Microstructures and petro-fabrics of lawsonite blueschist in the North Qilian suture zone, NW China: Implications for seismic anisotropy of subducting oceanic crust

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ABSTRACT

We conducted a detailed study on the microstructures and petro-fabrics of massive and foliated lawsonite blueschist (LBS) in North Qilian suture zone, NW China. The lattice preferred orientation (LPO) of glaucophane and lawsonite in foliated lawsonite blueschist (LBS) is considered to be dominantly formed by the deformation mechanism of dislocation creep and rigid-body rotation, respectively. The LPO of glaucophane is mainly characterized by the [001] axis aligning parallel to lineation and the [100] and [110] pole plunging perpendicular to foliation. In contrast, the LPO of lawsonite features the maximum [010] axis concentrated close to lineation and the [001] axis strongly clustered normal to foliation. The preferred orientation of [010] axis of lawsonite parallel to lineation is supported by a two-dimensional numerical modeling using the finite-volume method (FVM). The mineral LPOs are much stronger in foliated LBS than in massive LBS. In addition, a kinematic vorticity analysis suggests that both pure shear dominant ($W_\text{m} = 0.18–0.26$) and simple shear dominant ($W_\text{m} = 0.86–0.93$) deformation regimes are present in foliated LBS. The [001] and (010) pole of glaucophane, and the [100] and [010] axes of lawsonite, tend to distribute in a foliation–parallel girdle in the pure shear dominant samples, but simple shear dominant samples display more lineation–parallel concentrations of a [001] axis of glaucophane and a [010] axis of lawsonite. Because the whole-rock seismic anisotropies in foliated LBS are significantly higher than those in massive LBS and a counteracting effect on seismic anisotropies occurs between glaucophane and lawsonite, the delay time of fast S-wave polarization anisotropy induced by an actual subducting oceanic crust with a high subducting angle ($>45–60^\circ$) is expected to range from 0.03 to 0.09 s (lower bound for massive LBS) and from 0.1 to 0.3 s (upper bound for foliated epidote blueschist).

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1. Introduction

Subduction zones are regions where sediments, oceanic crust, and oceanic mantle lithosphere are extensively recycled into the Earth’s mantle and re-equilibrated therein (Stern, 2002). Depending on the P-T stability fields of hydrous silicate minerals, a variety of such minerals can occur over wide temperatures and depths in the subducted oceanic crust and in the slab–mantle boundary (Poli and Schmidt, 2002; Schmidt and Poli, 1998). Hydrous minerals are therefore considered to have enormous implications for the transportation of water, rheology, seismicity, and seismic properties within the subducted oceanic crust (e.g., Abers, 2000; Hacker et al., 2003a; Hacker et al., 2003b; Hilairet et al., 2007; Jung et al., 2004; Jung et al., 2009a; Kirby et al., 1996; Mainprice and Ildefonse, 2009).

Blueschist is an important high pressure (HP) and low temperature (LT) metamorphic rock dominated by hydrous minerals (e.g., glaucophane, lawsonite, epidote, chlorite, and pumpellyite). It forms the major portion of old and cold, as well as some relatively young and warm oceanic crusts, prior to its transformation into eclogite with progressive subduction. A number of experimental and thermodynamic phase equilibrium modelings using basaltic compositions have delineated the P-T stability field of blueschist. These results suggest that two main blueschist sub-facies – lawsonite blueschist (LBS, dominated by glaucophane and lawsonite) and epidote blueschist (EBS, dominated by glaucophane and epidote) – occur at different P-T conditions (e.g., Evans, 1990; Forneris and Holloway, 2003; Oh and Liou, 1998; Peacock, 1993; Schmidt and Poli, 1998). Because lawsonite blueschist is stable at a lower temperature and higher pressure within a larger P-T space ($P = 0.5–2.5$ GPa, $T = 200–500$ °C) than epidote blueschist ($P = 0.5–2.0$ GPa, $T = 300–550$ °C) (the P-T boundary between LBS and EBS is positive, and ranges from 0.5 GPa at 300 °C to 2.0 GPa at 500 °C, see Fig. 2), it is expected that lawsonite blueschist may constitute a significant portion of an old and metamorphosed oceanic crust that was subducted to a depth of greater than 70 km (Peacock, 1993). As potential evidence for this argument, findings of lawsonite (or its pseudomorphs from blueschist) have been reported in many subduction and suture zones in the world, such as in the...
Franciscan Complex, California (e.g., Maruyama and Liou, 1988); Ile de Groix, France (e.g., Ballevere et al., 2003); Kurosegawa Zone, SW Japan (e.g., Maruyama et al., 1984); North Qilian, NW China (e.g., Wu et al., 1993); Pam Peninsula, New Caledonia (e.g., Clarke et al., 1997); Sesia Zone, Western Alps, Italy (e.g., Pognante, 1989); Zermatt–Saas Zone, Western Alps, Switzerland (e.g., Angiboust et al., 2009); Seward Peninsula, Alaska (e.g., Forbes et al., 1984); Tavşanlı Zone, Turkey (e.g., Okay, 1984); and Syros, Cyclades, Greece (e.g., Philippin et al., 2013). An in-depth investigation of the deformation microstructures and rheological properties of blueschist, in particular lawsonite blueschist, is therefore of extreme importance for gaining an understanding of the mechanical strength and seismic properties (i.e. velocity and anisotropy) of the subducted oceanic crust.

However, only a few recent studies have been concerned with the deformation microstructures and seismic properties of deformed natural blueschist (Bezacier et al., 2010; Cao et al., 2013; Fujimoto et al., 2010; Kim et al., 2013a,b; Teysier et al., 2010), or have been focused on investigating the single crystal structures and elasticities of glaucophane and lawsonite at high pressures (Chantel et al., 2012; Mookherjee and Bezacier, 2012; Reynard and Bass, 2014). Based on these studies, several important findings and implications have been obtained: (1) the major constituent minerals (e.g., glaucophane, lawsonite, and epidote) in deformed blueschist can exhibit strong lattice preferred orientations (LPOs); and thus (2) cause moderate seismic anisotropies that might be partly responsible for the trench–parallel shear wave polarization anisotropy observed in fore-arc regions; (3) lawsonite blueschist has a contrastingly weaker anisotropy than epidote blueschist due to the destructive and constructive seismic anisotropic patterns between lawsonite and glaucophane, and between epidote and glaucophane, respectively; and (4) the low seismic velocity upper layer in the subducting slab can be explained by the existence of glaucophane, lawsonite, and epidote in blueschist and low-T eclogite.

