Serpentinite enigma of the Rakhabdev lineament in western India: Origin, deformation characterization and tectonic implications

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Serpentine mineralogy controls fault rheology in the ocean and continental rift settings to subduction settings and hence can be used to discern the paleo deformational conditions. The Rakhabdev lineament from Rajasthan, India, provides a unique opportunity to understand its tectonic evolution inferred from the deformation microstructures. However, the complexity of surrounding calc-silicate rocks had resulted in a long-driven debate on the origins of these serpentinite rocks. The source rocks of the serpentinites also cannot be determined previously due to complete serpentinization and metasomatism rendering complete alteration of the source rocks. In this study, the serpentinite mineral was analyzed using Raman spectroscopy to accurately characterize its molecular structure. The presence of the antigorite variety of serpentine mineral indicate towards the origin of Rakhabdev serpentinites in the upper mantle condition. The antigorite serpentinite of Rakhabdev is a hydration product of mantle materials showing high Mg# values obtained from EPMA data. The microstructural and EBSD analysis also indicates two stages of deformation, with deformation of antigorite at upper mantle conditions, followed by their shallow crustal carbonate metasomatism and subsequent deformation of the carbonates, with later stage calcite vein intrusion. This resulted in the appearance of antigorite in contact with calcite, dolomite, talc, tremolite, and chlorite. The exhumation of mantle wedge antigorite serpentinite is, therefore, indicating a paleo-subduction zone culminating in a crustal-scale collision boundary expressed as arcuate discontinuous bodies forming the Rakhabdev lineament.

Keywords: Rakhabdev serpentinite, Antigorite deformation, Calcite CPO, Raman spectroscopy

INTRODUCTION

Serpentinites typically form due to the hydration of peridotite at temperatures ranging from ~ 200 to ~ 600°C, resulting in the alteration of Mg-rich olivine and orthopyroxene to serpentine minerals (Evans et al., 2013). The common serpentine minerals chrysotile, lizardite, and antigorite have similar chemical composition, yet very different crystal structure (Wunder et al., 2001; Rinaudo et al., 2003). Chrysotile has a coiled structure responsible for its asbestiform properties, while lizardite has a planar structure, and antigorite has a wave-like structure (Wicks and Whittaker, 1975; Uehara, 1998). Structural type of serpentine mineral present provides insights into the depth of serpentinization (Wunder et al., 2001; Bromley and Pawley, 2003), and the microstructures developed within them help in characterization of the deformation processes activated in the region of their occurrence. The antigorite, formed as a result of serpentinization of mantle peridotites, is stable in the upper mantle condition. Their formation occurs in an MSH (MgO-SiO₂-H₂O) or MASH (MgO-Al₂O₃-SiO₂-H₂O) system (Wunder et al., 2001). The antigorite develops from water stored in mantle conditions in the high P-T stability field of the serpentine, primarily by slab dehydration below mantle wedge overlying a subducting slab (Arai and Ishimaru, 2008; Debret et al., 2019; Uno and Kirby, 2019). The unique alternating wave structure characteristic of antigorite and its crystal preferred orientation (CPO) are con-
trolled by the original olivine fabric of the mantle wedge (Boudier et al., 2009) and acts as a controlling factor in fluid flow pathways and seismic anisotropy of the subduction zones (Hirauchi et al., 2010; Kawano et al., 2011; Campione and Capitani, 2013; Mizukami et al., 2014).

The studies on antigorite deformation, however, are limited to recent subducting slab (Andreani et al., 2007; Hirauchi et al., 2010; Plissart et al., 2019), and studies on paleo-subduction zones have been rarely investigated especially the completely metasomatized paleo-subduction zones. Since, different serpentinite minerals can deform at variable depths, identifying the chemical and structural variety of the serpentine minerals help in their characterization as metasomatized mantle wedge materials. The study of such serpentinite bodies can help in the understanding of the conditions of the metasomatism, deformation mechanisms, and tectonic evolution of the subduction zone. Such paleo-subduction zones are major components of the orogenic belt that stich older cratonic blocks and occurs within present-day continental crust.

