Petrological evolution of the European lithospheric mantle: introduction

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This volume, together with its companion volume in *Journal of Petrology* (Volume 50, No. 7), is the result of the EMAW (European MAntle Workshop: Petrological evolution of the European Lithospheric Mantle: from Archean to Present Day) held in Ferrara from 29 to 31 August 2007. The meeting was organized by M. Coltorti (Earth Sciences Department, University of Ferrara), H. Downes (Birkbeck College, London University), M. Grégoire (Observatoire Midi Pyrénées, CNRS, Toulouse) and S. Y. O'Reilly (ARC National Key Centre, GEMOC, Macquarie University), and was sponsored by the University of Ferrara, the Istituto Universitario di Studi Superiori (IUSS) of the same university, the Gruppo Nazionale di Petrografia (GNP) and the Federazione Italiana di Scienze della Terra (FIST). The organizers would like to express their deep satisfaction with the success of the meeting and the enthusiasm it provoked, as well as a sincere thanks to all participants for their contributions. Almost 100 researchers participated in the meeting, coming from most European countries, China, Japan and Australia.

The meeting was an attempt to homogenize the different databases and models that have been developed from many years of study on European mantle xenoliths, peridotite massifs, ophiolites and mafic magmas spanning in age from Archaen to Recent times. Xenoliths from Europe are mostly entrained in Cenozoic mafic magmas, and the imprints of older events may be difficult to recognize in these materials. On the other hand, ophiolites and peridotite massifs record events confined to the Mesozoic history of the upper mantle, while the mafic magmas carrying the mantle xenoliths were generated beneath terrains that have been involved in different orogenic processes. The last major geological process was the Caledonian orogeny on Spitsbergen, the Hercynian orogeny at Calatrava (Spain) and the French Massif Central, and the Alpine *sensu lato* geological cycle for the Hungarian and Serbian localities.

The EMAW brought together different approaches in an attempt to integrate the findings of geophysical and geochemical investigations of the European lithospheric mantle. Most of the broad studies have already been published in *Journal of Petrology*, while those presented here provide particular emphasis on regional petrological studies of the European lithospheric mantle, from Spain to the Pannonian Basin, from Corsica and Serbia as far north as Svalbard. Six contributions are based on studies of mantle xenoliths, while the remaining four deal with ophiolitic and peridotitic complexes. A further article provides an update on the textural classification of mantle rocks initially proposed by Mercier & Nicolas (1975), using a computer-aided approach.

From subcontinental to suboceanic lithospheric mantle

The two papers by **Piccardo & Guarnieri** and **Piccardo** deal with two sectors of SCLM (subcontinental lithospheric mantle) that outcrop in ultramafic complexes in northern Corsica (Mt Maggiore Massif) and in NW Italy (Lanzo massif). These are believed to represent SCLM that was exhumed and exposed on the sea floor during the Late Jurassic opening of the Ligurian–Piedmont Basin, the westernmost branch of the Jurassic Tethys, between the Europe and Adria (Africa) margins. The peridotite massifs record composite histories of subsolidus

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exhumation and melt–peridotite interaction, depending on their location with respect to the axial zone of the extensional system, where MORB (mid-ocean ridge basalt) melts were formed by decompression melting in the upwelling asthenosphere and percolated the overlying lithospheric mantle by porous flow. Peridotites exposed at more marginal settings (i.e. the North Lanzo massif) escaped significant melt–rock interaction, contain widespread Sp(Gnt)-pyroxenites and preserve significant relicts of the lithospheric evolution (lithospheric Sp lherzolites). Peridotites exposed at more internal settings (i.e. South Lanzo and Mt Maggiore massifs) show extreme compositional heterogeneity induced by MORB-type melt–peridotite interaction (reactive Sp peridotites, impregnated Plg peridotites, replacive Sp harzburgites and dunites). Piccardo & Guarnieri show that the presence of decametric–hectometric remnants of pyroxenite-bearing fertile lherzolites in the melt-modified peridotites indicates that the melt–peridotite reaction processes affected SCLM protoliths and not refractory residua of the asthenospheric mantle after oceanic partial melting.