In this study, we concentrate on the microstructures and petro-fabrics of both weakly and strongly deformed natural lawsonite blueschists collected from the North Qilian suture zone, NW China. This differs from previous studies in that the comparisons between weakly and strongly deformed samples can help to provide greater details of the deformation mechanism, evolution of mineral fabric with deformation, and the seismic anisotropy of the subducting oceanic crust.

2. Geological setting

The North Qilian suture zone is an elongated NW–SE trending belt which is located in the northern margin of the Qilian orogenic belt, which is the central part of the Qinling–Qilian–Kunlun Fold System, or the Central China orogenic belt (Song et al., 2006; Song et al., 2009; Song et al., 2013; Yin et al., 2008) (Fig. 1a). The North Qilian orogenic belt is considered to be a typical oceanic-type subduction zone at the early Paleozoic (490–440 Ma); which is corroborated by a suite of subduction complexes including a Neoproterozoic to Early Paleozoic and granitoid plutons, Silurian and a Carboniferous to Triassic sedimentary cover sequence (see the review of Song et al., 2013). The HP metamorphic belt mainly consists of blueschist, eclogite, meta-greywacke/-pelite, and associated ophiolitic occurrences and micro-structures, the low-grade blueschist can be subdivided into areas of massive lawsonite blueschist in the north and foliated lawsonite blueschist in the south. In Baishuigou Creek, the massive lawsonite blueschist occurs as a 10 m × 20 m sized block and is composed of glaucophane and lawsonite (Lws), with minor amounts of pumpellyite (Pmp), chlorite (Chl), and albite (Ab). In contrast, the foliated lawsonite blueschist is strongly deformed and featured by intense foliation and lineation on either mineral reactions that produce and/or consume Lws, argonite (Arg), and Pmp in lawsonite blueschist. Based on mineral chemical compositions and petro-fabrics of deformed natural lawsonite blueschist, respectively. However, the exact deformation P–T condition is not well constrained, although it is supposed to be similar to the metamorphic P–T condition.

3. Description of samples

The lawsonite blueschist samples in this study were collected from Baishuigou Creek, ca. 20 km west of the town of Sunan, in Gansu Province, NW China (Fig. 1). Ten massive samples and three foliated samples were selected for analysis.

3.1. Massive lawsonite blueschist

Massive lawsonite blueschist generally displays a homogeneous texture with hardly any discernible foliation and lineation on either field- or hand-specimen scale. However, two subtypes of the massive lawsonite blueschist can still be categorized, based on an integrated consideration of their optical microstructures (Fig. 3) and lawsonite fabrics (see below). For convenience, we named them M1 type (Fig. 3a–c) within the blueschist-facies rocks suggests a precedent high-grade or high-pressure metamorphism (Song et al., 2007). The findings of lawsonite inclusions in eclogitic garnets (Song et al., 2007; Zhang and Meng, 2006; Zhang et al., 2007) and carpholite in meta-pelite (Song et al., 2007), further indicate that an eclogite-facies metamorphism occurred at low temperature, indicative of a “cold” oceanic-type subduction. These petrographic observations also agree well with P–T estimates (using a phase equilibrium diagram or Grt-clinoxyroxene (Cpx)–Ph thermobarometer) of blueschist, eclogite and eclogite-facies meta-pelite. Many studies have yielded P–T conditions of 2.1–2.6 GPa and 460–590 °C, and 1.8–2.2 GPa and 450–550 °C for peak lawsonite eclogite-facies and retrograde epidote eclogite-facies metamorphism, respectively (Cao et al., 2011; Song et al., 2007; Wei and Song, 2008; Wei et al., 2009; Zhang et al., 2007), as well as an epidote blueschist-facies metamorphic condition of 0.5–1.4 GPa and 480–620 °C (Cao et al., 2013; Li, 2010) (Fig. 2). In addition, Cao et al. (2011, 2013) examined the mineral chemical compositions and petro-fabrics of both blueschist and eclogite, and found that whole-rock seismic anisotropy and velocity decrease and increase with a transformation from blueschist to eclogite, respectively.

The low-grade blueschist belt also occurs as an elongated zone (~20 km in length and ~1 km in width) extending from NW to SE (Fig. 1b), with a well-preserved cross-section exposed in Baishuigou Creek (Fig. 1c). This blueschist belt is thrust southwestwards onto the Devonian molasses to the south, and overlain by an ophiolitic sequence to the north. The belt consists of a metamorphic rock assemblage of blueschist, meta-chert, and meta-greywacke, which changes sequentially from SW to NE. Based on field occurrences and microstructures, the low-grade blueschist can be subdivided into areas of massive lawsonite blueschist in the north and foliated lawsonite blueschist in the south. In Baishuigou Creek, the massive lawsonite blueschist occurs as a 10 m × 20 m sized block and is composed of glaucophane and lawsonite (Lws), with minor amounts of pumpellyite (Pmp), chlorite (Chl), and albite (Ab). In contrast, the foliated lawsonite blueschist is strongly deformed and featured by intense foliation and isoclinal folds in the outcrops. The mineral assemblage is mostly represented as Pmp + Glc + Lws + Chl + Ab + Qtz. In contrast to the high-grade blueschist belt, only sparse P–T estimations were available for the low-grade blueschist. Wu et al. (1993) first reported P–T conditions of 0.4–0.7 GPa and 150–250 °C, based on the first appearance of Lws, aragonite (Arg) and Pmp in lawsonite blueschist. Based on mineral reactions that produce and/or consume Lws, Pmp, Arg, and Ab, Song et al. (2009) recently determined P–T conditions of 0.6–1.1 GPa and 250–350 °C. Similarly, Zhang et al. (2009) employed a P–T pseudosection calculation using Domino/Theriak software, and obtained comparable results of 0.80–0.95 GPa, 335–355 °C and 0.75–0.85 GPa, 320–350 °C, for massive and foliated lawsonite blueschist, respectively. However, the exact deformation P–T condition is not well constrained, although it is supposed to be similar to the metamorphic P–T condition.

