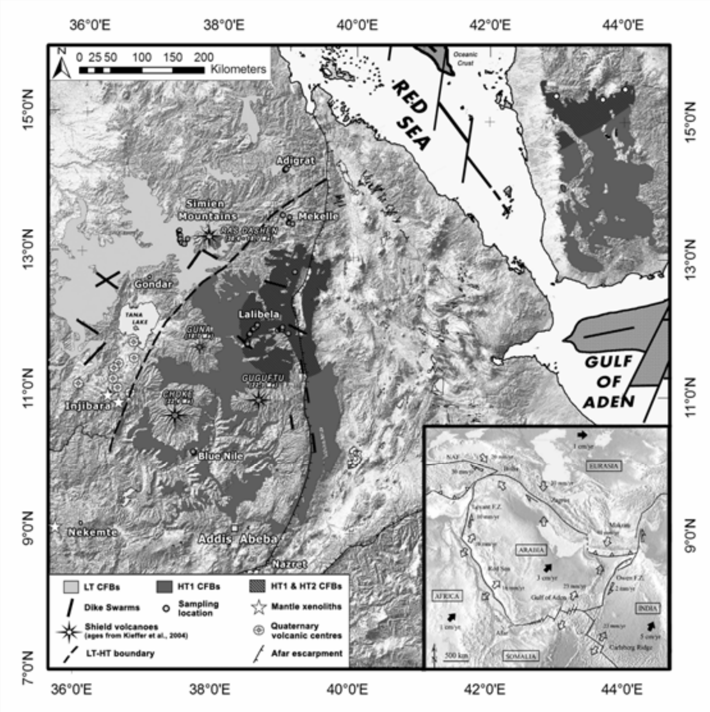

Fig. 1 - Sketch map of the of Early Oligocene continental flood basalts (CFBs, 31-29 Ma) from northern Ethiopia and the Yemen conjugate margin, based on the geological map by Merla *et al.* (1973), NASA STRM images, and data from Baker *et al.* (1996), Pik *et al.* (1998), Kieffer *et al.* (2004), and this work. Legend: LT = Low-TiO_2 basalts; HT1 = High-TiO_2 basalts; HT2 = very high-TiO_2 basalts and picrites. Dyke swarms after Mège & Korme (2004); locations of mantle xenoliths exhumed by Quaternary alkaline volcanics in the plateau area are also reported. Inset: regional geodynamic sketch with plate motions and velocities after Bellahsen *et al.* (2003).

Dyke swarms, that likely fed these Continental Flood Basalt (CFB) fissural eruptions (Mège & Korme, 2004; Fig. 1), are nearly parallel to the sea floor spreading axes of the Gulf of Aden and Red Sea suggesting multiple rifting and spreading processes radiating from the still active Afar zone (volcano-seismic crisis of autumn 2005; Ayele *et al.*, 2007).

Plateau volcanism in Ethiopia was preceded by (at least since Late Eocene, based on stratigraphical data) and partially synchronous with the uplift of the underlying basement up to 2500 m elevation (Bosellini *et al.*, 1987).

Plateau basalts are overlain by huge shield volcanoes (Mt. Choke and Gugugftu, 22 Ma; Mt. Guna, 10.7 Ma) mainly composed of alkaline lavas (Kieffer *et al.*, 2004). In the south western part of the plateau strong alkaline lavas were erupted from a number of quaternary volcanic centres. Basanite lavas from two of these volcanoes near Injibara and west of Nekemte (Dedessa River) carry abundant mantle xenoliths which have been also considered in this work.

GIS based digitalization of the 1:2000000 geological map by Merla *et al.* (1973) allows us to estimate the original volumes of the flood volcanics in the northern Ethiopian Plateau as 250000 km^3, leading to an eruption rate in the order of 0.1-0.3 km^3/y which is comparable to other CFB provinces.

