Exhumed subduction margins:
an important record of deformation and metamorphic processes

Mary Leech
Dept. of Geosciences, San Francisco State University, San Francisco, CA 94132; leech@sfsu.edu

Active subduction zones will be a fundamental part of the new Subduction Cycles and Deformation initiative in GeoPRISMS, nonetheless, some key aspects of their geology cannot be studied from the surface: seismic images are limited by km-scale wavelengths in the deep crust and upper mantle; monitoring active seismicity is limited to moderate to large earthquakes; deformation and rheology is inferred from geodetic observations that are filtered by the overlying lithosphere; and metamorphic processes must be inferred by the geochemical products returned to the surface, potentially transformed, through the overlying crust. All of these processes can and must be addressed by focused geological study of exhumed subduction margins; though examples abound worldwide, we should not restrict ourselves to any single fossil site, but certain locations offer unusual opportunities.

Exposures of pseudotachylite in lower crustal rocks in two locations in western Norway result from frictional melting during intermediate-depth paleo-earthquakes in the overriding plate during Caledonian subduction. Local pseudotachylite veins occur within or adjacent to eclogite-facies shear zones in otherwise metastable granulite-facies gabbroic rocks in both the Bergen Arcs and on Flakstadøy in the Lofoten Islands (e.g., Austrheim and Boundy, 1994; Steltenpohl et al., 2006). Field relations at both localities suggest a close interplay of multiple subduction-related processes in the deep crust near the plate interface between brittle and ductile deformation, metamorphic reactions, and fluid infiltration (Bachmann et al., 2009).

Estimates of P=1.5-2.1 GPa and T~700ºC suggests depths ≥50-60 km, nominally below the brittle-ductile transition, for eclogite-facies metamorphism and coexisting shear zone formation in both locations (Jamtveit et al., 1990; Markl and Bucher, 1997), and pseudotachylite formed at eclogite-facies conditions based on the presence of high-pressure garnet and omphacite crystals in these quenched frictional melts (Austrheim and Boundy, 1994; Steltenpohl et al., 2006). While the pseudotachylite has not been directly dated, eclogite-facies metamorphism and the coeval shear zone deformation occurred at c. 430 Ma (e.g., Steltenpohl et al., 2003; Glodny et al., 2008); these ages suggest a genetic link between pseudotachylite formation and subduction deformation in the overriding plate during the Scandian phase of the Caledonian orogeny.

Pseudotachylites are interpreted as quenched frictional melts resulting from localized deformation at seismic strain rates (0.1-1 m/s; Cowan, 1999). The melt volumes represented by these Norwegian pseudotachylite veins implies seismic energies corresponding to small magnitude earthquakes: micro-earthquakes up to a magnitude of ~1 for melt volumes approximating those in the Lofotens based on calculations in Wenk et al. (2000), while Bjornerud et al. (2002) estimate a minimum magnitude of ~3.3 for pseudotachylite veins in the Bergen Arcs. The correlation of pseudotachylite with eclogite-facies shear zones suggests deformation styles change between high-velocity brittle faulting and slow, ductile shear in the lower crust.

Whereas eclogite-facies metamorphism and the associated density increase and accompanying rapid(?) volume decrease probably did not trigger the earthquakes because pseudotachylite also occurs in uneclogitized gabbro (in the Bergen Arcs, Bjornerud et al., 2002), these brittle deformation events likely opened pathways for fluid infiltration that led to localized metamorphic reactions. It is clear that the rheology of the lower crust changed during Caledonian deformation:

a strong, dry granulitic lower crust deformed brittlely during the pseudotachylite-forming events; the resulting in fluid infiltration and eclogitization was accompanied by ductile shearing demonstrating significant strength reduction (Bjornerud et al., 2002).

Geological study of exhumed subduction margins such as this in western Norway should be part of the new Subduction Cycles and Deformation initiative in GeoPRISMS. Exhumed subduction margins are particularly well-suited for addressing key questions put forth in the Draft Science Plan as they relate to the interplay between brittle and ductile deformation, metamorphic reactions, and fluid infiltration: 1) What controls the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?; 2) How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?; and 3) How do subduction zone processes affect the rheology and dynamics of the plate interface?

Selected References

Austrheim, H. and Boundy, T.M., 1994, Pseudotachylytes generated during seismic faulting and eclogitization of the deep crust, Science, 265, 82-83.

Bachmann, R., Oncken, O., Glodny, J., Seifert, W., Georgieva, V., and Sudo, M., 2009, Exposed plate interface in the European Alps reveals fabric styles and gradients related to an ancient seismogenic coupling zone, Journal of Geophysical Research, 114, B05402, doi:10.1029/2008JB005927.

Bjørnerud, M.G., Austrheim, H., and Lund, M.G., 2002, Processes leading to eclogitization (densification) of subducted and tectonically buried crust, Journal of Geophysical Research, 107, doi:10.1029/2001JB000527.

Cowan, D. S. (1999), Do faults preserve a record of seismic slip? A field geologist's opinion, J. Struct. Geol., 21, 995– 1001, doi:10.1016/S0191-8141(99)00046-2.

Glodny, J., Kühn, A., and Austrheim, H., 2008, Geochronology of fluid-induced eclogite and amphibolite facies metamorphic reactions in a subduction-collision system, Bergen Arcs, Norway, Contributions to Mineralogy and Petrology, doi:10.1007/s00410-007-0272-y.

Jamtveit, B., Bucher-Nurminen, K., and Austrheim, H., 1990, Fluid controlled eclogitization of granulites in deep crustal shear zones, Bergen arcs, western Norway, Contributions to Mineralogy and Petrology, 104, 184-193.

Markl, G., and Bucher, K., 1997, Proterozoic eclogites from the Lofoten Islands, northern Norway, Lithos, 42, 15-35.

Steltenpohl, M., Hames, W., Andresen, A., and Markl, G., 2003, New Caledonian eclogite province in Norway and potential Laurentian (Taconic) and Baltic links, Geology, 31, 985-988.

Steltenpohl, M., Kassos, G., and Andresen, A., 2006, Retrograded eclogite-facies pseudotachylytes as deep-crustal paleoseismic faults within continental basement of Lofoten, north Norway, Geosphere, 2, 61-72.

Wenk, H.-R., Johnson, L.R., and Ratschbacher, L., 2000, Pseudotachylites in the eastern Peninsular Ranges of California, Tectonophysics, 321, 253-277.