The massive lawsonite blueschist samples in this study were collected from Baishuigou Creek, ca. 20 km west of the town of Sunan, in Gansu Province, NW China (Fig. 1). Ten massive samples and three foliated samples were selected for analysis.
and M2 type (Fig. 3d–f). Both M1 and M2 types have the same mineral assemblage of Gln + Lws + Pmp + Chl + sphene (Spn), in which Gln and Lws are dominant. The lawsonite crystals are euhedral (columnar, rectangular, rhombic, or polygonal), and large in size (0.2–1.0 mm in diameter), occurring as isolated single crystals or aggregates in the glaucophane matrix. Lawsonite crystals or aggregates in the M1 type are randomly oriented, but they frequently form elongated aggregates aligning sub-parallel to each other with random orientations in a single aggregate in the M2 type. Likewise, in the M1 type, the glaucophane crystals are column or needle shaped (up to ~1.0 mm in length) and randomly orientated, but are relatively smaller in size and aligned preferentially sub-parallel to the lawsonite aggregates in the M2 type. These microstructures indicate that the M2 type is probably more highly strained than the M1 type. In addition, the chemical pattern of glaucophane in the M1 type is gently varied (Fig. 3c), whereas the glaucophane in the M2 type shows a more abrupt change in chemical composition (Fig. 3f).

3.2. Foliated lawsonite blueschist

In contrast, the foliated lawsonite blueschist is significantly deformed, as indicated by the well-defined foliation and lineation defined by elongated and oriented fine-grained glaucophane or chlorite crystals (Fig. 4). The mineral assemblage is typically characterized by Gln + Lws + Chl + Pmp + Ab + Qtz, with varying mineral modal abundances among different domains in one sample (Fig. 4a–c). Lawsonite crystals are euhedral and display variable oblique angles between the long axis and foliation. In some samples, lawsonite crystals with large aspect ratios (R > 3) and oblique at a high angle to foliation are frequently observed (Fig. 4d and e). The orientations of the lawsonite long axis against foliation are dependent on their aspect ratios, since they tend to align parallel to foliation above a critical aspect ratio value (see Section 5). In comparison with massive lawsonite blueschist, glaucophane in the foliated lawsonite blueschist has an anhedral shape with an extremely small grain size (~5–10 μm in length) and a smaller aspect ratio (Fig. 4f). The composition of fine-grained glaucophane may vary slightly, as suggested by its fairly homogeneous brightness under a back-scattered image (Fig. 4f).

4. Lattice preferred orientations of glaucophane and lawsonite

Fine-polished thin-sections were used to measure the LPOs of glaucophane and lawsonite, under an electron back-scattered diffraction (EBSD) system (JEOL JSM6380 with HKL channel 5 housed at the School of Earth and Environmental Science, Seoul National University). The system operates in an experimental environment of 20 kV acceleration voltage, 15 mm working distance, and a spot size of 60. To avoid repeated data collection, we indexed the EBSD patterns manually for every grain where the Kikuchi pattern was obviously different from those of neighboring grains. Because the structural framework is difficult to ascertain in massive LBS, we used thin-sections taken from arbitrary directions for EBSD analysis. The obtained LPOs of glaucophane and lawsonite were later rotated by aligning the clusters of the [001] and [100] axes of glaucophane parallel to lineation and perpendicular to foliation, respectively (because this is the only fabric type that has been reported for natural glaucophane, see Fig. 11 for the 3D crystal
shapes of lawsonite and glaucophane) (Bezacier et al., 2010; Cao et al., 2013; Fujimoto et al., 2010; Kim et al., 2013a,b; Teyssier et al., 2010). In contrast, since the structural reference frame of foliated lawsonite blueschists is clear, and EBSD analysis was conducted on XZ thin-sections (X: parallel to lineation, Z: normal to foliation).

Both the pole figures and the inverse pole figures were drawn from individual orientation data (Euler angle triplets), which were obtained from EBSD measurements, using plotting programs of PFctf and IPFctf developed by David Mainprice. To quantify the strength of the LPOs, we applied both M-index (Skemer et al., 2005) and J-index (Bunge, 1982) algorithms. The misorientation index (M-index) is defined by

\[ M = \frac{1}{2} \int \left( \theta^2 - \theta^2(0) \right) d\theta, \]

which describes the differences between the observed \( \theta^2(0) \) (obtained from EBSD data) from a real fabric and the modeled distribution of uncorrelated misorientation angles \( \theta^2(0) \) for a theoretically random fabric. The M-index ranges from 0 (random fabric) to 1 (single crystal fabric). In contrast, the J-index is defined as

\[ J = \frac{1}{2} \int \left( f(\phi_1, \psi, \phi_2) - f(0) \right) dg, \]

where \( f(\phi_1, \psi, \phi_2) \) is the orientation distribution functions (ODFs), \( \phi_1, \psi, \phi_2 \) is the Euler angle triplet, and \( dg \) is a volume element in Euler angle space. The J-index theoretically ranges from 1 (random fabric) to infinity (single crystal fabric). We also used the pfJ index and ipfJ index, which are similar to the J-index, to describe the sharpness of a pole figure and an inverse pole figure, respectively. Because the values of J-index, pfJ and ipfJ index are dependent on number of discrete data in the orientation distribution function (ODF) (e.g., number of grains in LPO measurement) and arbitrary numerical parameters (e.g., the Gauss half width (GHW)) (Skemer et al., 2005), the same GHW of 8.5° was used in all calculations to minimize the systematic error. Even so, J-index, pfJ and ipfJ index may still not be powerful enough to distinguish the samples with similar fabric strengths due to their non-uniqueness and variable number of grains in the LPO measurement, whereas M-index could be more satisfying in this case.

4.1. LPO of glaucophane

The glaucophane in two subtypes of massive lawsonite blueschist displays a weak LPO (girdle-type or L-type), which is characterized by a [001] axis aligning parallel to lineation, both [100] axis and [110] poles forming girdles nearly normal to lineation with their maxima sub-perpendicular to foliation, and a (010) pole also lying in a girdle with its maximum sub-perpendicular to the lineation in the foliation (Figs. 5a, b and S1a–j). This fabric type of glaucophane has also been reported from garnet-rich blueschist and eclogite (Cao et al., 2013), suggesting that the L-type fabric of glaucophane in massive lawsonite blueschist may result from the fabric randomization effect by a large abundance of rigid lawsonite crystals (similar to the effect of rigid garnet crystals) and/or by a weak deformation. In contrast, foliated lawsonite blueschist mostly shows a strong glaucophane fabric (pointtype or SL-type), as featured by a [001] axis parallel to lineation, a [100] axis and a (110) pole perpendicular to foliation, and a (010) pole normal to foliation in the foliation (Figs. 5c, S1k, m and n). This is a typical fabric for natural glaucophane and other species of amphibole reported in many previous studies (Bezacier et al., 2010; Cao et al., 2010; Cao et al., 2013; Fujimoto et al., 2010; Kim et al., 2013b; Tatham et al., 2008; Teyssier et al., 2010). In addition, we also observed another glaucophane fabric (S-type) that exhibits clear foliation–parallel girdles of both [001] axis and [010] pole with the same maxima orientations as those in the SL-type fabric (Figs. 5d and S1l). The fabric patterns of L-type, SL-type and S-type were originally defined by Helmstaedt et al. (1972) and later updated by Zhang et al. (2006).