One such orogenic belt is the Aravalli-Delhi Mobile Belt (ADMB) in the state of Rajasthan, India, where few studies (Deb et al., 1989; Sarkar et al., 1989; Sugden et al., 1990; Verma and Greiling, 1995; Deb and Thrope, 2001; Singh et al., 2010; Purohit et al., 2015; Tiwari and Biswal, 2019) have reported the occurrence of serpentinites within Proterozoic meta-sediments. The fragmented bodies of serpentinite rock occur along Rakhabdev lineament between the Jharol Group and the lower-middle Aravalli Group of rocks. However, due to a lack of studies in chemical characterization and complexity of the deformation and metamorphism in the area, the origin of these rocks is still an enigma. Two prevalent theories about their origin are the serpentinization of structurally-controlled ultramafic intrusions and the serpentinization in the paleo-subduction zone (Sarkar et al., 1989; Verma and Greiling, 1995). Lack of evidence and dearth in studies have rendered both the theories debatable (Sugden et al., 1990; Abu-Hamattah et al., 1994; Gathania et al., 1995; Shekhawat et al., 2010).

The present study aims at identifying the molecular structure of the serpentinite mineral specimen present within the serpentinite bodies to give insights into its origin. The study of deformation microstructures is also attempted to determine deformation conditions and their relation to the Aravalli-Delhi orogeny (Prasad et al., 1998). Few studies have been undertaken based on microstructures and geochemistry of the antigorite (Bhu et al., 2006; Purohit et al., 2015). However, accurate characterization of serpentinite and usage of EBSD to determine deformation mechanisms have not yet been reported from this area. This could help in elucidating the origin of the serpentinites which is present as arcuate discontinuous bodies within the metamorphosed Aravalli Supergroup of the ADMB.

GEOLOGICAL BACKGROUND AND SAMPLE LOCALITY

Rakhabdev (or Risabhadev) serpentinites constitute a series of continuous to detached (at places) bodies, occurring with a linear N-S trend for a distance of about 90 km between Gogunda in the north and Antri in the south, that defines the Rakhabdev lineament (Fig. 1), within the Aravalli Supergroup (Bhu et al., 2006). The ADMB comprises two major supracrustal units, viz., the Aravalli Supergroup and the Delhi Supergroup, and deposited on an Archaean basement known as the Banded Gneissic Complex (BGC) (Gupta et al., 1995; Heron, 1953; Roy and Jakhar, 2002; Sharma, 2010). The Aravalli Supergroup has been subdivided into the Lower, Middle and Upper Aravalli Groups (Roy and Jakhar, 2002). The lowest part of the succession is dominated by stromatolitic phosphorites and U-bearing black shales along with metabasalts. The middle part mostly comprises greywacke, carbonaceous phyllite, and conglomerate, and the upper part is dominantly quartzite, conglomerate, and phyllite which grades into mica schists with thin quartzite bands in the western side. Roy and Jakhar (2002) has designat

LOCALITY

The thinsections (~ 30 µm) were prepared along XZ section (perpendicular to foliation and parallel to lineation) and polished with 1 µm diamond paste, for petrographic observations. For EBSD analysis, two chip samples (cut along XZ section) of 1 cm by 1 cm were polished using IS Polisher 1000 at Kochi Core Center JAMSTEC facility to minimize the surface damage during polishing, followed by osmium coating at Hiroshima University.
Principle of Raman spectroscopic analysis of serpentine minerals

Raman spectra of serpentines in low wavenumber spectral range (150–1100 cm$^{-1}$) corresponds to the inner vibrational modes of the lattice and to Si-O$_4$ vibrations, while the high wavenumber spectra (3550–3850 cm$^{-1}$) corresponds with the stretching vibrations of the OH groups of the water molecules (Petriglieri et al., 2015). Low wavenumber Raman spectra obtained shows strong peak of 230 cm$^{-1}$, which is present in all serpentine polymorphs due to O–H–O vibrations, O being the non-bridging oxygen of a SiO$_4$ tetrahedron and H being the hydrogen of the outer OH group of the adjacent layer (Griffith and Wickins, 1967; Loh, 1973; Petriglieri et al., 2015). The peak at 680 cm$^{-1}$, due to deformation vibrations of the Si–O layer, the peak at 1044 cm$^{-1}$, due to antisymmetric stretching mode ($v_{as}$) of S–O$_2$–Si groups, and the doublet at 3665 cm$^{-1}$ and 3695 cm$^{-1}$, implies the presence of antigorite variety of the serpentine mineral in the collected serpentinites (Auzende et al., 2004; Enami, 2006).

