

## Article

# Amagmatic Mylonitic Deformation of Mantle Peridotites from the Tosa Megamullion in the Shikoku Basin, Philippine Sea

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## Abstract

Mylonitic mantle peridotites exposed at the Tosa Megamullion in the Shikoku Basin, Philippine Sea, provide direct evidence for amagmatic ductile shear deformation of the upper mantle beneath a back-arc spreading center. Oceanic core complexes (OCCs), or megamullions, are dome-shaped structures formed by detachment faulting and occur locally along slow-spreading mid-ocean ridges and back-arc basins, where they expose fault rocks derived from ductile shear zones in the lower crust and upper mantle. The Shikoku Basin hosts several OCCs, including the Tosa Megamullion, which formed during the early stage of back-arc spreading. In this study, nine ultramafic rocks were collected from the Tosa Megamullion using the submersible Shinkai6500 during cruise YK23-05S. Although all samples were highly serpentinized, several preserved primary peridotitic textures were composed mainly of olivine, orthopyroxene, with subordinate clinopyroxene, plagioclase, and spinel. Seven samples exhibit well-developed foliation and porphyroclastic textures dominated by orthopyroxene porphyroclasts, ranging from rounded to strongly elongated forms, commonly showing microkinks and undulose extinction. Crystallographic preferred orientations (CPOs) of three representative samples, analyzed using SEM-EBSD, reveal E-type-dominant olivine fabrics characterized by the (001)[100] slip system, with a subordinate contribution from C-type (100)[001] slip. These CPOs suggest deformation under non-dry conditions involving moderate hydration and/or elevated differential stress. These results indicate that the ultramafic rocks from the Tosa Megamullion represent mantle-derived mylonitic peridotites formed by ductile shear beneath the spreading axis and subsequently exhumed under strongly magma-poor, amagmatic conditions. The Tosa Megamullion thus represents an amagmatic end-member of the OCC formation in back-arc basins, dominated by tectonic strain localization rather than by magmatic accretion.



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**Keywords:** oceanic core complex; megamullion; mylonitic peridotite; Shikoku Basin; back-arc spreading; EBSD; crystallographic preferred orientation (CPO); detachment fault

## 1. Introduction

Oceanic core complexes (OCCs), or megamullions, are dome-shaped topographic structures characterized by prominent corrugations [1,2]. They occur along slow-spreading mid-ocean ridges, including the Mid-Atlantic, Southwest Indian, Caribbean–North American, and Australia–Antarctic ridges, as well as in parts of back-arc spreading centers [2–4]. During lithospheric extension, detachment faults develop, and isostatic adjustment causes ductile material to rise from depth, exposing the lower crust and upper mantle at the seafloor [1,2].

In the Philippine Sea, the Godzilla and Mado Megamullions occur in the Parece Vela and Shikoku Basins (Figure 1; [5–7]). Ductilely deformed gabbros and peridotites have been reported from these OCCs, indicating derivation from deep portions of detachment faults [4,8–15].

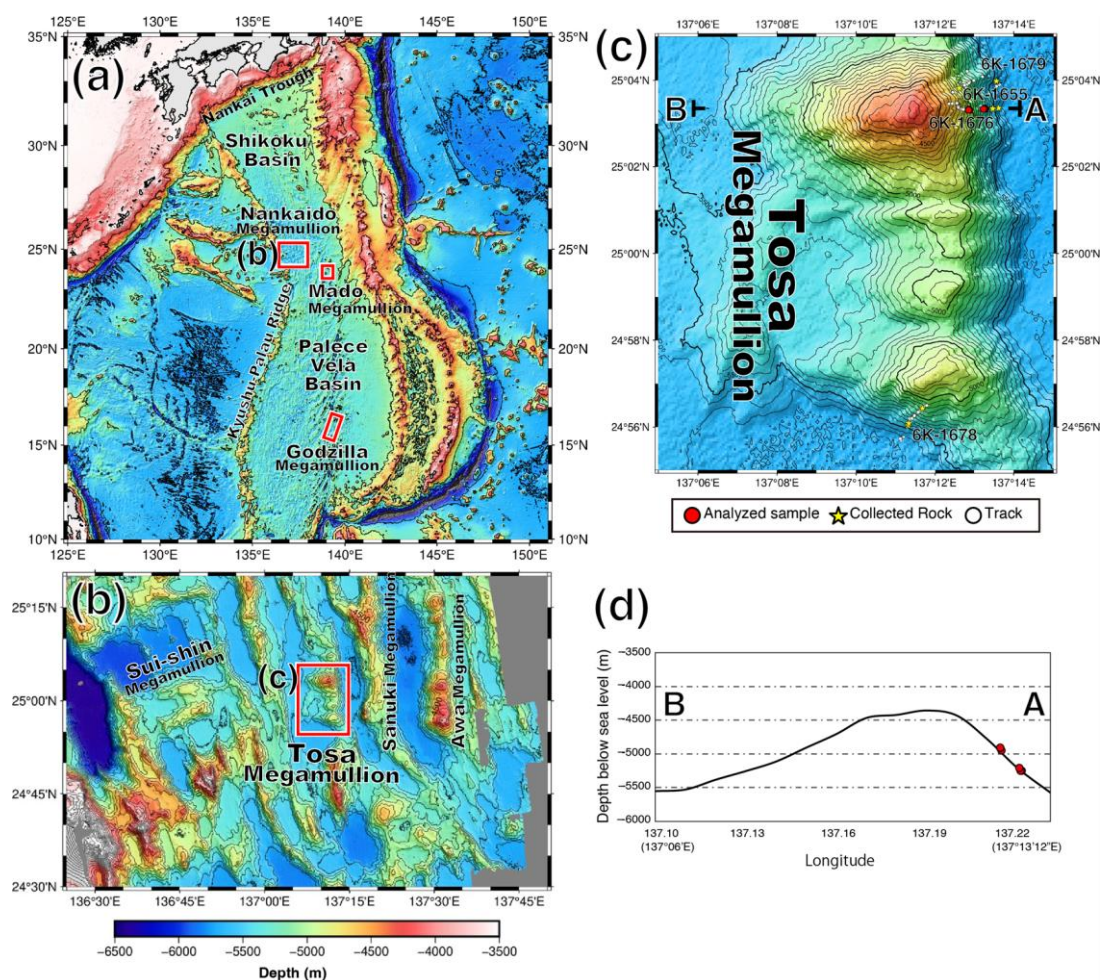


**Figure 1.** (a) Major topographic features on the Philippine Sea and its surrounding areas. The red rectangles indicate the locations of Nankaido Megamullions, Mado Megamullion, and Godzilla Megamullion, respectively. (b) Topographic features of the Nankaido Megamullions consisting of Sui-shin, Tosa, Sanuki, and Awa Megamullions. (c) Topographic feature of the Tosa Megamullion with four dive tracks of 6K-1655, 1676, 1678, and 1679. Red circle points: the location of the samples studied here along the track of 6K-1676; yellow star points: locations of the other samples; white circle points: the track of Shinkai6500. (d) Cross-section of the bathymetry of the Tosa Megamullion

between A and B shown in (c). The horizontal and vertical axes indicate the depth and the longitude, respectively. Red circle points: the location of the samples studied here.

The Tosa Megamullion is located near the Kyushu–Palau Ridge in the Shikoku Basin (Figure 1; [16]). Unlike the Mado Megamullion, which is dominated by magma-derived rocks such as gabbro and basalt [4,13], the Tosa Megamullion is almost devoid of such rocks, suggesting formation in an amagmatic environment [16].

In this study, we discuss the structural development of the Tosa Megamullion based on the microstructural and crystallographic fabric characteristics of peridotites collected from this OCC. Here, the term “mylonitic peridotite” is used in a descriptive sense, referring to peridotites that exhibit porphyroclastic textures and fine-grained recrystallized matrices, corresponding to protomylonite to mylonite [17].

## 2. Geological Setting

### 2.1. Shikoku Basin

The Shikoku Basin is an extinct back-arc basin that was active from the Late Oligocene to the Middle Miocene, breaking the Paleo-Izu–Bonin (Ogasawara)–Mariana Arc [18]. It forms a fan-shaped structure at the northern end of the Philippine Sea, bounded by the Izu–Bonin (Ogasawara) Trench to the west and the Kyushu–Palau Ridge to the east. Near the basin axis lies the Kinan Seamount Chain, a series of volcanoes that erupted on the spreading axis after spreading ceased (Figure 1; [19,20]).

The age of the Shikoku Basin has been inferred from geomagnetic anomalies [20,21]. The westernmost part of the basin shows anomaly C7n.2n (NNW–SSE strike), dated to 24.474–24.109 Ma. This anomaly is discontinuous between the northern Parece Vela Basin and the Nankai Trough, interrupted by the Kyushu–Palau Ridge. However, anomalies from 22.564–21.767 Ma (C6C series) are continuous from the northern Parece Vela Basin to the Nankai Trough, indicating that back-arc spreading propagated into the southern Shikoku Basin and that oceanic crust formed throughout the basin.

Around 23 Ma, the anomaly strike shifted slightly to N–S, and after 19.722–18.7748 Ma (C6n), it rotated further to NW–SE. The youngest anomalies, C5Bn.2n (15.160–15.032 Ma) and C5Bn.1n (14.870–14.775 Ma), indicate that spreading ceased around 15 Ma. Following this termination, the Kinan Seamount Chain, composed of alkali basalt overlying the youngest anomaly, is thought to have formed between ~8 and 15 Ma [22,23].

### 2.2. The Nankaido Megamullions

The southernmost part of the Shikoku Basin, adjacent to the eastern margin of the Kyushu–Palau Ridge (24°30′–25°35′ N, 136°30′–138°10′ E), contains a cluster of OCCs known as the Nankaido Megamullions (Figure 1a,b; [16]). This cluster comprises several megamullions, including the Sui-shin, Tosa, Awa, and Sanuki Megamullions (Figure 1b; [16]), which formed within the region of 136°30′–138°10′ E.

