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Shallow Mantle Composition and Dynamics: Fifth International Orogenic Lherzolite Conference

Foreword

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The First International Orogenic Lherzolite Conference was held in Montpellier, France, in 1990 (Menzies *et al.*, 1991). Subsequent Orogenic Lherzolite Conferences were held in Granada, Spain in 1995, Pavia, Italy in 1999 and Samani, Japan in 2002. A vital aspect of all these meetings was the opportunity to visit nearby exposures of mantle peridotites: to date, participants have visited Lherz in France; Baldissero, Balmuccia, Erro Tobio, Finero, Lanzo and Liguria in Italy; Ronda in Spain; Beni Bousera in Morocco; and Horoman in Hokkaido, Japan. Peer-reviewed papers from all four conferences were published in the *Journal of Petrology* in 1991, 2001 and 2004 and, in one instance, in *Chemical Geology* in 1996.

The Fifth Lherzolite Conference was held in Shasta City, California in September 2008. The conference was sponsored as a Chapman Conference by the American Geophysical Union (AGU), which also provided local logistical assistance. Funding for participants was provided by the AGU, US NSF Ridge Program, the NSF Earth Sciences Division, the US Science Support Program of the Consortium for Ocean Leadership, the Royal Society UK and the Lithosphere–Asthenosphere Interactions task force of the International Lithosphere Program. Present, from 14 countries, were 108 attendees including 36 students and 11 postdoctoral researchers. Sixty-six oral presentations and 67 posters were presented during the 5 day meeting. As is the tradition, field trips to classic mantle peridotite localities were incorporated into the program, including a pre-meeting trip to the Josephine peridotite led by Peter Kelemen, Henry Dick, and Greg Hirth for about 50 people; a mid-week field trip for all participants, led by Tim Grove and Christy Till; and a 2 day, post-meeting trip to the Trinity peridotite for about 50 people, led by Peter Kelemen, Francoise Boudier, and Kolya Stremmel.

The Fifth Lherzolite Conference covered a broader range of topics than previous meetings, including carbon sequestration in the mantle and low-temperature hydrothermal alteration. Underlying the presentations was the realization that previous distinctions between ‘orogenic’ peridotites (e.g. Lanzo Massif, Italy), and ‘ophiolitic’ peridotites (e.g. Troodos, Cyprus; Josephine, Oregon) and ‘abyssal’ peridotites from ocean ridges were in need of revision. It now appears that a continuum exists from sub-continental to oceanic mantle exposed in some complexes (e.g. Lanzo; Bodinier *et al.*, 1991; Piccardo *et al.*, 2007; Müntener *et al.*, this issue), and that much ocean

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*Corresponding author. E-mail: m.menzies@es.rhul.ac.uk 'crust' consists of mantle peridotite exposed on the seafloor without an overlying carapace of basaltic crust (Dick *et al.*, 2003; Michael *et al.*, 2003; Cannat *et al.*, 2006; Escartin *et al.*, 2008; Dick *et al.*, this issue). This has made the study of mantle massifs in different tectonic settings a far more unified field than in the past, with direct relevance to understanding the formation of non-volcanic rifted continental margins and the ocean floor.

The Fifth meeting demonstrated major advances in our understanding of the origin, evolution and relationships of orogenic lherzolites, ophiolite mantle massifs and abyssal peridotites as reflected in the papers in this thematic volume. Research papers are arranged in four themes, as follows.

(1) Experimental and natural peridotite studies (Josephine and Twin Sisters, USA; Lanzo, Italy; Mohelno, Czech Republic) dealing with the deformation of mantle rocks, temperature–fabric relationships and melt migration.
(2) The interaction between melts or Si-rich fluids and mantle peridotites and refertilization processes based on experimental work, studies of ophiolitic and orogenic peridotites (Josephine, USA; Oman; Malenco–Platta–Totalp, Switzerland), and basalt- and andesite-hosted spinel-facies mantle xenoliths (Tallante, Spain; Avacha, Kamchatka).
(3) High-temperature metasomatism to low-temperature serpentinization processes in mid-ocean ridges (Atlantis II Fracture Zone and Kane Megamullion core complex), exhumed oceanic peridotites (MacQuarie Island) and ophiolitic peridotites (Oman).
(4) The effects of melt migration on the dating of eclogites from the Kaapvaal craton and the dating of zircons in composite spinel-facies xenoliths from the North China craton.