PETROCHEMISTRY

Continental Flood Basalt from the northern Ethiopian plateau

New detailed sampling of selected plateau sections have been carried out in four areas (Fig. 2):

1. Simien Mountain (north of Gondar);
2. West of Adigrat;
3. Blue Nile (near Dejen);
4. Lalibela district.

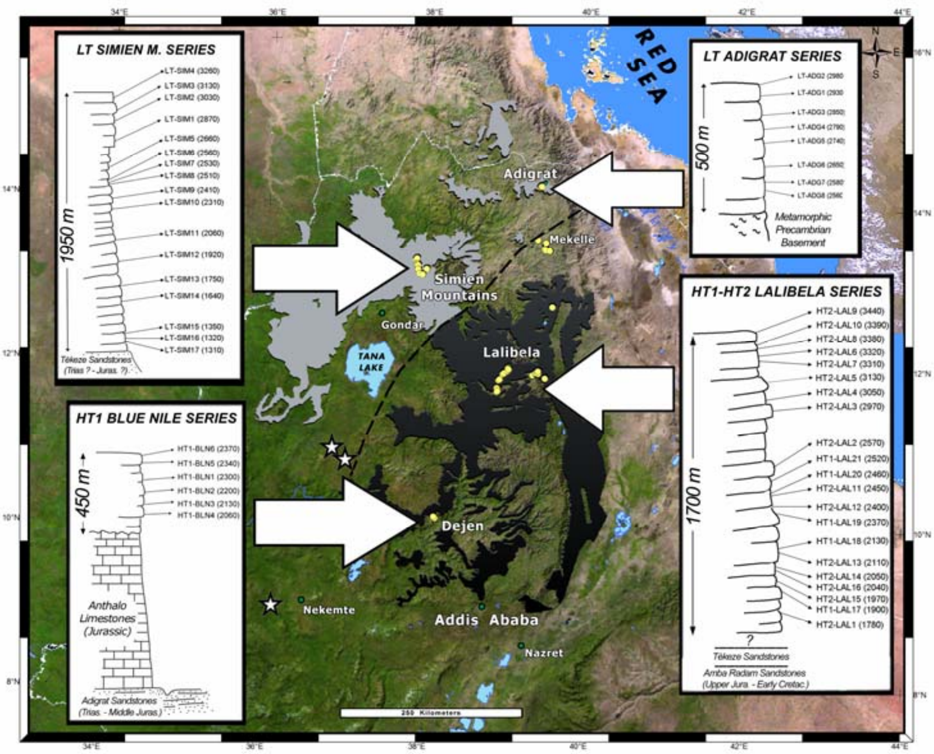

Fig. 2 – Generalized cross sections and sampling locations (yellow circles) of Oligocene lavas trough the northern Ethiopian plateau. Sampling elevation in meters (a.s.l.) is reported in brackets. Abbreviations as in the text. LT CFB is the light grey region while HT CFB is the dark grey region. Mantle xenoliths locations are identified by stars.

The new analyses on plateau basalts, while confirming the existence of three main magma types spatially zoned according to the TiO_2 content (Pik *et al.*, 1998), allow a more precise definition of their zonal arrangement (Fig. 1): Low-Ti tholeiites (LT) in the north-west, quantitatively predominant (150000 km^3) High-Ti lavas (HT1) eastwards, with ultra-titaniferous basalts and picrites (HT2) concentrated in the Lalibela area, closer to the centre of the Afar triangle

Low-Ti basalts show hypo-crystalline to sub-ophitic textures with variable porphyric index. Phenocrysts mainly consist of dominant plagioclase, augitic clinopyroxene and scarce generally iddingsitesed olivine in both Simien M. and Adigrat sequences. They vary from relatively unfractionated magmas (mg# 0.68) to ferrobasaltic composition (mg# down to 0.35) along a marked Fe-Ti enrichment trend.

HT1 basalts from both the Blue Nile and the lower part of Lalibela sequence show relatively differentiated ferrobasaltic compositions (mg# from 0.53 down to 0.34). They vary from aphiric to slightly plagioclase-phyric textured. Subophitic textures appear in the coarser grained samples. To be noted the significant presence of amphibole and/or phlogopite in some HT occurrences (Mekelle dolerites and Lalibela picrites).