Raman Spectroscopic analyses of two thin sections representative of the serpentine minerals were conducted by JASCO NRS–5100 Raman Spectrometer at the Geodynamics Research Center (GRC) facility of Ehime University. The analysis was done using 532 nm Nd–YAG laser and CCD detector. Collection times for Raman spectra were 6 or 12 accumulation of 10 s each.
Electron Micro Probe Analysis

The major element chemical compositions of the serpentines and the associated minerals including opaque minerals were done by EPMA (JEOL JXA–8200) at Natural Science Center for Basic Research and development (N–BARD) facility of Hiroshima University with accelerating voltage of 15 kV and 2 µm beam size. ZAF method was applied for matrix corrections.

Electron Backscatter Diffraction Analysis

The crystallographic preferred orientation (CPO) was obtained point by point, for the calcite and antigorite by electron backscattered diffraction (EBSD) using the Nordlys system attached to scanning electron microscope JEOL JSM6390A, with accelerating voltage of 15 kV and sample tilt of 70°. The obtained EBSD patterns were processed using the HKL Channel 5.0 software package.

RESULTS

The serpentinites occur in the field as detached bodies bounded by metapelites in the west and talc–tremolite schists (Fig. 2a) in the east. The actual contact of the metapelites and talc–tremolite schists with the serpentinites could not be identified in the studied area. The detached serpentinite bodies show a trend of NNE–SSW with subvertical foliation overprinted by crenulation cleavage trending NE–SW (Fig. 2b). The preliminary structural data of the foliation and lineation obtained from the serpentinite bodies and the measured crenulation cleavages are presented in Figure 3. The serpentinite samples, in thinsections show two types of assemblages. One assemblage shows the presence of dominantly serpentine minerals (the type of serpentine mineral is identified using Raman spectroscopy) with opaque minerals (mineral composition determined by EPMA). The opaque minerals of this assemblage are primarily magnetite, with few relict Cr–spinel. The other assemblage comprises of serpentine minerals with calcite, dolomite, talc, tremolite, and chlorite. The opaque minerals of the second assem-
blage include dominantly magnetite and also include minor alteration to ulvöspinel. Cr–spinel is not present in the serpentinite samples with calcite veins. Also, in the currently studied samples, no olivine grains could be identified. The serpentines exhibit massive (with interpenetrating blades) to foliated textures, with clasts of dolomite interspersed with massive serpentine minerals (discussed in later sections).

Raman spectral analysis of serpentine

The serpentinites primarily exhibit massive and randomly oriented blades or foliated nature observable in thinsections. Raman spectra of serpentines in low wavenumber spectral range (150–1100 cm⁻¹) shows strong peak at ~230, ~373, ~680, and ~1041 cm⁻¹ (Fig. 4). The high wavenumber spectra (3550–3850 cm⁻¹) shows the doublet at ~3665 and ~3695 cm⁻¹ (Fig. 4).

Microstructural characterization and CPO

The serpentinites contain dominantly antigorite and occur as massive or foliated. The massive antigorite shows the interpenetrative texture of the blades of antigorite (Fig. 5a). The Cr-spinel grains preserved in the massive antigorite are fractured and show gradational zoning (Fig. 5b) of progressive Fe-enrichment from the unaltered core towards the Fe-rich rim. They are present with the assemblage of interpenetrative antigorite without any secondary alteration minerals like chlorite. The massive antigorite is deformed into foliated antigorite (Fig. 5c), showing a slight variation in BSE contrast, corresponding to their variation in mineral content (composition). Few relict grains preserve the interpenetrative texture of the original antigorite and shape of original parent grains (Fig. 5d). The magnetite present in the foliated antigorite samples (Fig. 5e) does not exhibit any zoning. Prominent calcite veins (Fig. 5f) crosscut the foliation of the antigorite and
Figure 5. (a) XPL image of original antigorite shows interpenetrating structures. (b) SEM-BSE image of representative Cr-Spinel within the original antigorite shows Fe-enrichment from core to outer rim. (c) SEM BSE images of foliated antigorite. (d) Pseudomorphic grains preserving interpenetrative texture and showing alteration to foliated antigorite. (e) SEM-BSE image of magnetite grains in the foliated antigorite sample. (f) Thin section of foliated antigorite with later stage calcite veins cutting them at an angle. (g) Calcite vein crosscutting the foliated antigorite with assemblage of talc-tremolite-chlorite. (h) The XPL image of calcite veins [marked by rectangle in (f)], with recrystallized grains (arrows) and larger grains showing twin development and undulose extinction.
are deformed by twinning and recrystallization (Figs. 5g and 5h).