PERIDOTITE DEFORMATION, MELT MIGRATION, RHEOLOGY AND TEMPERATURE

Experimental constraints

The analysis of natural systems and laboratory experiments provide complementary information on the interplay between melts and deformation observed in natural systems, but the causal link can be further constrained in laboratory experiments. Does the presence of melt weaken the rock and thus facilitate deformation? Does deformation increase permeability and favor focused melt migration High-strain torsion experiments performed by **Kohlstedt *et al.*** on a series of samples composed of anorthite plus <1 to 12% melt demonstrate that stress-driven melt segregation helps to localize strain into shear zones, as seen in ophiolites and orogenic peridotite massifs. Networks of melt-rich, low-viscosity channels that allow for rapid extraction of melt from the mantle are produced during deformation because shear zones reduce the effective viscosity of the asthenosphere near the base of the lithosphere. The lithosphere–asthenosphere boundary may then be defined by melt segregating into melt-rich bands, which weakens the asthenosphere, and partitioning of water into the melt, which strengthens the lithosphere. Deformation and melt segregation were also investigated using torsion experiments on partially molten aggregates of olivine + chromite + 4 vol. % mid-ocean ridge basalt by **King *et al.*** They showed that melt segregates into distinct melt-rich bands oriented 20° antithetic to the macroscopic shear plane in deformed synthetic peridotites. These experiments provide new information on the likely evolution of melt distribution, the partitioning and localization of strain, and the scaling of experimental results to the Earth's mantle.

Orogenic and ophiolitic peridotites

Studies of natural peridotite systems reveal the importance of deformation in localizing strain and focusing melt migration. **Skemer *et al.*** present the results of a microstructural study of a high-strain mantle shear zone (Josephine Peridotite, SW Oregon, USA) and demonstrate how small-scale features may have implications at the plate-tectonic scale. Their data show that large strain deformation triggers the recrystallization of orthopyroxene. Strain-induced dispersion of the recrystallized orthopyroxene blocks olivine growth, allowing for development of persistent zones of lithospheric weakness. Because intra-lithospheric mineral or rock heterogeneities may lead to localized deformation **Toy *et al.*** focus on a region where ultramylonitic shear zones displace the pyroxenitic dikes in the Twin Sisters dunite, Washington. Their microstructural data suggest that the shear zone nucleated as a result of strain-rate or stress heterogeneity as a direct result of the rheological contrast between pyroxenite dikes and the peridotitic wall-rock. Deformation was focused into the weaker pyroxenitic material, resulting in shear instability. These observations indicate the importance of compositional heterogeneity to stress localization in the mantle. High stresses in the peridotitic lower lithosphere are implied by the study of **Piccardo *et al.***, who demonstrate near-complete melting of peridotite, at ambient $T = 600 \pm 100°C$ and $P < 0{\cdot}5$ GPa to produce ultramafic pseudotachylytes in the Lanzo peridotite massif, Italy. They propose that this high-stress deformation occurred during uplift of the lithospheric mantle in the early stages of formation of the Liguria–Tethys oceanic basin. **Kamei *et al.*** studied peridotite fabric–temperature relationships in the Mohelno peridotite, Czech Republic, and constrained a low-temperature, slowly cooled 'core' and a high-temperature, rapidly cooled 'margin' (garnet facies), consistent with the P–T conditions of the surrounding granulite. Because this occurred when the massif was emplaced into crustal granulites the implication is that the spinel to garnet peridotite transformation can happen in a crustal environment.

