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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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ABSTRACT

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.%)

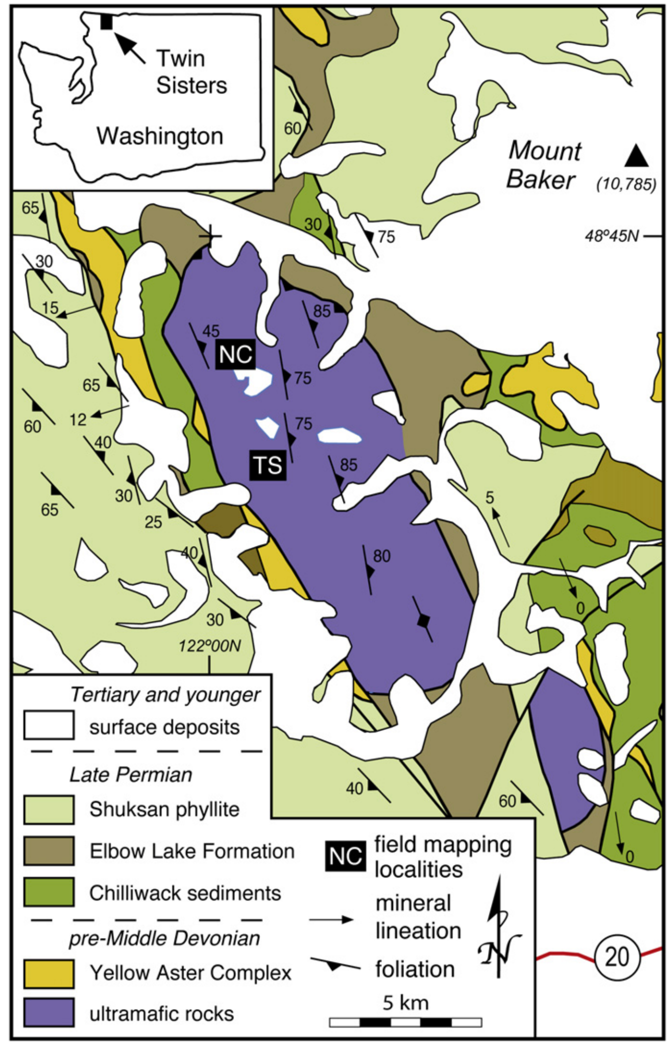

Fig. 1. Geologic map of the Twin Sisters ultramafic complex, Washington. Area of detailed field based mapping, and the location of map shown in Fig. 2, denoted as the 'NC' locality. Additional field observations in the central portion of the range shown as 'TS' locality, located approximately 2 km east 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.

3. Field observations

3.1. Study area

Observations from two studies areas are discussed (Fig. 1), which document the relationships between compositional and structural fabrics in the Twin Sisters complex. Detailed mapping was conducted using a laser total station in a 60 × 70 m area (Fig. 2A) in the northern Twin Sisters complex on the northeast side of North and South Twin peaks, immediately north of a retreating glacier ('NC' locality, Fig. 1). The continuous, un-weathered outcrop in this region provides excellent exposure of compositional and structural fabrics in the ultramafic rocks (e.g., banding, foliation, dikes, faults). The base station at the north end of the map area is located at N 48°42.956′ and W 121°59.387′ (0, −20 coordinate shown in Fig. 2A). Additional structural observations were also reported from the central portion of the complex ('TS' locality, Fig. 1). A synopsis of the geologic features observed in the study areas is presented here.

3.2. Host dunite–harzburgite layering

Throughout the Twin Sisters ultramafic massif, centimeter to meter-scale primary compositional layers of alternating orthopyroxene-absent dunite (>95% olivine) and orthopyroxene-present (∼85% olivine) harzburgite, with minor enstatite, comprise the majority of the host rock (Fig. 2A; Fig. 3A). Compositional layering is subparallel to a dominant NNW–SSE striking, steeply dipping (>70°) foliation defined by the shape preferred orientation of spinel, olivine, or, less commonly, enstatite (Fig. 2C). In the field area, the orientations of compositional layering and foliation are broadly consistent with observations reported elsewhere in the Twin Sisters (cf. Tikoff et al., 2010). Disseminated grains of spinel are also elongate, resulting in a shape-preferred orientation that defines a shallowly N–S-plunging (<30°) lineation in dunite and harzburgite domains (Fig. 2C). Discontinuous, cm-wide, deformed and isoclinally folded layers of chromite spinel are also common in banded dunite and harzburgite layers. For clarity in the discussion that follows, we refer to these

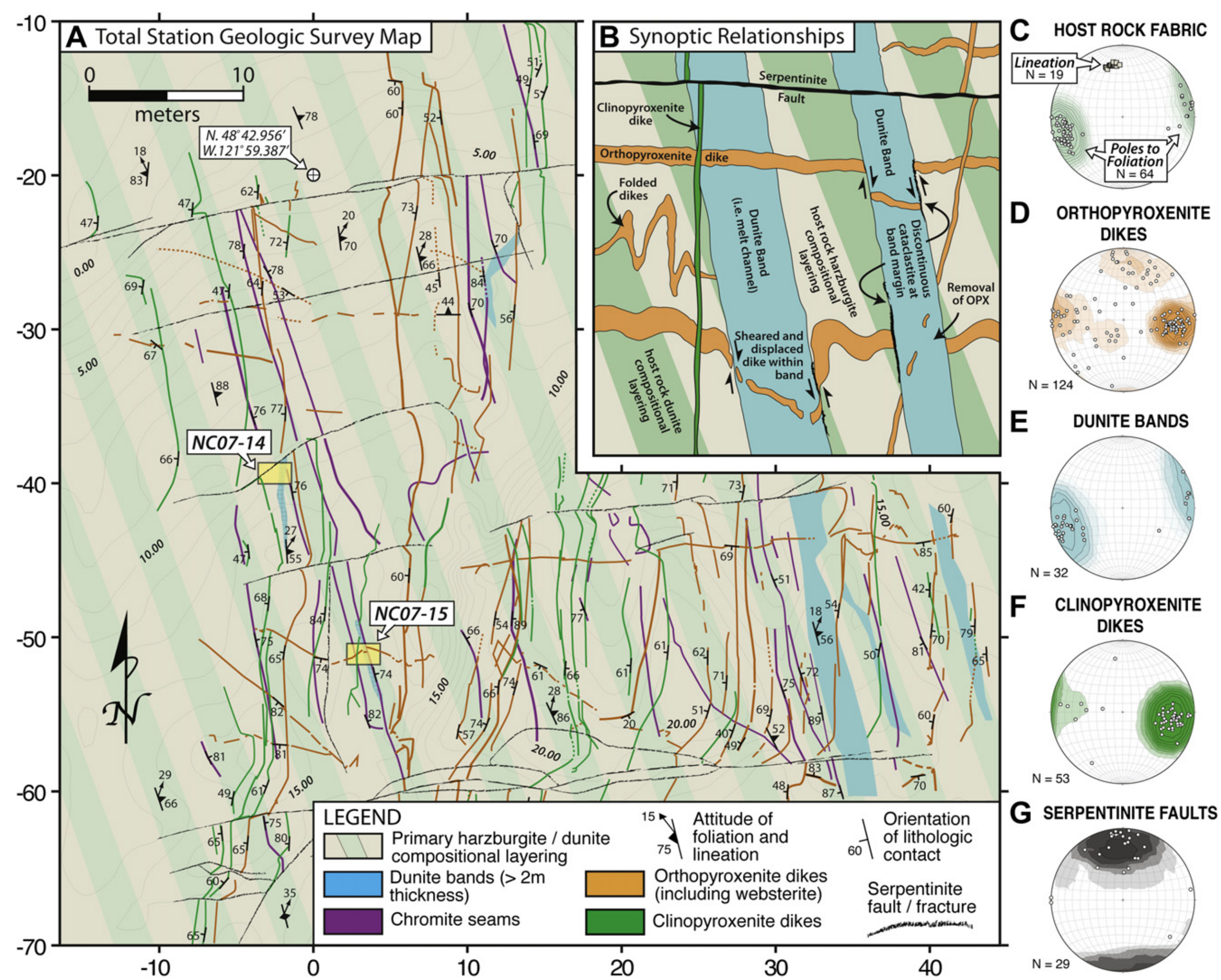

Fig. 2. (A) Geologic map of study area in northern Twin Sisters ultramafic complex, measured by laser total station survey. Patterning showed for primary compositional layers of dunite and harzburgite, which are layered on the cm- to m-scale, is schematic and intended as a reference for the orientation of compositional layering. Similarly, due to the abundance of thin, cross-cutting dunite bands in the study region, only those bands >2 m thickness are shown. Localities NC07-14 and NC07-15 are exceptions – approximate limits of these dunite bands are shown by hatched pattern. (B) Synoptic figure illustrating cross-cutting relationships, structures, and strain localization phenomena discussed in the manuscript. (C–G) Equal area, lower hemisphere stereonets of structural data. Kamb contours are shown with 2 sigma contour intervals. Equal-area stereographic projections were made with OSXStereonet by Nestor Cardozo and Richard Allmendinger (http://homepage.mac.com/nfcd/work/programs.html).

