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# Variable microstructure of peridotite samples from the southern Mariana Trench: evidence of a complex tectonic evolution

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ABSTRACT

We retrieved samples of peridotite from a dredge haul (KH92-1-D2) collected during Cruise KH92-1 undertaken by the research vessel (R/V) *Hakuho* in 1992 at the landward trench slope of the southern Mariana Trench (11°41.16'N, 143°29.62'E; depth 6594–7431 m), which is the deepest ocean in the world. Ten of 30 retrieved samples possessed both a foliation and lineation, as assessed from 46 thin sections of various orientations and observations of hand samples. The samples showed marked variation in microstructure, ranging from coarse (> 5 mm) equigranular and intensely elongated textures to finer (< 1 mm) porphyroclastic and fine-grained equigranular textures. Olivine fabrics also varied among the different samples, with (010)[100] and (010)[001] patterns (termed A- and B-type, respectively) observed in samples with coarse textures and no clear patterns observed in samples with fine textures. Even though the peridotite samples were retrieved from a single dredge site, some contain primary tectonic microstructures and some contain secondary microstructures. Recent bathymetric and topographic analyses indicate that the lithosphere in this region is as thin as 20 km. Such a thin lithosphere may have been intensely deformed, even perhaps in the ductile regime, during fore-arc extension; consequently, the observed variations in microstructure within the peridotite samples probably reflect the complex tectonic evolution of the southern Mariana region.

Keywords: mantle wedge, crystal-preferred orientation, olivine, Mariana Trench, subduction, slab tear, microstructure, Challenger Deep

## 1. Introduction

The Mariana Trench marks the location at which the Pacific plate subducts beneath the eastern edge of the Philippine Sea plate (Fig. 1A). The Challenger Deep, part of the southern Mariana Trench southwest of Guam, is the deepest oceanic trench in the world, and is up to 2 km deeper than the average depth along the axis of the Mariana Trench (Fujioka et al., 2002; Fryer et al., 2003; Gvirtzman and Stern, 2004). The strike of the trench changes from north–south in the northern section to east–west in the south (Fig. 1A). The fore-arc narrows southward and the trench–arc distance decreases until a point near the island of Guam where the Mariana Ridge comes within about 150 km of the Mariana Trench (Fig. 1A).

The southern Mariana Trench appears to be associated with active steepening of the subducting slab along a zone of weak coupling with the overriding plate related to tearing of the slab (Fryer et al., 2003; Gvirtzman and Stern, 2004). From north to south along the trench, the position of the asthenospheric wedge between the subducting and overriding plates progressively moves upward and trenchward; the wedge appears to be extremely shallow in the southern part of the trench (≤ 20 km; Fig. 1B; Gvirtzman and Stern, 2004).

The Mariana Trench lacks an accreted sedimentary prism (Ishii, 1985; Bloomer and Fisher, 1987) and consists mainly of mafic and ultramafic igneous rocks that are typical of island arc ophiolites (Natland and Tarney, 1982). Serpentinized peridotites have been dredged, drilled, and sampled by submersibles at several localities on the landward slopes of the trench (Dietrich et al., 1978; Bloomer, 1983; Fryer, 1992; Ishii et al., 1992, Ohara and Ishii, 1998). These peridotites have mostly been studied in terms of their petrological features. Although the active tectonics of the area in which the peridotites occur, along the southern and deepest part of the Mariana Trench, has been recently considered (e.g., Fujioka et al., 2002; Fryer et al., 2003; Gvirtzman and Stern, 2004), the structural characteristics of the peridotites remain ambiguous. In the present paper, we demonstrate that the peridotite samples record contrasting microstructures, ranging from coarse-grained to fine-grained textures and a wide range of olivine fabrics, and that this variation possibly reflects dynamic processes within the southern Mariana region.

