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# Strain localization associated with channelized melt migration in upper mantle lithosphere: Insights from the Twin Sisters ultramafic complex, Washington, USA

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We present results of field, microstructural, and textural studies in the Twin Sisters ultramafic complex (Washington State) that document localized deformation associated with the formation of dunite channels in naturally deformed upper mantle. The Twin Sisters complex is a well-exposed, virtually unaltered section of upper mantle lithosphere comprised largely of dunite and harzburgite (in cm- to m-scale primary compositional layers), and variably deformed orthopyroxenite and clinopyroxenite dikes. A series of ~N–S striking, m-scale dunite bands (typically with porphyroclastic texture) occur throughout the study area and crosscut both the primary compositional layers and older orthopyroxenite dikes. Structural relationships suggest that these dunite bands represent former zones of channelized melt migration (i.e., dunite channels), and that strain localization was associated with melt migration. Early formed orthopyroxenite dikes are either absent within cross-cutting dunite channels, or have been displaced within channels relative to their position in the adjacent host rocks. These pre-existing orthopyroxenite dikes provide strain markers illustrating that displacement was localized primarily along channel margins, which have opposite senses of shear. In all cases where offsets were noted, the center of the channel was moved southward relative to its margins. Material flow and strain was, therefore, partitioned within channels during melt migration, and dunite channels did not accommodate net shear displacement of the adjacent host peridotites. Primary compositional layers adjacent to dunite channels document opposite rotation of olivine [100] crystallographic axes on either side of channel margins, consistent with the kinematic reversal inferred from offset markers at the outcrop scale, suggesting that the formation of dunite channels also induced host rock deformation proximal to channels. Strain localization that was focused at the margin of the bands was likely facilitated by melt-induced weakening. Channelized movement within the dunite bands may have resulted from matrix compaction within channels, pressure gradients during melt migration, or a combination of these processes during coaxial deformation.



## 1. Introduction

Important relationships between upper mantle deformation, strain localization, and melt migration have been demonstrated by a number of field, experimental, and numerical studies. Shear zones, similar in scale to those observed in crustal rocks, have been reported in the Oman ophiolite (Boudier et al., 1988), Voltri massif (Hoogerduijn Strating et al., 1993), Rhonda massif (Van der Wal and Vissers, 1993; Précigout et al., 2007), Othris massif (Dijkstra et al., 2002), Lanzo massif (e.g., Boudier, 1978; Kaczmarek and Tommasi, 2011), Josephine peridotite (Kelemen and Dick, 1995; Warren et al., 2008; Skemer et al., 2010), Twin Sisters ultramafic complex (Toy et al., 2010), and the Red Hills ultramafic massif (Webber et al., 2008, 2010). In some cases, these upper mantle shear zones may have initiated as regions of focused melt flow, which further localized subsequent melt flow and strain into deforming regions (e.g., Kelemen and Dick, 1995; Dijkstra et al., 2002; Kaczmarek and Müntener, 2008). Melt flow in the upper mantle is thought to occur by porous intergranular flow, localized into chemically isolated conduits (e.g., Spiegelman and Kenyon, 1992; Daines and Kohlstedt, 1994; Hart, 1993;

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Aharonov et al., 1995) – the geological expression of which are dunite channels in exposures of upper mantle peridotites (e.g, Dick, 1977; Quick, 1981; Kelemen and Dick, 1995; Kelemen et al., 1995a,b). Experimental rock deformation studies that incorporate a melt phase have emphasized the role of stress-driven melt segregation during shearing to form melt-rich bands (e.g., Holtzman et al., 2003a,b; King et al., 2010, 2011a,b), and show substantial strain localization accommodated by microscale processes during melt weakening (Hirth and Kohlstedt, 1995a,b; Bai et al., 1997). Similarly, numerical simulations document the feedbacks between deformation, or reaction, on the fluid flow pattern in two-phase flow models (e.g., Katz et al., 2006; Butler, 2009; Liang et al., 2010).

Field-based investigations of exhumed upper mantle lithospheric sections remain critical for evaluating relationships between deformation and melt migration at geologically relevant scales, and under natural deformation conditions. We present results from field, microstructural, and textural studies in the Twin Sisters ultramafic complex (Washington State, USA) that illustrate the spatial and temporal associations between deformation and the formation of dunite channels (inferred zones of former melt migration) in naturally deformed upper mantle. Using these data, we document strain localization features associated with the formation of melt migration channels, including strain partitioned within channels, proximal host rock deformation, and subsequent cataclasis along imparted rheological heterogeneities. We suggest that deformation within and proximal to dunite channels was facilitated by melt-induced rheological weakening, presumably enhanced by compaction within dunite channels during percolative melt migration, pressure gradients associated with melt migration, variations in the distribution of melt within channels (cf. Liang et al., 2010), or a combination of these processes during coaxial deformation of the Twin Sisters ultramafic body.