HT2 lavas (Lalibela sequence) range in composition from picrites to basalts (mg# from 0.72 to 0.46) and are characterised by very high titanium content (TiO_2 from 3.5 up to 5.9). They are always porphyritic in texture with phenocrysts of olivine, clinopyroxene and rare plagioclase. In one case (LAL11) cumulus olivine is evidenced by glomero-porphyritic texture and extremely high mg# (0.83).

Chondrite-normalised REE distribution (Fig. 3) show positive fractionation and LREE enrichment gradually increasing from LT (La_N/Yb_N from 1.2 to 3.3) to HT1 tholeiites (La_N/Yb_N from 6.9 to 7.5) up to ultra-titaniferous basalts and picrites (La_N/Yb_N from 11.3 to 17.5).

While the LT, HT1 first two magma types are equivalent to those usually recognised in other CFB provinces, HT2 seems to be exceptional and only partially comparable with some picrites of the Karoo igneous province (Ellam & Cox, 1991; Sweeney *et al.*, 1991; Cawthorn & Biggar, 1993).

Moreover, High-Ti lavas from northern Ethiopia show striking compositional analogies with those of the Yemen plateau, suggesting that before the opening of the Afar/Red Sea these volcanic districts would have been part of the same magmatic province, extending up to *ca.* 700 km in an E-W direction.

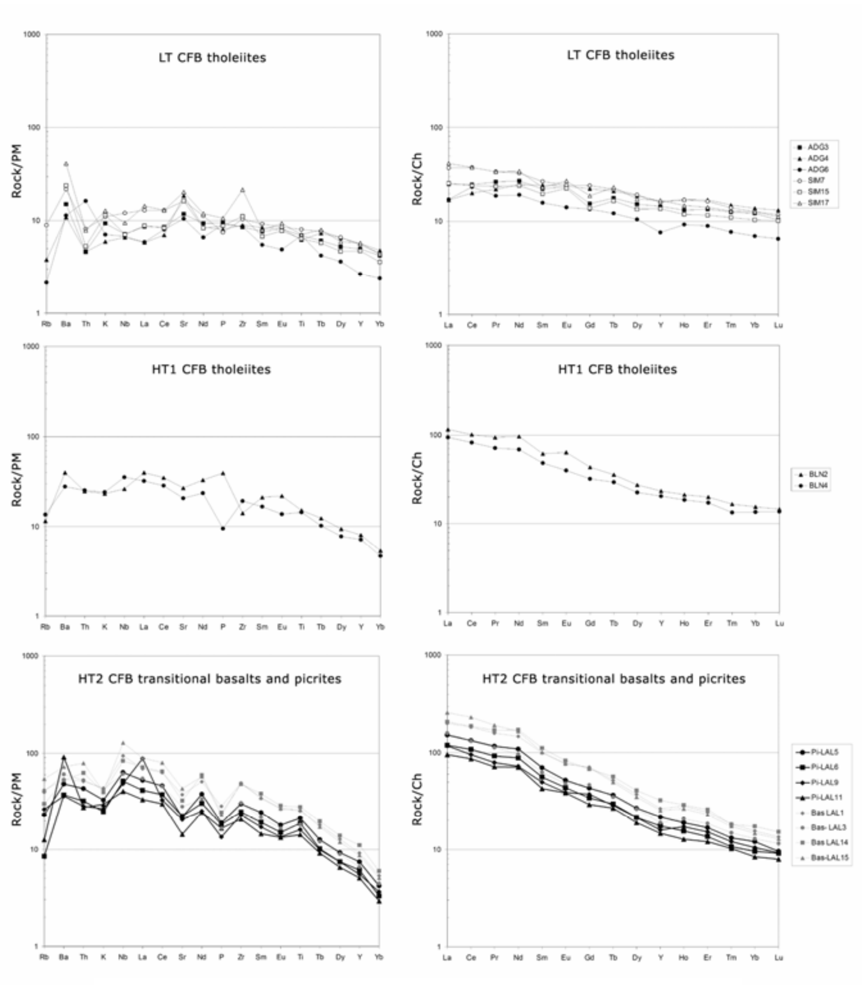

Fig. 3 – PM normalised incompatible elements (Sun & McDonough, 1989) and chondrite normalized REE (McDonough & Sun, 1995) patterns of Oligocene CFBs from the north Ethiopian plateau.