## 2. Dredge sampling and sample preparation

Peridotite samples analysed in this study were retrieved in 1992 from a dredge haul (KH92-1-D2) collected by the University of Tokyo research vessel *Hakuho* (now operated by the Japan Agency for Marine-Earth Science and Technology) during Cruise KH92-1 over the landward Mariana Trench slope at 11.5°N, adjacent to the Challenger Deep (Fig. 1A; Ishii et al., 1993; Ohara and Ishii, 1998). The dredge haul recovered more than 500 ophiolitic samples (280 kg in total weight), including serpentinized peridotite, pyroxenite, and various metamorphic rocks. The samples are angular, 1–50 cm in diameter, and have a thin coating of Mn-oxide. The samples appear to be derived from large talus ramps fed from outcrops on the inner trench slope, rather than from diapiric serpentinite seamounts (Ohara and Ishii, 1998).

We selected 30 samples for analysis; all samples were larger than 10 cm across with less serpentine. As our strategy involved microstructural and fabric analyses as a means of obtaining information about dynamic process within the mantle wedge, it was very important to identify foliation and lineation within the rock samples. The peridotite samples are dunites, meaning that the foliation and lineation within these samples are defined solely by the alignment of spinel grains (e.g., Nicolas and Poirier, 1978; Michibayashi et al., 2000). As it proved difficult to identify structures with the naked eye, we analysed saw-cut samples in the laboratory and thin sections cut at various orientations. We identified both foliation and lineation in 10 of the 30 samples, as assessed from 46 thin sections and observations of hand samples.

## 3. Microstructures

Three samples exhibit coarse equigranular textures (e.g., Fig. 2A and B). The structures in these samples are weakly developed, and analyses of several thin sections were required to identify the foliation and lineation in each case. Olivine grains vary in size from 2 to 6 mm. Although grain boundaries are commonly obscured by serpentinization, relatively unaltered areas reveal triple junction geometries. Locally, grains are weakly elongated and show undulose extinction, with minor patches of grain-size reduction up to 100 μm across.

Two samples possess elongate olivine textures (Fig. 2C and D). Coarse (≤ 5 mm) olivine grains are variably elongated with aspect ratios of up to 5:1. The long axes of the elongate grains are aligned within the plane of the foliation; this preferred orientation reflects slip along cleavage planes or kinking within grains with patchy extinction or moderately undulose extinction. Rare patches of fine-grained (≤ 100 μm) dynamically recrystallized grains occur along the boundaries between highly elongate grains. These features appear to indicate deformation under conditions of low-temperature plasticity.

The remaining five foliated samples exhibit either porphyroclastic textures or fine-grained equigranular textures. The porphyroclastic textures are variable in character (e.g.,

Fig. 2E): the shapes of porphyroclasts range from round to elongate (with aspect ratios of up to 3:1), resulting from slip along cleavage planes, and the grain sizes of neoblasts vary from ~10 to 200 μm. The effects of pervasive serpentinization mean that the detailed microstructure of these samples is unclear. Low-temperature plastic deformation mechanisms such as kinking appear to have been the primary agent of grain-size reduction. In contrast, the fine-grained equigranular textures are homogeneous (e.g., Fig. 2F), with grain sizes of ~200 μm. Grain boundaries show triple junction geometries. Relict porphyroclasts occur locally and have irregular shapes, indicating dynamic recrystallization of the coarse primary grains.

**4. Fabric analysis**

To examine the deformation conditions in more detail, we used a scanning electron microscope equipped with an electron-backscatter diffraction system (housed at the Center for Instrumental Analysis, Shizuoka University, Japan; e.g., Michibayashi et al., 2006b) to measure the crystal-preferred orientations (CPOs) of olivine from highly polished thin sections. We measured the orientations of between 161 and 327 olivine crystals per sample (Fig. 3) and visually checked the computerized indexing of the diffraction pattern for each crystal orientation. As we are unable to measure strain from naturally deformed samples, the fabric strength (i.e., J-index) is used to evaluate the intensity of the CPO (e.g., Ben Ismail and Mainprice, 1998; Michibayashi and Mainprice, 2004; Michibayashi et al., 2006a; Michibayashi et al., 2006b).