The EBSD analysis of the foliated antigorite (Fig. 6) obtained from XZ sections of the samples, exhibit well developed CPO (Fig. 7a), with multiples of uniform distribution (m.u.d) values 0.03–5.46. The [010] axes of antigorite are concentrated parallel to the lineation and [100] axes subnormal to lineation. This CPO pattern suggests the activation of [010] (001) slip system in antigorite. The calcite within the veins crosscutting the foliated antigorite has also developed a weak but distinctive CPO (m.u.d. 0.19–2.15), with [0001] axes parallel to vein direction and <11–20> axes spread normal to the vein (Fig. 7b). This CPO pattern is due to the dislocation creep with (0001) as the dominant slip plane for calcite deformed at mid– to high temperatures (de Bresser and Spiers, 1993; Austin et al., 2008; Vauchez et al., 2015).

**Mineral Chemistry**

The detailed compositions of the antigorite (inferred by the textural similarity with the representative antigorite grains determined by Raman spectroscopy) are listed in Supplementary Table S1 (available online from https://doi.org/10.2465/jmps.191016).

The major total oxide of the antigorite ranges 84.58–88.25%. Recalculations of atomic proportions were done

![Figure 6. Representative area showing foliated antigorite grains for EBSD analysis.](image)

![Figure 7.](image)
based on the seven oxygen and yields Mg number (88.80–91.13) for samples containing calcite and dolomite. The antigorite from zones without calcite and dolomite assemblage shows a higher Mg number (93.78–98.70). No zoning within the individual antigorite grains was observed in SEM BSE, however, there is a variation in the Fe content of all the antigorite samples. The Mg versus (Fe + Mg) plot (Fig. 8a) shows clustering in two distinct zones, representing alteration in the antigorite chemistry in response to the presence of carbonate phases. The representative composition of the talc, chlorite, and spinel are also listed in Table S1. The mineralogical variation in Cr-spinels is inferred by plotting its Mg number against its Cr number (Fig. 8b) and shows the compositional affinity of the spinel in the common region of forearc and abyssal peridotites (Gamal El Dien et al., 2019).

DISCUSSIONS

Generation and deformation of antigorite

The absence of mantle minerals like olivine and pyroxenes within the observed samples renders the determination of source rock mineralogy difficult. However, the predominance of only antigorite within the serpentinite (inferred from Raman spectroscopic analysis), and the mineralogy of the Cr-spinels (Fig. 8b) suggest the possibility of forearc peridotites as the source rock (Gamal El Dien et al., 2019).

The interpenetrating microstructures of the original antigorite (Fig. 5a) that is also preserved in pseudomorph (Fig. 5d) shows deformation into oriented blades of antigorite forming the foliated antigorite (Figs. 5c and 5d). Since, all other phases are post to this massive antigorite and the foliated antigorite, therefore the serpentinization is a product of olivine + orthopyroxene system at pressure >1.5 GPa (Nakatani and Nakamura, 2016). The hydration of olivine and orthopyroxene resulting in the formation of antigorite is given by the following reaction (Pawley, 1998; Murata et al., 2009; Watanabe et al., 2011; Auzende et al., 2015).

\[
\text{Mg}_2\text{SiO}_4 + \text{MgSiO}_3 + 2\text{H}_2\text{O} \rightarrow \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4
\]

Olivine + Orthopyroxene + water → Antigorite

The presence of the Cr-Spinel as opaque mineral (without any hydrous phases like chlorite) and the Mg-rich antigorite (Fig. 5b) also suggest a high temperature (400–600 °C) for the serpentinization, accommodated by compositional adjustment of olivine at higher rates of Mg–Fe diffusion (Evans, 2010; Evans et al., 2012). The subsequent Fe rich alteration of the Cr-spinel and presence of Fe-oxides and Fe-Ti oxides suggests their mobilization in later metasomatic process, post to the serpentinization of the peridotites (Gamal El Dien et al., 2019; Nozaka, 2018).