Mantle xenoliths from the plateau area

The mantle xenoliths from north Ethiopian plateau have been sampled from two quaternary alkaline lava flows, one south of Tana Lake (Injibara), the other on the southern border of the north Ethiopian plateau (Dedessa). The mantle xenoliths generally show a wide compositional range varying from spinel lherzolites to harzburgites and olivine-websterites (Fig. 4).

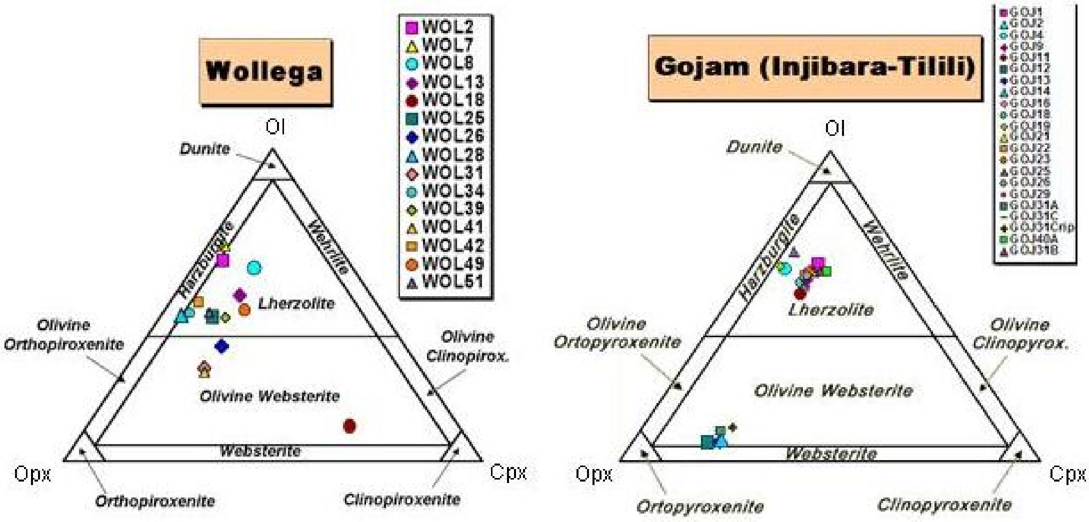

Fig. 4 – Ol-Cpx-Opx modal composition of the Dedessa and Injibara mantle xenoliths.

The dominant lherzolitic compositions are protogranular textured generally lacking modal evidences of metasomatic reaction. Their modal composition is in the following range: olivine 60-61%, orthopyroxene 22%, clinopyroxene 14-15%, spinel 3%. Their Primordial Mantle (PM)-normalised incompatible element patterns are generally “flat” ranging between 0.7-1 x PM. Thermobarometric estimates according to Brey & Köhler (1990) and Köhler & Brey (1990) give nominal equilibration temperature between 930 and 1050°C and pressure range of 9-12.5 kbar, which are compatible with spinel peridotite.

PETROGENETIC MODELLING BASED ON MAJOR ELEMENTS OF NORTHERN ETHIOPIAN CFBs

Major element petrogenetic modelling was used to constrain pressure (P), temperature (T), degree of melting (F), phase equilibria and composition of magma sources. The Niu & Batiza (1991) empirical model was first applied to the least differentiated plateau basalts to estimate the degree of melting (F), initial (P_0) and final (P_f) pressure of magma formation.

These data were integrated with pressure (P_A) and temperature of melt segregation using the Albarede’s algorithm (1992). For picrites, that fall outside the compositions investigated by Niu & Batiza (1991), only the Albarede thermobarometric approach was used, and F = 25-30% was assumed in accordance with experimental petrology data (Green & Falloon, 2005, and references therein).

Overall results (Fig. 5) show that melting temperatures diminish in concomitance with the East-West spatial zonation from 1400°C for HT to 1200°C for LT basalts. The highest segregation temperatures recorded in picrites (up to 1500°C) are consistent with both the exceedingly high Ni content (1100-650 ppm in bulk rock) and the high Cr content of their olivine phenocrysts (up to 1000 ppm) which conform with plume-derived super-heated magmas (Campbell, 2001).

