Seismic properties of subducting oceanic crust: Constraints from natural lawsonite-bearing blueschist and eclogite in Sivrihisar Massif, Turkey

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A R T I C L E   I N F O

Article history:
Received 11 April 2015
Received in revised form 20 August 2015
Accepted 2 October 2015
Available online 8 October 2015

Keywords:
Lawsonite
Blueschist
Eclogite
Mineral fabric
Seismic properties
Subduction zone

A B S T R A C T

Investigating the seismic properties of natural lawsonite (Lws)-bearing blueschist and eclogite is particularly important for constraining the seismic interpretation of subducting oceanic crust based on seismological observations. To achieve this end, we analyzed in detail the mineral fabrics and seismic properties of foliated Lws-blueschist and Lws-eclogites from Sivrihisar Massif in Turkey. In both blueschists and eclogites, the lawsonite fabric is characterized by three different patterns: [001] axes aligning sub-normal to foliation, and [010] axes aligning sub-parallel to lineation (normal type); [001] axes aligning sub-parallel to lineation, and [100] axes aligning sub-normal to foliation with a girdle sub-normal to lineation (abnormal type); and [001] axes aligning both sub-normal to foliation and sub-parallel to lineation, [010] axes aligning sub-parallel to lineation, and [100] axes aligning sub-normal to foliation (transitional pattern). In contrast, glaucophane and omphacite mostly present consistent axial fabrics with the [001] axes aligning to lineation. These mineral fabrics produce whole-rock seismic anisotropies with similar patterns. However, the variations in seismic anisotropies are mainly controlled by the rock type, to a lesser extent are determined by the lawsonite fabric type, and to only a small extent are affected by mineral fabric strength. Despite the constructive abnormal-type lawsonite fabric on whole-rock seismic anisotropies, because of their weaker mineral fabric strength (or deformation degree), the abnormal-type Lws-blueschist still exhibit comparatively lower seismic anisotropies than those normal-type Lws-blueschist from other localities. Based on the calculated seismic anisotropies and velocities, we estimated that when oceanic crust transforms from Lws-blueschist to Lws-eclogite with increasing subduction depth, (1) P-wave and max. S-wave polarization anisotropies reduce about 70% and 40%, respectively; and (2) variations of Vp and Vs contrasts relative to mantle peridotites are about −7% to −3% and −8% to −6%, respectively. These results corroborate the important roles of Lws-bearing blueschist and eclogite in interpreting the existence and gradual weakening of low-velocity layers in subducting oceanic crust, during the subduction process.

1. Introduction

Plate tectonics comprises the creation of oceanic lithosphere from the spreading ridges, initiation of subduction zone, and ensuing annihilation of oceanic lithosphere (Kearey et al., 2009). The oceanic crust, the uppermost layer of oceanic plate, has thickness that is generally positively related to its spreading rate (e.g., Klein and Langmuir, 1987; Reid and Jackson, 1981) (A recent review can be referred to Smith (2013)), and is an important component of oceanic lithosphere. In contrast to the underlying ultramafic lithospheric mantle, the oceanic crust has dominantly mafic composition and is more extensively hydrated with time due to its proximity to sea water (e.g., Faccenda, 2014; Peacock, 2004; Poli and Schmidt, 2002). Hence, once the oceanic slab is descended into the mantle, its direct contact with the overlying warm mantle wedge and abundance of water, permit more vigorous dehydration or melting, and results in drastic changes in petrological, geochemical, and geophysical properties in the subducting oceanic crust (Hacker et al., 2003a). The subducting oceanic crust thus has critical roles in many geodynamic processes, such as transport of materials (e.g., water, carbon and silicate), seismicity (e.g., intermediate-depth earthquake and slow-earthquake), formation and diminishing of low-velocity layers or anomalies, and genesis of arc-volcanism (e.g., Abers, 2000; Abers et al., 2013; Audet and Bürgmann, 2014; Hacker et al., 2003b; Jung and Green, 2004; Jung et al., 2004; Kim et al., 2015; Spandler and Pirard, 2013; Stern, 2002; Sun et al., 2014; van Keken et al., 2011).