Fig. 2. P-T diagram showing the equilibrated P-T conditions of low-grade blueschist belt (lawsonite blueschist) and high-grade blueschist belt (epidote blueschist, massive and foliated eclogite) in North Qilian suture zone. LEC: lawsonite eclogite facies, LBS: lawsonite blueschist facies, EBS: epidote blueschist facies, EAEC: epidote-amphibole eclogite facies, EAM: epidote amphibolite facies, GS: greenschist facies, and PP: prehnite–pumpellyite facies. Metamorphic facies boundaries were adopted from Liou et al. (1998) and Zhang et al. (2009).
These different LPOs of glaucophane can also be presented in the inverse pole figures (Figs. 6 and S2). SL- and L-type fabrics display strong concentrations of [001] axes of glaucophane parallel to lineation (Figs. 6a–c, S2a–j and 1–n), whereas the S-type fabric shows a girdle distribution of lineation parallel to the plane containing a [010] and [001] axis, with its maximum aligning to the [001] axis (Figs. 6d and S2k). The maximum of foliation normal direction (Z) is consistent with the [001] and [100] axes of glaucophane in the SL- and S-type fabrics (Figs. 6c, d and S2k–n). However, in the L-type fabric, it forms a clear girdle sub-parallel to the (001) plane with its maximum aligning sub-parallel to the [001] and [101] axes (Figs. 6a, b and S2a–j).

The strength of the L-type fabric is significantly weaker in massive LBS (M = 0.06–0.09, J = 1.9–3.6) than those of the SL- and S-type fabrics in foliated LBS (M = 0.40–0.29, J = 6.7–17.8) (Table 1). Therefore, a combined variation of the fabric pattern and fabric strength of glaucophane between the two types of LBS is especially indicative of the increasing degree of deformation from massive to foliated LBS. In addition, although the mineral textures suggest that the M2 type is relatively more strongly deformed than the M1 type LBS, the fabric strength of glaucophane is not significantly different between these two subtypes.

4.2. LPO of lawsonite

Even though the fabric is very weak, a non-random LPO of lawsonite is still discerned in the massive LBS. Different from glaucophane, two subtypes (M1 and M2) of the massive LBS present distinctive fabrics
for lawsonite (Figs. 7a, b and S3a–j). The most important difference is that the maximum of the [001] axis is aligned close to the center of the pole figure normal to lineation in foliation in the M1 type LBS, whereas it tends to align sub-perpendicular to foliation in the M2 type LBS. This characteristic is also exhibited in the inverse pole figures of lawsonite, which features Y- and Z-directions concentrated sub-parallel to the [001] axis in the M1 and M2 type massive LBSs, respectively (Figs. 6a, b and S2a–j). The distribution of the [100] and [010] axes is diffused, with their maxima mostly aligning either at low angles around lineation, or sub-normal to foliation. In contrast, the fabrics of lawsonite in the foliated LBS are much stronger (Figs. 7c, d and S2k–n). Because both foliated and M2 type LBS are more strongly deformed than the M1 type LBS, the transition of the concentration of the lawsonite [001] axes from aligning parallel to normal to foliation, probably results from the increasing degree of deformation.

Similar to glaucophane, the fabric strength of lawsonite in massive LBS ($M = 0.05, J = 1.7–2.5$) is significantly smaller than that in foliated LBS ($M = 0.15–0.23, J = 3.0–6.3$), and there is no significant fabric strength difference of lawsonite between the M1 and M2 type LBSs, although deformation is relatively stronger in the M2 type than in the M1 type LBS (Table 1).

5. Vorticity analysis

The kinematic vorticity number ($W_{K}$) is a measure of the non-coaxiality that is involved in the progressive deformation history (Means et al., 1980). It can be expressed as a ratio of the rotational to the stretching components in the velocity field, as $W_{K} = 0$ for coaxial deformation and $W_{K} = \infty$ for rigid body rotation. For plane strain deformation, $W_{K}$ ranges from 0 to 1, which corresponds to a non-linear transition from pure shear to simple shear (an equal contribution of pure shear and simple shear components at $W_{K} = 0.71$) (Law et al., 2004). Because the vorticity of deformation in natural rock may vary with space and time (e.g., non-steady state deformation), a mean kinematic
Vorticity number $W_m$ (in which the vorticity is integrated over space and time) is more appropriate to use (Passchier, 1988). There exist three techniques for quantifying the vorticity number in a deformed natural rock using a two-dimensional XZ thin-section (Law et al., 2004); herein, we employ the method proposed by Wallis et al. (1993). This method is based on analyzing the orientations and aspect ratios of rigid porphyroclasts rotating in a homogeneously deformed matrix, and determining the critical aspect ratio ($R_c$) below which porphyroclasts rotate continuously (and hence display no shape preferred orientation), and above which they achieve a stable alignment parallel to foliation (Law et al., 2004). In another word, this statement assumes that the variations in the orientation of rigid porphyroclasts and the inferred vorticity values are only controlled by their aspect ratios, and are not affected by interactions between the porphyroclasts (e.g., Passchier, 1987; Tikoff and Teyssier, 1994; Wallis, 1995) and slip at the interfaces between porphyroclasts and their matrix (e.g., Johnson et al., 2009; Marques et al., 2007). In the case of plane strain, the mean kinematic vorticity number $W_m$ can be calculated as $W_m = \frac{(R_c^2 - 1)}{(R_c^2 + 1)}$ (Passchier, 1987), where $R_c$ is the critical aspect ratio.