A (010)[100] CPO pattern, which is termed an A-type pattern (e.g., Jung et al., 2006), was observed in two samples: one with a coarse granular texture (Figs. 2A and 3A) and another with an intensely elongated texture (Figs. 2C and 3C). The sample with the intensely elongated texture shows a greater degree of scatter in the obtained CPO pattern and a lower J-index value (Fig. 2C) compared with the sample with coarse equigranular texture (Fig. 3A). This may indicate that the CPO pattern was partly altered during retrogressive deformation.

A (010)[001] CPO pattern, which is termed a B-type pattern (e.g., Jung et al., 2006), was observed within two samples: one with coarse granular texture (Figs. 2B and 3B) and another with intensely elongated texture (Figs. 2D and 3D). In both cases, the intensity of the CPO is relatively weak: J-index values are less than 4. In terms of the CPO pattern for the sample with coarse equigranular texture, although the maximum densities of the three axes are consistent with a B-type pattern, the [100] and [001] axes define a weak girdle subparallel to the foliation (Fig. 3B). The CPO pattern for the sample with intensely elongated texture reveals scattered [100] axes, relatively concentrated [010] axes, and [001] axes that define a weak girdle (Fig. 3D). As with the A-type pattern, these results may imply that the CPO pattern was partly altered during retrogressive deformation.

Despite possessing well-defined foliations and lineations, the CPO patterns for samples with porphyroclastic and fine-grained equigranular textures are too weak to reliably identify A- or B-type patterns; J-index values for these samples are up to 4 (e.g., Fig. 3E and F). These weak CPO patterns probably reflect the effects of low-temperature deformation (e.g., Michibayashi and Mainprice, 2004; Michibayashi et al., 2006a).

## 5. Interpretation and discussion

### *5.1. Variable microstructures and fabrics along the southern Mariana Trench*

The peridotite samples obtained from the southern Mariana Trench record a wide range of microstructures, varying from coarse-grained to fine-grained textures. In general, the coarse-grained textures indicate high-temperature deformation at solidus or hyper-solidus temperatures typical of asthenospheric flow; these are therefore interpreted as primary mantle textures. In contrast, the fine-grained textures reflect ductile flow at relatively low temperatures (Nicolas and Poirier, 1978). Accordingly, we classify the samples into two categories: those with coarse equigranular textures (i.e., primary textures; Fig. 2A–D) and those resulting from various degrees of deformation at relatively low temperatures (i.e., late-stage modified textures; Fig. 2E–F). The former category can be further subdivided into two types based on CPO patterns: A-type (Fig. 3A and C) and B-type (Fig. 3B and D).

It is generally accepted that A-type patterns probably reflect primary asthenospheric flow (i.e., high temperatures and low stress); however, the development of B-type patterns is less certain, being variously ascribed to low temperatures, high degrees of stress, and/or high water contents (e.g., Nicolas and Poirier, 1978; Jung and Karato, 2001; Jung et al., 2006; Katayama and Karato, 2006). Given the uncertainty in the provenance and geographic relationships among the samples described in the present study, it is difficult to explain the contrasting fabrics obtained from a single dredge haul; nonetheless, our results indicate that peridotite in the source region of the dredge site has been variably deformed and/or recrystallized under a range of temperature, stress, and water fugacity conditions. Therefore, while the peridotite samples were collected from a single dredge site, the rocks may have been derived from significantly different geological settings.