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To reach a comprehensive understanding of the geodynamics of subducting oceanic crust, joint research from multidisciplinary aspects is required. As complements to geophysical observations and numerical/experimental simulations, examining deep-derived natural rocks has the advantage of directly reflecting the chemical and physical properties of a subducting oceanic crust. These results can also be used as natural constraints on interpretations of large-scale geophysical observations. Based on field occurrence and phase equilibrium modeling, blueschist (mainly containing glaucope) and eclogite (mainly containing omphacite and garnet) are the most important types of rocks, because they are thought to represent the composition of the subducting oceanic crust with increasing depth. Specifically, two sub-types of blueschist [epidote(Ep)-blueschist and lawsonite(Lws)-blueschist], and two sub-types of hydrous-phase-bearing eclogite (epidote(Ep)-eclogite and lawsonite(Lws)-eclogite), as well as hydrous-phase-poor (dry) eclogite can be distinguished under different P–T conditions (e.g., Evans, 1990; Okamoto and Maruyama, 1999; Tsujimori and Ernst, 2014; Wei and Clarke, 2011). Regarding the composition of mid-ocean ridge basalt (MORB), blueschist and eclogite are stable at lower and higher P–T conditions, respectively. Epidote-bearing rocks (i.e. Ep-blueschist and Ep-eclogite) have a narrow P–T stability field at higher temperatures and lower pressures compared to lawsonite-bearing rocks (i.e. Lws-blueschist and Lws-eclogite). The latter are stable under wide-range, low-temperature (LT), and high-pressure (HP) conditions (for details, refer to Wei and Clarke, 2011), and are thus considered to indicate a typical Pacific-type ‘cold’ paleo-subduction zone (Maruyama, 2012) and lawsonite (e.g., Chantel et al., 2012; Reynard and Bass, 2006). The characteristic P–T conditions of a subduction zone. These previous studies have highlighted that the rock assemblage meta-peridotite (Davis, 2011; Plunder et al., 2013; Topuz et al., 2013) and eclogites (e.g., Ep/Gln-eclogite:Cao et al., 2013a and Bezacier et al. (2010); dry eclogite: Abalos et al. (2011), Bascou et al. (2001) and Sun et al. (2012)], as well as the single-crystal elasticities of their rock-forming minerals such as glaucope (e.g., Bezacier et al., 2010; Mookherjee and Bezacier, 2012) and lawsonite (e.g., Chantel et al., 2012; Reynard and Bass, 2014; Schilling et al., 2003; Singoelink et al., 2000) under the characteristic P–T conditions of a subduction zone. These previous studies have suggested that (1) the major constituent minerals (e.g., glaucope, lawsonite, and epidote) in deformed blueschist have strong crystal preferred orientations (CPOs); (2) considering heterogeneously deformed Lws- and Ep-blueschists, these blueschists can cause weak-to-moderate trench-parallel S-wave polarization anisotropy (delay time ~ 0.03–0.3 s) in fore-arc regions, in the case of steeply subducted slab; (3) Lws-blueschist has a contrastingly weaker anisotropy than Ep-blueschist due to the destructive seismic anisotropic pattern of lawsonite CPO which is formed by the mechanism of rigid-body rotation; (4) the low-velocity layers (LVs) in the uppermost subducting slab can be attributed to the existence of hydrous phases (e.g., glaucope, lawsonite, and epidote) in blueschist and eclogite; (5) Ep-eclogite has relatively greater velocities and smaller anisotropies than Ep-blueschist; and (6) dry eclogite has the highest velocities and weakest anisotropies which make it hard to be distinguished from mantle peridotites in terms of seismic velocities (diminish of LVs).

Because of the wide P–T stability of lawsonite in a ‘cold’ subduction geotherm (up to 8–9 GPa and ~ 800 °C), it is actually expected that an old and ‘cold’ deep-subducted oceanic crust should be mainly represented by lawsonite-bearing blueschist and eclogite over a wide range of depth. However, the seismic properties of natural Lws-eclogites have not been studied hitherto, probably owing to the lack of well-preserved Lws-eclogite samples. The investigation of seismic properties of natural Lws-blueschist and Lws-eclogite would thus provide important insights into the nature of the low-velocity layer and characteristics of seismic anisotropy in the oceanic crust subducted to a great depth. Fortunately, the exquisite preservation of Lws-bearing blueschist and eclogite in the Sivrihisar Massif of Turkey offer us such an opportunity. In this paper, we first analyzed the microstructures and mineral fabrics of foliated Lws-blueschist and Lws-eclogite samples. These mineral fabric data were then used to calculate the whole-rock seismic velocities and anisotropies. Based on these results, the seismic properties of a subducting oceanic crust were discussed last.

2. Geological background

The Sivrihisar Massif is a part of the Tavşanlı Zone, which is a ~250-km-long east-west-trending high-pressure metamorphic belt situated in the western segment of the Izmır-Ankara-Erzincan suture zone in NW Turkey (Fig. 1a). It is one of the largest and best-exposed HP-PT belts in the world (e.g., Okay, 1982, 1984, 1986). The Tavşanlı Zone represents the exhumed slices of a subduction zone that was formed during the convergence between the Anatolian microplate and Eurasia in the Late Cretaceous, which resulted in the closure of Neo-Tethys Ocean (e.g., Okay et al., 1998; Okay and Kelley, 1994). In the field, the Tavşanlı Zone consists of basal meta-clastic and marble units, overlying schist and a tectonic mélangé containing blueschist-facies meta-sedimentary, felsic meta-volcanic and meta-basaltic rocks, and uppermost overlying meta-peridotite (Davis, 2011; Plunder et al., 2013; Topuz et al., 2006). Specifically, in the Sivrihisar Massif, the rock assemblage is mainly characterized by the HP metamorphic rocks, especially lawsonite-bearing meta-basaltic units (i.e. blueschist and eclogite) and meta-sedimentary layers (e.g., marble, quartzite and mica-/calc-schists) (Fig. 1b). The dominant meta-sedimentary rocks and less occurring interlayered meta-basaltic rock assemblages, agree with the general view that the Tavşanlı Zone is the northern continental passive margin of the Anatolide-Tauride Block dragged into subduction as a result of obduction (e.g., Okay et al., 1998; Plunder et al., 2013).