The CPO pattern in the foliated antigorite (Fig. 7a)
represents the antigorite CPO pattern common with other antigorite samples reported from forearc mantle body (Nishii et al., 2011), with the c-axis perpendicular to the foliation and the b-axis parallel to the stretching lineation. The σ1 direction being parallel to foliation suggests horizontal orientation. The antigorite deformation behavior is controlled by the structural relationship between olivine in peridotite and antigorite, which again depends on the fluid flow pathways controlled by the geometry of the initial olivine fabric and the topotactic relationship between olivine and antigorite (Watanabe et al., 2011). Few pseudomorphs of antigorite are present (Fig. 5d). However, in the absence of parent mantle mineral grains such inferences cannot be drawn from these samples.

Metasomatism and deformation at shallow crust

The presence of calcite + talc + tremolite + chlorite + dolomite assemblage suggests secondary metasomatism of already-hydrated mantle peridotite at a shallower depth, with high CO2 partial pressure (Schandl and Naldrett, 1992; Soda and Takagi, 2010) leading to alterations of the relict forsterite grains associated with bladed antigorite. This secondary metasomatism led to the generation of talc–tremolite–calcite–dolomite–chlorite assemblage. This was followed by intrusion of calcite veins (at a later stage of CO2 metasomatism), cutting across all other features (Fig. 5f). No relict upper mantle minerals except Cr–spinels (with Fe-enrichment towards the rim) are observed in the analyzed samples since the entire rock is metasomatized. The exhumation of the hydrated upper mantle material and its subsequent shallow crustal metasomatism is possible during ongoing subduction, along the exhuming channels at the interface of the subducting slab and mantle wedge. Also, since metamorphosed deep-sea sediments are reported from the western margin of the presently studied antigorite exposures (Roy and Jakhar, 2002), it further supports the idea of Rakhabdev being a tectonic lineament preserving hydrated mantle rocks. Further studies are required on the regional deformation pattern of the Rakhabdev lineament to elucidate the related tectonic scenario. The timing of this tectonism is also important to determine the integrated tectonics of this paleo-subduction zone and the eventual closure of the paleo-ocean in the overall evolution of ADMB.
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SUPPLEMENTARY MATERIALS

Supplementary Figure S1 and Table S1 are available online from https://doi.org/10.2465/jmps.191016.

REFERENCES

Abu-Hamateh, Z.S.H., Raza, M. and Ahmad, T. (1994) Geochemistry of early Proterozoic mafic and ultramafic rocks of Jharel Group, Rajasthan, Northwestern India. Journal of Geological Society of India, 44, 141–156.

Andreani, M., Mével, C., Boullier, A.-M. and Escardin, J. (2007) Dynamic control on serpentine crystallization in veins: Constraints on hydration processes in oceanic peridotites. Geochemistry, Geophysics, Geosystems, 8. doi:10.1029/2006GC001373.

Arai, S. and Ishimaru, S. (2008) Insights into Petrological Characteristics of the Lithosphere of Mantle Wedge beneath Arcs through Peridotite Xenoliths: a Review. Journal of Petrology, 49, 665–695.

Austin, N., Evans, B., Herwegh, M. and Ebert, A. (2008) Strain localization in the Morcles nappe (Helvetic Alps, Switzerland). Swiss Journal of Geosciences, 101, 341–360.

Auzende, A.-L., Daniel, I., Reynard, B., Lemaire, C. and Guyot, F. (2004) High-pressure behaviour of serpentine minerals: a Raman spectroscopic study. Physics and Chemistry of Minerals, 31, 269–277.

Auzende, A.-L., Escardin, J., Wolte, N.P., Guillot, S., et al. (2015) Deformation mechanisms of antigorite serpentinite at subduction zone conditions determined from experimentally and naturally deformed rocks. Earth and Planetary Science Letters, 411, 229–240.