In the western part of the Nankaido Megamullions, dome structures strike nearly N–S, whereas in the eastern part, the strike shifts slightly to NNW–SSE. These OCCs exhibit dome-like shapes with multiple corrugations trending E–W. The mantle Bouguer anomaly in this region is strongly positive (~200 mGal; [16,21]), suggesting a thin oceanic crust and extensive exposure of mantle material.

The western margin of the Nankaido Megamullions lies along a continuous geomagnetic anomaly from the northern Parece Vela Basin to the Nankai Trough, likely corresponding to C6B, whereas the eastern margin is associated with anomalies C6A1 or C6A2, consistent with its NNW–SSE orientation [20,21]. These observations indicate that the western margin formed at ~22 Ma and the eastern margin at ~20 Ma.

### 2.3. The Tosa Megamullion

The Tosa Megamullion is situated near the center of the Nankaido Megamullions (Figure 1a,b; 24°54′–25°06′ N, 137°06′–137°14′ E; [16]) and covers an area of approximately 290 km<sup>2</sup>. It exhibits an elliptical, dome-shaped structure elongated in the E–W direction (Figure 1c). The distance from its western margin to the eastern terminus is about 13 km, and the seafloor surface is marked by a series of parallel corrugations trending E–W (Figure 1c). These corrugations are interpreted as morphological traces of shear movement along low-angle detachment faults, providing key evidence for the OCC's formation process [16].

Topographically, the central part of the OCC forms a dome-like uplift (Figure 1c,d), whereas steep fault scarps occur along its northern and southern flanks (Figure 1c). This tectonic configuration has exposed lower-crustal to upper-mantle rocks directly on the seafloor, making the Tosa Megamullion an important “tectonic window” for investigating the internal structure of the oceanic lithosphere [16]. Notably, gabbros and peridotites are well preserved in this area, offering valuable material for reconstructing crustal formation and deformation processes in a back-arc basin setting [16].

Because of its central position within the Nankaido Megamullions (Figure 1b), the Tosa Megamullion serves as a suitable target for comparative studies with adjacent OCCs. Compared to the Sui-shin Megamullion located to the west of Tosa, it displays more clearly developed E–W corrugations (Figure 1b), which may reflect regional variations in spreading dynamics and magma supply. With an areal extent of ~290 km<sup>2</sup>, it ranks among the medium- to large-sized OCCs in the Shikoku Basin, representing one of the characteristic tectonic structures formed by crustal extension in this region [16].

In summary, the Tosa Megamullion preserves both morphological and geological features in excellent condition, constituting a key natural laboratory for understanding the exposure mechanisms of lower-crustal and upper-mantle rocks in a back-arc spreading system.

### 3. Dredge Samples

The Tosa Megamullion was investigated during two research cruises of the JAMSTEC-operated R/V Yokosuka [16]: cruise YK22-18S (1–12 October 2022) and cruise YK23-05S (2–18 April 2023). Rock sampling was conducted using the manned submersible *Shinkai6500*, which performed four dives targeting steep fault scarps along the eastern flank of the megamullion. The dives were designated YK22-18S-6K-1655, YK23-05S-6K-1676, YK23-05S-6K-1678, and YK23-05S-6K-1679 (Figure 1c; [16]).

During dive 6K-1655, 17 samples were recovered: three mudstones, two gabbros, and twelve ultramafic rocks with cross-cutting gabbroic veins. Dive 6K-1676 yielded 14 samples, including one mudstone and thirteen ultramafic rocks. Dive 6K-1678 produced ten samples: three mudstones, two pumices, and five ultramafic rocks. Finally, dive 6K-1679 yielded 15 samples: six mudstones, three scoria, and six ultramafic rocks.

In total, 56 rock samples were obtained from the Tosa Megamullion across the two cruises [16]. Ultramafic lithologies constituted the majority (33 samples), followed by mudstones (13), gabbros (2), pumices (2), and scoria (3). The predominance of ultramafic rocks indicates that the eastern flank of the Tosa Megamullion (Figure 1c, d) provides direct exposures of upper mantle material and associated intrusive lithologies, offering a unique opportunity to investigate crust–mantle interaction and detachment fault exhumation processes in a back-arc basin setting.

## 4. Methods

Nine ultramafic rock samples recovered during dive YK23-05S-6K-1676 (Figure 1c,d) were selected for detailed petrographic and microstructural analyses (Table 1). As described below, many of these specimens exhibit well-developed foliation, defined by the alignment and elongation of orthopyroxene and plagioclase, and lineation, characterized by the preferred orientation of minerals within the foliation plane.

**Table 1.** List of the studied samples.

| Sample      | Latitude (N) | Longitude (E) | Water Depth (m) | Lithology                           |
|-------------|--------------|---------------|-----------------|-------------------------------------|
| 6K-1676-R03 | 25° 3.3489   | 137° 13.2546  | 5253            | Sepentinized plagioclase peridotite |
| 6K-1676-R04 | 25° 3.3489   | 137° 13.2546  | 5253            | Sepentinized plagioclase peridotite |
| 6K-1676-R05 | 25° 3.3489   | 137° 13.2546  | 5253            | Sepentinized plagioclase peridotite |
| 6K-1676-R06 | 25° 3.3489   | 137° 13.2546  | 5253            | Sepentinized plagioclase peridotite |
| 6K-1676-R08 | 25° 3.3392   | 137° 13.2325  | 5253            | Sepentinized plagioclase peridotite |
| 6K-1676-R09 | 25° 3.3138   | 137° 13.8806  | 4959            | Sepentinized plagioclase peridotite |
| 6K-1676-R10 | 25° 3.3138   | 137° 13.8806  | 4959            | Sepentinized plagioclase peridotite |
| 6K-1676-R11 | 25° 3.3120   | 137° 13.8608  | 4917            | Sepentinized plagioclase peridotite |
| 6K-1676-R12 | 25° 3.3169   | 137° 13.8588  | 4915            | Sepentinized plagioclase peridotite |

### 4.1. Polished Slab Surface and Thin Sections

Rock slabs were cut with a diamond saw and mounted on glass slides to produce standard thin sections approximately 30 µm thick. For each specimen, the XZ plane—perpendicular to foliation and parallel to lineation mostly defined by alignment of pyroxene and plagioclase grains—was selected for observation. Three samples (6K-1676-R03, R04, and R06) were too small to prepare in the XZ orientation; therefore, alternative orientations were used. Thin sections were examined under a polarized light microscope to describe mineral size, shape, and modal abundance.

### 4.2. SEM-EBSD Analyses

SEM-EBSD analyses were conducted on samples 6K-1676-R10, R11, and R12. Mineral phase maps and crystallographic orientation data were acquired using a HITACHI S-3400N scanning electron microscope equipped with an electron backscatter diffraction (EBSD) system at the Rock and Mineral Laboratory, Nagoya University, Japan (e.g., [24,25]). Analytical conditions were as follows: acceleration voltage of 20 kV, chamber pressure of 30 Pa, probe current ranging from 85 to 100 (depending on filament condition), working distance of 27 mm, and a sample tilt angle of 70°.

#### 4.2.1. Crystallographic Orientations of Minerals

Crystallographic orientations of minerals were measured over the entire thin section using an EBSD mapping mode. Mineral phase maps were acquired with step sizes of 5 or 30 µm, depending on the sample. The EBSD map data were processed using the MATLAB MTEX Toolbox (version 6.1; <http://mtex-toolbox.github.io/> (accessed on 25 November 2025); [26,27]). During data processing, isolated single-pixel spikes were removed, and the orientations of non-indexed pixels were extrapolated from the average orientations of neighboring indexed pixels. Grain boundaries were then defined in the phase maps using a critical misorientation angle of 10°.

Crystallographic preferred orientations (CPOs) of olivine, orthopyroxene, and clinopyroxene were calculated for each thin section based on extrapolated pixels and projected onto lower-hemisphere, equal-area stereonet using one orientation per grain. The strength of the CPOs was quantified using the *J* index [28], for which a value of 1 indicates a random fabric and infinity corresponds to a single crystal. In addition, the pole figure *J* index (*pff*)

was calculated;  $pff$  equals 1 for a random distribution and reaches a maximum value of approximately 60 for a single olivine crystal in the present dataset [29]. Fabric strength was also evaluated using the  $M$  index [30], where  $M = 0$  represents a random fabric and  $M = 1$  corresponds to a single crystal. All CPO indices ( $J$ ,  $pff$ , and  $M$ ) were calculated using the MATLAB MTEX Toolbox (version 6.1; [31,32]).

#### 4.2.2. Olivine Fabric Type Analyses

Olivine CPOs are commonly classified into six fabric types: A, B, C, D, E, and AG [33–36]. These fabric types are generally attributed to the dominant activity of specific olivine slip systems: A-type with (010)[100], B-type with (010)[001], C-type with (001)[001], D-type with {0kl}[100], and E-type with (010)[100] [32]. The AG-type, introduced by Mainprice (2007) [33], corresponds to the [010]-axial or [010]-fiber fabric (e.g., [37,38]).

The six olivine fabric types can be quantitatively mapped onto P-wave velocities ( $V_p$ ) derived from olivine crystallographic preferred orientations (CPOs) [35,36]. In this study, three principal P-wave velocities ( $V_1$ ,  $V_2$ , and  $V_3$ ) were calculated from olivine CPOs using the MATLAB MTEX Toolbox, where  $V_1$  represents the maximum  $V_p$ ,  $V_3$  the minimum  $V_p$ , and  $V_2$  the intermediate  $V_p$  oriented perpendicular to both  $V_1$  and  $V_3$  [36].

To define the fields of the six olivine fabric types, the orientations of the three principal velocity axes were evaluated within a structural reference frame (x–y–z-axes) defined by the finite strain ellipsoid (e.g., [39]). In this framework, the foliation corresponds to the x–y plane, and the lineation is parallel to the x-axis. Accordingly,  $V_x$ ,  $V_y$ , and  $V_z$  denote P-wave velocities parallel to the x-, y-, and z-axes, respectively.

