White Paper: Mapping a Mantle Wedge: Directly Constraining Mantle Flow, Melt Generation, and Volatiles Above the Subduction Zone

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Introduction

Arcs and ridges are the most extensive volcanic systems on the planet, playing a major role in the global geochemical cycle. The two systems, however, are fundamentally different: ridges erupt tholeiitic basalt of remarkably uniform chemistry, while arc lavas range from primitive tholeiite similar to MORB, andesite, and alkaline basalts with silica contents ranging from <50% to >70% [*Miyashiro*, 1974]. This contrast is a fundamental manifestation of extensional versus convergent margin dynamics, the contrasting role of volatiles, and the underlying patterns of mantle flow. At ridges, a relatively dry lherzolitic mantle undergoes adiabatic decompression melting to produce MORB. At convergent margins, with the under-thrusting of sediments and altered ocean crust beneath the plate edge, dehydration of the down-going plate introduces water and slab derived melts into the overlying plate: inducing hydrous melting in the mantle wedge. While magma genesis beneath ocean ridges is relatively well understood, this is not the case at subduction zones due to their inherent complexity.

In particular, the relative contributions of the slab component derived from the down-going plate, and that from melting the overlying mantle in arcs is controversial. The pattern of mantle flow in the wedge both during and prior to melt generation above the slab is largely a matter of inference. Conventionally, the slab contribution problem is approached by inverting magma compositions: basalt, andesite, or whatever erupts in the many diverse arc environments (arc, fore-arc, back-arc, etc) involving a mass balance of putative slab to mantle components, often focusing on isotopic and incompatible trace element components enriched in the slab, such as B, Li, Rb, Cs, Sr, Th, Pb, and Ba (e.g. [*Parkinson and Pearce*, 1998]). This is intrinsically difficult due to the inherent complexity of a system involving a down-going reheated slab composed of sediment and variously altered crust and mantle, an overlying mantle wedge, and melt migration through the crust: all effecting final melt composition. This is clearly expressed by temporal variations in melt composition both across and within arcs (e.g.: [*Kuno*, 1966; *Leeman et al.*, 2005; *Miyashiro*, 1974; *Smith and Leeman*, 2005]). Ophiolites, on the other hand, expose broad regions of mantle peridotite where many aspects of this complex process can be directly studied. Most ophiolites are believed, on the basis of their lavas and mantle residues, to have formed in, or passed through, a supra-subduction zone environment (SSZ) (e.g.: [*Miyashiro,* 1973; *Alabaster et al.*, 1982; *Shervais*, 1982; *Metcalf and Shervais* 2008]). While the specific environment, back-arc, arc, fore-arc etc., is debated, it is clear that these peridotites offer the possibility of constraining the mechanisms by which water and hydrous melt interacts with the mantle wedge in the subduction factory as well as the accompanying patterns of mantle flow and deformation (e.g., [*Choi et al 2008a,b; Jean et al 2009*]).

A Focus Study Site In An Exposed Mantle Wedge

We propose, then, the designation of a large North American ophiolite peridotite massif as a MARGINS focus site for the study of subduction zone processes in the mantle wedge. Major questions that can be addressed by the study of such a massif include the nature and extent of mantle-slab interactions (*e.g.,* addition of volatiles to the mantle from the down-going slab, either as fluids at shallow depth or as melts deeper in the asthenosphere), the nature, source, extent, and pattern of fluid/melt flow into and out of SSZ peridotites, the cumulative extent of melt extraction and the nature of the melts formed. Microstructures and macrostructures that document deformation processes the mantle wedge can constrain the pattern of mantle flow prior to and during mantle melting. With deep canyons cutting down to the base of the peridotite massif, patterns of alteration produced in a mantle wedge due to underthrust sediments can also be directly studied. In-situ seismic studies in such a massif will provide direct observations of mantle seismic anisotropy that will help interpretation of the new and emerging geophysical observations of mantle-wedge properties - much as such observations in the Oman Ophiolite have given us a decent model of anisotropic fabric in the uppermost mantle at fast spreading ridges.