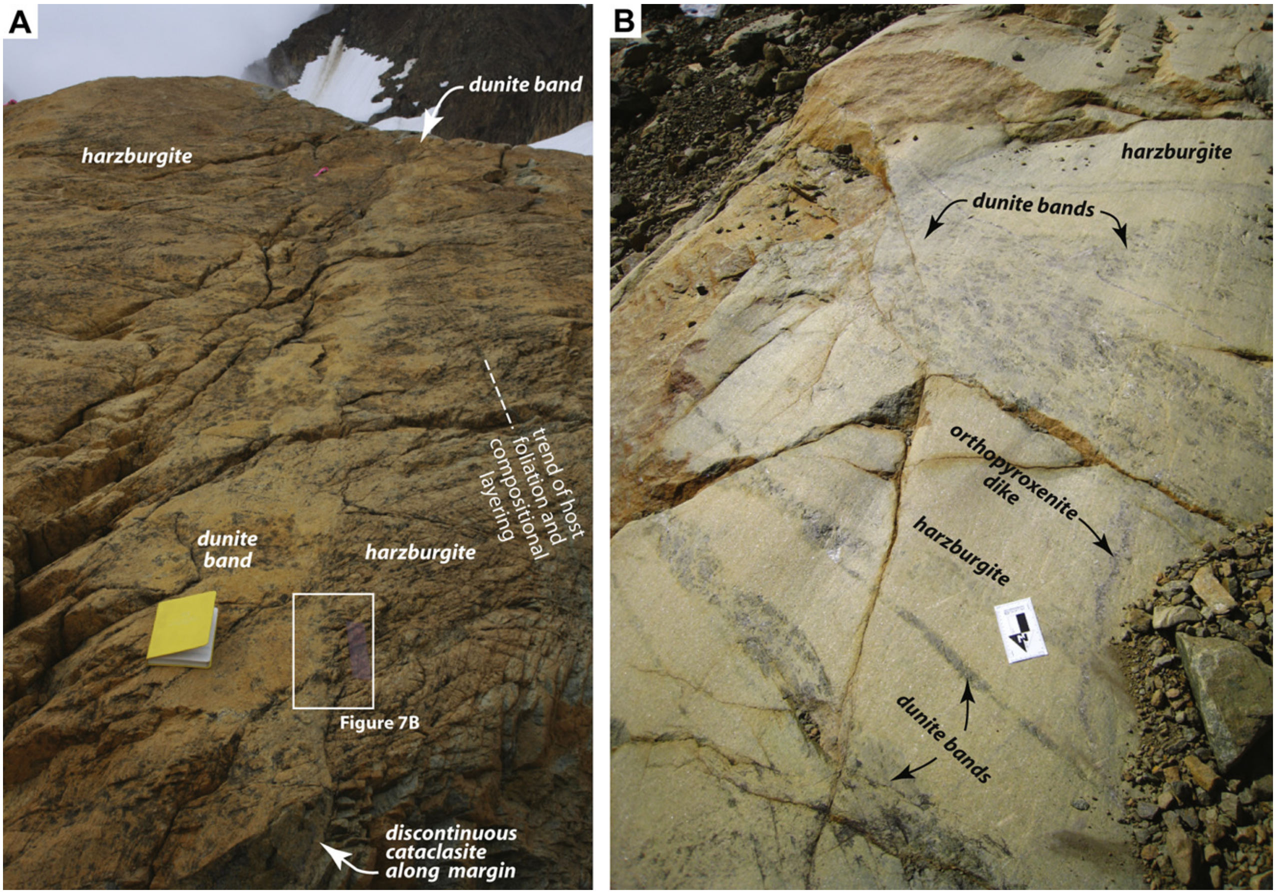

Fig. 3. (A) View to the south of locality NC07-14 showing primary compositional layers of dunite and harzburgite crosscut by a tabular dunite band at low angle. Note also the location of Fig. 7B, which describes the zone of discontinuous cataclasite at the margin of this dunite band. (B) Glacially polished outcrops in the map area showing host harzburgite (light color) and cross-cutting dunite bands. Note the general NNW orientation of dunite bands and the conjugate nature of some bands at the top of the photo (card in image is ~15 cm in length, points north).

compositional layers of dunite and harzburgite as either 'host rock' or 'primary compositional layering'.

3.3. Orthopyroxenite dikes

Abundant orthopyroxenite dikes crosscut compositional layers of dunite and harzburgite in the host rocks (Fig. 2A and B). These dikes are dominantly composed of orthopyroxene (>90%), with minor clinopyroxene. Some orthopyroxenite dikes, however, contain mm- to cm-thick clinopyroxenite cores, and therefore correspond to zoned dikes of overall websteritic composition. The clinopyroxenite-dominated cores of these dikes are not laterally continuous; rather, they appear in discontinuous segments (up to m-scale). Dike thicknesses range from the cm- to m-scale with most dikes having thicknesses less than 10 cm. Orthopyroxenite dikes are variable in orientation (Fig. 2D), but generally strike approximately N–S or E–W with intermediate to steep dip (average orientation 005°/60° W).

Two styles of orthopyroxenite dikes are recognizable within the ultramafic units: older, variably deformed (i.e., folded, boudinaged) dikes (Figs. 4 and 5A and B; Fig. 6A–C) and, younger, tabular dikes (including websteritic varieties) (Fig. 2). Early formed orthopyroxenite dikes are generally E–W striking and folded about N–S oriented, steeply dipping axial planes (i.e., subparallel to foliation and the orientation of primary compositional layers). The older, deformed orthopyroxenite dikes are also thinned and/or boudinaged, typically when oriented ~N–S. The pattern of deformation inferred from deformed orthopyroxenite dikes in the study area is consistent with coaxial deformation (E–W shortening, vertical and N–S elongation), as suggested by previous studies of Tikoff et al. (2010) in a region along the western flank of the central Twin Sisters range approximately 6 km south of our present area of study ('TS' locality, Fig. 1).

3.4. Dunite bands

A series of dominantly NNW–SSE oriented, cm- to m-scale tabular dunite bands, commonly with porphyroclastic-textured olivine, are found throughout the Twin Sisters ultramafic complex (Figs. 2–4) (Ragan, 1963). These dunite bands crosscut the host dunite–harzburgite compositional layering, typically at a low-angle (Fig. 3A), and generally have coarser olivine grain sizes (e.g., olivine crystal aggregates up to ~12 cm in length) relative to host rock layers (e.g., Fig. 4B; Fig. 5C–F). For clarity, we refer to these features either as 'dunite bands' or 'dunite channels', thereby distinguishing them from layers of dunite within the primary dunite–harzburgite compositional layering. Structural relationships indicate that dunite bands crosscut both variably deformed (i.e., folded, boudinaged) orthopyroxenite dikes and, in some localities tabular (i.e., undeformed) orthopyroxenite dikes (Figs. 3–6). Dunite bands are also cut by planar orthopyroxenite and websterite dikes. Structural relationships associated with dunite bands are discussed in more detail in Section 4.

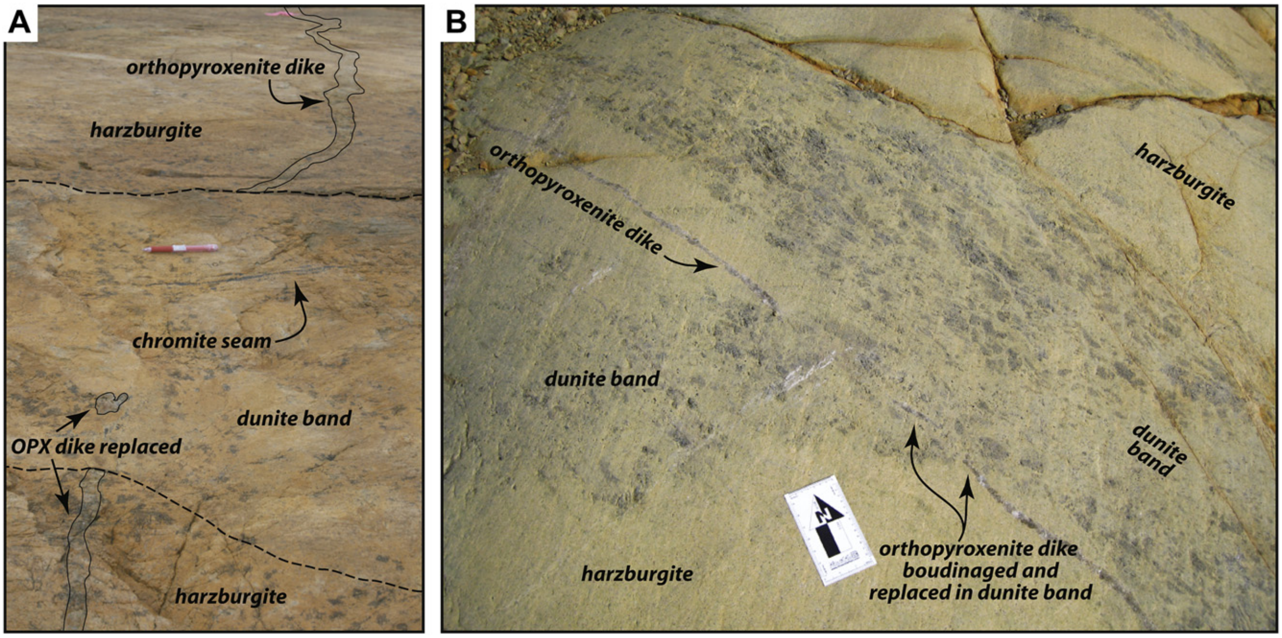

Fig. 4. (A) Representative field photograph illustrating contact relationships between early formed, variably deformed orthopyroxenite dikes and dunite bands. Notice that no relative displacement of the dike has occurred on either side of the dunite band, and that it is replaced within the band itself. (B) Characteristic porphyroclastic texture of olivine (up to 12 cm crystals) in dunite bands (i.e., melt channels) and, as in A, notice the replacement/boudinage of orthopyroxenite dike in dunite band.