The S–L tectonite structure consisting of foliation and lineation is very well developed in our studied foliated lawsonite blueschist, indicating that the deformation may not deviate far from plane strain (Teyssier et al., 2010). The lawsonite grains are mostly isolated and surrounded by deformed fine-grained Gln and/or Chl matrix (e.g., Fig. 4b–e), suggesting that the lawsonite was probably formed prior to deformation and that there was no significant interaction between the lawsonite crystals during deformation. In addition, the very fine-grained matrix may imply that glaucophane was deformed by recovery and dynamic recrystallization processes, which probably minimizes the slip along lawsonite boundaries (Teyssier et al., 2010). Based on these textures, we considered that lawsonite could be treated as a rigid porphyroclast rotating in a ductile matrix, and that the estimation of kinematic vorticity using the above-mentioned relationship between $W_m$ and $R_c$ is reasonable. Because lawsonite grains are frequently observed in contact with each other, which could imply interactions between porphyroclasts, we chose domains without significant grain-to-grain interactions among lawsonite crystals for the vorticity analysis.
Fig. 6. Inverse pole figures of lawsonite and glaucophane in representative massive (a) M1 type and (b) M2 type, and (c, d) foliated lawsonite blueschist. $N_{\text{Lws}}$ and $N_{\text{Gln}}$ are the numbers of lawsonite and glaucophane grains, respectively. X: lineation, Z: foliation normal, Y: orthogonal to both X and Z, ipfJ: inverse pole figure J-index.
As shown in Figs. 8 and S4, two distinct $W_m$ values are found in foliated LBS. Two different lawsonite-rich domains in a single sample display a very low $W_m$ value (0.18–0.26) (Figs. 8a, S4a and b), corresponding to dominant pure shear deformation. In contrast, the other two samples have remarkably higher values of $W_m$ (0.86–0.93) (Figs. 8b, S4c and d), indicative of dominant simple shear deformation. It is of interest to notice that Teyssier et al. (2010) studied the lawsonite vorticity of blueschist layers in the Sivrihisar Massif, Turkey and reported vorticity values in-between our results of $W_m = 0.4–0.6$.

6. Rock seismic properties


6.1. Single crystal

Identical to the result of Bezacier et al. (2010), the seismic properties of glaucophane single crystal are characterized by the fastest (9.27 km/s) and slowest (6.30 km/s) P-wave velocities aligning parallel to the [001] and [100] axis, respectively, which yield a large P-wave anisotropy (ΔVp = 27.30%). The shear-wave polarization anisotropy forms a lower P-wave anisotropy (0.69). The shear-wave velocity along the [001] axis, but is the slowest (7.23 km/s) sub-parallel to the [110] axis. This velocity pattern produces a lower P-wave anisotropy ($AV_p = 23.5\%$) compared to that of the glaucophane. Both [010] and [100] axes show similar intermediate P-wave velocities and the largest magnitude of shear-wave polarization anisotropy (Fig. 9a).
6.2. Glaucophane polycrystals

Glaucophane aggregates of SL- and L-type fabrics display an overall consistent P-wave anisotropy pattern (Figs. 9b–d, S5 and S6), which is characterized by maximum and minimum P-wave velocities aligning parallel to lineation and normal to foliation, respectively. This P-wave anisotropy pattern can be well interpreted by the glaucophane fabric of the [001] axis (fastest $V_p$ direction) that is concentrated parallel to lineation and the [100] axis (slowest $V_p$ direction) that is plunging perpendicular to foliation. However, the fast P-wave velocity shows a much stronger girdle distribution sub-parallel to foliation in the S-type glaucophane fabric, although the maximum velocity still aligns along the lineation (Fig. 9e). The strong polarization anisotropies ($A_{Vs}$) in the glaucophane aggregates within the massive LBS lie mostly at a low angle to foliation and a high angle to lineation, whereas weak polarization anisotropies dominantly form a girdle along the XZ direction, with their minimum close to lineation. In contrast, the glaucophane aggregates in foliated LBS exhibit a more symmetrical pattern of polarization anisotropy, such as strong and weak polarization anisotropies residing at low and high angles to the foliation, respectively. In the glaucophane aggregates in both massive and foliated LBSs, the direction of fast-shear wave polarization is nearly parallel to lineation when shear-waves propagate nearly normal to foliation, but fast shear-waves tend to polarize parallel to foliation when the incident angle is low relative to foliation. The magnitude of seismic anisotropies of glaucophane aggregates is significantly larger in the foliated LBS ($A_{V_p} = 23.9–29.8\%$, max. $A_{V_s} = 13.84–17.95\%$) than in the massive LBS ($A_{V_p} = 5.4–11.6\%$, max. $A_{V_s} = 2.88–5.63\%$) in which

![Diagram of glaucophane polycrystals](http://example.com/diagram.png)

Fig. 7. Pole figures of lawsonite in representative massive (a) M1 type and (b) M2 type, and (c, d) foliated lawsonite blueschist. Pole figures are presented in the upper hemisphere and equal-area projection, with a default Gauss half width of 8.5°. X: lineation, Z: foliation normal, N: number of grains, M: M-index, J: J-index, pfJ: pole figure J-index.
no significant difference between the M1 and M2 types is exhibited (Table 2 and Fig. 10).

6.3. Lawsonite polycrystals

Because the [001] axis of lawsonite has the fastest P-wave velocity, the seismic anisotropy patterns of lawsonite aggregates are greatly affected by the preferred orientation of the [001] axis. For the M1 type LBS, the [001] axis of lawsonite is clustered close to the Y-direction, and thus results in the same direction of maximum $V_p$ (Figs. 9b and S5). However, the [001] axis of lawsonite and the fastest $V_p$ of lawsonite aggregates are sub-perpendicular to foliation in the M2 type (Figs. 9c and S6) and the foliated LBS (Fig. 9d and e). In all the lawsonite aggregates, the fast shear-wave mostly polarizes sub-perpendicularly to lineation when the incident ray propagates sub-normal to foliation. Similar to the glaucophane aggregates, the magnitudes of seismic anisotropies of lawsonite aggregates vary in a similar range for both M1 and M2 type LBSs ($AV_p = 2.2–3.5\%$, max. $AV_s = 15.94–20.62\%$) (Table 2 and Fig. 10).