Bhu, H., Sarkar, A., Purolai, R. and Banerjee, A. (2006) Characterization of fluid involved in ultramafic rocks along the Rakhabdev Lineament from southern Rajasthan, northwest India. Current Science, 91, 1251–1256.

Boudier, F., Barrouzet, A. and Mainprice, D. (2009) Serpentine mineral replacements of natural olivine and their seismic implications: Oceanic lizardite versus subduction-related antigorite. Journal of Petrology, 51, 495–512.

Bromley, G.D. and Pawley, A.R. (2003) The stability of antigorite in the systems MgO–SiO2–H2O (MSH) and MgO–Al2O3–SiO2–H2O (MASH): The effects of Al3+ substitution on high-pressure stability. American Mineralogist, 88, 99–108.

Burkhard, M. (1993) Calcite twins, their geometry, appearance and significance as stress-strain markers and indicators of tectonic regime: a review. Journal of Structural Geology, 15, 351–368.

Campione, M. and Capitani, G.C. (2013) Subduction-zone earthquake complexity related to frictional anisotropy in antigorite. Nature Geoscience, 6, 847–851.

de Bresser, J.H.P. and Spiers, C.J. (1993) Slip systems in calcite single crystals deformed at 300–800 °C. Journal of Geophysical Research: Solid Earth, 98, 6397–6409.

Deb, M., Thorpe, R.I., Cumming, G.L. and Wagner, P.A. (1989) Age, source and stratigraphic implications of Pb isotope data for conformable, sediment-hosted, base metal deposits in the Proterozoic Aravalli-Delhi orogenic belt, northwestern India. Precambrian Research, 43, 1–22.

Deb, M. and Thrope, R.I. (2001) Geochronological constraints in the Precambrian Geology of Northwestern India and their Metallogenic Implication. In International Workshop on Sediment-Hosted Lead-Zinc/Sulfide Deposit in the Northwestern Indian Shield (Deb, M. and Goodfellow, W.D. (Eds.). Delhi: Udaipur, India, 127–152.

Debret, B., Alberi, E., Walker, B., Price, R., et al. (2019) Shallow forearc mantle dynamics and geochemistry: New insights from IODP Expedition 366. Lithos, 326–327, 230–245.

Enami, M. (2006) Mineralogical methods for identification of asbestos and their limitations. Japanese Magazine of Mineralogical and Petrological Sciences, 35, 11–21 (Japanese with English abstract).

Evans, B.W. (2010) Lizardite versus antigorite serpentinite: Magnetite, hydrogen, and life?). Geology, 38, 879–882.

Evans, B.W., Dyar, M.D. and Kuehner, S.M. (2012) Implications of ferrous and ferric iron in antigorite. American Mineralogist, 97, 184–196.

Evans, B.W., Hartori, K. and Baronnnet, A. (2013) Serpentine: What, Why, Where? Elements, 9, 99–106.

Gamal El Dien, H., Arai, S., Doucet, L., Li, Z., et al. (2019) Cr-spinel records metasomatism not petrogensis of mantle rocks. Nature Communications, 5103.

Gathania, C.R., Chattopadhyay, A.K., Sharma, B., Ameta, S.S. and Ghosal, A.K. (1995) Occurrence of ultramafics of komatitic affinity in the Rikhabdev-Dungarpur belt, Udaipur and Dungarpur districts, Rajasthan. Journal of Geological Society of India, 46, 585–594.

Griffith, W.P. and Wikkins, T.D. (1967) Studies on transition-metal peroxo-complexes. Part V. Peroxoxyalates. Journal of the Chemical Society A: Inorganic, Physical, Theoretical, 590–592.

Gupta, P., Fareeduddin, Reddy, M.S. and Mukhopadhyay, K. (1995) Stratigraphy and structure of Delhi Supergroup rocks in the central part of the Aravalli range. Recordings in Geological Survey of India, 120, 12-26.

Gupta, S.N., Arora, Y.K., Mathur, R.K., Iqballuddin, Prasad, B., et al. (1997) The Precambrian Geology of the Aravalli region, Southern Rajasthan and Northeast Gujarat. pp. 266. Memoirs of the Geological Survey of India, 123.