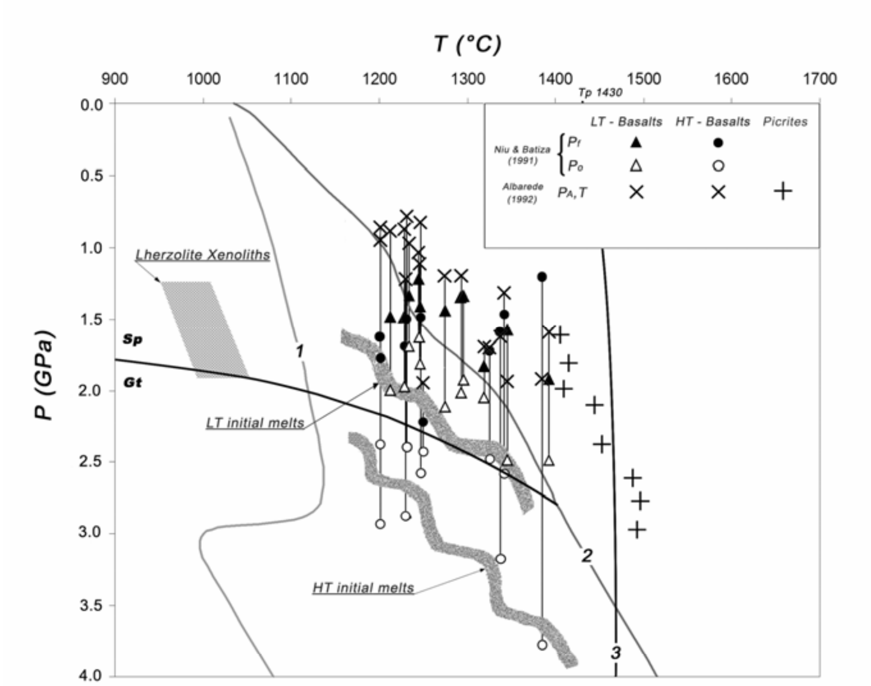

Fig. 5 – Pressure-temperature petrogenetic grid depicting the melting conditions of northern Ethiopian CFBs based on the models proposed by Niu & Batiza (1991, P_0 and P_f: initial and final pressures of melt formation) and Albarede (1992; P_A and T: pressure and temperature of melt segregation). Volatile (H-O-C) bearing (1) and dry (2) lherzolite solidi, spinel (sp) and garnet (gt) stability fields, and adiabat (3) for mantle potential temperature T_p 1430°C are after Green & Falloon (2005). P-T equilibration conditions of lherzolite mantle xenoliths from the plateau area are also reported (shaded field). Analyses from this work and Pik *et al.* (1998). See text for further explanation.

Further temperature estimates have been obtained using olivine-liquid thermometers according to Ford *et al.* (1983) and Herzberg & O'Hara (2002) for picrites giving temperatures of 1400-1402°C (in equilibrium with Fo_{90} olivine) and 1360-1365°C (in equilibrium with Fo_{88} olivine) in samples LAL6 and LAL9 respectively. As expected, olivine liquidus temperatures are systematically lower (in the order of 50-100°C) than those calculated for magma segregation from the mantle sources.

Based on the estimated F, the source composition for each magma type was subsequently constrained by major element mass balance calculations between basalts and the most fertile lherzolite xenoliths sampled in the plateau area.

The modal mineral composition of the mantle sources, as well as the melting proportions, were defined by iterative least-square calculations based on major element compositions of constituent minerals plus additional mantle phases such as amphibole/phlogopite- or an equivalent chemical budget, ilmenite and garnet, generally not present in the studied xenoliths, but required by computation.

This petrogenetic modelling indicates that:

1) a chemical component corresponding to amphibole (or an equivalent metasomatic component) is always required in magma sources, varying from 4% for LT tholeiites up to 6-9% for HT basalts and picrites, and is the predominant melting phase; this phase, rarely observed in Ethiopian mantle xenoliths, has to be related to metasomatizing agents interacting with the pristine mantle parageneses;

2) titanium-rich minerals (*e.g.* ilmenite, rutile, armalcolite) are additional metasomatic phases required in mantle sources of ultratitaniferous (HT2) magmas.