## 2. Tectonic setting and geologic background

The Twin Sisters ultramafic complex forms an elliptical body (∼6 × 16 km) located in the North Cascades Mountains of the North American Cordillera, approximately 40 km east of Bellingham, Washington (Fig. 1) (Ragan, 1963; Christensen, 1971; Dragovich et al., 2002). The ultramafic complex is exposed within the Bell Pass mélange zone, a faulted assemblage of accreted oceanic terranes, and is one of several large ultramafic bodies accreted to North America during the mid-Cretaceous (ca. 85–100 Ma) (Misch, 1966; Davis et al., 1978; Miller, 1985; Miller and Mogk, 1987; Brandon et al., 1988).

Ultramafic rocks comprising the Twin Sisters complex are situated between pre-Jurassic phyllites of the Shuksan thrust plate and the upper Paleozoic Chilliwack Group of the Church Mountain thrust plate (Misch, 1966; Ragan, 1963) (Fig. 1). Based on the results of gravity modeling, the Twin Sisters ultramafic rocks likely extend to a depth of ∼2 km as a flat-bottomed, fault bound tectonic panel (Thompson and Robinson, 1975; Brown et al., 1987). The age of the ultramafic complex is unknown. However, it has been suggested to have once been part of a continuous unit (Vance et al., 1980) based on correlations with the much better understood Jurassic Ingalls and Fidalgo ophiolites (Garver, 1988; Blake and Engebretson, 1994; Miller, 1985; Metzger et al., 2002). Unlike these other complexes, which contain lherzolite, gabbro and basalt, the Twin Sisters complex consists solely of ultramafic rocks and consequently may not directly correlate with these other ophiolites (cf. Metzger et al., 2002). Ultramafic rocks in the complex are dominated by dunite and harzburgite with a remarkably low degree of serpentinization (0–15 vol.%)

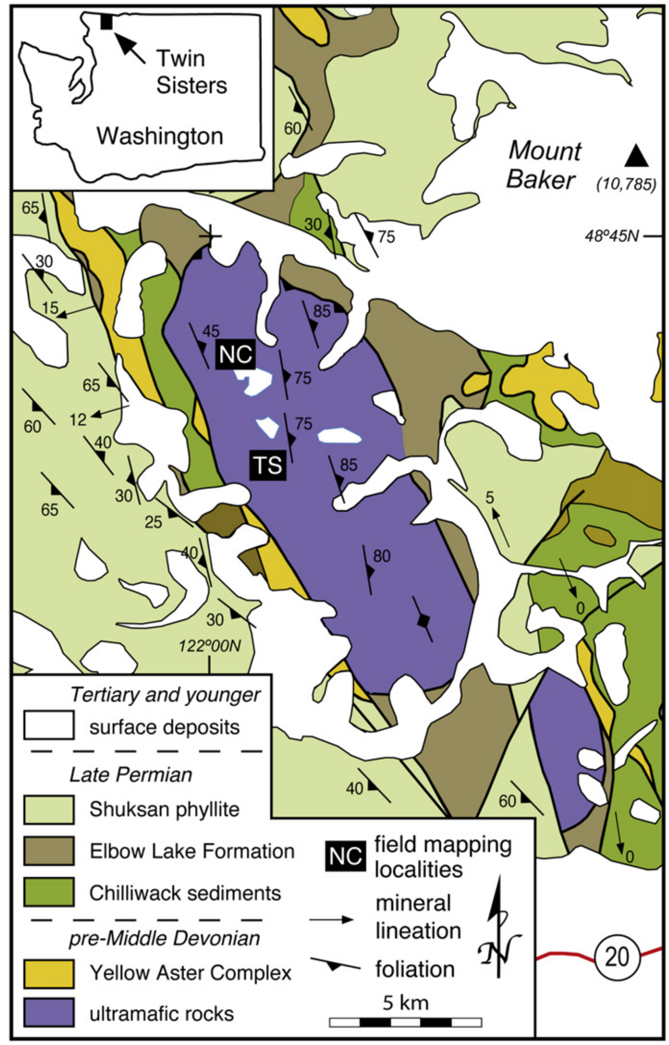


**Fig. 1.** Geologic map of the Twin Sisters ultramafic complex, Washington. Area of detailed field based mapping, and the location of map shown in Fig. 2, denoted as the 'NC' locality. Additional field observations in the central portion of the range shown as 'TS' locality, located approximately 2 km east of the study areas described by Tikoff et al. (2010).

(Gaudette, 1963; Ragan, 1963). Deformation of the host peridotites in the Twin Sisters complex occurred at upper mantle conditions (Ragan, 1963; Christensen, 1971), with estimated temperatures of deformation ranging from ∼800 °C (Toy et al., 2010; based on two-pyroxene and olivine + spinel geothermometry) to ∼1000 °C (Onyeagocha, 1978; based on olivine + spinel geothermometry).

Christensen (2002) noted that the Twin Sisters ultramafic rocks are in fault contact with high-grade crustal rocks of the Yellow Astor Complex (Fig. 1), and therefore interpreted the ultramafic rocks to represent an exhumed slice of continental mantle. However, other units within the Bell Pass mélange zone are of oceanic and island arc origin (Lapen, 2000), suggesting that these ultramafic rocks may instead represent oceanic or sub-island arc upper mantle lithosphere. Despite the currently ambiguous tectonic setting of Twin Sisters complex, the ultramafic rocks that comprise the massif provide access to some of the most pristine exposures of upper mantle materials in the world, thus informing on fundamental mantle processes under natural deformation conditions.