3.5. Clinopyroxenite dikes

Clinopyroxenite dikes are characteristically tabular and range in width from ~1 mm to 3 cm. Dike orientations are less variable than those of earlier-formed orthopyroxenite dikes; an average orientation is approximately 009/51W (Fig. 2F). Based on field relationships, these undeformed dikes are the youngest magmatic feature in the study area and crosscut all of the structures and compositional fabrics mentioned previously, including dunite–harzburgite layers, deformed orthopyroxenite dikes, dunite bands, and tabular orthopyroxenite to websterite dikes (Fig. 2B).

3.6. Serpentinite faults

Discrete, approximately E–W striking (Fig. 2G) serpentine-bearing faults and fractures crosscut all of the magmatic features in the study area (Fig. 2A and B), and are the youngest structural features recognizable elsewhere in the Twin Sisters complex. Serpentinization associated with these features is largely restricted to fault or fracture planes and alteration of the host rock is minimal except directly adjacent to these structures (i.e., decimeter scale).

4. Deformation and strain localization features associated with dunite bands

Orthopyroxenite dikes in the Twin Sisters complex form the critical structural markers of deformation associated with the formation of dunite bands. These early formed dikes are either absent within cross-cutting dunite bands (Fig. 4), or have been displaced within bands relative to their position in the adjacent host rocks (Fig. 5A and B; Fig. 6A–C). These structural relationships preserve various styles of strain localization (e.g., continuous versus discontinuous deformation) associated with dunite band formation. In the following sections, we distinguish structural observations indicative of deformation localized *within* dunite bands, and strain localization at the margins of dunite bands that also affected proximal host rocks.

4.1. Deformation localized within dunite bands

Segments of orthopyroxenite dikes within some dunite bands have been displaced relative to their position in adjacent dunite–harzburgite layers (Fig. 5A and B; Fig. 6A–C). Where preserved, these pre-existing dikes provide structural markers of the deformation and indicate a reversal of shear sense on opposite sides of dunite bands. Abrupt gradients in the inferred displacement field in these instances suggest that strain was highly partitioned within the bands, and primarily concentrated along band margins (Fig. 5A and B; Fig. 6A–C). One such relationship is illustrated at locality NC07-15 in the surveyed map area (Fig. 2A). In this locality, an otherwise continuous and gently folded orthopyroxenite dike is displaced ~20 cm southward within a cross-cutting dunite band (Fig. 5A). To be clear, there is no net shear offset of the dike in the host rock from one side to the other of the dunite band; the offset is of the orthopyroxenite dike inside of the dunite band relative to its position on the outside. Consequently, the observed displacements require opposite sense of shear on either margin of the dunite band; dextral offset occurs on the western margin and sinistral offset on the eastern margin, indicating southward displacement of the dike segment relative to its position outside the dunite band.

These features are not found exclusively in the northern portion of the Twin Sisters massif. A particularly spectacular locality in the central portion of the Twin Sisters massif (locality TS007, Figs. 1 and 6A), approximately 2 km east of the study area of Tikoff et al. (2010), shows similar strain localization features within dunite bands. At this locality, a folded orthopyroxenite dike becomes partially dismembered and offset within a dunite band – also in a southward direction. Outside of the dunite band, there is no relative displacement of the western and eastern segments of the orthopyroxenite dike (Fig. 6A and C). However, this orthopyroxenite dike is thinned and sheared at the band margins, particularly along the eastern margin of the band (Fig. 6A–C).

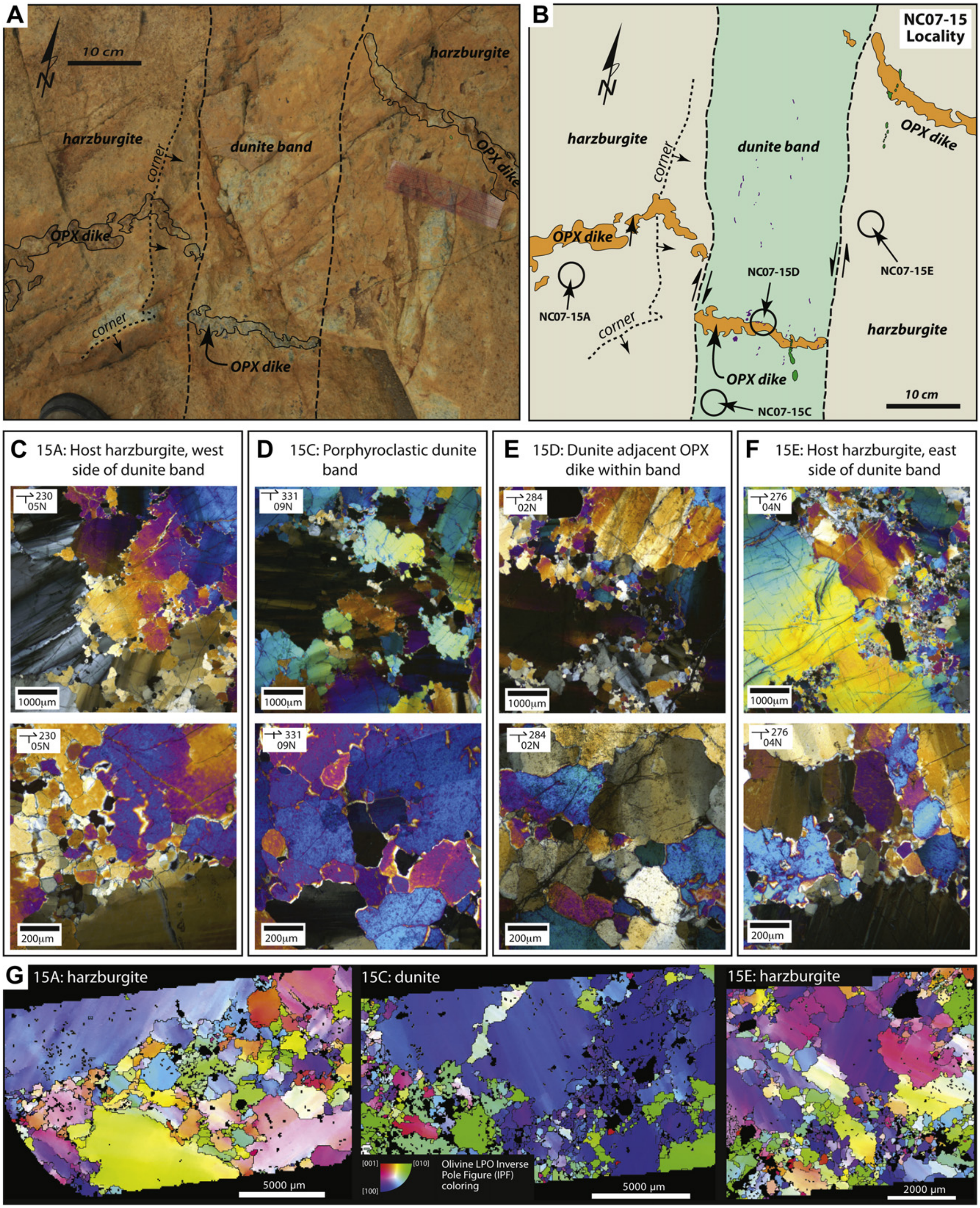

Fig. 5. Structural relationships at locality NC07-15 (see Fig. 2). (A and B) Annotated field photograph showing offset orthopyroxenite dike segment within the dunite band. Note the opposite sense of shear inferred from displacements on either side of the band (dextral on western margin, sinistral on eastern). The apparent bending of the orthopyroxenite dike outside of the dunite band is largely due to topographic effects. To be clear, the dike is gently folded to planar and the offset dike segment within the band represents true displacement along parallel margins of the dunite band relative to the continuity of the dike in the adjacent harzburgite. (C–F) Photomicrographs illustrating rock microstructures (e.g., deformation bands, undulose extinction, subgrain development, cuspate–lobate grain boundaries) and variations in the size of dynamically recrystallized grains in dunite versus harzburgite samples. (G) Electron backscatter diffraction (EBSD) Inverse Pole Figure (IPF) maps of olivine crystallographic fabrics, which are colored as a function of the olivine crystal axis orientations relative to the sample lineation. Note the strong alignment of olivine [100] in the dunite band and higher variability of the crystallographic fabrics in adjacent harzburgite samples, as shown by patchy IPF coloring.