6.4. Whole rocks

It is apparent that the seismic anisotropy pattern of whole rock is controlled by the volume proportions of each of the monomineralic aggregates and their individual seismic properties (which are governed by the seismic properties of single-crystals and their polycrystal fabrics). As shown in Figs. 9b–e, S5 and S6, the overall anisotropy patterns of P-wave and shear-wave polarization resemble those of glaucophane in both massive and foliated LBSs, due to the larger volume proportions of glaucophane than lawsonite. Similar to glaucophane and lawsonite aggregates, the magnitudes of seismic anisotropies for whole rock are higher for foliated LBS ($AV_p = 13.2–19.7\%$, max. $AV_s = 5.54–9.94\%$) compared to both subtypes of massive LBSs that have similar magnitudes of seismic anisotropy ($AV_p = 2.6–7.9\%$, max. $AV_s = 1.6–4.53\%$) (Table 2 and Fig. 10). Because the seismic anisotropy patterns of glaucophane and lawsonite aggregates are opposite (counteracting with each other) (Fig. 9b–e), the whole-rock seismic anisotropies are strongly reduced in both massive and foliated LBSs. Specifically, the P-wave anisotropy is higher in glaucophane than lawsonite aggregates, but shows an intermediate value for whole rocks (Fig. 10a). In contrast, the maximum shear-wave polarization anisotropy is larger in lawsonite than glaucophane aggregates, but both are higher than that of whole rocks (Fig. 10b). Thus, these data suggest that the counteracting effect of the seismic anisotropy between glaucophane and lawsonite aggregates (same as “countervailing effect” in Kim et al., 2013a) is more significant in shear-wave polarization anisotropy than P-wave polarization anisotropy. Assuming that glaucophane and lawsonite have constant LPOs with their modal abundances, we calculated the variations of seismic anisotropies with mineral volume proportions for two foliated LBS, under either a simple shear or pure shear dominant deformation regime (Fig. 10c). This result shows that both the whole-rock P-wave and the polarization anisotropies decrease with increasing lawsonite abundance in a similar slope, irrespective of the deformation regime, and that they reach minimum values at 70–80 vol.% ($AV_p = 3\%$ and $40–50\%\text{vol.}\%$ ($AV_s = 5\%$) lawsonite, respectively.

7. Discussions

7.1. Deformation mechanisms of glaucophane and lawsonite

Previous studies have proposed that natural amphiboles can be deformed by a variety of deformation mechanisms (Díaz Aspiroz et al., 2007), such as cataclastic flow (Imon et al., 2004; Nyman et al., 1992), rigid-body rotation (Berger and Stunzit, 1996; Ildefonse et al., 1990; Siegesmund et al., 1994), dislocation creep (Biermann, 1981; Dollinger and Blacic, 1975; Reynard et al., 1989; Skrotzki, 1992), and dissolution—precipitation creep (Imon et al., 2002; Imon et al., 2004; Miller, 1988; Wintsch and Yi, 2002). Several previous studies have advocated that dislocation creep can dominantly account for the deformation of natural glaucophane (Kim et al., 2013b; Reynard et al., 1989; Zuccal et al., 2002). In this study, the very fine-grained and well-oriented anhedral glaucophane grains in foliated LBS (Fig. 4f) clearly indicate a dynamic recrystallization process without extensive grain-boundary sliding and subsequent anisotropic growth (Poirier, 1985). The development of very pronounced glaucophane LPOs may also support the principal deformation mechanism of dislocation creep (Fig. 5c and d).

Kim et al. (2013b) studied the microstructures of naturally deformed LBS and suggested that the mechanical strength of glaucophane is weaker than that of lawsonite. This significant viscosity contrast causes lawsonite crystal to behave as a nearly rigid body that rotates passively and deforms slightly in a soft glaucophane matrix in a non-coaxial deformation regime (Passchier and Sokoutis, 1993; Piazolo et al., 2002). The euhedral morphology, lack of intra-crystalline plasticity, and dispersed long axis orientation of lawsonite grains, confirm that lawsonite has a deformation mechanism dominated by rigid-body
Fig. 9. Seismic anisotropies of (a) lawsonite and glaucophane single crystals, (b) M1 type, (c) M2 type, and (d, e) foliated lawsonite blueschist. Data are presented on a [100]–[010] plane for single crystals and on a foliation plane (XY) for polycrystals and whole rocks, with an equal-area and upper hemisphere projection. The volume proportions of normalized bi-mineralogical assemblage of Gln + Lws are manually measured using their area proportions in optical photo-micrographs and are shown in the upper right of the figure. X: lineation, Z: foliation normal, Y: orthogonal to both X and Z.
torque is always negative with time in this process, indicating that increases shortly afterwards and then decreases, until a nearly constant perturbation instantaneously exerts a torque on the lawsonite, which the [100] axis of lawsonite from the underval perturbation incom homogeneous incoming foliation plane), and analyzed the stabilities of these two orientations cases where either the [100] or [010] axis of lawsonite align sub-parallel straightforward. Because of the complexity in modeling simple shear fltional flow employed in this modeling limits an effective application to a fluid flow and.

Many previous studies have proposed that rigid-body rotation is capable of developing lattice and shape-preferred orientations for the anisotropic rigid particles in a flowing matrix, which are generally characterized by a tendency for the longest and shortest axes to approach the directions of maximum extension and shortening, respectively (e.g., Gay, 1968; Masuda et al., 1995; Passchier, 1987; Piazolo et al., 2002; Wallis et al., 1993). Employing the axis notations of lawsonite from Libowitzky and Armbruster (1995), the [100] and [001] axes are the longest and shortest axes for lawsonite single crystal, respectively (Fig. 11). In agreement with the prediction from previous studies above, the results of lawsonite LPO in foliated LBS show that the [001] axis is strongly aligned perpendicular to foliation (maximum shortening direction) (Fig. 7c, d). However, the intermediate-length [010] axis, rather than the [100] axis, is preferentially oriented sub-parallel to lineation that indicates the direction of maximum extension, especially in a dominant simple shear deformation regime (Fig. 7c). To understand the reason for this discrepancy, we modeled the preferred orientation of a lawsonite single crystal under an incoming flow, using a finite-volume method (FVM) that is frequently applied in computational fluid dynamics (CFD). The idea of this modeling is very straightforward. Because of the complexity in modeling simple shear deformation in a three-dimensional space, we designed two simple cases where either the [100] or [010] axis of lawsonite align sub-parallel to the flow direction in a two-dimensional space (corresponding to the foliation plane), and analyzed the stabilities of these two orientations under a small perturbation in a homogeneous incoming flow.