We now place our results in the context of regional tectonics by considering regional-scale analyses based on sidescan surveys and topographic and seismic studies (Fryer et al., 2003; Gvirtzman and Stern, 2004; Miller et al., 2006). Side-scan sonar data reveal numerous normal faults on the sea floor in the forearc west of Guam (Fryer et al., 2003). Moreover, the forearc immediately west of Guam is broken by two N–S striking left-lateral fault zones that each record approximately 20 km of displacement; these faults separate the Santa Rosa Bank from Guam (Fig. 1A). The sea floor west of the Santa Rosa Bank shows widespread deformation, including numerous faults of varying scales (Fryer et al., 2003). These bathymetric features suggest active tectonics in this region.

Karig (1971) calculated that 25% east–west extension across the southern boundary of the Marina system would be required to separate the Santa Rosa Bank from the remnant arc of the West Mariana Ridge. Fryer et al. (2003) argued that north–south fore-arc deformation in this region resulted from slab rollback and trench retreat associated with a tear in the subducting plate. This proposal was supported by Gvirtzman and Stern (2004), who suggested that the lithosphere within the Challenger Deep is as thin as 20 km (Fig. 1B). Such a thin lithosphere could well have been intensely deformed, even in the ductile regime, during forearc extension. This scenario is consistent with the wide range of microstructures observed within the peridotite samples described in the present study.

### *5.2. Peridotites from the Southern Mariana Trench: a key to understanding the tectonics and rheology of the fore-arc side of the Mariana mantle wedge*

We demonstrated that the peridotite samples obtained from a dredge haul on the landward trench slope of the southern Mariana Trench, which is the site of the deepest ocean in the world, represent various components of the mantle wedge. As observed previously in the southernmost Mariana Trench across the Challenger Deep, vertical and lateral thinning of the overriding lithosphere leads to the upward and trenchward propagation of the asthenosphere (Fig. 1B; Gvirtzman and Stern, 2004). Hence, one might argue that the peridotites with primary textures were derived from the region of highly uplifted asthenospheric mantle (Fig. 1B).

The peridotites analysed in the present study represent highly refractory residue following extensive mantle melting (Ohara and Ishii, 1998; Michibayashi and Tasaka, unpublished data). Dehydration of the subducting slab might lead to hydration of the uplifted region of shallow asthenosphere (Fig. 1B; e.g., Iwamori, 1998), leading in turn to partial melting of the mantle wedge. The presence of arc volcanics across the entire width of the southern Mariana system west of Guam (Fryer et al., 1998) is consistent with this hypothesis.

In summary, the variable microstructural features of the analyzed samples could well reflect the complex structural evolution of the southern Mariana region, where the trench extends across the forearc to the back-arc side of the Mariana arc system (Fig. 1A). Further detailed studies of peridotites sampled from the world's deepest ocean will reveal additional details of the regional tectonics, from the sea floor to the deep lithospheric mantle and asthenospheric mantle within the southern Mariana mantle wedge.