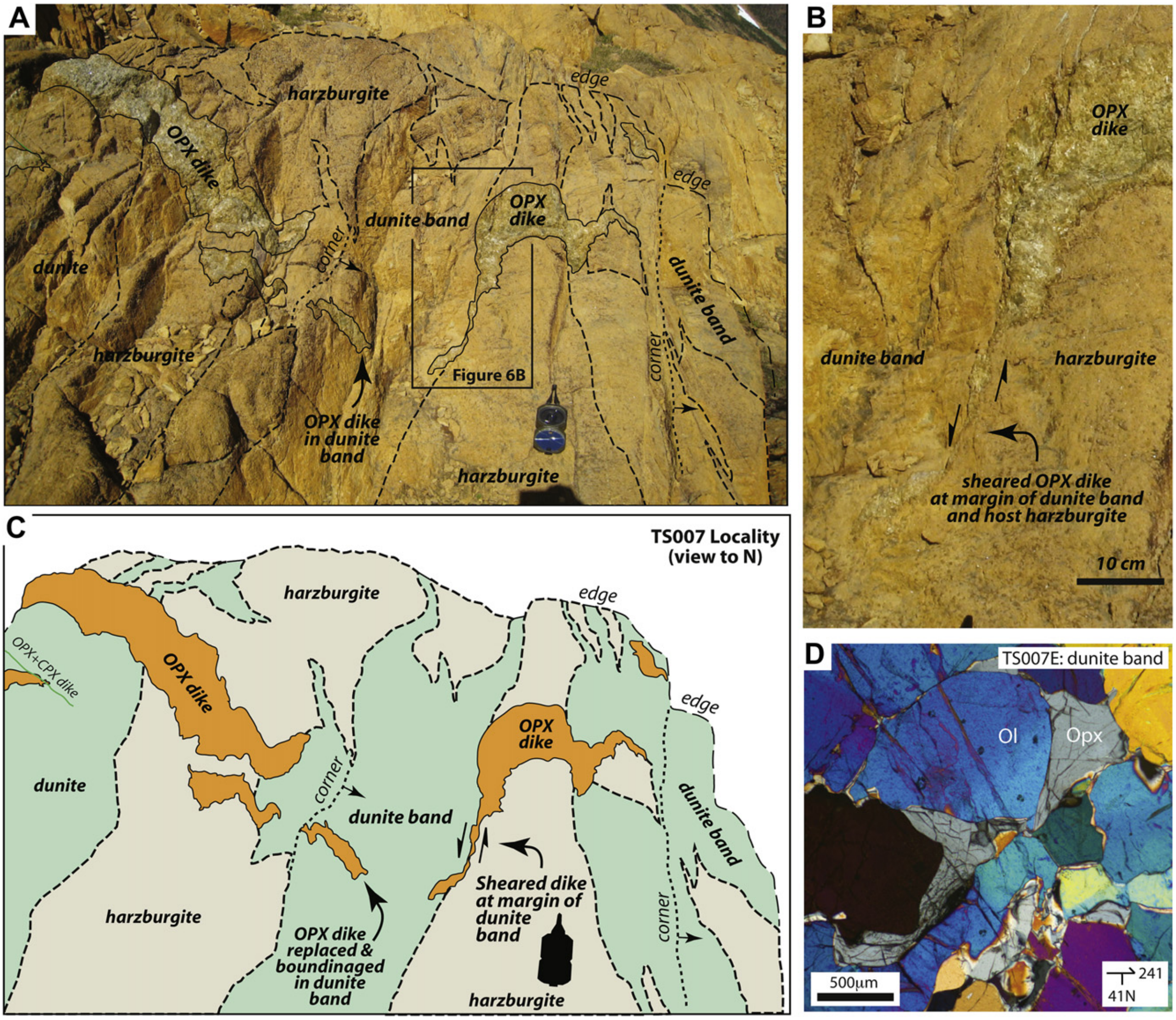

Fig. 6. (A–C) TS007 locality in the central portion of the Twin Sisters complex (see Fig. 1) showing similar localization structures to those described at NC07-15 (Fig. 5). Here, a deformed orthopyroxenite dike is discontinuous at the dunite band margin, and the segments of the dike within the band are translated south relative to their host rock continuity (Brunton for scale, points north). Strain within the dunite band was highly localized along the margin, as shown in 'B' by ductile shearing of the orthopyroxenite dike at the contact with adjacent harzburgite. (D) Photomicrograph of sample TS007E from within the dunite band illustrating the replacement of orthopyroxene by olivine + spinel, consistent with reactive melt migration in dunite channels.

4.2. Marginal dunite band deformation

The abrupt displacement gradient inferred from offset dikes within dunite bands, suggest that deformation within dunite bands was highly localized along band margins, as mentioned previously. Marginal strain localization is also recorded by discontinuous zones of cataclastic deformation that occur along the contact of some dunite bands with adjacent host rock compositional layers. At map locality NC07-14 (Fig. 2A; Fig. 3A; Fig. 7), an approximately 1–2 cm wide zone of cataclasite outcrops over a horizontal distance of ~50 cm along the western margin of a dunite band at the contact with host harzburgites. This zone of cataclasite is discontinuous (Fig. 7A and B), terminating to the south along its contact and truncated to the north by a serpentinized fault (Fig. 2A). Discrete offset of mm-scale spinel aggregates within angular grains of brecciated olivine (Fig. 7C) indicate dextral shear sense; because this deformation occurs on the western edge of the dunite band, it is consistent with south-directed shear within the dunite band.

5. Microstructural and textural analyses

Samples were collected from localities within the surveyed map area in order to characterize the rock microstructure and crystallographic fabric in dunite bands and adjacent host rock harzburgite layers associated with strain localization features. Samples were collected from two regions (NC07-14 and NC07-15; Fig. 2A; Figs. 5 and 7) using a hand-held, gasoline-powered rock drill, and rock cores were oriented in the field.

5.1. Microstructures

Host dunite–harzburgite layers and cross-cutting dunite bands show a range of dynamic microstructures, which include: (1) deformation bands (Fig. 5C and D; Fig. 7D and H), (2) patchy undulose extinction (Fig. 5E; Fig. 7D), (3) lobate–cuspate grain boundaries (Fig. 5D–F), (4) subgrains (Fig. 5E; Fig. 6D), and (5) smaller, recrystallized grains (e.g., Fig. 7G). Olivine and pyroxene