The principal velocity set [ $V_1$ ,  $V_2$ ,  $V_3$ ] was therefore transformed into [ $V_x$ ,  $V_y$ ,  $V_z$ ], where each component corresponds to  $V_1$ ,  $V_2$ , or  $V_3$  depending on the relative orientations of the velocity axes with respect to foliation and lineation in each sample. Finally, the three directional velocities ( $V_x$ ,  $V_y$ , and  $V_z$ ) were plotted on a Flinn-type diagram using  $V_y/V_z$  as the horizontal axis and  $V_x/V_y$  as the vertical axis, with the origin fixed at (1, 1). This diagram enables quantitative characterization of olivine fabric types and their intensities based on seismic anisotropy (e.g., [35,36,40–45]).

## 5. Microstructures

All studied samples are classified as plagioclase peridotites, characterized by the occurrence of plagioclase and porphyroclastic textures dominated by orthopyroxene porphyroclasts (Figure 2, Table 2). Well-developed foliations were observed in seven of the nine specimens (Table 2), with particularly strong planar fabric in samples 6K-1676-R09, R10, R11, and R12 (Figure 2). The mineral assemblages are broadly consistent among the samples, comprising orthopyroxene, clinopyroxene, plagioclase, spinel, and secondary serpentine after olivine. Notably, primary olivine is only preserved in samples 6K-1676-R10, R11, and R12, suggesting local variations in the degree of serpentinization. The presences of plagioclase in all samples indicate their occurrences in the plagioclase stability field, typically at shallow lithospheric mantle levels beneath slow- to ultraslow-spreading ridges. In summary, the Tosa Megamullion peridotites exhibit plagioclase-bearing porphyroclastic textures, well-developed foliations in most specimens, and a consistent mineralogy with localized preservation of olivine (Table 2).

Detailed petrographic characteristics of each sample are described separately in the following section.

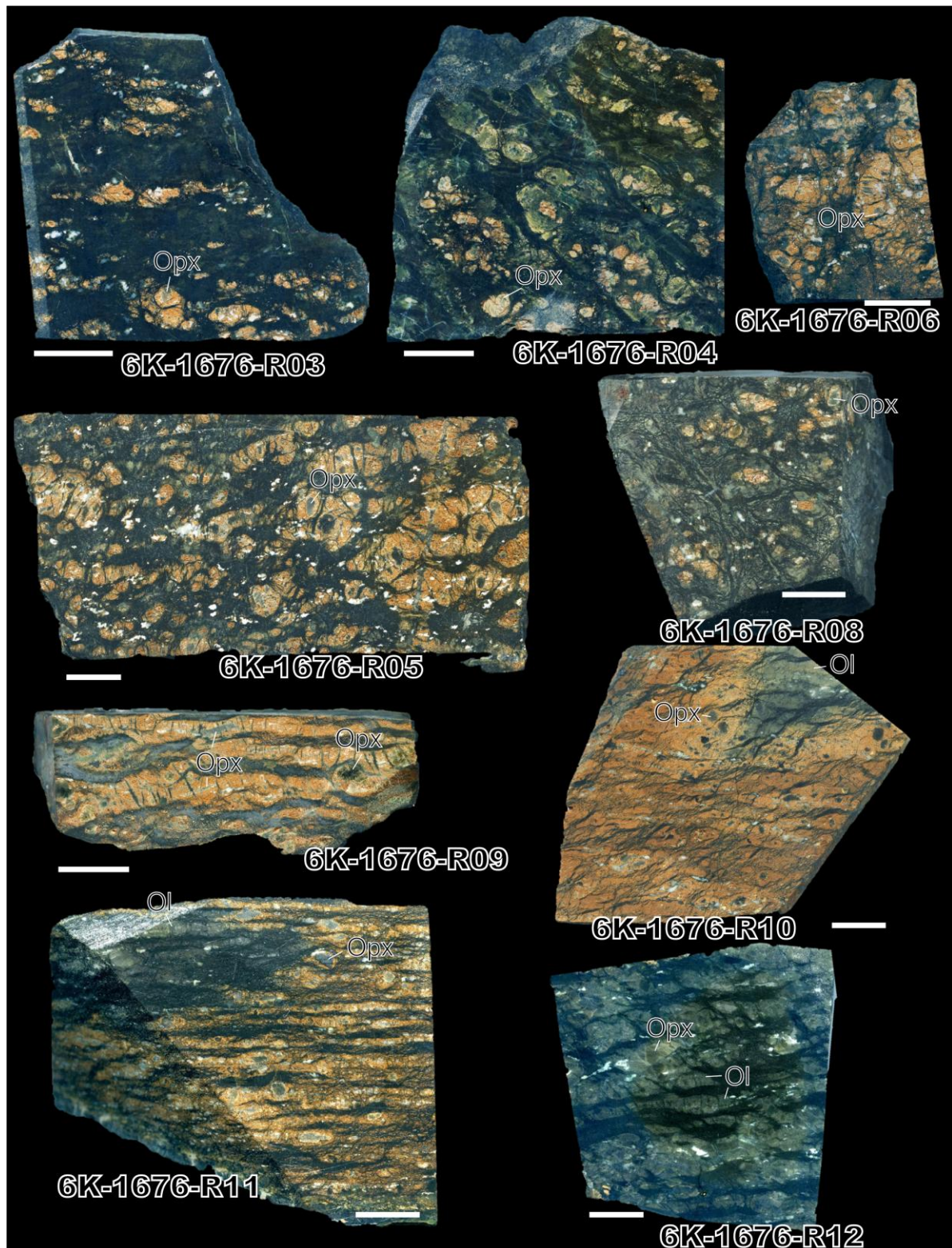


**Figure 2.** Polished surfaces of ultramafic rock samples. Scale bar is 1 cm. Opx: Orthopyroxene, Ol: Olivine. 6K-1676-R03: White plagioclase and brownish areas appear horizontally elongated. 6K-1676-R04: Overall greenish with a weak alignment of slightly rounded brownish domains. 6K-1676-R05: White plagioclase elongated parallel to foliation. 6K-1676-R06: Plagioclase elongated in varying orientations. 6K-1676-R08: No preferred orientation identified. 6K-1676-R09 on XZ plane: Orthopyroxene, plagioclase, and blackish serpentinite layers define foliation. 6K-1676-R10 on XZ plane: Greenish to gray domains are weakly serpentinitized; white plagioclase and orthopyroxene elongated parallel to foliation. 6K-1676-R11 on XZ plane: Gray to blackish domains are weakly serpentinitized; rounded

orthopyroxene porphyroclasts display symmetric textures. 6K-1676-R12 on XZ plane: Gray to blackish domains are weakly serpentinized; plagioclase aligned parallel to foliation.

**Table 2.** Modal characteristics and textures of the studied samples.

| Sample      | Ol | Opx | Cpx | Sp | Pl | Amp | Serp | Foliation | Texture         |
|-------------|----|-----|-----|----|----|-----|------|-----------|-----------------|
| 6K-1676-R03 |    | ○   | ○   |    | △  |     | ⊙    | Weak      | Porphyroclastic |
| 6K-1676-R04 |    | ○   | ○   |    | △  |     | ⊙    | Weak      | Porphyroclastic |
| 6K-1676-R05 |    | ○   | ○   | △  | △  |     | ⊙    | Weak      | Porphyroclastic |
| 6K-1676-R06 |    | ○   | ○   |    | △  | △   | ⊙    |           | Not identified  |
| 6K-1676-R08 |    | ○   | ○   | △  | △  |     | ⊙    |           | Not identified  |
| 6K-1676-R09 |    | ○   | ○   | △  | △  |     | ⊙    | Moderate  | Porphyroclastic |
| 6K-1676-R10 | ○  | ○   | ○   | △  | △  |     | ○    | Intense   | Porphyroclastic |
| 6K-1676-R11 | ○  | ○   | ○   | △  | ○  | △   | ○    | Intense   | Porphyroclastic |
| 6K-1676-R12 | ○  | ○   | ○   | △  | ○  | △   | ○    | Intense   | Porphyroclastic |

⊙: Abundant, ○: Common, △: Minor, Blank: None.

### 5.1. 6K-1676-R03, R04, R05, R06, and R08

**R03:** The cut surface of this specimen is blackish in color, with elongated white plagioclase forming a flattened shape (Figure 2). In the thin section under polarized light, the main constituent minerals were identified as serpentine, orthopyroxene, and plagioclase. Approximately 90% of the thin section is composed of serpentine, and no primary olivine remains, suggesting complete replacement during serpentinization. The serpentine shows a characteristic mesh texture (Figure 3a). Orthopyroxene porphyroclasts and fine-grained clinopyroxenes were also present (Figure 3a). The white areas on the cut surface appear altered in the thin section and are interpreted as pseudomorphs after plagioclase.

**R04:** The cut surface is generally greenish, with rounded brownish domains (Figure 2). As the section was not cut in the XZ orientation, no clear foliation is developed. Under the polarizing microscope, the mineral assemblage consists mainly of serpentine and pyroxene, with complete absence of olivine due to serpentinization. A notable feature of this sample is the occurrence of microkinks in orthopyroxene porphyroclasts accompanied by undulatory extinction (Figure 3b). Fine-grained clinopyroxene is partially preserved.

**R05:** On the cut surface, white plagioclase appears aligned subparallel to the foliation and shows evidence of deformation, having been displaced by approximately 4 mm relative to its elongation direction. A large, circular orthopyroxene porphyroclast, approximately 7 mm in diameter, is also observed (Figure 2). In the thin section, serpentine, pyroxene, plagioclase pseudomorphs, and spinel are identified (Figure 3c). Aggregated domains are present, where fine-grained clinopyroxene occurs around coarse-grained clinopyroxene porphyroclasts (Figure 3c).