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Figure captions

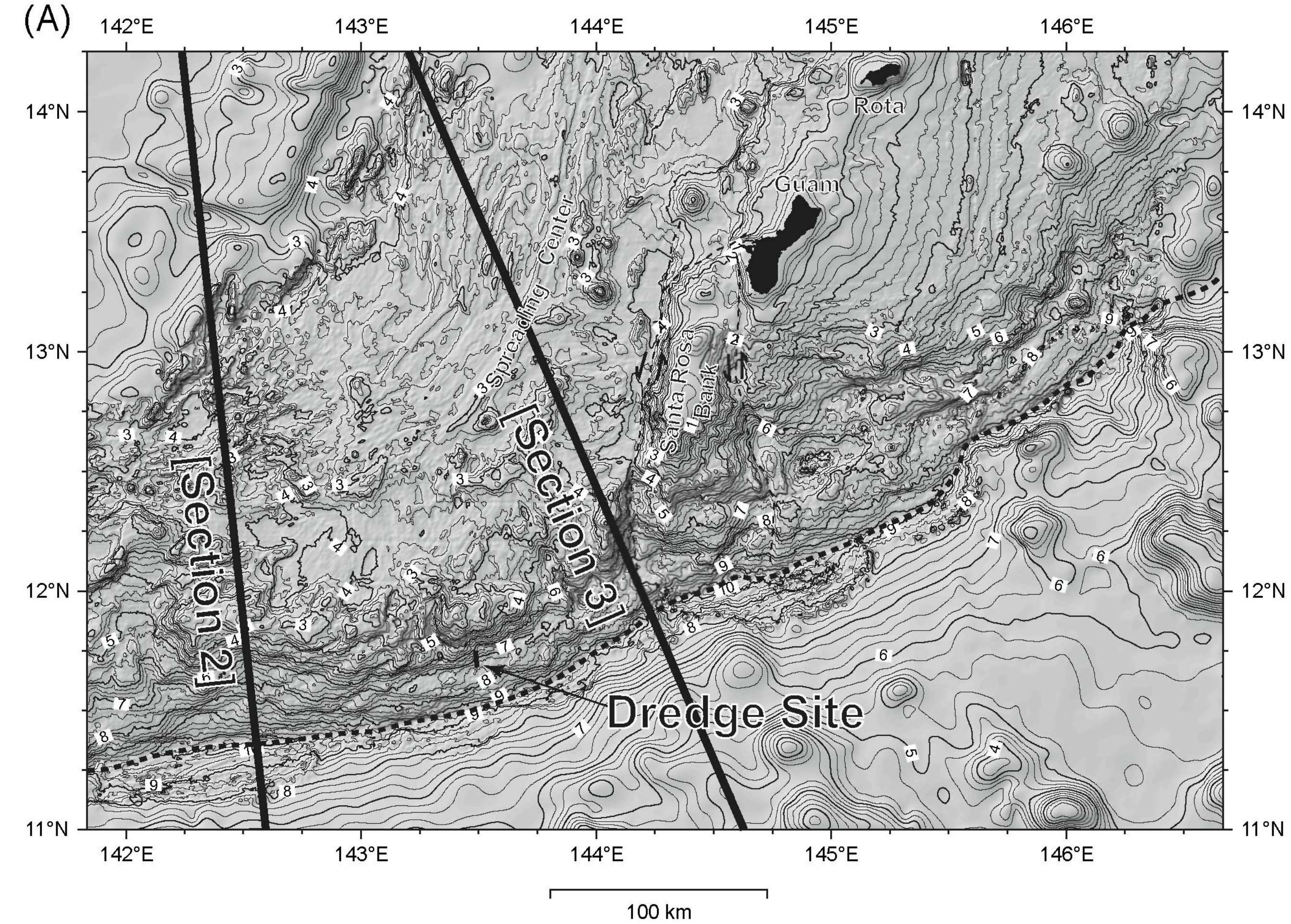
Figure 1. (A) Bathymetric map showing the location of dredge site KH92-1-D2 (11°41.16'N, 143°29.62'E; depth 6594–7431 m), the southern Mariana Trench (solid barbed line), N–S striking strike-slip faults that bound the Santa Rosa Bank (dashed lines west of GuamFryer et al., 2003), the Challenger Deep, and the locations of the two cross-sections (after Gvirtzman and Stern, 2004) shown in Fig. 1B. The dredge site is adjacent to the Challenger Deep, the deepest site within the world's oceans. The unit used for the labeled bathymetric contours is 1000 m. (B) Schematic cross-sections across the southern Mariana Trench based on the lithospheric sections inferred by Gvirtzman and Stern (2004). The asthenosphere propagates toward the tip of the mantle wedge, reaching a point approximately 20 km below the sea floor (Gvirtzman and Stern, 2004). The thinned lithosphere above the propagating asthenosphere in the area close to the southern Mariana Trench is possibly intensely deformed under low-temperature conditions (see the Discussion section).