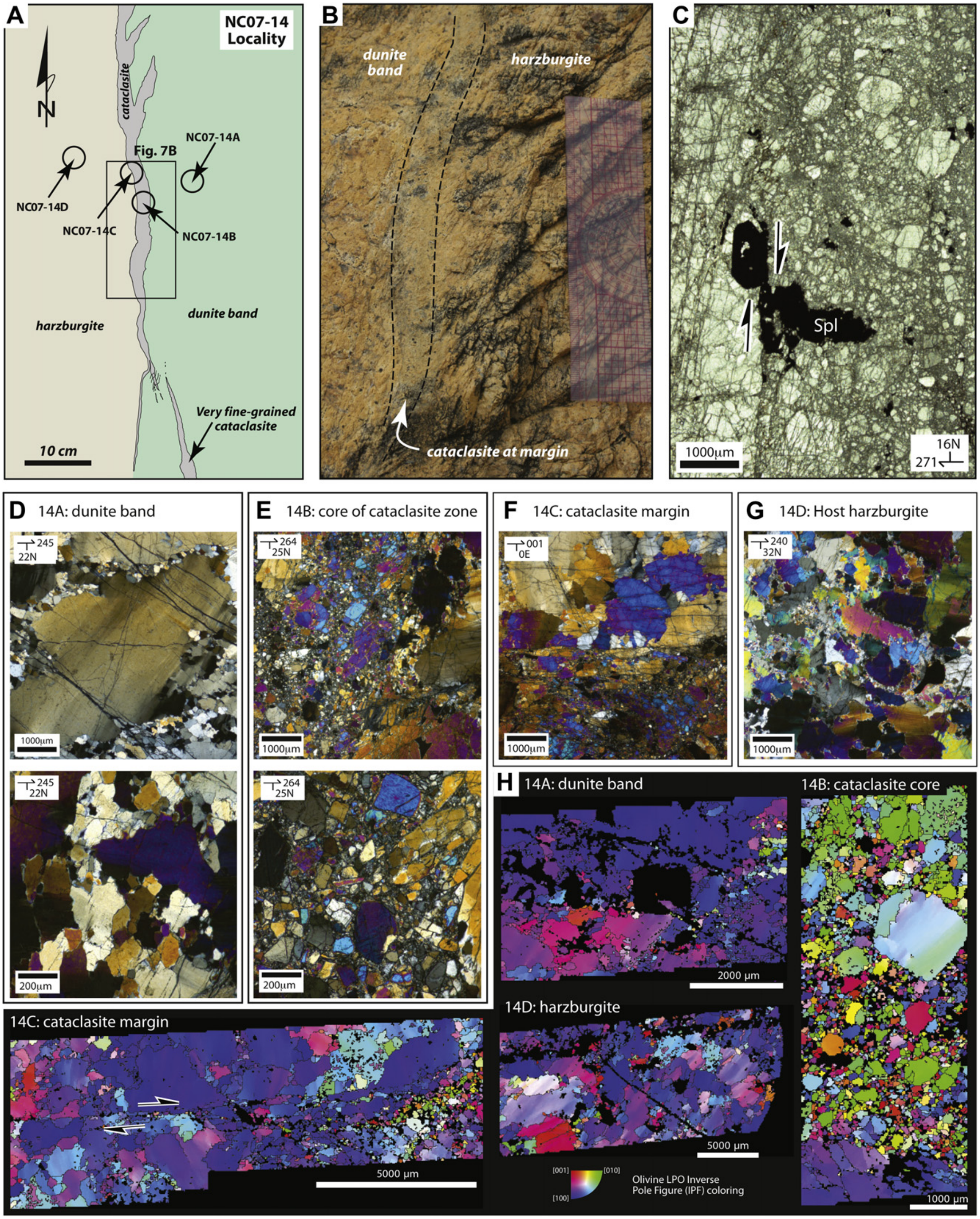

Fig. 7. Structural relationships at locality NC07-14 (see Fig. 2). (A and B) Close up of the dunite band – harzburgite contact shown in Fig. 3A, highlighting a zone of marginal, discontinuous cataclasite. (C) Plane light photomicrograph of sheared spinel grain at the cataclastic margin of dunite band; note also the orientation of the thin section and observed dextral offset indicating southward-directed shear in the cataclasite. (D–G) Photomicrographs illustrating similar rock microstructures to those in Fig. 5 and deformation features associated with the development of cataclasite (microfracture, angular fragments of olivine). Note also the lack of serpentinization in the groundmass of the cataclasite. (H) Electron backscatter diffraction (EBSD) Inverse Pole Figure (IPF) maps of olivine crystallographic fabrics, which are colored as a function of the olivine crystal axis orientations relative to the sample lineation. All samples show a strong alignment of olivine [100] parallel to lineation, with the exception of NC07-14B which is in the core of the cataclasite zone. The olivine IPF map of sample NC07-14C also illustrates the partial resetting of olivine crystallographic fabrics in the adjacent dunite during subsequent progressive shear development of the cataclasite zone.

grain sizes are highly variable in all of the samples analyzed, placing poorly constrained estimates on average grain sizes. However, large grains typically range in size from 0.5 to 10 mm in diameter (e.g., sample NC07-15C: Fig. 5D and G), and are commonly decorated by smaller (30–400 μm diameter) recrystallized grains of olivine, giving rise to a characteristic porphyroclastic olivine texture in both host dunite–harzburgite layers and dunite bands (Fig. 5E; Fig. 7D). Optical photomicrographs and textural maps of olivine lattice preferred orientation (LPO; discussed in more detail in the following sections) from large porphyroclasts illustrate numerous deformation bands with undulose extinction, which are commonly kinked at twin boundaries (Fig. 7D and H). Fine-grained olivine (∼30–50 μm diameter) is also observed as dynamically recrystallized grains along some deformation bands within larger porphyroclasts.

Subgrains and grains without undulose extinction (i.e., dynamically recrystallized grains) are present in both host-rock dunite–harzburgite layers and cross-cutting dunite bands. Recrystallized grain sizes and neoblasts of olivine are typically coarser in dunite bands than host harzburgite layers. These relationships are visible in Figs. 5 and 7 by comparison of the recrystallized grain size surrounding olivine porphyroclasts in dunite bands (∼50–100 μm diameter) versus adjacent harzburgite (∼30–50 μm diameter). Textural maps of olivine LPO similarly document a finer recrystallized grain size of olivine in harzburgite domains (e.g., sample NC07-15E; Fig. 5G), the implications of which are discussed in later sections.

A number of microstructural observations suggest the replacement of orthopyroxene by olivine (±spinel) within dunite bands. One such relationship is illustrated in Fig. 6D where an undeformed olivine neoblast impinges upon reacted orthopyroxene along its margins. In other samples, orthopyroxene grains show partially reacted and serrated grain boundaries adjacent to olivine. All phases show irregular interpenetrating grain boundaries (e.g., lobate–cuspate boundaries in olivine; Fig. 5D), with olivine and pyroxene sometimes displaying a weak shape-preferred orientation parallel to the lineation defined by spinel. Spinel is distributed randomly in most samples and it has irregular, elongate grain shapes generally <1 mm (Fig. 7C).

Samples from discontinuous zones of cataclasite at the margins of dunite bands show additional features indicative of discontinuous, subsolidus deformation. Ortho- and clinopyroxene are largely absent in the samples of cataclasite, indicating that the cataclasite preferentially formed within dunite at the contact with adjacent harzburgite. Alteration minerals, such as serpentinite, are largely absent in the groundmass of the cataclasite (Fig. 7C and E). Textural maps of olivine LPO (from sample NC07-14C; Fig. 7H) illustrate the evolution of microstructural development of cataclasite within the pre-existing dunite. Porphyroblasts of olivine record intracrystalline shearing on highly localized fracture planes and a progression to pervasively distributed fracture (Fig. 7F) and dynamic recrystallization. Angular grains of brecciated olivine are variably rotated during progressive shear along cataclastic margins and range in size from ∼10 μm to >1 mm in diameter (Fig. 7E).

5.2. Lattice preferred orientation (LPO) data

5.2.1. Methods

Lattice preferred orientation (LPO; textural) data were collected using electron backscatter diffraction (EBSD). Oriented thin sections were polished using chemical–mechanical methods (employing either colloidal silica or alumina oxide) to remove mechanical damage of the sample surface and ensure defined backscattered electron patterns. EBSD data were collected at the University of Wisconsin–Madison on a Hitachi S3400N scanning electron microscope (SEM) equipped with an Oxford Instruments phosphor screen EBSD detector. The SEM was operated in ‘variable pressure’ mode, with a typical beam current of 70–85 and accelerating voltage of 20 keV. Backscatter patterns were acquired and matched to simulated patterns (i.e., indexed) using HKL CHANNEL5 software. The analytical method is described in detail by Prior et al. (1999).

Crystallographic orientation data were collected using a range of step sizes depending on the grain size. Step sizes were commonly 2.5–3 times smaller than the diameter of the smallest average grain of interest (∼30 μm diameter), in order to ensure multiple solutions within each single grain. Consequently, apparent ‘grains’ composed of only one or two indexed points were removed from the dataset in order to minimize the impact of mis-indexed crystal orientations on the resulting LPO. The methodology described by Bestmann and Prior (2003) was used in order to produce microstructural maps of the EBSD data (Fig. 5G; Fig. 7H), from which one point per grain orientation data sets were calculated for grains separated by misorientation boundaries of ≥10°. Only one orientation point per automatically-detected grain was plotted on the pole figures in order to produce results comparable with data collected by universal stage techniques (c.f. Webber et al., 2008). In the samples analyzed, pyroxenes constitute a relatively minor phase by mode, and consequently insufficient grains were analyzed to yield statistically meaningful pole figures for pyroxene. We therefore restrict our discussion in the following sections to LPO fabrics in olivine. Olivine pole figures are plotted in both the kinematic and geographic (lower hemisphere) reference frames (Fig. 8) in order to facilitate correlation between standard olivine LPO fabric types that are defined in the kinematic reference frame and structural fabrics measured in the field.

In the following section, we present the results of new olivine LPO data from dunite bands and adjacent host rock harzburgites associated with strain localization features in the current study area. We then discuss these LPO patterns in the context of previous studies of LPO fabric in the Twin Sisters complex.

5.2.2. Results

The host rock adjacent to dunite bands in both the NC07-14 and NC07-15 localities is dominated by harzburgite. Olivine [100] in harzburgite define point maxima of varying intensity (Fig. 8), which are moderately inclined relative to the lineation measured in the field (15°/354° average orientation; Fig. 2C). Olivine [010] are typically distributed in girdles (NC07-14D; Fig. 8A) or display multiple maxima (NC07-15A; Fig. 8B) perpendicular to [100]; no consistent patterns of [001] were observed in harzburgite samples. Dunite bands record a less complex olivine LPO than observed in the harzburgite layers (e.g., NC07-14A; Fig. 8D). In these bands, [100] are consistently sub-parallel to the lineation measured in the field, and [010] maxima are typically subparallel to the pole to foliation; sample NC07-14C is one exception that shows [010] maxima in the plane of the foliation, suggesting slip on (001).