**R06:** No aligned plagioclase is visible on the cut surface, and no distinct foliation is developed (Figure 2). The mineral assemblage comprises serpentine, orthopyroxene, clinopyroxene, tremolite, and altered plagioclase. Thin-section observations reveal orthopyroxene porphyroclasts and aggregates of fine-grained clinopyroxene (Figure 3d). The most distinctive feature of this sample is the presence of needle-shaped tremolite crystals, approximately 0.6 mm in diameter, distributed in a manner that overlies the surrounding serpentine minerals (Figure 3d).

**R08:** On the cut surface, plagioclase shows no preferred alignment, and foliation is not clearly developed (Figure 2). The mineral assemblage consists of serpentine, pyroxene, plagioclase pseudomorphs (Figure 3e,f), and spinel. Serpentine constitutes the majority of the rock, whereas orthopyroxene porphyroclasts occur in minor amounts. These porphyroclasts are nearly circular, non-elongated grains that exhibit undulatory extinction and exsolution lamellae (Figure 3e). Additional microstructures, including serpentine mesh

textures, aggregates of fine-grained clinopyroxene, and altered plagioclase pseudomorphs, are also observed and are consistent with features identified in other samples.

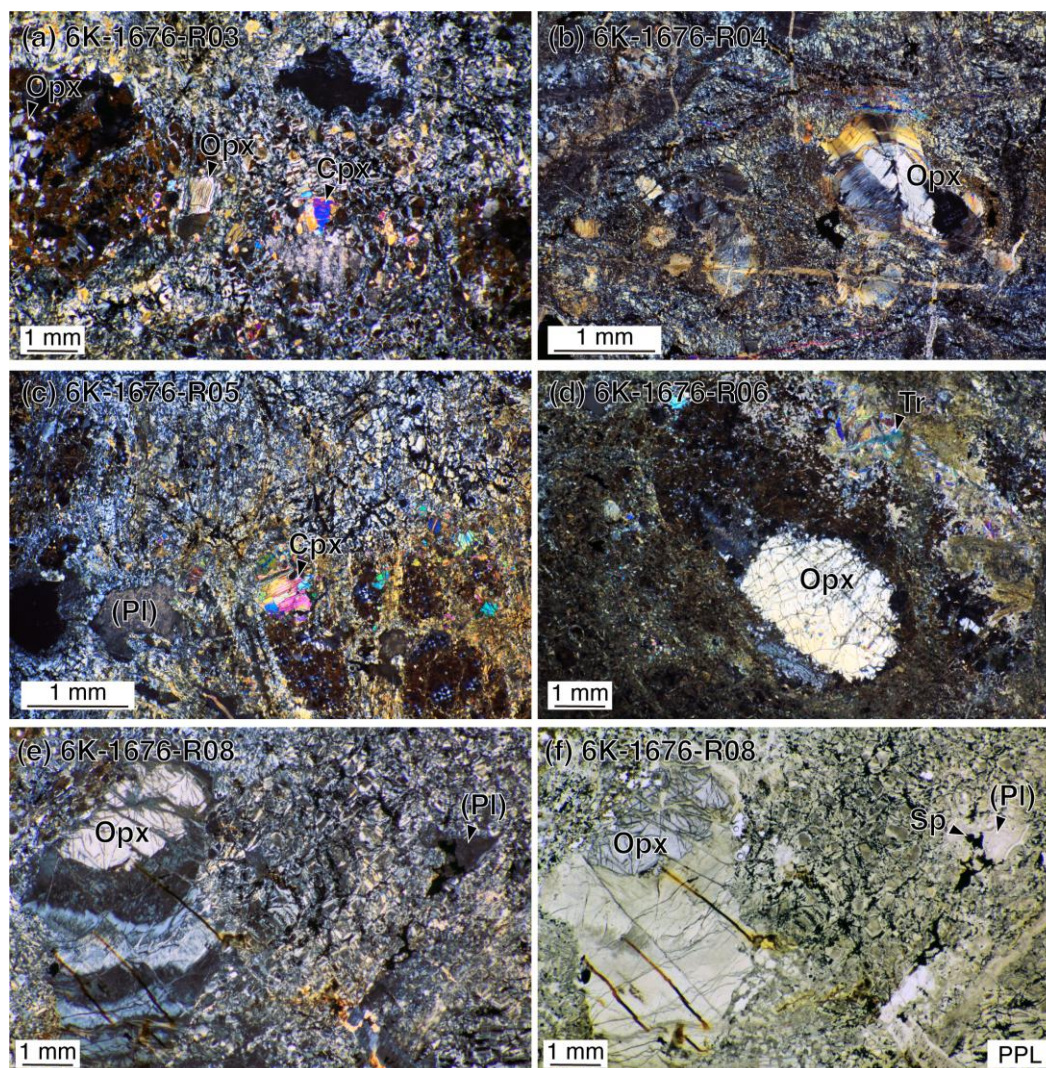


**Figure 3.** Five (R03, R04, R05, R06, and R08) ultramafic rocks sampled by *Shinkai6500* during dive 6K-1676. Although these rocks are heavily serpentinized, some relics of primary minerals such as olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx), and spinel (Sp) occur, some of which show evidence of plastic deformation such as kinking and fine-grained aggregate. The presence of needle-shaped tremolite (Tr) crystals in 6K-1676-R06. Plagioclase (Pl) is completely altered. (a) 6K-1676-R03, (b) 6K-1676-R04, (c) 6K-1676-R05, (d) 6K-1676-R06, (e) 6K1676-R08. (f) 6K-1676-R08, which is the same texture as (e) under plane-polarized light (PPL).

### 5.2. 6K-1676-R09, R10, R11, and R12

**R09:** The cut surface exhibits weakly developed foliation, resulting from the preferred alignment of orthopyroxene, plagioclase, and black serpentinized domains (Figure 2). Under polarized light, the mineral assemblage comprises serpentine, pyroxene, plagioclase pseudomorphs, and spinel. Orthopyroxene porphyroclasts occur in two forms: coarse, equigranular grains with rounded diameters of approximately 4 mm, and elongated ribbons with short diameters of ~0.5 mm and long diameters ranging from 3 to 6 mm. Plagioclase grains vary from 0.1–0.4 mm in short diameter to 0.5–4 mm in long diameter. Distinctive features include elongated orthopyroxene ribbons up to 6 mm in length (Figure 4a), which display exsolution lamellae, undulatory extinction, and microkinks. A fine-grained polygonal clinopyroxene (~0.1 mm) layer occurs locally (Figure 4b).

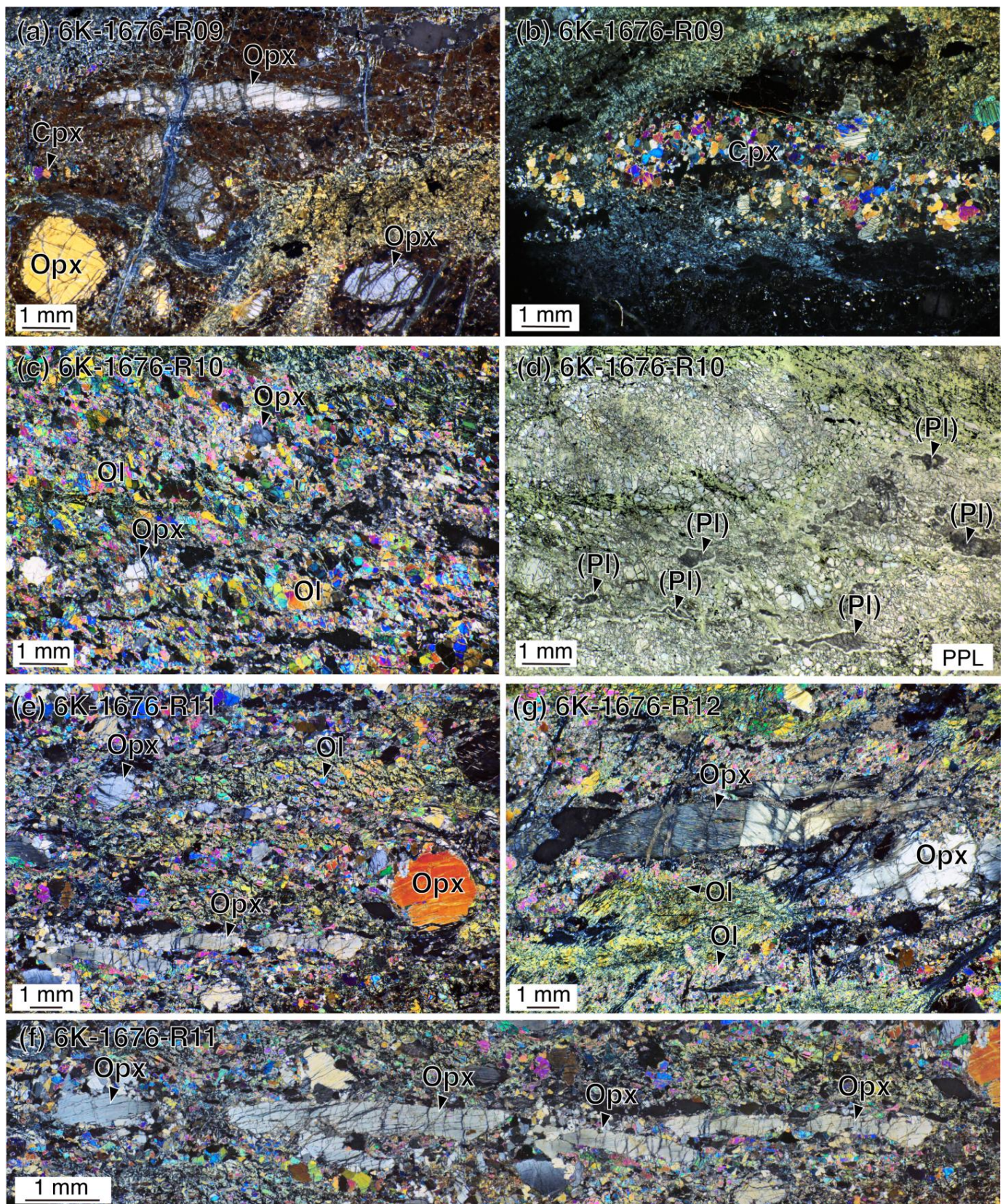


**Figure 4.** Four (R09, R10, R11, and R12) ultramafic rocks sampled by Shinkai6500 during dive 6K-1676. Since these rocks are relatively less serpentinized, primary minerals such as olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx), and spinel (Sp) occur, some of which show evidence of plastic deformation such as elongation, kinking, and fine-grained aggregate. (Pl) is plagioclase pseudomorph. (a,b) 6K-1676-R09, (c,d) 6K-1676-R10, (e) 6K-1676-R11, (f) 6K-1676-R11 showing elongated orthopyroxene

(Opx) boudins, (g) 6K-1676-R12. Photo images were taken under cross-polarized light, unless it is labeled as plane-polarized light (PPL).