The Lanzo massif exposes, in particular, a transect from more marginal, pyroxenite-bearing lithospheric Sp lherzolites (the North Lanzo massif) to more distal strongly melt-modified, extremely heterogeneous peridotites (the South Lanzo massif). Piccardo proposes that the marginal North Lanzo peridotites were exhumed from shallower lithospheric levels and escaped the significant melt–rock interaction that affected the more internal South Lanzo peridotites which were exhumed from deeper lithospheric levels. Field relationships in the more distal, strongly heterogeneous peridotites reveal the evolution of progressive exhumation and melt–rock interaction events in these peridotites, which were percolated during continental extension and stretching. Inception of asthenospheric melting during adiabatic upwelling caused porous-flow diffuse percolation of pyroxene-undersaturated MORB-type melts that reacted (dissolving mantle pyroxenes and precipitating olivine) with the percolated SCLM under Sp peridotite-facies conditions and transformed it to depleted reactive Sp peridotites. At shallower depth (Plg-facies conditions), under increasing conductive heat loss, the percolating MORB-type melts were silica-saturated, reacted with the percolated peridotite (dissolving olivine and clinopyroxene/forming orthopyroxene (+Plg)) and underwent interstitial crystallization, enriching the peridotites in plagioclase and gabbroic microgranular aggregates. Melt impregnation and interstitial crystallization clogged the melt pathways and further melt migration was focused into structural and compositional discontinuities, giving rise to replacive olivine-rich, harzburgite and dunite channels. The replacive channels were locally (e.g. at South Lanzo) exploited for upwards migration of aggregated MORB melts and sporadic alkaline melts. Alkaline melts in Lanzo post-date the onset of MORB magmatism and mark an abrupt compositional change in the melting source: a mechanism of delamination of sectors of the lower-mantle lithosphere is proposed by Piccardo to explain sinking of Gnt-pyroxenite-bearing lithospheric mantle into the upwelling mantle asthenosphere. Partial melting of these pyroxenite-bearing sections under the appropriate pressure conditions could have formed the alkaline melts, which migrated upwards and percolated through the extending lithospheric mantle after the MORB percolation and impregnation events.

Although the sizes of mantle xenoliths limit structural studies of the reaction and refertilization processes like those described above, **Grégoire *et al.*** propose a similar model for composite xenoliths from Spitsbergen Island (Svalbard archipelago). These xenoliths have websterite veins cutting lherzolite protoliths. Unusually, major element analyses of minerals and trace element analyses of clinopyroxene are similar in both lithotypes. Grégoire *et al.* propose a tholeiitic (MORB-like) metasomatism that, taking also into account the higher melt/rock ratio involved, resembles the refertilization process invoked by Piccardo in this volume for Lanzo. The LREE-depleted clinopyroxenes of the composite websterite–lherzolite are comparable to those that are often interpreted as residues of mantle melting (Ionov *et al.* 2002). However, in this case the presence of websterite veins, which could not survive the homogenization caused by a melting process, requires a different mechanism. This LREE-depleted pattern could be caused by MORB-like tholeiitic melts circulating within the upper-mantle peridotites. As extensive tholeiitic (MORB-like) magma percolation would be expected during extension and rifting, it is highly probable that the LREE-depleted patterns usually found in Cpx could simply be the result of this metasomatic–refertilization process. The influx of relatively large volumes of magma would also change the thermal and rheological properties of the SCLM, strongly constraining the geometry and composition of the lithosphere during the opening of the basin. The finding of portions of SCLM left stranded within clearly oceanic settings (Delpech 2004; Bonadiman *et al.* 2006; Coltorti *et al.* 2008, 2010; O'Reilly *et al.* 2009) are consistent with this scenario.