Relationships between olivine LPO and microstructure are illustrated by Inverse Pole Figure (IPF) maps, which are colored as a function of the olivine crystal axis orientations relative to the sample lineation (Fig. 5G; Fig. 7H). Porphyroclasts of olivine show alignment of [100] parallel to the lineation in both dunite and harzburgite samples, as indicated by the predominance of olivine grains with blue-indigo coloring in the IPF maps. Some olivine porphyroclasts also show a weak alignment of [001] parallel to lineation (magenta grains: Fig. 5G; Fig. 7H), particularly in grains with abundant deformation bands (e.g., sample NC07-14D; Fig. 7H).

Patterns of olivine LPO from harzburgite samples immediately adjacent, and on opposite sides of a dunite band at locality NC07-15 (Fig. 5A) record a complex pattern of olivine LPO (relative to dunite

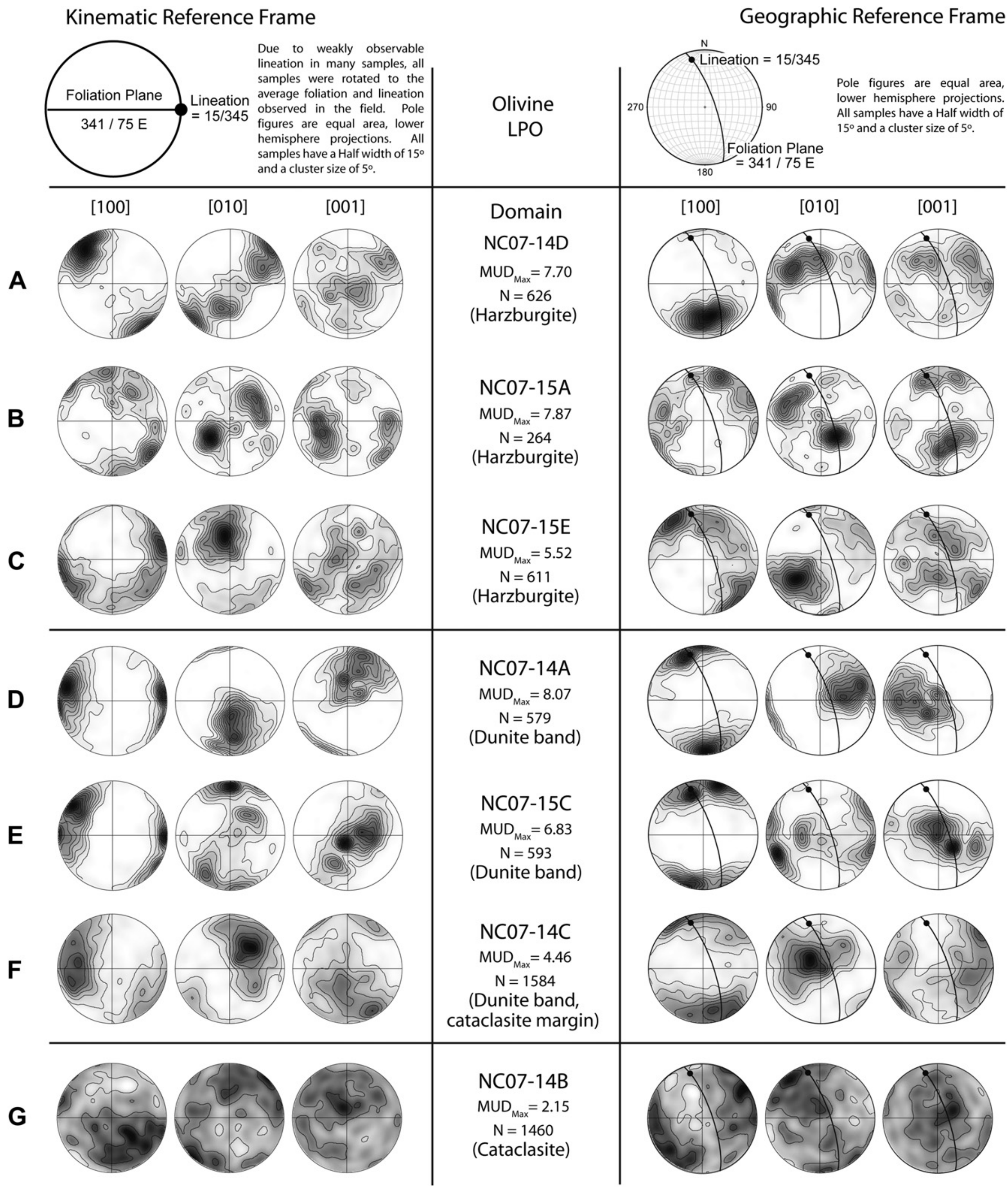

Fig. 8. Olivine pole figures plotted in the standard kinematic and geographic reference frames for select samples of the Twin Sisters peridotites at the NC07-14 and NC07-15 localities (see Fig. 2). All pole figures are plotted as lower-hemisphere, one point per grain. MUD = multiples of uniform density.

bands) with concentration of olivine [100] inclined relative to lineation measured in the field (Fig. 8B and C). When LPO data are plotted in the geographic reference frame (Fig. 8), the rotation of olivine [100] maxima are consistent with the sense of shear inferred from dike offsets within dunite bands. For example, at locality NC07-15, harzburgite adjacent to the western margin of a dunite band (sample NC07-15A; Fig. 9) shows clear clockwise rotation of olivine [100] by approximately 15° relative to the orientation of lineation, and olivine [100] maxima from samples within the adjacent dunite band (Fig. 9). This rotation is consistent with dextral shear of the host harzburgite along this margin, and with offsets inferred from orthopyroxenite dike segments

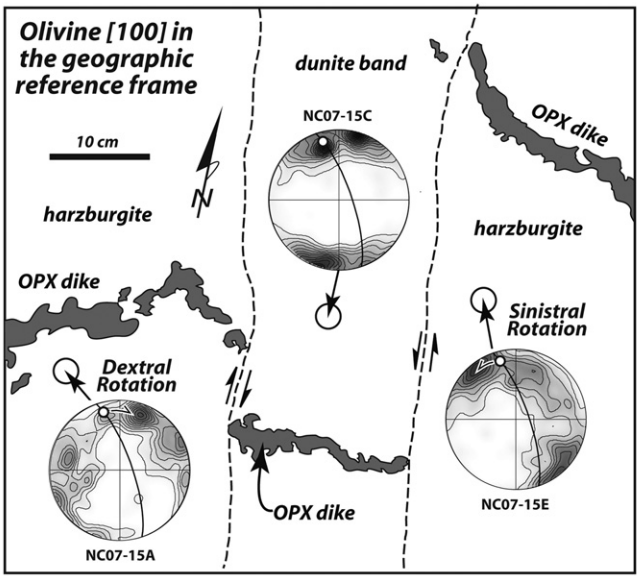

Fig. 9. Olivine [100] plotted in the geographic reference frame and their position relative to the localization feature described at the NC07-15 locality. Olivine [100] within dunite bands are parallel to band margins and the lineation orientation measured in the field. However, maxima of olivine [100] in harzburgite adjacent to dunite bands are rotated relative to the trend of regional fabrics, and in a sense consistent with the observed offset of the orthopyroxenite dike in the dunite band.

(Fig. 5A and B). In contrast, harzburgite adjacent to the eastern margin of the dunite band (NC07-15E) demonstrates counterclockwise rotation of [100] (also by approximately 15°), consistent with sinistral shear of the harzburgite host rock along this margin (Fig. 9). The patchy coloring of olivine IPF maps in harzburgite from locality NC07-15 also indicate the variable orientation of olivine axes relative to the orientation of lineation mapped in the field (e.g., samples NC07-15A, E; Fig. 5G).

Samples taken from the margin of discontinuous cataclasites (NC07-14C; Fig. 7A; Fig. 8F) show olivine LPO patterns that are broadly consistent with those in the adjacent dunite bands (cf. NC07-14A; Fig. 8D). LPO results and olivine IPF maps also indicate a weakening of [100] alignment at the dunite–cataclasite margin, as shown by increasingly variable IPF coloring within the core of the cataclasite in sample NC07-14C (Fig. 7H). The weakening of the olivine fabric is most pronounced for samples entirely within cataclasite domains (NC07-14B; Fig. 7H; Fig. 8G).

6. Discussion

6.1. Dunite bands as former zones of melt migration

The most striking structural features in the ultramafic rocks of the Twin Sisters involve the presence, and interactions with, porphyroclastic-textured dunite bands. Dunite bands in exposures of upper mantle peridotites are commonly interpreted to represent former conduits of melt migration (e.g., Quick, 1981; Kelemen et al., 1997 and references therein). Since mid-ocean ridges basalts (MORB) are not in chemical equilibrium with the upper mantle materials through which they ascend, it requires that partial melt migration be focused through chemically isolated high-permeability melt-enriched channels (e.g., Spiegelman and Kenyon, 1992; Hart, 1993; Kelemen et al., 1995a,b; 1997). Dunite bands are inferred to develop as percolating, olivine-normative basalts react with residual harzburgites in the upper mantle, preferentially dissolving pyroxene and precipitating olivine – the geologic expression of this melt migration process being dunite channels in exhumed mantle peridotites (e.g., Braun and Kelemen, 2002, and references therein).

