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A new mantle xenolith locality from Simien shield volcano, NW Ethiopia

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Abstract – Thin-section observations and electron probe analyses, and trace element data are reported from a new mantle xenolith hosted in Miocene alkali basalt from the western flank of Simien shield volcano, Ethiopia. The spinel lherzolite enclaves contain variable proportions of olivine, orthopyroxene, green clinopyroxene and brown spinel, and have undergone deformation and partial recrystallization. They represent unmetasomatized, fertile xenoliths which were subjected to a late-stage melt–rock reaction. Trace element contents of clinopyroxene crystals are extremely low and quite different from those of the other xenoliths within the East African Rift System.

Keywords: lithospheric mantle, Simien, spinel lherzolites, xenolith.

1. Introduction

The Quaternary alkaline volcanic fields of Ethiopia contain abundant peridotite xenoliths and xenocrysts which have been the subjects of petrological and geochemical study (Bedesa, Debre Zeyit-Silite Butajira, Injibara and Mega-Megado: Morten *et al.* 1992; Roger *et al.* 1997, 1999; Bedini *et al.* 1997; Bedini & Bodinier, 1999; Conticelli *et al.* 1999; Ayalew *et al.* 2003; Lorand *et al.* 2003; Rooney *et al.* 2005; Ferrando *et al.* 2008). Prior work on peridotite xenoliths from NW Ethiopia has shown that the lithospheric mantle underneath (1) has experienced partial melting, probably linked to the pan-African orogenesis event, (2) subsequently, was slightly re-enriched by a metasomatic process, possibly prior to or during the emplacement of the Oligocene Afar mantle plume, (3) has undergone some deformation which was followed by a later partial recrystallization and (4) deviates to higher temperatures with respect to the continental geotherm.

We sampled a newly discovered mantle xenolith from Miocene alkali basalts dated to 18.7 Ma (Kieffer *et al.* 2004) from the uppermost series on the western flank of Simien shield volcano, Ethiopia (13°11’27” N, 37°58’32” E, near Debark town, Fig. 1). Spinel lherzolites represent the only ultramafic lithology recovered from the area. Here we document thin-section observations and electron probe analyses of major phases, and trace element data for clinopyroxene from these samples. These outline data yield insight into mantle processes beneath Ethiopia during Miocene times, and will serve as background for further detailed geochemical and isotopic investigations. The xenoliths have apparently experienced interaction with the host lavas, and sufficient care is used in the paper to distinguish the primary chemical features reflecting mantle processes and compositional modifications induced in xenoliths by incorporation in the host lavas.

As yet, there are few well-studied xenolith localities in East Africa (especially in the northern sectors of the rift, such as Ethiopia). Xenolith suites are crucial to obtaining first-hand information on mantle processes in this rift and to interpret indirectly the geochemistry of mantle-derived, xenolith-free lavas. The paper will contribute to the understanding of the evolution and composition of the lithospheric mantle beneath the East African Rift System.

2. Simien shield volcano

The eroded Simien shield volcano forms the highest point in Ethiopia (4533 m peak of Ras Dashan). The shield volcano overlies 1600 m of flood basalt and interlayered felsic rocks (Pik *et al.* 1998; Ayalew & Yirgu, 2003; Kieffer *et al.* 2004). $^{40}Ar/^{39}Ar$ ages and palaeomagnetic constraints (Hofmann *et al.* 1997; Rochette *et al.* 1998; Kieffer *et al.* 2004) show that the entire volcanic sequence, including the shield volcano, erupted in less than 1 million years, about 30 Ma ago. The flood basalts and most of the shield volcano, except for a thin veneer of alkali basalt (18.7 Ma), are composed of tholeiitic basalts.