Moreover, the inferred presence of garnet in the sources of HT magmas conforms to P_0 estimates of their initial melting which plot well in the garnet lherzolite stability field (Fig. 5).

CONCLUSIONS

The presented petrological model fits the first order requirements for a deep plume hypothesis as modelled by Farnetani & Richards (1994), *i.e.* shape, dimension (*ca.* 450 km radius), temperature excess ($\Delta T \geq 350$°C), lithosphere bulging (2-3 km uplift), and CFB timing.

The above petrogenetic P-T-X constraints for the northern Ethiopian CFBs enable us to figure out shape, size and location of the mantle region where magmas were generated (Fig. 6). Results lead to melting region in the sublithospheric mantle, likely representing the head of an impinging deep plume that induced a dramatic thermal anomaly, lithospheric bulging/faulting and the Early Oligocene CFB volcanism.

Modelling elemental distribution provides estimates of the P-T-X conditions of magma sources showing that LT and HT melts could be generated in the pressure range of 3.0-1.3 GPa (*ca.* 40-100 km depth) from mantle sources increasingly metasomatized (*ca.* 4% to 6-9% amphibole ± 1-2% Ti-phase for HT) and hotter (1200-1500°C) from West to East. Metasomatizing agents can be envisaged as alkali-silicate melts which integrate various geochemical components (*e.g.*: Ti, Fe and related HFSE, LFSE, LREE, H_2O, noble gases etc.) with different depths of provenance and mobility, scavenged and pooled along the plume axis. This has significant implications for the current debate on mantle plumes, since the modelled compositionally and thermally zoned plume head (temperature excess ≥ 350°C

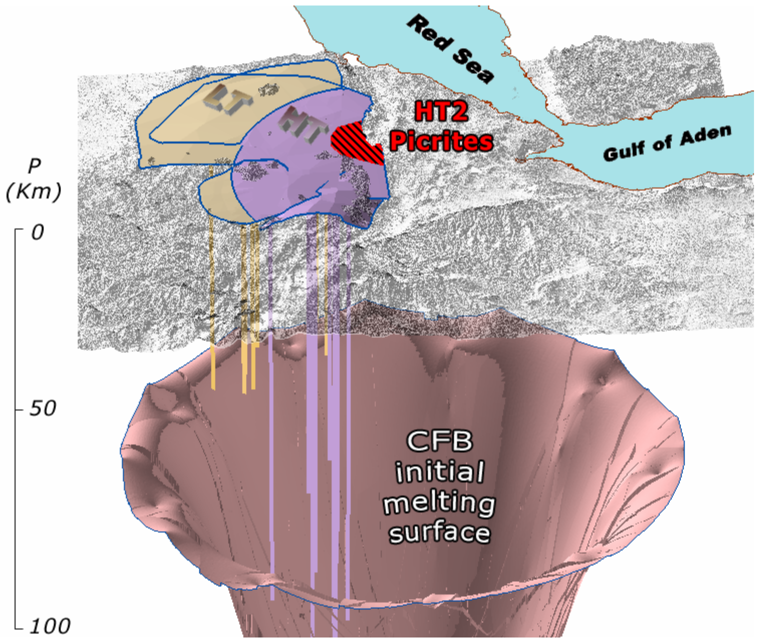

Fig. 6 – 3D GIS-based reconstruction of the melting mantle domain carried out by major element modelling on Oligocene plateau lavas. The topographic map, in grey scale, is obtained by NASA SRTM images.

with respect to mantle xenoliths) is in accordance with seismic tomography, buoyancy flux characteristics, and the high ^{3}He signal (Pik *et al.*, 2006), thus supporting a deep provenance of the Afar plume, possibly originated in the lower mantle. The peculiar composition and the zonal arrangement of the northern Ethiopia-Yemen CFBs centred in the Afar triple point suggest a relationship with a distinct mantle plume independent from the Kenyan plume, as also suggested by Rogers *et al.* (2000) on the basis of the diverse isotopic fingerprints.

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