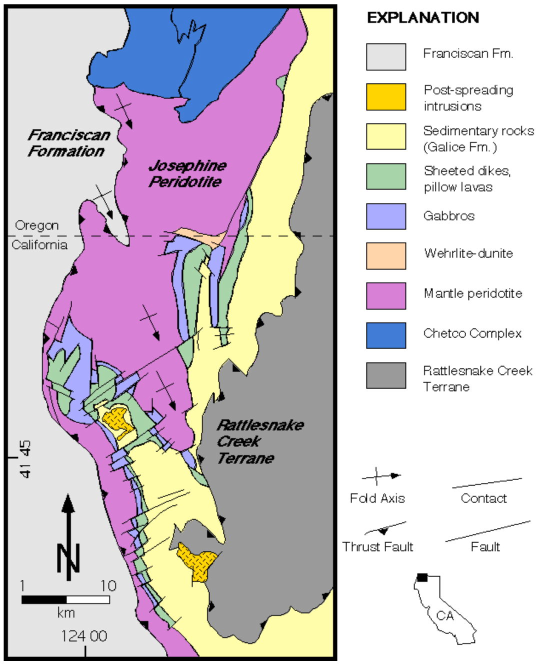

Figure 1. Geologic map of Josephine ophiolite, based on mapping of Harper (1980, 1984, 1988, 1990-94) and Yoshinobu (1996-1999).

The Josephine Peridotite in the western US, for example, offers an enormous peridotite massif that can be used to study geochemical fluxes in the mantle wedge above a subduction zone at a truly representative scale.The Josephine Ophiolite contrasts to the well-studied Oman Ophiolite in that it is clearly does not represent a fast-spreading ridge environment, and its petrogenesis involved melting and crust formation in a hydrous supra-subduction zone environment with the formation of boninitic and andesitic magmas (Harper, 2003b). It encompasses a large swath of NW California and SW Oregon (Fig 1). Harper and coworkers have extensively mapped portions of the ophiolite *(Harper 1984; 2003a, 2003b),* documenting a complete crustal section overlain by a thin, siliceous volcanopelagic sequence and turbidites of the Galice formation. They interpret the ophiolite as initially formed in a back-arc basin crust, based on the observed rock associations, and on its position west of the Chetco arc complex *(Harper 1984, 2003a, 2003b)*. The Josephine Peridotite forms the base of the ophiolite. This ~800 km^2 massif consists of harzburgite with less common dunite, wehrlite, pyroxenite, and chromitite that represent the residues of partial melting, melt transport, and magmatic deposits in a late hydrous melting environment (*Dick, 1977; Dick & Bullen, 1984; Kelemen et al., 1992; Kelemen and Dick 1995*). Several workers, however, have shown that dunite “dikes” and layers in the Josephine peridotite represent melt flow channels where pyroxene was dissolved and olivine precipitated at relatively low pressures in the mantle (*Dick, 1976, 1977; Dick & Bullen, 1984; Kelemen et al., 1992; Kelemen and Dick 1995*). An alternative site for such a focused study project could be the Paleozoic Bay of Islands Complex in Newfoundland, which also has an arguably arc affinity (e.g.: Elthon, 1991).

Project Proposal

We envision an initial 5-year project to map and systematically sample the entire mantle section at a scale of 1:12000 as well as a concurrent seismic study. This would establish foundation geologic, geochemical and geophysical datasets for a large community and that can provide a gateway into this focus site for investigators unfamiliar with the location and the basis for focused studies. Oriented samples would be taken on a closely spaced grid to allow detailed micro structural analysis, and these samples should be of sufficient size for correlated studies of whole rock major and trace element chemistry, mineral analyses, and in select cases, the physical separation of residual pyroxene for isotopic analysis. Detailed sampling at this scale in a peridotite massif has previously only occurred in the Oman ophiolite, and has directly constrained the processes of mantle flow, melt generation, and crust formation in a fast spreading ridge environment [e.g., Mée et al 2004]. A North American peridotite massif, clearly reflecting a SSZ setting, would also be easily accessible to the US research community. Full mapping of a massif, such as the Josephine Peridotite or Bay of Islands Ophiolite, however, will require extensive backpacking and helicopter support. This would require a large field effort likely involving 5 or more PhD projects as well as masters students. The primary goal of constraining the nature and extent of the geochemical fluxes, can be documented by systematic regional sampling of the massif using whole-rock major oxide and trace element analyses, electron microprobe, ion microprobe, and laser ablation ICP-MS mineral analysis, and by isotopic analyses of hand-picked mineral separates. The full spectrum detailed study of micro fabrics, igneous and metamorphic petrology, and isotopic and trace element analyses across hundreds of km^2 of exposed mantle requires a large-scale multi-institutional laboratory effort well beyond anything that can be attempted under conventional NSF funding. For this purpose, all samples should be collected in a uniform manner, placed in a single repository, and all sampling done there by a qualified technician to insure equitable, and conservative use of the material, and future availability for studies by new P.I.'s.

References

Alabaster, T., Pearce, J. A., and Malpas, J., 1982, The volcanic stratigraphy and petrogenesis of the Oman ophiolite complex: *Contrib. Min. & Petr.y*, v. 81, no. 3, p. 168-183.