3. Petrography

Ultramafic nodules entrained in alkali basalts from the Simien shield volcano are sub-angular to rounded in shape and reach up to 5 cm in length. They contain abundant olivine (40–75 vol. %), with orthopyroxene (10 vol. %), green clinopyroxene (15–30 vol. %) and

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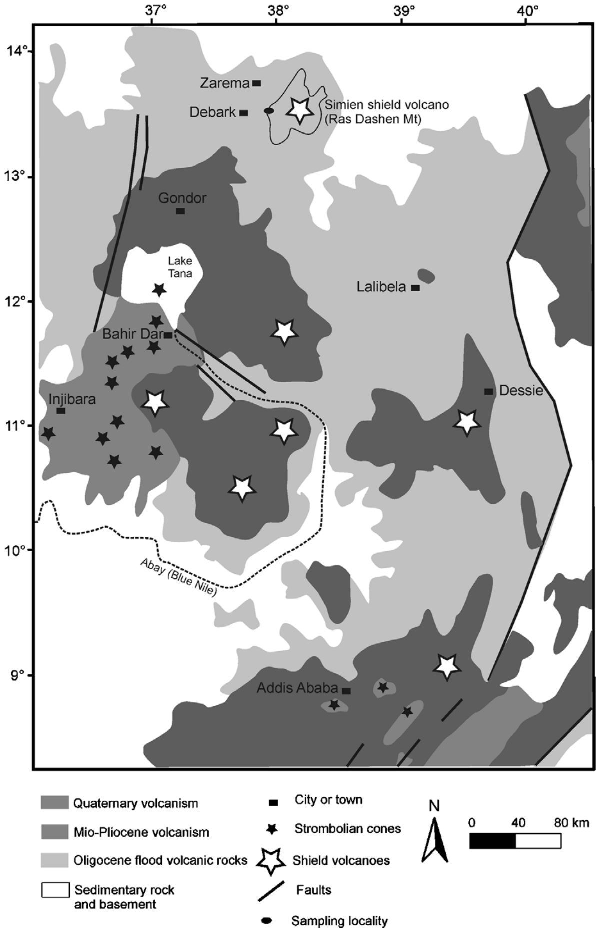

Figure 1. Geological map of the northern part of the Ethiopian plateau showing the extent and distribution of shield volcanoes and underlying flood basalts (modified from Pik *et al.* 1998; Ayalew *et al.* 2002); locality of the studied peridotite xenoliths denoted by small circle.

brown spinel (5–20 vol. %), and hence they are spinel lherzolite. The xenoliths are relatively coarse grained; crystals are on average 2 to 3 mm in size. The Simien xenoliths show porphyroclastic texture, comprising large (3–5 mm), fractured and deformed porphyroblasts of mostly olivine surrounded by small grains (< 1 mm). The small grains (neoblasts) consist of approximately polygonal crystals with rectilinear or slightly curved grain boundaries displaying numerous triple-grain junctions. The porphyroclastic texture is considered to reflect dynamic recrystallization while the presence of neoblasts indicates that a second stage of recrystallization need not have taken place, at high temperature.

3.a. Olivine

Olivine is the most important abundant mineral in the Simien xenoliths. Two types of olivine are clearly visible, one with large (up to 5 mm), deformed (presenting very clear kink bands or mechanical twinning) anhedral or locally euhedral crystals (porphyroblasts) and the other with very small (0.5–1 mm), generally euhedral crystals (neoblasts) with little or no deformation, often forming triple points with adjacent minerals.

3.b. Pyroxene

Pyroxene tends to have a tabular habit and displays a weak preferential orientation. Both ortho- and clinopyroxene are found. Orthopyroxene occurs as strained (mechanically twinned) porphyroblasts or neoblasts. Clinopyroxene also occurs as porphyroblasts and neoblasts, and shows exsolution features. Both types of pyroxene show reaction coronae enriched in small olivine granules at the contact with the host-lava. Clinopyroxenes show textural evidence for partial melting, notably along fractures. Many processes may explain such features, including metasomatism-induced melting, flux melting by fluids and decompression melting during xenolith transport to the surface (see, e.g. Ionov, Hofmann & Shimizu, 1994; Shaw, Heidelbach & Dingwell, 2006; Kaeser, Kalt & Pettke, 2007). Alternatively, such reaction textures may form in the mantle prior to entrainment of the xenoliths (Ionov, Hofmann & Shimizu, 1994; Demény *et al.* 2004; Ionov *et al.* 2006; Bali *et al.* 2008; Kaeser, Kalt & Pettke, 2007).