MELT–PERIDOTITE REACTION AND REFERTILIZATION

Experimental constraints

The fundamentals of melt formation, migration and reaction were studied by **Liang & Parmentier**, who develop mass conservation equations for a mantle analogue comprising low-porosity peridotite wall-rock and a high-porosity dunite channel network. They conclude that the melt in the channel is a mixture of matrix melt extracted along the column from below and matrix materials dissolved into the channel melt. Mixing within the channel produces a range of melt compositions that accounts for the variability observed at the surface (i.e. melt inclusions, erupted products). Once melt fractions have formed and migrated through the shallow mantle the potential exist for these melts to interact with the thermal boundary layer (TBL) of the overlying lithosphere. Tholeiitic melt-depleted peridotite reaction experiments undertaken by **Van den Bleeken** indicate that reactive porous flow can occur below the peridotite solidus. However, for channelized flow to occur temperatures $\geq$1260°C are necessary and where melt migration is 'slow' melts will 'freeze', refertilizing the otherwise depleted TBL.

Dunite channels and impregnated peridotites

These processes may well explain the occurrence of discordant tabular dunite veins in harzburgite–lherzolite massifs in the Josephine and Oman ophiolites. **Sundberg *et al.*** use mass-balance to quantify the trapped melt fraction in the Josephine peridotite and demonstrate a threshold porosity for melt extraction of $<0{\cdot}2$ vol. %. This constrains the bulk viscosity during compaction of *c.* 10^{23} Pa s at low melt fractions and temperatures. The proposed small amount of melt is consistent with near fractional melting in the upper mantle as defined by geochemical data. Tabular dunites in the Oman peridotite studied by **Hanghøj *et al.*** have major and trace element, mineral and Os isotope compositions consistent with models of highly focused flow of aggregated mid-ocean ridge basalt (MORB)-like melts in high-porosity dunite channels.

Melt impregnation has been suggested as a mechanism for generating plagioclase peridotites found in both abyssal peridotite suites and orogenic massifs (e.g. Lanzo, Othris). Subsolidus experiments were undertaken by **Borghini *et al.*** to constrain the stability of plagioclase in fertile and depleted lherzolites and to assess the role of bulk composition and mineral changes during P–T changes. Plagioclase is stable at higher pressures in fertile rocks and lower pressures in depleted rocks such that the plagioclase- to spinel-facies boundary has a positive slope in P–T space. Bulk composition also exerts a strong influence on the high-pressure stability of the plagioclase lherzolite assemblage and plagioclase chemistry may be a suitable geobarometer for plagioclase peridotites. Plagioclase peridotite can also form ultramafic seafloor in ocean–continent transition zones. Exposures in Switzerland and Italy are interpreted by **Müntener *et al.*** to indicate that the chemical and thermal boundary between 'cold' subcontinental and 'hot' refertilized mantle is well defined by changes in lithology and mineral chemistry. The Malenco–Platta–Totalp peridotites are similar to those recovered from the Newfoundland margin, allowing for an estimation of the distribution of 'cold' and 'hot' mantle.

Supra-subduction zone fluids and melt migration

Melt migration from the asthenosphere through the lithosphere leaves a mineralogical and chemical record that can be used to unravel mantle geodynamics in time and space. Spinel-facies peridotite xenoliths from Cabezo Tallante (Spain) studied by **Rampone *et al.*** reveal a multi-stage history of deformation, recrystallization, melt–rock interaction and melt intrusion that tracks the progressive exhumation of the lithosphere. Using microstructural and *in situ* mineral chemistry data, those workers convincingly show that the melt migration and intrusion stages recognized in the Tallante peridotite xenoliths record the switch in volcanism from subduction-related to intraplate-type alkaline magmatism in the Alboran region during the Neogene. Supra-subduction zone melt and fluid migration processes are recorded in refractory spinel harzburgite xenoliths from Avacha, Kamchatka. **Ionov** notes the distinctive character of the Avacha peridotites and the similarities to cratonic peridotites rather than continental xenoliths as a result of their low clinopyroxene and high orthopyroxene modes. He proposes that this may indicate fluid fluxing in the mantle wedge. **Soustelle *et al.*** investigate the relations between fluids and deformation in Avacha peridotites. Based on the analysis of microstructures, mineral reactions, and crystal preferred orientations they propose that reactive percolation of Si-rich fluids started synchronously with deformation under high-temperature, asthenospheric conditions and continued after the incorporation of the protolith of these xenoliths into the upper plate lithosphere. Despite the presence of fluids, olivine deforms essentially by dislocation glide on [100] systems. Crystallization of olivine + opx + sp + amphibole along grain boundaries and variable water contents in olivine and orthopyroxene suggest more focused fluid flow or hydrous melt transport in the late stages.