R10: The cut surface exhibits a strong preferred alignment of plagioclase and orthopyroxene porphyroclasts, with serpentinized black domains distributed subparallel to these planes (Figure 2). Relatively unaltered gray to greenish-gray zones contrast with the surrounding brownish serpentinized matrix. Thin sections from relatively unaltered domains reveal olivine, spinel, serpentine, and plagioclase pseudomorphs. Orthopyroxene porphyroclasts occur as both circular grains (~2 mm) and elongated ribbons. Plagioclase grains are elongated, ranging from 0.2–1 mm in short diameter to 1–5 mm in long diameter. Olivine grains are fine (~0.3 mm) compared to other phases (Figure 4c). Circular orthopyroxene porphyroclasts (~1.5 mm) exhibit undulatory extinction (Figure 4c). Orthopyroxene ribbons are not developed in the XZ plane but appear slightly parallel to foliation in thin sections. Plagioclase pseudomorphs vary from 0.1–0.4 mm in short diameter to 0.5–1 mm in long diameter (Figure 4d).

R11: This sample exhibits the strongest foliation among the suite, characterized by well-aligned plagioclase and orthopyroxene porphyroclasts visible on the cut surface (Figure 2). Serpentinized domains occur subparallel to foliation, whereas relatively unaltered gray-to-black areas contrast with the surrounding brown regions (Figure 2). Plagioclase grains range from 0.3 to 1.5 mm. Thin sections from unaltered domains reveal olivine, pyroxene, plagioclase, serpentine, amphibole, and spinel. The matrix consists of small-grained (~0.3 mm) olivine and clinopyroxene (Figure 4e). Orthopyroxene porphyroclasts occur as circular grains (2–4 mm) and elongated ribbons (2 × 6 mm up to 2 × 30 mm) (Figure 4e). Orthopyroxene porphyroclasts (~2.5 mm) exhibit undulatory extinction and form asymmetric relationships with the surrounding matrix. A long orthopyroxene ribbon (~2.5 cm) is observed in the thin section (Figure 4e), with exsolution lamellae parallel to its elongation, some of which show microboudin microstructures (Figure 4f). Unlike other samples, plagioclase in this specimen is unaltered and displays twinning.

R12: The cut surface displays gray-to-black, relatively unaltered domains interspersed with serpentinized zones (Figure 2). Weak foliation is indicated by the alignment of plagioclase and orthopyroxene porphyroclasts. Thin sections from less-serpentinized regions reveal olivine, pyroxene, spinel, amphibole, serpentine, and plagioclase pseudomorphs. Orthopyroxene porphyroclasts are coarser than those in samples R10 and R11, generally asymmetric and non-circular. Plagioclase grains measure approximately 0.5 × 0.2 mm. The matrix is dominated by small-grained olivine (<1 mm; Figure 4g), with extinction orientations locally aligned. Orthopyroxene porphyroclasts exhibit undulatory extinction, whereas elongated orthopyroxene ribbons display exsolution lamellae and abundant microkinks (Figure 4g).

## 6. SEM-EBSD Results

### 6.1. Phase Map

The phase maps of 6K-1676-R10, R11, and R12 are presented in Figure 5. The green, blue, yellow, brown, light blue, and magenta colors indicate olivine, orthopyroxene, clinopyroxene, spinel, plagioclase, and amphibole, respectively. The gray color in Figure 5a–c indicates areas that could not be analyzed, such as serpentinized regions. Figure 5d–f show the expanded phase maps in which the gray regions in Figure 5a–c were systematically filled with the neighboring mineral phases.

In the phase maps, olivine occupies the matrix, and orthopyroxene remains as porphyroclasts, whereas the elongated orthopyroxene porphyroclasts, clinopyroxene, and plagioclase were distributed subparallel to the foliation (Figure 5).

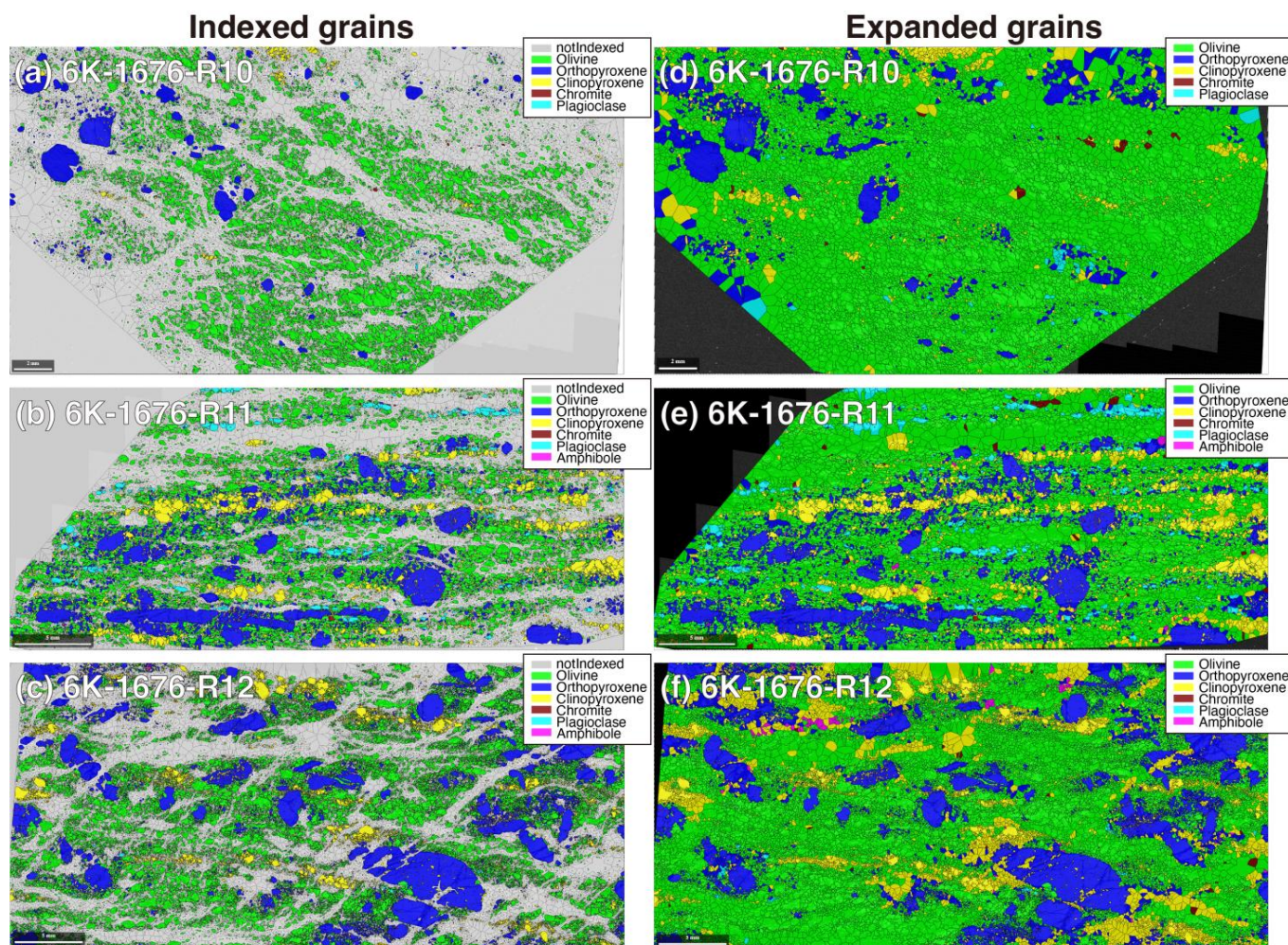


**Figure 5.** Phase maps obtained by SEM-EBSD. (a–c) Phase maps of 6K-1676-R10, R11, and R12 showing the distribution of indexed mineral phases and non-indexed domains. (d–f) Phase maps of 6K-1676-R10, R11, and R12 showing the expanded distribution of indexed mineral phases with filling of the non-indexed domains by neighboring indexed mineral phases. The green color indicates olivine; the blue color indicates orthopyroxene; the yellow color indicates clinopyroxene; the brown color indicates spinel; the light blue color indicates plagioclase; the magenta color indicates amphibole; the gray color indicates areas that could not be analyzed such as serpentine.

## 6.2. Grain Size

Olivine grain sizes were measured by extracting grain boundaries from the phase maps shown in Figure 5. Grain size determination was performed using the MTEX toolbox for MATLAB, in which grain boundaries were defined using a misorientation threshold of  $10^\circ$ . To evaluate the effect of serpentinization on grain size distributions, grain sizes were separately analyzed for the indexed grains (Figure 5a–c) and the expanded grains (Figure 5d–f).

The grain size distributions obtained from the indexed grains represent minimum estimates, reflecting the effects of serpentinization that locally disrupts olivine grains. In contrast, the distributions derived from the expanded grains provide maximum estimates, approximating the original olivine grain sizes prior to serpentinization.

The mean olivine grain sizes for samples 6K-1676-R10, R11, and R12 are 2.10 and 2.40, 2.15 and 2.35, and 2.10 and 2.30 (log grain size,  $\mu\text{m}$ ), respectively, for the indexed and expanded grains (Figure 6). These values correspond to olivine mean grain sizes of around  $200\ \mu\text{m}$  (i.e., 2.30 in log grain size), indicating broadly consistent grain sizes among the studied samples.