3.c. Spinel

Spinels are brown in colour and show opaque reaction rims at the contact with the host lava. They are generally anhedral and preferentially situated along grain joints in which the spinels often occur at the triple junctions between grains in the lherzolites. Spinels often contain inclusions of pyroxene. No spinel–pyroxene symplectite textures are observed. The presence of corona textures developed around pyroxene and spinels suggests that the spinel lherzolites were not in equilibrium with the host lava.

4. Mineral chemistry

Mineral compositions were determined by electron probe microanalysis at Lausanne University, on a Cameca SX 50 instrument using analytical conditions including accelerating voltage of 15 kV and sample currents of 30.2 nA. Summary results are presented in Tables 1–3.

4.a. Olivine

Olivine porphyroblasts (Table 1) have uniform, unzoned compositions around $Fo_{89.6}$, characteristic of mantle olivine compositions ($Fo_{86–90}$). Olivine neoblasts are more Fe-rich (Fo_{83}) and show compositional variation from core to rim (Fo_{83} v. Fo_{77} in the rim). Anhedral olivine megacrysts (which are often rounded, fractured and crossed by alteration veins), dispersed in the alkaline basaltic lava, display compositional heterogeneity within the same crystal, with magnesian

Table 1. Microprobe analyses of olivine crystals from Simien spinel lherzolites

	Olivine porphyroblast						Olivine neoblast			Olivine xenocryst				
	Core	Rim	Rim	Core	Rim	Rim	Core	Rim	Rim	Rim	Core	Rim	Core	Rim
SiO_2	40.91	40.66	40.53	40.82	40.76	40.64	39.56	39.07	38.21	38.51	40.8	39.67	39.45	38.49
FeO	10.02	10.06	10.08	10.08	10.15	10.24	16.46	19.43	23.12	22.08	10.3	17.36	18.48	21.62
MnO	0.18	0.17	0.19	0.16	0.17	0.15	0.28	0.37	0.46	0.43	0.17	0.26	0.27	0.37
MgO	49.05	49.14	49.28	49.03	48.99	49.11	43.9	41.22	38.54	38.93	48.89	42.69	42.95	40.26
CaO	0.03	0.07	0.09	0.07	0.07	0.05	0.06	0.29	0.31	0.4	0.09	0.21	0.16	0.28
Total	100.2	100.1	100.2	100.2	100.1	100.2	100.3	100.4	100.6	100.4	100.3	100.2	101.3	101.0
% Fo	89.72	89.69	89.7	89.66	89.58	89.53	82.62	79.09	74.82	75.85	89.43	81.42	80.55	76.84

Mg no. = 100 ∗ Mg/(Mg + Fe^{2+}). All analyses are from one xenolith.

Table 2. Microprobe analyses of pyroxene crystals from Simien lherzolites

	Orthopyroxene						Clinopyroxenes				
	Core	Rim	Rim	Rim	Core	Rim	Core	Rim	Core	Rim	Melt
SiO_2	55.5	55.3	55.7	54.8	55.3	55.3	51.03	51.72	51.87	52.34	51.7
TiO_2	0.11	0.15	0.12	0.12	0.15	0.16	0.69	0.74	0.74	0.6	0.65
Al_2O_3	3.88	3.99	3.89	3.87	3.76	3.97	7.53	7.43	7.15	4.32	5.68
FeO	6.79	6.83	6.74	6.92	6.84	6.94	2.71	2.63	2.72	3.7	2.64
MnO	0.13	0.18	0.16	0.14	0.2	0.17	0.07	0.12	0.06	0.13	0.1
MgO	33.3	33.1	32.8	33.1	33.4	32.9	14.18	13.85	14.31	16.64	15.55
CaO	0.47	0.43	0.69	0.47	0.38	0.42	19.72	20.4	20.4	21.13	21.87
Na_2O	0.11	0.12	0.15	0.13	0.09	0.11	2.19	2.22	2.03	0.6	1
Cr_2O_3	0.2	0.23	0.22	0.3	0.26	0.23	0.8	0.77	0.75	0.76	0.84
Total	101	100	101	99.9	100	100	98.92	99.88	100	100.2	100
%Wo	0.91	0.84	1.33	0.91	0.73	0.82	48.94	50.07	49.03	44.9	48.5
%En	88.9	88.9	88.5	88.7	89	88.7	48.97	47.29	47.87	49.19	48
%Fs	10.2	10.3	10.2	10.4	10.2	10.5	2.09	2.64	3.1	5.92	3.5