Dunite bands in the Twin Sisters ultramafic rocks display structural features suggesting that these zones also likely formed as a result of reactive, channelized melt migration. These features include: (1) cross-cutting relationships between dunite bands and primary compositional layers and early-formed orthopyroxenite dikes (Figs. 3 and 4); (2) the absence, or partial replacement, of orthopyroxenite dikes within dunite bands – these dikes are otherwise continuous within the host rock on either side of bands (Fig. 4); and (3) reaction microstructures within dunite bands indicating the formation of olivine (±spinel) at the expense of orthopyroxene (Fig. 6D). We therefore interpret these distinct porphyroclastic-textured dunite bands to represent former pathways of melt migration in the mantle (i.e., melt channels). It is in this context that we evaluate the formation of strain localization features within the Twin Sisters ultramafic complex.

6.2. Melt-strain interactions and implications for deformation localization

Results from experimental rock deformation studies (e.g., Hirth and Kohlstedt, 1995a,b; Bai et al., 1997; Holtzman et al., 2003a,b; Holtzman and Kohlstedt, 2007; King et al., 2010), numerical simulations (e.g., Katz et al., 2006; Butler, 2009; Liang et al., 2010), and geological investigations (e.g., Kelemen and Dick, 1995; Dijkstra et al., 2002; Le Roux et al., 2008; Kaczmarek and Tommasi, 2011) have shown that a positive feedback exists between melt segregation and deformation in the upper mantle. Deformation may favor the stress-driven segregation of melt into high permeability bands (e.g., Kohlstedt and Holtzman, 2009, and references therein; King et al., 2010, 2011a,b), thereby also increasing melt flux through channels (Daines and Kohlstedt, 1994; Aharonov et al., 1995). Similarly, the presence of melt-rich regions may focus deformation (and therefore subsequent melt flow), as has been suggested for the initiation of some upper mantle shear zones in exhumed peridotite bodies (e.g., Kelemen and Dick, 1995; Dijkstra et al., 2002). Field-based studies in naturally deformed upper mantle rocks which address the dynamic feedbacks between melt migration and deformation are therefore fundamental to furthering our understanding of the mechanical behavior and evolution of the lithosphere.

Strain localization features associated with melt migration (i.e., dunite channels) in our study include: (1) the presence of offset orthopyroxenite dike segments within dunite bands; (2) host rock deformation proximal to dunite bands; and (3) discontinuous cataclastic deformation at the contact of some dunite bands with primary host rock compositional layers. These features highlight the importance of dynamic feedbacks between channelized melt flow and the partitioning of deformation in the ultramafic rocks of the Twin Sisters complex, with some important distinctions.

The fact that orthopyroxenite dike segments on either side of cross-cutting dunite bands project along strike to one another (i.e., are not offset) suggests that dunite bands (melt channels) did not act to accommodate net shear displacement across channel margins (i.e., they did not at as simple or general shear zones). This observation is consistent with patterns expected for dunite bands formed by reactive melt migration, compelling field examples of which are illustrated in Kelemen et al. (1995b). However, the displacement of orthopyroxenite dike remnants contained entirely within dunite bands (Fig. 5A and B; Fig. 6A–C) suggest that strain localization, and thus material flow, also accompanied the formation of melt channels.

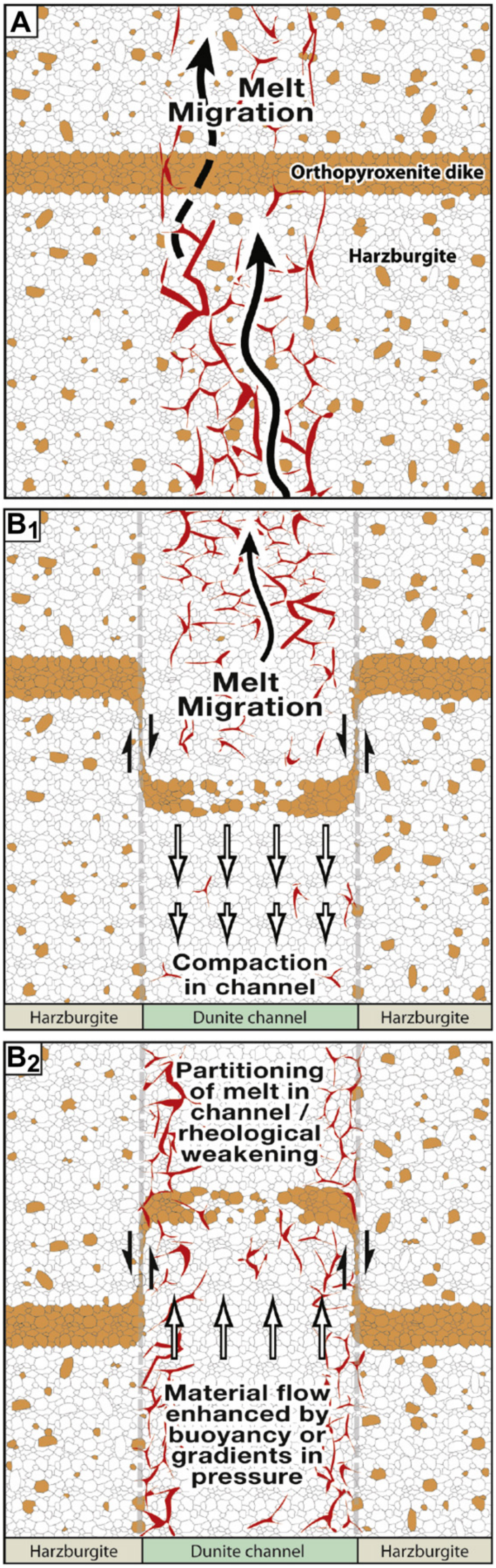

Fig. 10. (A) In the Twin Sisters complex, the formation of dunite bands likely initiated by migration of ascending partial melts that organized into high permeability channels, preferentially dissolving pyroxene and precipitating olivine (±spinel). Schematic diagrams (B_1 and B_2) illustrate processes that may have facilitated (or enhanced) the localization of strain during melt channel formation and coaxial deformation throughout the peridotite body. It should be noted that the processes shown in B_1 and B_2 are not mutually exclusive. During melt migration, the velocity fields of melt segregation and matrix compaction are coupled such that reaction, melt migration, and incremental matrix compaction within the channel over time could have produced the observed offsets and inferred displacement gradients seen in the field (B_1). Numerical simulations have shown that compaction in the central and portions of dunite channels, potentially enhanced by in situ crystallization, may also force melt to localize along opposite boundaries of a dunite channel (B_2) (cf. Liang et al., 2010). The redistribution of melt within channels in this manner would also promote rheological weakening and strain localization by reducing the local viscosity at the margin of the dunite bands (Hirth and Kohlstedt, 1995a,b; Bai et al., 1997; Rosenberg and Handy, 2005); this process could also explain localized displacements primarily along band margins. Buoyancy and/or pressure gradients within channels during melt migration may also have been important driving forces that enhanced strain localization and the partitioning of deformation within channels.

The displacement field inferred from structural markers in our study area indicate that deformation was localized almost entirely within melt channels, particularly at channel margins, and in the absence of relative displacement of the adjacent host rocks. An important observation is that the margins of dunite bands containing orthopyroxenite dike offsets are parallel, and therefore the observed displacements cannot be explained by motion of shallowly intersecting conjugate shear zones. The inferred velocity gradient is similar to that of plug flow (i.e., confined flow in a pipe or channel without a pronounced radial velocity gradient), movement of a syringe, a “punched” laccolith (bysmalith), or flow of magma within dikes. Strain patterns similar to those inferred from the dike offsets are consistent with strain partitioning in a non-Newtonian fluid during coaxial deformation in which the direction of maximum shortening is normal to the band orientation, producing a 2-D-like Poiseuille flow. Dunite band margins are orientated N–S in the study area and coaxial deformation involving E–W shortening and vertical and N–S elongation has been documented by Tikoff et al. (2010), suggesting that localized coaxial shear could result in the observed displacements. Similar displacement gradients have also been described around sinking blocks in Newtonian salt structures (Burchardt et al., 2011), which may correspond to deformation zones formed in the wake of a body moving through a viscous medium (Koyi et al., 2011). An important question remains, however, as to whether or not the observed strain localization occurred contemporaneous with melt migration.