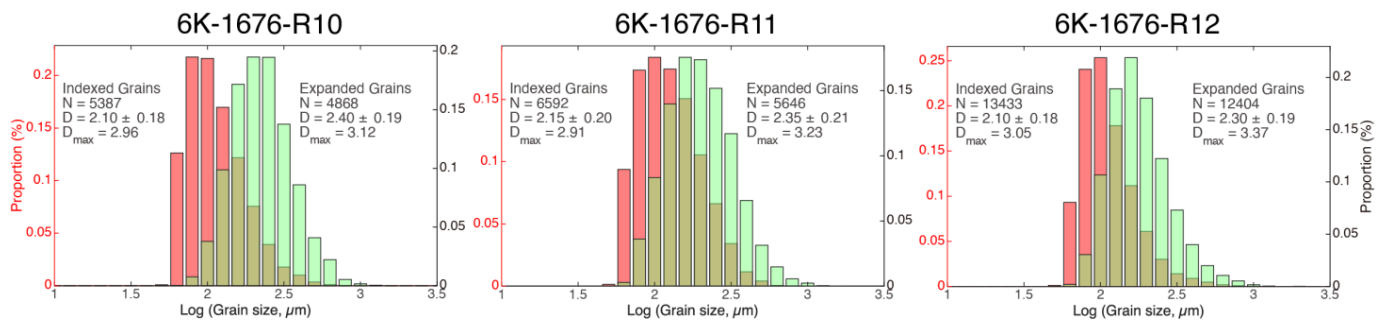


**Figure 6.** Olivine grain size distributions for samples 6K-1676-R10, R11, and R12. Grain sizes were determined from EBSD phase maps (Figure 5) using the MTEX toolbox with a misorientation threshold of 10°. Red histograms represent grain size distributions of indexed grains (Figure 5a–c), which provide minimum estimates owing to the effects of serpentinization, whereas green histograms represent expanded grains (Figure 5d–f), approximating the maximum grain size distributions prior to serpentinization. Note that red and green histograms overlap, producing an olive-colored region. Number of grains (N) and mean (D) and maximum (D<sub>max</sub>) grain sizes are indicated in each panel.

### 6.3. Crystallographic Preferred Orientation (CPO)

In this study, mineral CPOs were calculated based on expanded grains. This approach was adopted because pervasive serpentinization commonly causes fragmentation of originally single olivine grains into multiple indexed domains, which can artificially bias CPO statistics if only indexed grains are used.

For olivine CPOs (Figure 7a), samples prepared in the XZ plane—perpendicular to foliation (Z-axis) and parallel to lineation (X-axis)—show weak but systematic crystallographic alignments. In all samples, the [100]-axes display a slightly girdle- to lineation-parallel distribution, whereas the (001) planes exhibit a weak concentration subparallel to foliation. Samples 6K-1676-R10 and R12 show a stronger axial concentration of [010] than of [100].

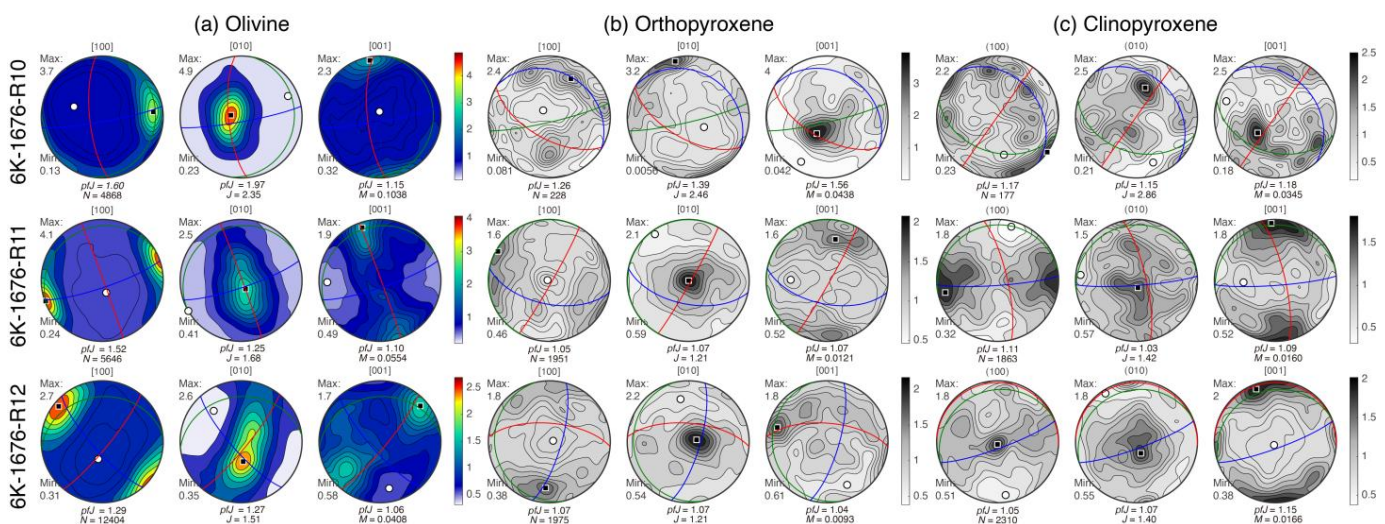


**Figure 7.** Crystallographic preferred orientations (CPOs) of (a) olivine, (b) orthopyroxene, and (c) clinopyroxene obtained by SEM-EBSD analysis for samples 6K-1676-R10, R11, and R12 using one orientation per grain. Pole figures for [100], [010], and [001] directions are shown in the XZ section, where X is parallel to lineation and Z is perpendicular to foliation. Contours are plotted in equal-area, lower-hemisphere projection and are normalized to multiples of a uniform distribution (MUD). Red, green, and blue great circles in each crystal-axis pole figure show planes normal to the direction of [100], [010], and [001] maximum densities (solid square in each pole figure), respectively. Max: maximum density, Min: minimum density, N: number of grains, J: J index, M: M index, pff: pff index.

The strength of olivine CPOs, quantified using the  $J$  and  $M$  indices, indicates overall weak to moderate fabrics. The  $J$  index values are greater than unity, confirming non-random crystallographic orientations, but remain far below those expected for strongly developed fabrics. Similarly, the  $M$  index values are significantly larger than zero but substantially lower than one. Among the samples, 6K-1676-R10 shows slightly higher  $J$  and  $M$  values than 6K-1676-R11 and R12, consistent with their more pronounced [010]-axial concentrations.

Orthopyroxene CPOs are the weakest among the analyzed mineral phases (Figure 7b). Although their CPOs do not exhibit any consistent orientation patterns among the samples, sample 6K-1676-R10 shows slightly higher  $J$  and  $M$  values with a [001] alignment subparallel to the Y-axis, whereas samples 6K-1676-R11 and R12 show lower  $J$  and  $M$  values with weak [010] alignments subparallel to the Y-axis. These features suggest that orthopyroxene participated in the deformation but accommodated strain less efficiently than olivine, resulting in weaker fabric development.

Clinopyroxene CPOs are generally weak and characterized by broadly dispersed pole figures (Figure 7c). No systematic concentration of the principal crystallographic axes is observed. Although a very weak tendency for the [001]-axes to align subparallel to the Z-axis may be recognized in samples 6K-1676-R11 and R12, the corresponding  $J$  and  $M$  values are very low, indicating an extremely weak fabric. Such weak clinopyroxene CPOs likely reflect either a limited contribution of clinopyroxene to bulk deformation and/or post-deformational processes, such as recrystallization or alteration that partially obscured the original fabrics.

Overall, the contrasting CPO strengths among olivine, orthopyroxene, and clinopyroxene indicate that deformation was dominantly accommodated by olivine, with subordinate participation of orthopyroxene and minimal contribution from clinopyroxene.

#### 6.4. Olivine Fabric Types

Figure 8 shows that the calculated P-wave anisotropy ranges from 5.9% to 8.8%, with sample 6K-1676-R10 showing the highest anisotropy and sample 6K-1676-R12 the lowest. In all samples, the fast P-wave propagation direction is broadly aligned with the structural lineation, consistent with the dominant olivine CPO patterns. In the  $V_x/V_y$ – $V_y/V_z$  space, all samples plot in a blank domain but close to the E-type olivine fabric field (Figure 8). Samples 6K-1676-R10 and R11 fall close to the boundary to the E-type field, whereas sample 6K-1676-R12 plots far from the E-type field.

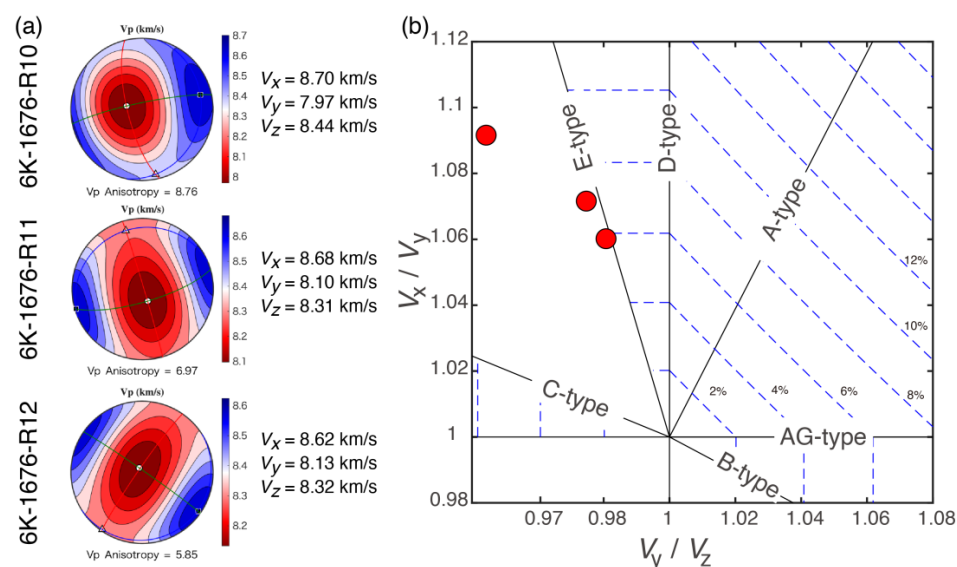


**Figure 8.** (a) Calculated P-wave velocity ( $V_p$ ) distributions and seismic anisotropy derived from olivine CPOs for samples 6K-1676-R10, R11, and R12 with color scales indicating velocity magnitude

and calculated P-wave anisotropy values in equal-area, lower-hemisphere projections. Red, green, and blue great circles in each pole figure show planes normal to the direction of  $V_x$  (solid square),  $V_y$  (triangle), and  $V_z$  (open circle), respectively. (b)  $V_x/V_y$ – $V_y/V_z$  space used to classify olivine fabric types. The blue dashed lines represent contours of P-wave velocity ( $V_p$ ) anisotropy. Red circles represent the analyzed samples 6K-1676-R10, R11, and R12 shown in (a). Fields for A-, B-, C-, D-, E-, and AG-type olivine fabrics are shown for reference. All samples plot in a blank domain between C- and E-type field.