Figure 2. Photomicrographs of microstructures within the analysed peridotite samples. The scale bar in all images is 1 mm, and all images were taken under crossed polarized light. (A) Sample D2-23. Coarse ($\leq$ 5 mm) equigranular texture. Locally intensely serpentinized and carbonated. Grain boundaries in relatively fresh parts of the sample show triple junction geometries. (B) Sample D2-13. Coarse (ca. 5 mm) equigranular texture. Olivine grains show moderate undulose extinction and have serrated grain boundaries. Grains are locally weakly elongate in areas where grain-size reduction is evident (grain sizes reduced to $\leq$ 100 μm). Numerous inclusions occur within olivine grains. (C) Sample D2-18. Coarse but intensely elongate texture. Olivine grains are intensely elongated due to slip along cleavage planes. Kinking or bending is recognized in olivine grains with patchy or undulose extinction. Rare fine-grained ($\leq$ 100 μm) recrystallized grains occur along grain boundaries between highly elongate grains. Grain boundaries are dominantly serpentinized. This texture resembles the low-strain textures that are transitional from coarse granular texture to porphyroclastic texture at the margin of a ductile shear zone described from the Oman Ophiolite (Michibayashi and Mainprice, 2004). (D) Sample D2-58. Coarse but intensely elongate texture. Coarse ($\leq$ 5 mm) olivine grains are variably elongated up to aspect ratios of 5:1 due to slip along cleavage planes. Parts of the sample exhibit equigranular textures, within which a narrow high-strain zone occurs with very small (ca. 10 μm) recrystallized grains. Some grains contain numerous

inclusions. (E) Sample D2-52. Porphyroclastic texture, although the microstructure is strongly heterogeneous. Porphyroclasts are several millimeters in size and are locally elongated up to aspect ratios of 3:1 due to slip along cleavage planes or kinking. Neoblasts vary in size from ~10 to 200 μm. Although the nature of the microstructure is obscured by serpentinization, low-plasticity deformation such as kinking appears to be the mechanism behind the observed grain-size reduction. (F) Sample D2-110. Relatively homogeneous fine-grained (< 1 mm) equigranular texture. Olivine grains show triple junction boundaries. Locally, relict porphyroclasts possess irregular shapes.

Figure 3. Pole figures for the crystallographic axes of olivine grains. All plots are equal area, lower hemisphere projections in the structural (XZ) reference frame, with the foliation oriented vertically east–west and the lineation being horizontal. (A) Sample D2-23; possibly a (010)[100] pattern. (B) Sample D2-13; (010)[001] pattern. (C) Sample D2-18; (010)[100] pattern. (D) Sample D2-58; (010)[001] pattern. (E) Sample D2-52; olivine CPO is weak, with a maxima of (001) normal to the foliation. (F) Sample D2-110; olivine CPO is very weak.

(A)




(B)