All analyses are of porphyroclasts from one xenolith.

Table 3. Microprobe analyses of spinel crystals from Simien lherzolites

	Core	Core	Core	Rim	Rim	Core	Rim	$Rim_{reaction}$
Al_2O_3	55.2	55	55.1	55.6	55.3	58.8	57.3	8.21
FeO_t	11.1	11	11.1	10.8	11.1	11	12.6	61.8
MnO	0.06	0.08	0.12	0.14	0.12	0.14	0.14	0.57
MgO	20.5	20.4	20.5	20.6	20.6	20.9	20.5	5.08
TiO_2	0.09	0.09	0.15	0.1	0.09	0.17	0.18	15.7
Cr_2O_3	11.7	11.9	11.5	11.4	11.6	7.78	7.67	7.57
NiO	0.4	0.38	0.4	0.41	0.34	0.47	0.45	0.18
Total	99.2	98.8	98.9	99.1	99.2	99.3	98.8	99.1
FeO	8.66	8.77	8.55	8.55	8.55	8.56	8.91	38.4
Fe_2O_3	2.48	2.21	2.51	2.29	2.51	2.4	3.66	23.5
Mg no.	80.9	80.5	81	81.1	81.2	81.3	80.3	19.1
Cr no.	12.5	12.7	12.3	12.1	12.4	8.17	8.22	38.2

Mg no. = 100 ∗ Mg/(Mg + Fe^{2+}), Cr no. = 100 ∗ Cr/(Cr + Al).
All analyses are from porphyroclasts from one xenolith.

cores (Fo_{89}) and rim compositions similar to those of the olivine neoblasts (Fo_{77}).

The compositional similarity of olivine megacrysts and xenoliths suggests that individual megacrysts result from disaggregation of spinel lherzolite xenoliths during the ascent of the magma. Disaggregation of the xenoliths is likely accompanied by the partial diffusive re-equilibration of olivine.

4.b. Pyroxene

Pyroxene compositions are reported in Table 2. Clinopyroxenes are homogeneous diopsides with low Cr_2O_5 (0.75–0.80 wt %) and high TiO_2 (0.69–0.74 wt %), Al_2O_3 (7.15–7.53 wt %) and Na_2O (2.03–2.22 wt %) contents. Clinopyroxene compositions in the melt zone are characterized by low Al_2O_3 and Na_2O, and high CaO and MgO contents, compatible with an event of fusion. At the contact with the host lava, clinopyroxene tends towards augite composition. Orthopyroxene compositions fall in the field of enstatite.

4.c. Spinel

Spinels are compositionally homogeneous (Table 3) and are highly aluminous (55–59 wt %). They occupy the field of fertile lherzolites (not shown) with Cr no.

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Table 4. Trace element concentrations (ppm) in clinopyroxene for Simien spinel lherzolite xenoliths

Cs	Rb	Ba	Th	U	Nb	Pb	Sr	Zr	Y			
0.01	0.18	8.68	0.02	0.01	0.17	0.34	12.7	5.16	4.18			
La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu
0.35	0.66	0.12	0.65	0.28	0.12	0.47	0.09	0.63	0.15	0.42	0.38	0.06

The clinopyroxene was extracted, dissolved and analysed by ICP-MS at Joseph Fourier University in Grenoble, France using the analytical methods outlined in Barrat *et al.* (1996). Grains were acid-leached before analysis, in order to remove reaction rims and grain boundary components. Results are from single grain.