As shown in Fig. 12a, a small perturbation is imposed by deviating the [100] axis of lawsonite from the flow direction at 5°. This small perturbation instantaneously exerts a torque on the lawsonite, which increases shortly afterwards and then decreases, until a nearly constant value is reached after some small variations (Fig. 12b). The sign of the torque is always negative with time in this process, indicating that lawsonite crystal will rotate clockwise and further deviate its [100] axis from the flow direction (the coefficient of moment is defined as positive when the rotation is counter-clockwise). Therefore, aligning the [100] axis of lawsonite sub-parallel to lineation may not be a stable orientation in naturally deformed LBS. In contrast, when the [010] axis of lawsonite is perturbed at 5° with the flow direction (Fig. 12c), a positive torque is instantaneously created. This torque then decreases shortly afterwards, and is followed by an oscillation pattern in which the coefficient of moment varies between positive and negative values, with a positive average (Fig. 12d). Hence, this result suggests that although lawsonite crystal may rotate either clockwise or counter-clockwise with time, the averaged tendency is to rotate counter-clockwise. In other words, the probability of a counter-clockwise rotation is larger than that of a clockwise rotation, causing the [010] axis of lawsonite more likely to return parallel to the flow direction. It may thus be reasonable to consider that the [010] axis of lawsonite plunging sub-parallel to lineation is a more preferable orientation compared to the [100] axis in naturally deformed LBS. It should be noted that this modeling process is fairly simplified and qualitative due to two main reasons. (1) Most importantly, the assumption of homogeneous fluid flow employed in this modeling limits an effective application to a three-dimensional case, because the [001] axis of lawsonite would be expected to align in any directions perpendicular to the flow direction and the rotation of lawsonite long axis around foliation cannot be simulated if the fluid flows homogeneously in a 3D space. This pattern of fluid flow is very different from simple shearing in natural rocks which have clear shear planes, and thus a sophisticated 3D numerical simulation employing more appropriate layered flow and incorporating other factors (e.g., grain size, mineral growth) is needed. (2) The exact viscosities of lawsonite and glaucophane are unknown, which is thus incapable of describing the explicit evolution of lawsonite fabric in a geological time-scale. Despite the limitations in current simplified modeling, the consistent modeling result with the observations of the lawsonite LPOs in this study suggests that our 2D numerical simulation still has some merits in this preliminary study.

### Table 2

<table>
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<tr>
<th>Sample</th>
<th>Rock type</th>
<th>Mineral volume proportion (%)</th>
<th>Gln aggregate</th>
<th>Lws aggregate</th>
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<td></td>
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<td>Max. Gln (%)</td>
<td>Gln (%)</td>
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<td>Foliated EBS</td>
<td>60</td>
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</table>

Abbreviations: lawsonite blueschist (LBS), epidote blueschist (EBS), glaucophane (Gln), lawsonite (Lws), albite (Ab).

a Data from Kim et al. (2013a).
b Data from Cao et al. (2013).
c Data from Bezier et al. (2010).
rotation. Because the fabric produced by rigid-body rotation is supposed to be dominantly controlled by the geometry of the rigid particle, the similar lawsonite fabric is expected to be produced from these lawsonite blueschists. Although we currently have no clear explanation for these different lawsonite fabrics, one possibility which is particularly relevant to lawsonite fabric measurement might be noteworthy. The axis designations of the lawsonite [100] and [010] axis are not consistent in literature: two notation systems are widely used at present (Baur, 1978; Comodi and Zanazzi, 1996 versus Libowitzky and Armbruster, 1995; Meyer et al., 2001; Pawley and Allan, 2001). If they are used in EBSD measurement, these two different notation systems can thus result in different LPOs with either the [100] or [010] axis of lawsonite aligning sub-parallel to lineation.

7.2. LPO variations of glaucophane and lawsonite

Many factors are considered to influence the characteristics of mineral LPO formed by deformation. As described in detail earlier, glaucophane and lawsonite in massive and foliated LBS display perceptibly different LPOs, which are manifested in both fabric type and fabric strength (Figs. 5–7). Generally, the LPOs are transformed from weak and diffused types in massive LBS, to strong and clustered types in foliated LBS, in response to an increase of deformation or strain. Deformation geometry is another factor that can affect the mineral LPO. Based on the vorticity analysis of foliated LBS, two contrasting deformation geometries – simple shear and pure shear dominant – were recognized, and secondary variations of glaucophane and lawsonite LPOs were also observed between these two deformation geometries. The pure shear dominant samples tend to have strong foliation–parallel girdle distributions of a [001] axis and a [010] pole of glauconphane (Figs. 5d and S11, S-type fabric) and a [010] axis of lawsonite (Figs. 7d, S3k and l), whereas the simple shear dominant samples display more lineation–parallel concentrations of a [001] axis of glauconphane (Figs. 5c, S1k, m and n) and a [010] axis of lawsonite (Figs. 7c, S3m and n). This feature can be quantitatively displayed using the inverse pole figure J-index (ipf) of lineation (X) and foliation normal (Z) for glauconphane and lawsonite (Table 1 and Fig. 13). The sum of ipf(X) and ipf(Z) can be considered as the fabric strength of inverse pole figures and thus roughly represent the deformation degree, and the ratio of ipf(Z)/ipf(X) indicates the extent of the mineral crystallographic axis orienting perpendicular to foliation relative to aligning parallel to foliation. Because a value of ipf equivalent to 1 indicates a random fabric, it denotes a very weak fabric for massive LBS (M1 and M2 types) when the sum of ipf(X) and ipf(Z) is slightly higher than 2 for both glauconphane and lawsonite. In contrast, if the sums of ipf(X) and ipf(Z) for both glauconphane and lawsonite are very large, it thus indicates a strong fabric, such as foliated LBS. In addition, the ratios of ipf(Z)/ipf(X) for glauconphane and lawsonite are remarkably higher in pure shear dominant samples than simple shear dominant samples, and both of them are higher than that in massive LBS. In another word, the mineral axes tend to be more concentrated perpendicularly to foliation in a coaxial deformation regime, whereas they predominantly become clustered parallel to lineation in non-coaxial deformation geometry. Because glauconphane and lawsonite show the same trend of fabric variation in spite of their different deformation mechanisms, such a variation of mineral fabrics is supposed to be principally controlled by deformation geometry and is irrespective of the deformation mechanism. Similar results have also been implied in the LPO developments of olivine and clinopyroxene due to dislocation creep under simple shear and pure shear deformation regimes, which were modeled using a viscoplastic self-consistent method (VPSC) (Bascou et al., 2002; Tommasi et al., 1999, 2000). Therefore, this relationship between mineral LPOs and deformation geometry may provide a useful approach to qualitatively infer the deformation regime through the patterns of mineral LPOs (Fig. 13).
7.3. Seismic anisotropy of subducting oceanic crust