Eclogites and pyroxenites in the SCLM

Garnet- and spinel-bearing pyroxenites are relatively abundant in the lithospheric mantle of both the European and Adriatic plates (Montanini *et al.*

2006; Piccardo & Vissers 2007; Piccardo *et al.* 2007). A rare case of graphite-bearing garnet clinopyroxenite occurs in an ultramafic complex in the External Ligurides. **Montanini *et al.*** suggest that this body equilibrates within the SCLM at approximately 2.8 GPa and 1100 °C. Carbon phases (graphite or diamond) typically occur in cratonic SCLM (Pearson *et al.* 1994; Haggerty 1995), and this rare occurrence extends the debate on the nature of C within the mantle, that is, deep provenance v. crustal recycling. Graphite-bearing mantle rocks have been reported in the orogenic peridotite massifs of Ronda (Davies *et al.* 1993) and Beni Bousera (Pearson *et al.* 1993). Carbon in the pyroxenites of the External Ligurides has a typical mantle isotopic signature (-4.5 ± 0.5 ‰: Thomassot *et al.* 2007) and the associated sulphide assemblage (Ni-free pyrrhotite, pentlandite, Cu–Fe sulphides) indicates exsolution from a high-temperature monosulphide solution (MSS). The crystallization of elemental carbon from a silicate melt is not considered a suitable mechanism owing to the low solubility of C in silicate melts (Bulanova 1995). Recent experimental results on graphite/diamond precipitation from alkaline carbonate melts (e.g. Arima *et al.* 2002; Palyanov *et al.* 2007) do not seem appropriate for the system under investigation. Thus, on the basis of the graphite–sulphide association, the authors suggest that C was reduced by the interaction of CO_2-rich fluids and S-rich immiscible melt (see also Haggerty 1986; Bulanova 1995; Bulanova *et al.* 1998; Luque *et al.* 1998).

The Cenozoic Calatrava volcanic field comprises more than 200 volcanic centres in an area of about 5500 km^2 (Ancochea & Nixon 1987). Strombolian cones, tuff rings and maars transport abundant mantle xenoliths to the surface, providing a splendid opportunity for studying the lithospheric mantle beneath central Spain. Lherzolites are the most abundant lithotypes; wehrlites, websterites and dunites are very subordinate (**Bianchini *et al.*** and **Villaseca *et al.***). Some of these lherzolites are anomalously rich in Fe (and Ti), which Bianchini *et al.* attribute to Fe–(Ti)-rich metasomatizing agents, derived from eclogite material present beneath the lithospheric mantle of central Spain. The HIMU signature of the Cpx appears to be the result of long-term recycling of oceanic basalts/gabbros (or their eclogitic equivalent) via ancient subduction. According to the authors, the recent subduction along the Betic collisional belt would have remobilized these old relicts from the lower–upper mantle transition zone (410–660 km). Fe–Ti rich melts characterized by a HIMU isotopic signature would be generated, and infiltrate and metasomatize the shallower lithospheric mantle. Villaseca *et al.* focus their study on Mg-('normal') lherzolites and wehrlites, some of them bearing amphibole and phlogopite. Based on the chemistry of minerals and glasses, they envisage at least two different metasomatic agents: the first is a subduction-related one, which in this case refers to the Tertiary subduction; the second one, just before xenolith entrainment, is related to undersaturated silicate alkaline melt. The latter may also be responsible for the origin of the Fe-rich wehrlite, suggesting a bridge toward the Fe-lherzolite enrichment model of Bianchini *et al.*

Fingerprints of subduction and intraplate metasomatism

The paper of **Yoshikawa *et al.*** attempts to precisely constrain the temperature and depth of derivation of xenoliths from the Massif Central (France), using Raman-based spectroscopy geobarometry. On the basis of mineral composition (both major and trace element) they also identify two different metasomatizing agents: a carbonatitic subduction-related one that affected the shallower, northern part of the lithosphere; and an asthenospheric melt that modified its deeper southern portion. The silicate-rich carbonatite melt may be derived from carbonate sediments brought into the lithospheric mantle of the French Massif Central via subduction. The age of this subduction is questionable, but geological reconstruction (Shaw *et al.* 1993; Pin & Paquette 1997), Hf model ages (Wittig *et al.* 2006) and a DM (depleted mantle) model age determined by Sr–Nd on Cpx favour a Hercynian event.