Choi, S.H., Mukasa, S.B., Shervais, J.W. (2008) Initiation of Franciscan Subduction along a Large-offset Fracture Zone: Evidence from Mantle Peridotites, California, California, *Geology*, v 36, #8, 595-598. doi: 10.1130/G24993A.1

Choi, S.H., Shervais, J.W., Mukasa, S.B. (2008) Supra-Subduction and Abyssal Mantle Peridotites of the Coast Range Ophiolite, California, *Contrib. Min. & Petr.,* v155, 551-576. DOI: 10.1007/s00410-008-0300-6.

Dick, H. J. B. (1977), Evidence of partial melting in the Josephine Peridotite, in *Magma Genesis*, edited by H. J. B. Dick, pp. 59-62, Oregon Dept. of Geology and Mineral Industries, Portland, Oregon.

Dick, H.J.B., 1976, The Origin and Emplacement of the Josephine Peridotite. Yale University PhD thesis, 400 pp.

Elthon, D., (1991) Geochemical evidence for formation of the Bay of Islands ophiolite above a subduction zone. Nature 354, 140-143.

Harper, G.D. (1984) The Josephine ophiolite, northwestern California, GSA Bulletin, 95 (9), 1009-1026.

Harper, G. D., 2003a, Fe-Ti basalts and propagating-rift tectonics in the Josephine Ophiolite: GSA Bulletin, v. 115, no. 7, p. 771-787.

Harper, G. D., 2003b, Tectonic implications of boninite, arc tholeiite, and MORB magma types in the Josephine Ophiolite, California, Oregon, in Dilek, Y., and Robinson Paul, T., eds., Ophiolites in Earth history: Geological Society of London. London, United Kingdom.

Jean, M.M., Shervais, J.W., Choi, S.H., Mukasa, S.B., (2009) Melt Extraction and Melt Refertilization in Mantle Peridotite of the Coast Range Ophiolite: An LA-ICP-MS Study, *Contrib. Min. & Petr.y*, v.159, n.1, DOI:10.1007/s00410-009-0419-0. [2009 online, 2010 print]

Kelemen, P. B., Dick, H.J.B., and Quick, J.E. (1992), Formation of harzburgite by pervasive melt/rock reaction in the upper mantle, Nature, 358, 635-641.

Kelemen, P. B., and H. J. B. Dick (1995), Focused melt flow and localized deformation in the upper mantle: Juxtaposition of replacive dunite and ductile shear zones in the Josephine peridotite, SW Oregon, *J Geophys. Res.*, 100(B1), 423-438.

Kuno, H. (1966), Lateral variation of basalt magma types across continental margins and island arcs. *Bull. Volc.*, ser. 2, vol.29, 195-222..

Leeman, W. P., et al. (2005), Petrologic constraints on the thermal structure of the Cascades arc, *J. Volcanology and Geothermal Research*, *140*, 67-105.

Mée, L. L., Girardeau, J., and Monnier, C., 2004, Mantle segmentation along the Oman ophiolite fossil mid-ocean ridge: *Nature* (London), v. 432, no. 11.

Metcalf, R.V., and Shervais, J.W. (2008) Supra-Subduction Zone (SSZ) Ophiolites: Is There Really An "Ophiolite Conundrum"?, in James E. Wright and John W. Shervais, editors, Ophiolites, Arcs, and Batholiths: A Tribute to Cliff Hopson: *GSA Special Paper 438*, p. 191–222, doi: 10.1130/2008.2438(07).

Miyashiro, A. (1973), The Troodos ophiolitic complex was probably formed in an island arc, *Earth & Planet. Sci. Lett.*, *19*, 218-224.

Miyashiro, A. (1974), Volcanic rock series in island arcs and active continental margins, *American Journal of Science*, *274*, 321-355.

Parkinson, I. J., and J. A. Pearce (1998), Peridotites from the Izu-Bonin-Mariana Forearc (ODP Leg 125): evidence for mantle melting and melt-mantle interaction in a supra-subduction zone setting, *Journal of Petrology*, *39*, 1577-1618.

Shervais, J. W. (1982) Ti-V plots and the petrogenesis of modern and ophiolitic lavas. *Earth & Planet. Sci. Lett.,* 59, 101-118.

Smith, D. R., and W. P. Leeman (2005), Chromian spinel–olivine phase chemistry and the origin of primitive basalts of the southern Washington Cascades, *J. Volcanology & Geothermal Research*, *140*, 49-66.

Vail, S., 1978, University of Oregon masters thesis.