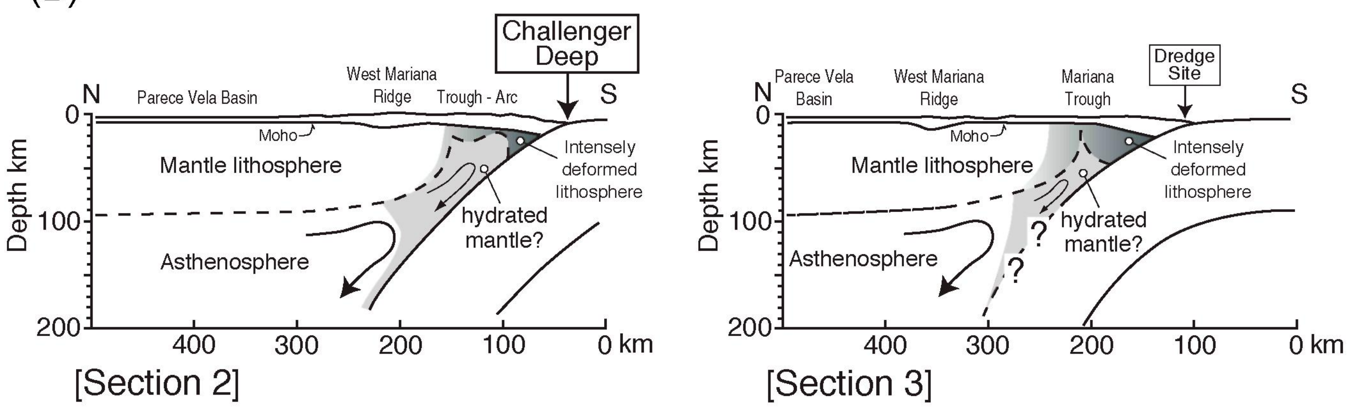



Figure 1: Michibayashi et al.