## 7. Discussion

### 7.1. Mylonite

Macroscopic and microstructural observations indicate that most ultramafic rocks from the Tosa Megamullion exhibit well-developed porphyroclastic textures, locally accompanied by strong planar fabrics, asymmetric olivine aggregates around orthopyroxene porphyroclasts, and small-grained olivine matrices (Figures 3–6). These features are diagnostic of ductile deformation [17]. In particular, the asymmetric distribution of olivine around orthopyroxene porphyroclasts and the development of fine-grained olivine aggregates are typical features of mylonitic deformation produced under simple-shear-dominated flow. Such mylonitic textures commonly develop within deep-seated shear zones in the upper mantle (e.g., [1,46]). Therefore, the ultramafic rocks from the Tosa Megamullion examined in this study are interpreted to represent mantle-derived mylonites formed within a deep ductile shear zone.

### 7.2. Olivine CPO and Deformation Mechanism

The three samples selected for EBSD analyses were chosen because they best preserve primary olivine and well-developed mylonitic fabrics (Table 2; Figure 2). Petrographic observations indicate that the remaining samples share similar microstructural characteristics, despite more intense serpentinization (Figures 3 and 4), suggesting that the olivine CPOs presented here are representative of the dominant deformation regime within the Tosa Megamullion.

Figure 9 illustrates olivine fabric transitions in the  $V_x/V_y$ – $V_y/V_z$  space, together with schematic representations of the corresponding crystallographic preferred orientations (CPOs) and P-wave velocity ( $V_p$ ) patterns for single crystals, following Kakhata et al. [42]. This framework summarizes both general fabric transition trends ( $\alpha_1$ – $\alpha_2$ ,  $\beta_3$ ) and specific fabric transition trends ( $\beta_1$ – $\beta_2$ ), which describe systematic variations in olivine CPOs under different deformation conditions [42].

The general transition trends ( $\alpha_1$ – $\alpha_2$ ,  $\beta_3$ ) reflect broad, progressive changes in olivine CPOs from B- through AG-, A-, D-, to E-type fabrics (Figure 9a,b), representing systematic shifts in dominant olivine slip systems driven by large-scale variations in stress, temperature, and water content during mantle deformation [33,34]. In contrast, the specific transition trends ( $\beta_1$ – $\beta_2$ ) describe more restricted evolutionary paths between selected fabric types (Figure 9a,c), reflecting deformation under more narrowly defined mechanical conditions rather than continuous thermodynamic evolution [42].

The olivine CPOs obtained in this study (samples 6K-1676-R10, R11, and R12) plot in a transitional domain between the E- and C-type fields and closely follow the  $\beta_2$  transition trend rather than the general trends (Figure 9a). This distribution suggests that deformation was dominated by E-type fabrics characterized by the (001)[100] slip system, with a subordinate contribution from C-type fabrics associated with the (100)[001] slip system. Importantly, the position along the  $\beta_2$  trend implies deformation associated with progressive strain localization, potentially involving increasing differential stress and limited but non-negligible hydration during simple-shear-dominated flow (e.g., [47–49]).

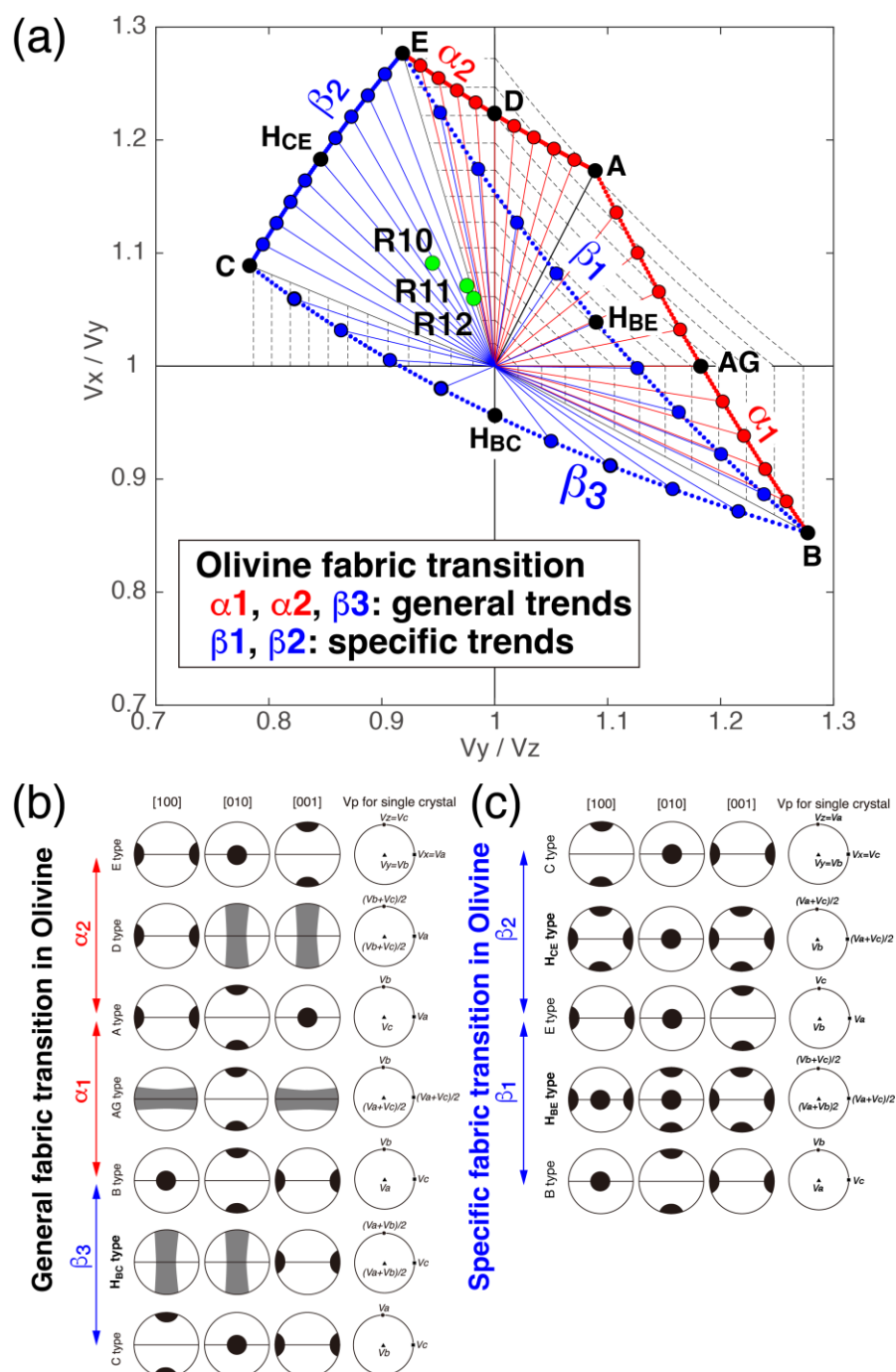


**Figure 9.** Olivine fabric transitions illustrated in the  $V_x/V_y$ – $V_y/V_z$  space and their relationships to crystallographic preferred orientations (CPOs) and seismic properties. **(a)** Diagram showing general olivine fabric transition trends ( $\alpha_1$ – $\alpha_2$ : red,  $\beta_3$ : blue) and specific transition trends ( $\beta_1$ – $\beta_2$ ; blue), following Kakiyama et al. [42]. Fields for A-, B-, C-, D-, E-, AG-, H<sub>BE</sub>-, H<sub>BC</sub>-, and H<sub>CE</sub>-type fabrics are indicated. Green symbols represent olivine CPOs of samples 6K-1676-R10, R11, and R12 from this study. **(b,c)** Schematic pole figures of olivine CPOs and corresponding P-wave velocity ( $V_p$ ) patterns for single crystals associated with each fabric type. The black and grey colors in each pole figure represent the preferred orientations of the respective crystallographic axes. **(b)** General fabric transition in olivine ( $\alpha_1$ – $\alpha_2$ : red,  $\beta_3$ : blue). **(c)** Specific fabric transition in olivine ( $\beta_1$ – $\beta_2$ : blue). The studied samples plot close to the E-type field and follow the  $\beta_2$ -type specific transition trend, indicating a mixture of E- and C-type olivine fabrics.

Comparable E-type-dominated fabrics have been reported from other oceanic core complexes, including the Godzilla Megamullion in the Parece Vela Basin [10] and the

Gakkel Ridge [50]. The recurrence of similar fabric patterns across distinct tectonic settings suggests that E-type-dominant olivine CPOs may represent a characteristic deformation style of mantle shear zones beneath the back-arc basins and amagmatic or magma-poor detachment faults. In this context, the absence of classical A-type olivine fabrics, typically associated with dry upper-mantle conditions [31,32], further supports deformation under non-dry conditions.