HIGH- AND LOW-TEMPERATURE MID-OCEAN RIDGE PROCESSES

Abyssal peridotites from the Atlantis II Fracture zone in the Indian Ocean exhibit a large range of variation in the trace element composition of clinopyroxene, interpreted by **Warren & Shimizu** as evidence for cryptic metasomatic processes involving low melt volumes. The length-scale of these variations indicates a late-stage, off-axis melt–rock reaction process during uplift at a ridge transform. In contrast, **Dick *et al.*** show that large-scale melt migration across the Kane oceanic core complex near the Mid-Atlantic Ridge locally produced nearly complete plutonic sequences. They demonstrate that mantle melting was retarded within 10 km of the transform; plagioclase peridotites are abundant in this region as a result of shallow impregnation of the mantle with MORB-like melts. Despite representing a low-degree end-member for melting at slow-spreading ridges, the Kane peridotites away from the transform are harzburgites. Mantle peridotites formed at a Miocene slow-spreading ridge are exposed on Macquarie Island. **Dijkstra *et al.*** show that these are highly refractory harzburgites affected by melt–rock reaction. This is inconsistent with formation at a slow-spreading ridge and points to crust–mantle decoupling. Re–Os data confirm that the sub-crustal metamorphic peridotites formed during a Proterozoic depletion event and were not synchronous with crustal formation. Many shallow mantle peridotites formed at ridge systems preserve strong olivine preferred orientations imposed during asthenospheric flow. This fabric is maintained and reinforced by the growth of lizardite according to the results presented by **Boudier *et al.*** Using optical and TEM data they demonstrate how the crystallographic orientation of olivine in mantle rocks from Oman and in a xenolith from Moose Rock (USA) has a major control on the orientation of low- and high-temperature serpentines, respectively. They show that this control of the olivine crystallographic orientation on antigorite formation in supra-subduction zone mantle may produce trench-parallel fast S-wave polarization and an anisotropy that is reduced at low degrees of serpentinization but increased with increasing serpentinization.

ON-CRATON AGES

With so much evidence for fluid processes and melt migration within mantle rocks it is perhaps unsurprising that extracting relevant 'age' information from mantle rocks is beset with problems. Using clinopyroxene–garnet isochrons, **Gonzaga *et al.*** demonstrate that for eclogites and garnet pyroxenites the Lu–Hf system records 'events' as much as 1000 Myr older than those recorded by Sm–Nd. For one Robert's Victor eclogite a multi-isotope approach reveals a range of protolith ages (933–3105 Ma), with the durability of clinopyroxene revealing it as a possible proxy for protolith age. Although it has been argued that Lu–Hf is more robust than Sm–Nd, in some circumstances Rb–Sr is even more robust. **Liu *et al.*** studied zircon-bearing garnet pyroxenite veins in spinel-facies peridotites from the North China Craton. The garnet pyroxenite veins contain Precambrian zircons that cluster into three age groups (0·6–1·5 Ga, 1·7–2·1 Ga and 2·4–2·5 Ga) that coincide with major tectonic events. These zircons are xenocrysts in contrast to igneous zircons that also occur in the mantle rocks and yield 64–315 Ma ages. Overall the large range in zircon ages supports the longevity of the craton and its reactivation in the last 400 Myr, eventually leading to its destruction.

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