< 0.2 within the olivine–spinel mantle array of Arai (1994). The spinels with the reaction rim are depleted in Al_2O_3, Cr_2O_5 and MgO, and enriched in FeO_t and TiO_2 with respect to the core.

5. Trace elements in clinopyroxene

The concentrations of selected trace elements in a single clinopyroxene mineral separate were determined by solution ICP-MS (Table 4). Chondrite-normalized rare earth element (REE) patterns for Simien clinopyroxene, compared with other xenolith occurrences within or at the border of the Ethiopian plateau, namely Mega-Sidamo in southern Ethiopia (Bedini *et al.* 1997; Bedini & Bodinier, 1999), Marsabit in northern Kenya (Kaeser, Kalt & Pettke, 2006, 2007) and from Yemen (Chazot, Menzies & Harte, 1996), are illustrated in Figure 2a. This allows us to constrain further the nature of the lithosphere underneath the East African Rift System.

The Simien clinopyroxenes show depletion in light-REE (Ce/Yb_N = 0.38), flat heavy-REE abundances (Dy/Yb_N = 1.04) and a positive La anomaly ($La/Ce_N = 1.35$). These patterns are interpreted to reflect light-REE depletion by partial melting and subsequent La-enrichment by metasomatic event. The flat HREE pattern suggests no dominant control from an HREE-fractionating phase such as garnet. The Simien peridotites have low contents of REE, especially light REE, compared to the other xenoliths from the region. Peridotite xenoliths from Maga and Marsabit show similar patterns probably as a result of their close geographic location. Peridotite xenoliths from Yemen display much enriched REE patterns. This comparison clearly demonstrates that clinopyroxene from the spinel peridotites from East African Rift System exhibit extremely heterogeneous REE abundances.

Plots of primitive mantle-normalized incompatible trace element variation (Fig. 2b) show an irregular pattern for the more incompatible and mobile elements, with many peaks (with distinctive peaks at Ba and Pb and to a lesser extent at Cs, U and La) and valleys (with troughs at Rb, Th, Nb, Ce and Zr). Ba contents are quite high for mantle-derived clinopyroxene. In such unmetasomatized xenoliths (that is, light-REE-depleted) they should be much lower (e.g. < 1 ppm; see Bedini & Bodinier, 1999; Kaeser, Kalt & Pettke, 2006). This could be related to fluid inclusions or to reaction rims. The same accounts for the Pb and Cs contents.

Comparison of incompatible trace element variation among xenoliths from the region reveals that the Simien peridotites are depleted in incompatible elements. Peridotite xenoliths from Maga and Marsabit exhibit identical patterns in the less incompatible elements, but the Marsabit xenolith shows depletion in the more incompatible elements (e.g. Cs, Rb and Ba), probably as a result of their close geographic location. Peridotite xenoliths from Yemen display extremely enriched patterns.