Taken together, these olivine fabric characteristics indicate deformation under conditions involving moderate hydration and/or elevated differential stress, consistent with experimental and natural constraints on the development of E- and C-type fabrics [34,51]. Although these conditions are inferred indirectly from olivine CPO systematics, the results suggest that mantle deformation beneath the Tosa Megamullion occurred within a ductile shear at the base of a magma-poor detachment fault system, where strain was accommodated primarily by crystal-plastic flow rather than by melt-assisted processes.

### 7.3. Orthopyroxene Deformation Features

Orthopyroxene CPOs exhibit generally weak intensities in the analyzed samples (Figure 7). Despite the weak CPOs, orthopyroxene displays clear and systematic evidence of crystal-plastic deformation in microstructures. In particular, orthopyroxene porphyroclasts are highly elongated and aligned parallel to the mylonitic foliation in samples 6K-1676-R10, R11, and R12 (Figures 4 and 5). These porphyroclasts locally exhibit internal deformation features such as undulose extinction, microfracturing, and incipient boudinage, indicating significant strain accommodated by orthopyroxene during ductile shearing.

Notably, thin sections of sample R11 contain elongated orthopyroxene microboudins (Figure 4f), which likely formed by fragmentation of orthopyroxene porphyroclasts during extreme elongation under high-strain conditions [52,53]. The crystallographic orientation of these elongated orthopyroxene porphyroclasts is characterized by [001] parallel to the x-axis and [100] parallel to the z-axis, consistent with deformation dominated by the (100)[001] slip system [54,55]. For instance, Dornbusch et al. [52] reported that orthopyroxene porphyroclasts deform preferentially by this slip system during high-temperature ductile flow. Therefore, the elongated orthopyroxene grains indicate that the mylonite in R11 experienced intense ductile shear deformation. To estimate the original aspect ratios of orthopyroxene porphyroclasts prior to microboudin formation, the connected lengths of individual porphyroclasts were measured. The major and minor axes are approximately 2.5 cm and 0.1 cm, respectively, yielding an aspect ratio of ~25:1.

Previous studies have demonstrated that orthopyroxene porphyroclasts can attain aspect ratios of up to ~100:1 under upper-mantle conditions at temperatures approaching 1000 °C [56,57]. Although the aspect ratio observed in sample 6K-1676-R11 is lower than these extreme values, the measured ratio of ~25:1 is compatible with high-temperature ductile deformation under upper-mantle conditions.

In addition to elongation, numerous microkinks are observed in orthopyroxene porphyroclasts in samples 6K-1676-R10 and R12 (e.g., Figure 4g). These microkinks likely formed under stress conditions that differed from those responsible for porphyroclast elongation. Although their precise origin remains uncertain, one plausible explanation is that they developed in response to compressive stresses associated with post-deformational processes, such as isostatic uplift or cooling during exhumation. Alternatively, microkinks may also form within the brittle–ductile transition zone under conditions comparable to those of ductile deformation. Further detailed microstructural and experimental studies are required to fully constrain the formation mechanisms of these microkinks.

#### 7.4. The Formation of Tosa Megamullion Under Magma-Poor Conditions

Recent numerical modeling studies of OCC formation [58–60], together with drilling results documenting gabbroic rocks [61–63], suggest that magma supply plays an important role in the development of detachment faults. In particular, Tucholke et al. [59] proposed that megamullion structures preferentially form when a moderate magma supply—approximately 30%–50% of the full spreading rate—is available.

The Mado Megamullion, which formed during the late stage of spreading of the Shikoku Basin, provides a representative example of such magma-influenced OCC formation. Rock samples recovered from the Mado Megamullion include abundant magma-derived lithologies, such as gabbro and basalt, which together account for approximately 70% of the total recovered mass (270 kg; [13]). This compositional dominance indicates that magma supply played a significant role in its development.

In contrast, the Nankaido Megamullions, including the Tosa Megamullion, is characterized by mantle Bouguer anomalies that are significantly more positive than those observed elsewhere in the Shikoku Basin [16,21]. These geophysical signatures indicate a thin oceanic crust and extensive exposure of lower crustal and upper-mantle rocks. Consistent with this interpretation, most rocks collected from the Tosa Megamullion are mantle-derived peridotites rather than magma-derived lithologies [16]. These observations suggest that the Tosa Megamullion developed under a strongly magma-poor, amagmatic environment during the early stage of Shikoku Basin spreading (Figure 10).

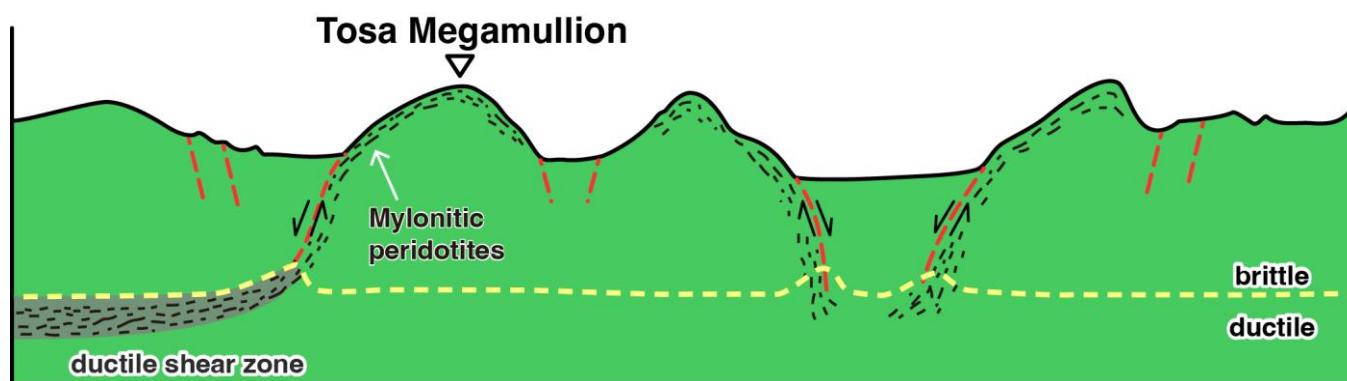


**Figure 10.** Schematic cross-section model illustrating the proposed formation of the Tosa Megamullion under magma-poor conditions. The model highlights a deep-seated ductile shear zone within the upper mantle, where mylonitic peridotites developed and were subsequently exhumed along a detachment fault. In contrast to magma-rich megamullions, limited magmatic accretion resulted in a thin oceanic crust and extensive exposure of mantle rocks. The transition from ductile to brittle deformation is indicated schematically.

Similar magma-poor OCCs have been documented at mid-ocean ridges, particularly along the Southwest Indian Ridge (SWIR), where strain localization beneath detachment faults is accommodated largely within the upper mantle under melt-starved conditions [64]. Detailed microstructural and petrological analyses from the SWIR further demonstrate that ductile shear deformation of peridotites can dominate OCC formation in the absence of significant magmatic accretion [65].

In addition to melt-starved OCCs at mid-ocean ridges, studies of fossil mantle shear zones preserved in ophiolites provide important constraints on deformation and hydration processes under magma-poor conditions. Vieira Duarte et al. [66] documented amphibole-bearing peridotite mylonites from the Lanzo massif, interpreting them as the products of ductile mantle shear zones that acted as long-lived fluid pathways beneath ultraslow-spreading ridges. Their study demonstrates that hydration and strain localization can

occur at depths beyond serpentine stability, without significant magmatic accretion, and are accompanied by changes in olivine and pyroxene CPOs.

Similarly, Zhang et al. [67] investigated peridotite mylonites from the Yarlung–Tsangpo ophiolite and showed that intense ductile shear deformation of the upper mantle can develop under limited melt supply, with strain localization primarily accommodated by crystal-plastic flow of olivine and pyroxenes. These ophiolitic examples highlight that mylonitic peridotites represent a fundamental rheological response of the mantle to tectonic extension in magma-poor settings.

Together with observations from the Southwest Indian Ridge [64,65], these studies indicate that ductile mantle shear zones and mylonitic peridotites are a common feature of OCC formation when magma supply is limited, irrespective of whether the tectonic setting is a mid-ocean ridge, a back-arc basin, or a fossil oceanic lithosphere preserved in ophiolites. In this context, the Tosa Megamullion can be interpreted as a modern back-arc analogue of magma-poor OCC formation dominated by mantle shear deformation rather than by magmatic accretion.

Accordingly, it is unlikely that the OCC structure in the Nankaido Megamullions formed under the moderate magma supply conditions assumed in prevailing structural models. Instead, the Tosa Megamullion likely represents a distinct end-member of OCC formation, in which detachment faulting and mantle exhumation were primarily accommodated by ductile shear deformation within the upper mantle, with little contribution from magmatic accretion. The close similarity between the Tosa Megamullion and magma-poor OCCs at the SWIR suggests that common deformation mechanisms may operate across both back-arc basins and mid-ocean ridges when magma supply is limited, despite differences in tectonic setting.

## 8. Conclusions

This study demonstrates that ultramafic rocks from the Tosa Megamullion record ductile shear deformation in the upper mantle within a deep-seated shear zone at the base of a detachment fault during the early stage of Shikoku Basin spreading. The predominance of E-type olivine CPOs, with a subordinate contribution from C-type fabric, together with the pronounced elongation and boudinage of orthopyroxene porphyroclasts, is consistent with deformation under non-dry conditions involving moderate hydration and/or elevated differential stress. These microstructural and crystallographic characteristics provide direct evidence that mantle deformation beneath the Tosa Megamullion occurred in a magma-poor, largely amagmatic tectonic environment, where strain was accommodated primarily by crystal-plastic flow rather than by melt-assisted processes. Subsequent exhumation of these mantle rocks to the seafloor contrasts sharply with the more magma-rich tectonic regime that characterized the later stage of Shikoku Basin spreading. This contrast highlights a fundamental temporal change in the mechanical and magmatic conditions governing detachment faulting and mantle exposure in the Shikoku Basin and established the Tosa Megamullion as an amagmatic end-member of OCC formation in back-arc basins.

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