Rock deformation studies by Holtzman et al. (2005) convincingly demonstrated that strain partitioning between melt-enriched bands and melt-depleted lenses was necessitated by the coupling of the velocity fields in the two regions which were undergoing simultaneous melt reorganization and matrix compaction during deformation. Accordingly, interactions between compaction, dissolution/reaction, and melt migration could account for some of the observed offsets within dunite bands (Fig. 10B_1). Evidence for dissolution and reaction are well documented in the Twin Sisters dunite bands by olivine (±spinel) replacement of orthopyroxene within dunite bands (Fig. 6D), suggesting that these processes likely contributed to modification of features within dunite bands. Recent numerical simulations by Liang et al. (2010) show that compaction in the central portions of dunite channels, potentially enhanced by in-situ crystallization, may force melt to localize along opposite boundaries of a dunite channel (Fig. 10B_2). Experimental rock deformation studies in melt–solid systems further show substantial rheological weakening that is driven by a decrease in rock viscosity, even at low melt fractions (Hirth and Kohlstedt, 1995a, 1995b; Bai et al., 1997; Rosenberg and Handy, 2005). If melt was partitioned along the margin of dunite channels, as suggested by the results of Liang et al. (2010), this redistribution of melt would have favored a reduction in local viscosity and the localization of strain along dunite band margins.

These results are particularly relevant to our current study in light of the inferred abrupt displacement gradients at the margins of melt channels with the adjacent host rocks. Variations in melt fraction within dunite bands may also have resulted in gradients in the effective pressure of the melt phase, causing melts to migrate from regions of higher melt fraction to lower melt fraction (Stevenson, 1989; Kohlstedt and Holtzman, 2009, and references therein). The redistribution of melt via this process may have also facilitated the localization of strain within some dunite channels and adjacent host peridotites, particularly if enhanced by buoyancy (Rabinowicz et al., 1987; Butler, 2009) or pressure-driven flow (Fig. 10B_2) during coaxial deformation of the host peridotites.

6.3. Host rock deformation and strain localization at the margin of dunite bands

Previous studies of olivine LPO in samples distributed throughout the Twin Sisters complex document a concentration of olivine (010) planes sub-parallel to the average NNW-SSE-striking, steeply ENE-dipping tectonite foliation, indicating this orientation is the preferred glide plane (Christensen, 1971, 2002). Ferré et al. (2005) reported olivine LPOs indicating [100](010) slip, consistent with dislocation creep at temperatures exceeding 1000 °C. Girdle-type [100]{0kl} olivine LPO (i.e., Pencil Glide) have also been reported in primary compositional layers of the Twin Sisters ultramafic complex (e.g., Christensen, 1971; Toy et al., 2010).

The results of our new EBSD textural analysis indicate that dislocation creep was the dominant deformation mechanism during high-temperature plastic flow of the Twin Sisters peridotites at upper mantle conditions. Olivine in harzburgites have [100] aligned parallel to the macroscopic field lineation (Fig. 2C) and girdled distributions of [010], which is broadly consistent with activation of [100]{0kl} slip (Fig. 8). The preservation of double maxima in some samples (e.g., NC07-15A; Fig. 8B) may, however, suggest incomplete overprinting of an inherited olivine fabric in the harzburgite during subsequent deformation (cf. Webber et al., 2010). Olivine LPO in dunite bands is dominated by [100](010) slip and, in some samples, may also indicate slip on (001) (e.g., NC07-14C, Fig. 8F). For olivine, [100](010) slip ("Type A") is inferred to occur at high-T and low-strain rate or low flow stress conditions, whereas [100]{0kl} (i.e., pencil glide, "Type D") slip, is thought to be activated at lower temperatures and higher strain rates or higher flow stresses (cf. Carter and Ave'Lallemant, 1970; Ben Ismail and Mainprice, 1998). Variations in olivine LPO between dunite bands and harzburgite, therefore, likely correspond to variations in the local deformation conditions experienced by both domains; for example, dunite bands may have experienced lower flow stress or higher temperature conditions relative to host harzburgite layers. The larger recrystallized grain size in dunite bands (~50–100 μm diameter) relative to harzburgite domains (~30–50 μm diameter) is consistent with this interpretation. However, differences in the modal abundance of pyroxene between domains may have also influenced the dominant olivine slip systems due to the effects of grain boundary pinning or grain boundary sliding (e.g., Warren et al., 2008). A change in the dominant slip plane from (010) to (001) in some dunite samples may also suggest that some of the variation in olivine LPO results from the effects of melt present deformation, as has been described in other studies (e.g., Holtzman et al., 2003b; Tommasi et al., 2006; Kaczmarek and Tommasi, 2011).

Olivine LPO in harzburgite adjacent to dunite bands documents opposite rotation of olivine [100] on band margins (Fig. 9). There are two important results to this LPO data: First, the host rock immediately adjacent to the dunite bands is deformed. The extent of this deformation is unknown, and the fact that the offset dike is gently folded does not allow us to evaluate this amount with confidence. Second, the sense of shear given by the rotation of olivine [100] is consistent with the offset of deformed orthopyroxenite dike segments observed at the outcrop scale (Fig. 5A and B). Thus, the strain that localized within dunite bands to produce the observed dike offsets also induced host rock deformation proximal to the dunite bands. The observation that olivine crystallographic fabrics within dunite bands are parallel to dunite band margins and to structural fabrics measured in the field (Fig. 8E), suggests that the rotation of crystallographic fabrics likely occurred during distributed coaxial shear in the host rock, which was localized within the dunite bands and facilitated by melt-induced rheological weakening (e.g., Hirth and Kohlstedt, 1995a,b). This inference is supported by microstructural observations indicative for former melt migration in dunite channels, as discussed previously. Strain localization within and proximal to dunite channels may have been further enhanced during deformation if other processes (e.g., compaction, heterogeneous melt distribution) were significant.

Discontinuous zones of cataclasite adjacent to dunite bands mark a change from continuous (i.e., 'ductile') deformation conditions to discontinuous (i.e., 'brittle') deformation that was highly localized at the contact of dunite bands with the adjacent host rocks (Fig. 7). Zones of cataclastic deformation lack significant serpentinite (Fig. 7E and F), suggesting that they were formed under relatively high deformation temperatures, and/or in the absence of fluids. For clarity, we do not associate the formation of these cataclasites with melt-present deformation features that are inferred to have resulted in the observed dike offsets within dunite channels. Rather, we suggest that subsequent sub-solidus deformation localized shear along dunite band margins due to the rheological heterogeneity that was imparted within the host peridotites by their formation and subsequent crystallization. This inference is supported by the discontinuous nature of cataclasites observed in the field, and the incomplete resetting of olivine [100](010) fabrics during progressive shear along dunite band margins that resulted in the development of the cataclasite zones.

Sub-solidus shear localization has also been reported within the Twin Sisters complex in a region less than 20 m east of our map area shown in Fig. 2A; here, an ultramylonite shear zone displaces orthopyroxenite and (structurally late) clinopyroxenite dikes with a sinistral sense of shear (Toy et al., 2010). Strain localization in this locality is inferred to have been promoted by a switch from dislocation creep to grain size sensitive creep in a region between orthopyroxenite dike segments within the host peridotites, due to the effects of grain boundary pinning and rheological heterogeneities associated with the orthopyroxenite dike (Toy et al., 2010). The results of two-pyroxene geothermometry indicates that this shear zone equilibrated at temperatures of ~650–750 °C, and therefore formed late relative to the host-rock fabrics, perhaps coeval with the formation of discontinuous zones of cataclastic deformation along some dunite band margins.

7. Conclusions

The results of our study document the interactions between deformation and melt migration in naturally deformed ultramafic rocks of the Twin Sisters complex, Washington state. Dunite bands that crosscut primary compositional layers in the host rock, and variably deformed orthopyroxenite dikes record numerous structural features indicative of dynamic mesoscale strain localization associated with the formation of melt channels. Orthopyroxenite dikes that are offset within melt channels relative to their position in the adjacent host rocks provide structural markers of this localized deformation, and indicate a reversal of shear sense on opposite sides of channels. We interpret these displacement patterns to suggest that melt-induced weakening facilitated the localization of strain within channels, which may have been enhanced by matrix compaction within channels, anisotropic melt distribution, pressure-driven flow in channels, or a combination of these processes.

An important implication arising from our study, is that a significant portion of finite strain, and hence bulk material flow, may actually be accommodated within the channelized melt migration networks in the upper mantle. In our study area, strain is largely isolated to within melt channels. These zones did not act as simple or general shear zones to accommodate differential motion of host peridotites on opposite sides of melt channels, though they may have formed in part by strain localization in a coaxial deformation regime. The recognition of both continuous (i.e., proximal host rock deformation, ductile shear of orthopyroxenite dikes) and discontinuous deformation zones (i.e., zones of cataclasite) at the margins of dunite bands are interpreted to reflect strain localization in the upper mantle under changing deformation conditions and material properties (cf. Drury et al., 1991). Strain localization within the Twin Sisters ultramafic complex was facilitated by channelized melt migration, which also imparted compositional heterogeneities that further localized shear deformation.

Furthermore, our results document strain localization structures in the upper mantle on spatial scales similar to those observed in the crust. These data add to a growing body of experimental and numerical data and field studies that emphasize the dynamic feedbacks between melt and strain localization in the upper mantle, and the effects of compositional heterogeneities on patterns of mantle deformation.

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