Dobosi *et al.* analysed clinopyroxenes and orthopyroxenes in anhydrous mantle peridotite xenoliths from the western part of the Pannonian Basin. HREE contents of the clinopyroxenes suggest that most of the xenoliths experienced less than 15% partial melting. The lowest degrees of melting occur in the LREE-depleted xenoliths, and the highest degree in the LREE-enriched xenoliths, although the refertilization caused by the interaction of large volumes of magma with the lithosphere (Piccardo, Piccardo & Guarnieri and Grégoire *et al.* in this volume) has to be kept in mind. The authors reconstruct the composition of the asthenosphere-derived metasomatizing agents and suggest that they are similar to alkali lamprophyres that were emplaced in the area during Cretaceous time. They also exclude any evidence for subduction-related melt, except for a family of Cpx with U-shaped REE patterns. These findings appear to contrast with the hypothesis put forward by Coltorti *et al.* (2007) to explain amphibole-bearing mantle xenoliths from Kapfenstein (Styria Basin), where a subduction-related, adakite-like metasomatic agent was inferred. It also suggests that the western Pannonian lithospheric mantle experienced repeated intraplate alkaline metasomatism from Cretaceous to Quaternary times despite the Neogene calc-alkaline (*sensu lato*) magmatism that has been described in the area (Seghedi *et al.* 2004, 2005). Particular attention in this paper is also given to textural features, which, according to Downes *et al.* (1992), are also correlated with enrichment style and extent.

Mantle textures revisited

Tabor *et al.* focus on the microstructures of mantle rocks, and propose a method for quantitative characterization of grain size by means of optical scanning and computer measurement of individual grain areas. They apply this technique to spinel peridotite xenoliths from the Massif Central and Eifel regions, and note that: (i) the three main groups of textures, that is, protogranular, porphyroclastic and equigranular, proposed by Mercier & Nicolas (1975) form a continuous series rather than discrete groups; and (ii) protogranular samples have standard deviations higher than porphyroclastic samples. Thus, large crystals embedded in a finer grain matrix do not uniquely characterize the porphyroclastic microstructure. The study of Tabor *et al.* is based only on peridotite xenoliths without obvious modal metasomatism, and further measurements on deeper (garnet-bearing) samples and xenoliths from different tectonic settings are needed to fully understand the geological and petrological meaning of these results.

Relationships between metasomatim and magmatism

Cvetković *et al.* discuss the origin of enrichment in East Serbian mantle xenoliths, reversing the concept that metasomatism could be related to magmatism as proposed by many authors, at least for Na-alkaline products (Wulff-Pedersen *et al.* 1999; Coltorti *et al.* 2004). According to these authors, metasomatism represents the infiltration of a small volume of magma rising up to the surface, thus metasomatism would be successive to magmatism. Most of the Serbian mantle xenoliths are harzburgites with abundant both modal and cryptic metasomatic features, while lherzolites, which are devoid of secondary modal enrichment, appear to have Al_2O_3, Cr_2O_3 and FeO content higher than undepleted peridotites. The petrological study of these mantle xenoliths, together with the inversion modelling applied on the most uniform and least contaminated basanite from the area, suggests that the enrichment in the mantle source of the basanite is similar to that observed in the metasomatised harzburgite. The model proposed by Cvetković *et al.* involves the percolation of CO_2- and H_2O-rich fluids that strongly metasomatized the lithosphere prior to it being uplifted and heated by asthenospheric upwelling. In this way metasomatism represents a precursor to alkaline magmatism.

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