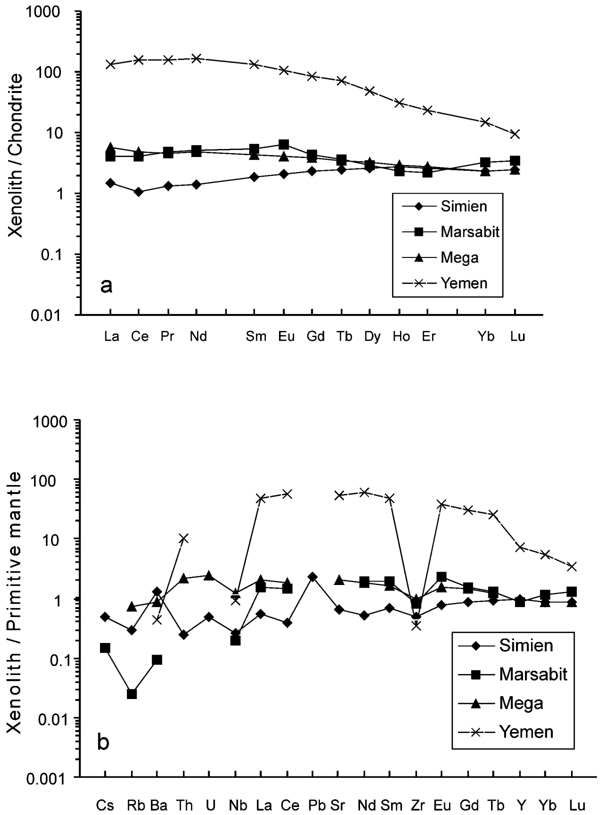

Figure 2. Incompatible trace element variations of Simien peridotites compared with other xenoliths from the East African Rift System (Mega-Sidamo in southern Ethiopia: Bedini *et al.* 1997; Bedini & Bodinier, 1999; Marsabit in northern Kenya: Kaeser, Kalt & Pettke, 2006, 2007; from Yemen: Chazot, Menzies & Harte, 1996). (a) Chondrite-normalized (McDonough & Sun, 1995) rare earth element (REE) patterns. Note the Simien peridotites have low abundances of REE. (b) Primitive mantle-normalized (McDonough & Sun, 1995) incompatible trace element abundances, showing spiked patterns. Trace element data are from clinopyroxene of spinel lherzolites.

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6. Discussion

The Simien mantle xenoliths belong to the spinel lherzolite facies and thus come from depths between 30 and 80 km. The absence of pyroxene–spinel intergrowths, along with the flat heavy-REE patterns and the absence of a positive Zr anomaly in clinopyroxene, argue against the lherzolites having originated in the garnet stability field (Shimizu, 1975). This leads us to interpret the lherzolite xenoliths as samples of the regional lithospheric mantle beneath the western Ethiopian plateau derived within the stability field of spinel.

6.a. Melt–rock interaction

Few spinel rim and core analyses show relatively Ti-rich composition (0.15–0.18 wt % and 15.7 wt % in reaction rim). TiO_2 contents in spinel lie generally < 0.1 wt % in normal mantle peridotite. High TiO_2 in spinel commonly indicates reaction of peridotite spinel with percolating basaltic liquids (e.g. Dick & Bullen, 1984; Barnes & Roeder, 2001). This may indicate that the primary spinel composition has been modified, possibly during melt–rock reaction processes (that is, formation of the reaction rims or xenolith–host magma interaction). Further, an important role of melt–rock reaction in these samples is also indicated by the Fe- and Mn-rich compositions of olivine neoblasts. Such compositions must have a relationship to some sort of 'basaltic' liquids. Therefore, the major element compositions of olivine and spinel possibly reflect the result of late-stage melt–rock reaction (perhaps during xenolith transport in the host magma).

6.b. Fertile mantle composition

The main question is whether the samples experienced hydrous metasomatism. The core compositions of large spinel grains of the Simien peridotites are characterized by a low Cr no. < 0.13; this lies well in the range of fertile peridotite with Cr no. < 0.2 in the subcontinental lithosphere (Barnes & Roeder, 2001). Furthermore, the lack of secondary Al-rich minerals such as amphiboles (e.g. pargasite) and mica (e.g. phlogopite) strongly argues that the Simien spinel peridotites were not metasomatized by melt or fluid enriched in incompatible elements. Therefore, trace element patterns of clinopyroxene may still show the geochemical characteristics of the rock prior to melt–rock reactions. On the basis of spinel composition, we conclude that the Simien spinel peridotite is unmetasomatized, fertile xenolith of subcontinental lithosphere origin.

7. Conclusions

Based on the lack of hydrous phases, high clinopyroxene mode (< 30 vol. %), low TiO_2 in spinel (with $TiO_2 < 0.1$ wt %) and light-REE depeletion, we conclude that the Simien spinel lherzolites represent unmetasomatized, fertile peridotite from the subcontinental lithosphere. The presented data illustrate that the Simien spinel lherzolites have extremely low contents of trace elements compared to other xenolith occurrences within or at the border of the Ethiopian plateau in the East African Rift System.

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