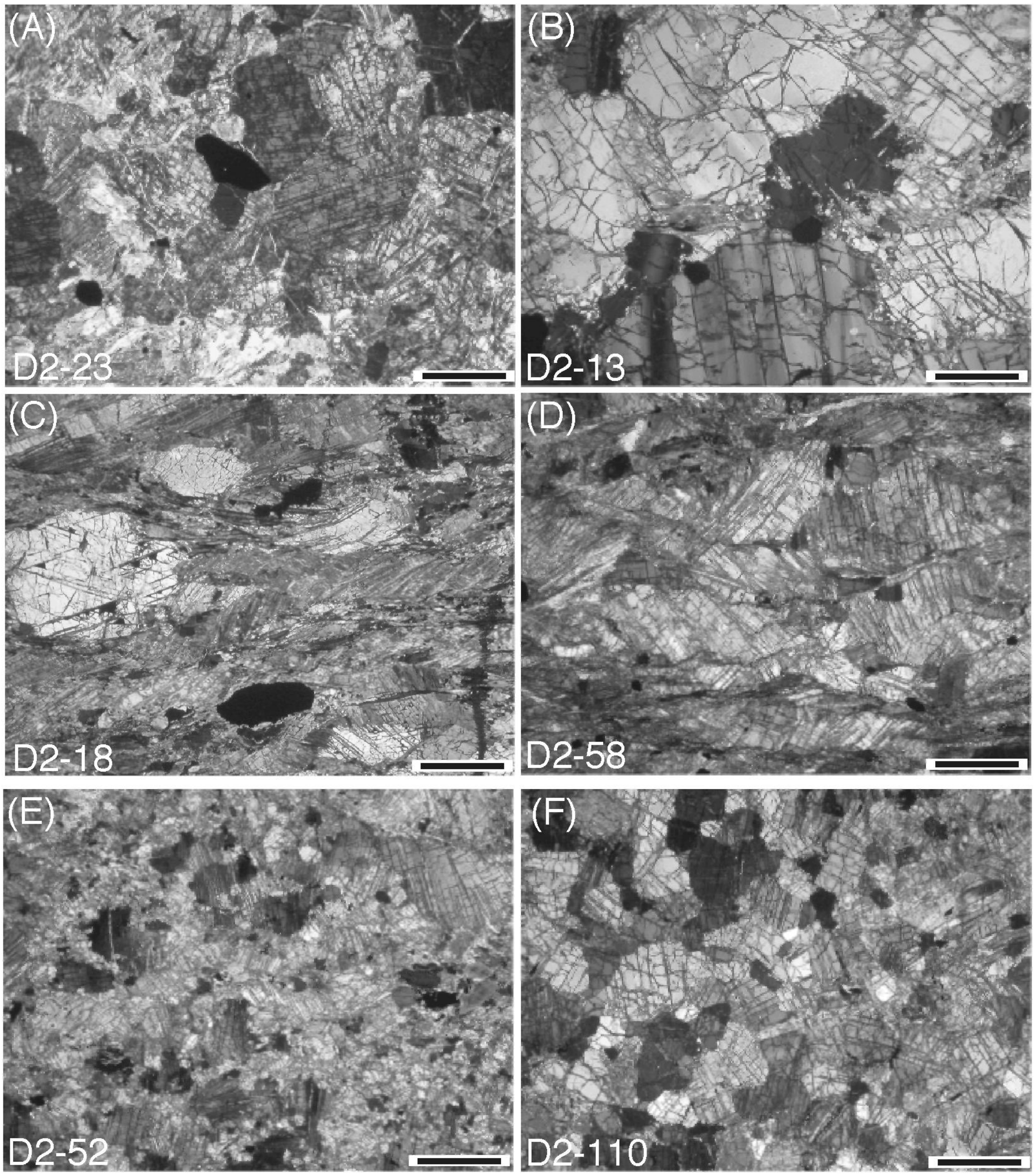



Figure 2: Michibayashi et al.

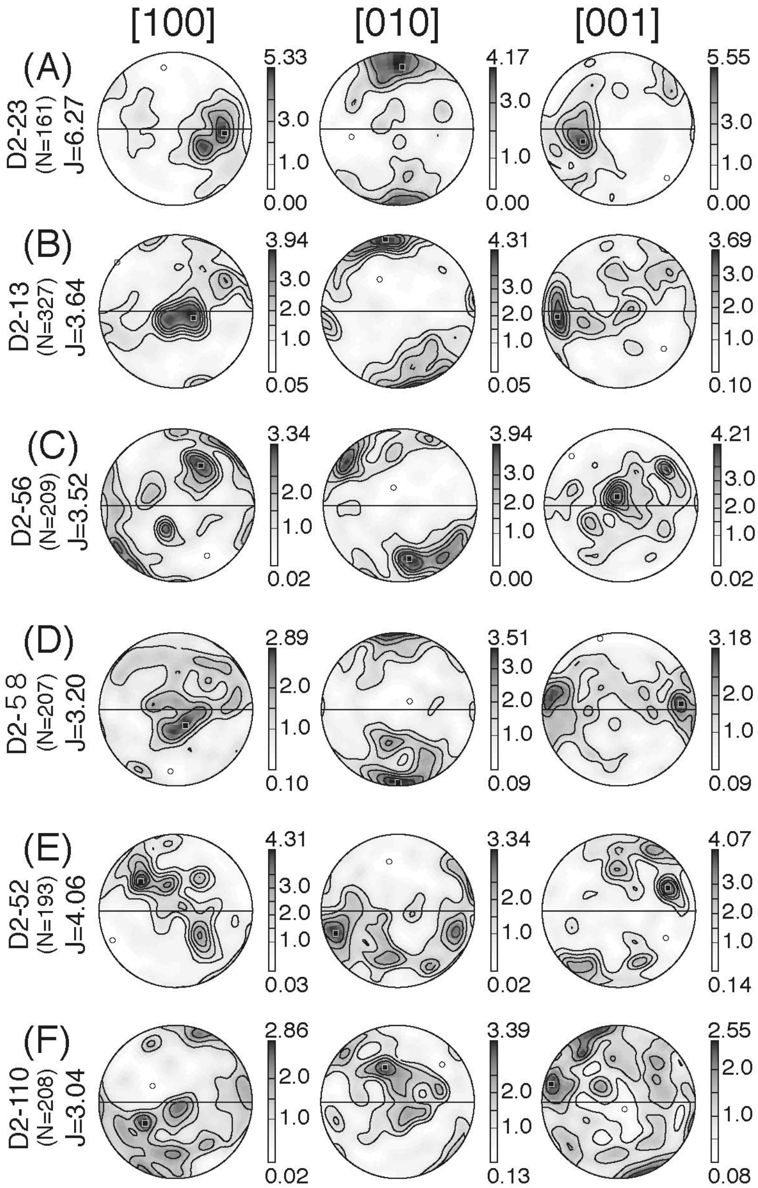



Figure 3: Michibayashi et al.