Subduction zones are seismologically unique areas where trench-parallel polarization anisotropy is observed in most of the fore-arc regions (e.g., Huang et al., 2011; Long and Silver, 2008; Long and van der Hilst, 2005; Nakajima and Hasegawa, 2004; Russo and Silver, 1994; Smith et al., 2001; Zhao, 2012). To explain this seismic observation, previous studies proposed that an anisotropic fore-arc mantle is the major source of trench-parallel polarization anisotropy. This anisotropic structure of the fore-arc mantle is formed by a variety of mechanisms, such as mantle flow parallel to trench associated with slab rollback (Long and Silver, 2008; Russo and Silver, 1994), crustal foundering (Behn et al., 2007) or oblique subduction (Mehl et al., 2003), B-type olivine LPO induced by water (Jung and Karato, 2001; Jung et al., 2006; Kneller et al., 2005, 2008) or pressure (Jung et al., 2009b; Ohuchi et al., 2011), and the LPO of antigorite in the serpentized mantle wedge (Ji et al., 2013; Jung, 2011; Katayama et al., 2009). Some researchers also suggest that rather than the fore-arc mantle, the fore-arc crust is the major source of trench-parallel anisotropy (Huang et al., 2011). In addition, the subducting oceanic slab is also proposed as a potential contributor for the seismic anisotropies in the subduction zone (e.g., Healy et al., 2009; Wang and Zhao, 2010).

Although it is relatively thin (~7 km), the oceanic crust in a “cold” subducting slab is mainly composed of blueschist which can be seismically very anisotropic. Hence, the contribution of the subducting oceanic crust to the seismic anisotropy in the subduction zone should not be completely ignored. In general, the anisotropic structure of deep-seated blueschist can be manifested in two forms: dehydration-induced fluid-filled cracks (Healy et al., 2009), and the LPO of the constituent minerals (Bezacier et al., 2010; Cao et al., 2013). In this study, we focus on the latter manifestation. Applying the seismic properties that are obtained from natural blueschists in outcrops to those deep-seated blueschists in subducting oceanic crust may not be apparently straightforward, mainly because the exhumation-related deformation process can overprint the original deformation textures formed during subduction. Based on the microstructural observations, it is noted that blueschist was most likely plastically deformed in the blueschist facies, which suggests a deep origin, therefore their deformation textures are supposed to reflect the deformation behaviors and seismic properties in the deep subducting oceanic crust although some overprinting of the deformation of rock during exhumation is likely. Moreover, we consider that it is the deformation mechanism and geometry that dominantly control the microstructures of blueschist. Since blueschists are likely to experience the same deformation geometry (simple shear dominant) and the similar deformation mechanism during both subduction and exhumation, the subduction-related deformation is supposed to cause similar deformation texture to those formed during exhumation.

Because glauconephane and lawsonite aggregates display opposite seismic anisotropy patterns (Fig. 9; also see Kim et al., 2013a) and an abundance of lawsonite may weaken the fabric strength of glauconephane, a significant weakening of whole-rock seismic anisotropies, particularly polarization anisotropy, is expected to occur in lawsonite blueschist (Figs. 9 and 10). This counteracting effect between the glauconephane and lawsonite aggregates can induce a significant weaker seismic anisotropy for LBS than that of epidote blueschist, because glauconephane and epidote show similar seismic anisotropy patterns (Cao et al., 2013; Fujimoto et al., 2010; Kim et al., 2013a). As shown in Table 2 (excluding one outlier of foliated epidote blueschist), the magnitude of the polarization anisotropy of foliated lawsonite
blueschist (max. $A_{\text{VP}} = 5.5\text{–}9.9\%$) is about 25% lower than that of foliated epidote blueschist (max. $A_{\text{VP}} = 6.8\text{–}11.3\%$), whereas there is no significant difference in the P-wave anisotropy between foliated lawsonite blueschist ($A_{\text{VP}} = 12.0\text{–}19.7\%$) and foliated epidote blueschist ($A_{\text{VP}} = 11.8\text{–}19.6\%$). In addition, the deformation degree can also significantly affect the magnitude of seismic anisotropy, as the massive lawsonite blueschist exhibits about 65% lower P-wave anisotropy ($A_{\text{VP}} = 2.7\text{–}7.9\%$) and about 60% lower S-wave polarization anisotropy (max. $A_{\text{VS}} = 1.6\text{–}4.5\%$) than those of foliated lawsonite blueschist. Cao et al. (2013) suggested that a trench–parallel polarization anisotropy with a moderate delay time (0.1–0.3 s) in a high-angle subducting slab (>45°–60°) can be produced, assuming that the subducting oceanic crust is dominated by strongly foliated epidote blueschist. However, this delay time would be reduced down to 0.08–0.23 s (>25% lower) if the strongly deformed lawsonite blueschist dominates in the subducting oceanic crust, and it would become further smaller (down to 0.03–0.09 s; 60% lower) if the weakly deformed lawsonite blueschist is assumed to be dominant in the subducting oceanic crust. Therefore, the delay time of 0.03–0.09 s and 0.1–0.3 s can be considered as the lower and upper bound induced by an actual subducting oceanic crust, respectively. The contribution of deformed blueschists to the seismic anisotropy would thus be smaller than originally thought.

In addition, it is noteworthy that Teyssier et al. (2010) reported a unique LPO of lawsonite, in which lawsonite aggregate aligns in a fast $V_p$ direction ([001] axis) parallel to the fast $V_p$ direction of the glaucophane aggregate ([001] axis), and the slow $V_p$ direction ([100] axis) of the lawsonite aggregate is aligned consistently with the slow $V_p$ direction of the glaucophane aggregate ([110] axis). In this case, it is possible that the seismic anisotropies of lawsonite blueschist are strengthened instead of weakened, and thus a larger delay time is expected to be generated by the subducting oceanic slab. However, before drawing this conclusion, further research on the causes of the different LPOs of lawsonite is required.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2014.04.028.

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and pure shear. The ratio of $ipf_J(Z)/ipf_J(X)$ can be reliably used to compare the samples normal, respectively. Dashed-arrow lines indicate the potential trends of simple shear.