Heron, A.M. (1953) The geology of central Rajputana. Memoirs of the Geological Society of India, 79.

Hiraiuchi, K., Michibayashi, K., Ueda, H. and Katayama, I. (2010) Spatial variations in antigorite fabric across a serpentinite subduction channel: Insights from the Ohmachi Seamount, Izu-Bonin frontal arc. Earth and Planetary Science Letters, 299, 196–206.

Kamb, W.B. (1959) Theory of Preferred Crystal Orientation De-
developed by Crystallization under Stress. The Journal of Geology, 67, 153–170.

Kawano, S., Katayama, I. and Okazaki, K. (2011) Permeability anisotropy of serpentinite and fluid pathways in a subduction zone. Geology, 39, 939–942.

Loh, E. (1973) Optical vibrations in sheet silicates. Journal of Physics C: Solid State Physics, 6, 1091–1104.

Mizukami, T., Yokose, H., Yamamoto, K., et al. (2009) Two types of antigorite serpentinite controlling heterogeneous slow-slip behaviours of slab-mantle interface. Earth and Planetary Science Letters, 401, 148–158.

Nakatani, T. and Nakamura, M. (2016) Experimental constraints on the serpentinitization rate of fore-arc peridotites: Implications for the upwelling condition of the slab-derived fluid. Geochemistry, Geophysics, Geosystems, 17, 3393–3419.

Nishii, A., Wallis, S.R., Mizukami, T. and Michibayashi, K. (2011) Subduction related antigorite CPO patterns from forearc mantle in the Sanbagawa belt, southwest Japan. Journal of Structural Geology, 33, 1436–1445.

Nozaka, T. (2018) Compositional variation of olivine related to high-temperature serpentinitization of peridotites: Evidence from the Oeyama ophiolite. Journal of Mineralogical and Petrological Sciences, 113, 219–231.

Pawley, A.R. (1998) The reaction talc+forsterite=enstatite+H2O; Nozaka, T. (2018) Compositional variation of olivine related to high-temperature serpentinitization of peridotites: Evidence from the Oeyama ophiolite. Journal of Mineralogical and Petrological Sciences, 113, 219–231.

Pawley, A.R. (1998) The reaction talc+forsterite=enstatite+H2O; new experimental results and petrological implications. American Mineralogist, 83, 51–57.

Petriglieri, J.R., Salvioli-Mariani, E., Mantovani, L., Tribaudino, M., et al. (2015) Micro-Raman mapping of the polymorphs of serpentine. Journal of Raman Spectroscopy, 46, 953–958.

Plissart, G., González-Jiménez, J.M., Garrido, L.I.F., Colás, V., et al. (2019) Tectono-metamorphic evolution of subduction channel serpentinites from South-Central Chile. Lithos, 336–337, 221–241.

Prasad, B.R., Tewari, H.C., Rao, V.V., Dixit, M.M., et al. (1998) Structure and tectonics of the Proterozoic Aravalli-Delhi Fold Belt in northwestern India from deep seismic reflection studies. Tectonophysics, 288, 31–41.

Purohit, R., Bhu, H., Sarkar, A. and Ram, J. (2015) Evolution of the ultramafic rocks of the Rakhabdev and Jharol belts in southeastern Rajasthan, India: New evidences from imagery mapping, petro-mineralogical and O-H stable isotope studies. Journal of the Geological Society of India, 85, 331–338.

Rinaudo, C.A., Gastaldi, D.A. and Belluso, E. (2003) Characterization of Chrysotile, Antigorite and Lizardite by FT-Raman Spectroscopy. The Canadian Mineralogist, 41, 883–890.

Romeo, I., Capote, R. and Lunar, R. (2007) Crystallographic preferred orientations and microstructure of a Variscan marble mylonite in the Ossa-Morena Zone (SW Iberia). Journal of Structural Geology, 29, 1353–1368.

Roy, A.B. and Jakhar, S.R. (2002) Geology of Rajasthan (Northwest India) Precambrian to recent. Scientific Publishers.

Sarkar, G., Barman, T.R. and Corfu, F. (1989) Timing of Continental Arc-Type Magmatism in Northwest India: Evidence from U-Pb Zircon Geochronology. Journal of Geology, 97, 607–612.