Based on rock type and metamorphic P–T condition, the Sivrihisar Massif can be divided into four lithologically distinct belts (i.e. Halilbağ, Okçu, Karacaören, and Kertek) with decreasing peak P–T values from north to south (Fig. 1b). The Halilbağ belt contains layers/pods of blueschist and eclogite within meta-sedimentary rocks. The blueschist has peak P–T value of 1.2–1.5 GPa and 350–500 °C, whereas eclogite is metamorphosed at higher pressure (1.5–2.5 GPa) and temperature (475–650 °C). The Okçu Belt is composed of massive white calcite marble without explicitly reported P–T data. The Karacaören Belt mainly consists of mica-rich meta-sedimentary rocks that contain fewer blueschist layers. The blueschist from this belt shows similar peak P–T conditions to those of the Halilbağ Belt. In contrast, the southernmost Kertek Belt is dominantly composed of impure marble intercalated with thin layers of mica-schist, calc-schists, and quartzite. The rare blueschist layers in this belt, record incipient blueschist-facies peak metamorphism (P = 0.8–1.0 GPa and T = 350–450 °C). More detailed petrological and structural descriptions on various types of rocks (especially blueschist and eclogite), as well as the tectonic evolution of the Sivrihisar Massif, can be found in the comprehensive studies by Davis and Whitney (2006,2008), and Davis (2011).

In this study, the lawsonite-bearing blueschist and lawsonite samples were all collected from Halilbağ Belt. About ten samples that display obvious foliation or compositional layering were selected for petrographic observation and mineral fabric analysis.
This collection of samples thus represents the well-deformed portion of subducted oceanic crust.

3. Petrography and microstructure

As shown in Fig. 2, all blueschist and eclogite samples exhibit fairly good, flat foliations defined by mineral shape preferred orientations (SPOs) and/or compositional layers of accumulated lawsonite, glaucophane, and omphacite crystals. Except for variations of mineral modal abundance, grain size, and degree of foliation, as well as occasional occurrence of Lws-rich layers (sample T2025, T2028 and T2021); most samples display overall similar and homogeneous textures. For the convenience of description, we categorized the studied blueschists and eclogites into three groups, based on their distinctive lawsonite fabrics: normal type, transitional type and abnormal type (see Section 4). In all samples, both blueschist (Gln-rich) and eclogite (Omp-rich) and/or their parallel layers within a single specimen (sample T2021 and T2024) are characterized by the dominant mineral assemblage of Lws ± Gln ± Omp (>90 vol.%). The secondary mineral assemblage of garnet (Grt) + phengite (Phn) ± epidote (Ep) ± rutile (Rt) ± titanite (Tnn) ± chlorite (Chl) ± quartz (Qtz) ± calcite (Cal) is less than 10 vol.% (except for Grt-rich sample T2028). The grain size of

Fig. 1. (a) Tectonic map of western and central Turkey, showing the location of the Tavşanlı Zone and other major tectonic-metamorphic units. CACC: Central Anatolian crystalline complex, CAFZ: Central Anatolian fault zone, NAF: North Anatolian fault. (b) Simplified geological map of the northwestern Sivrihisar Massif, showing the major metamorphic belts with corresponding peak P–T conditions. Inset is the enlarged area in the northernmost part of Halibaği Belt. For the detailed rock types and locations of blueschist and eclogite samples, refer to Davis (2011). Figures (a) and (b) were modified after Davis and Whitney (2008) and Davis (2011), respectively.

Fig. 2. Photomicrographs showing the overall texture of three different groups of samples, classified based on lawsonite fabric types: (a–e) normal type, (f and g) transitional type, and (h–I) abnormal type. Figure (i) was adopted from Teyssier et al. (2010), in which the image of one Lws-blueschist (without scale bar) was presented from the same locality as in this study. All images were taken from the XZ plane thin sections under plane-polarized light.
lawsonite varies within a wide range (from <0.1 to 1 mm long) either within a single specimen or among different specimens, whereas Gln and Omp mostly form a fine-grained matrix (<0.1 mm wide) surrounding lawsonite grains.

Regardless of their fabric type, lawsonite grains are mostly sub-euhedral to euhedral in shape, and behave as coarse-grained porphyroclasts with their long axes aligning preferentially sub-parallel to the foliation of fine-grained Gln + Omp matrix (Figs. 2 and 3). The SPO of lawsonite varies with samples and textures. For example, lawsonite crystals display less consistent orientations in Lws-rich layers, relative to those lawsonite grains occurring in neighboring matrix (Fig. 2d and e). The strongest SPO of lawsonite is observed in transitional-type sample (T2021, Fig. 2f and g). In addition to the ubiquitous cracks and inclusions inside lawsonite crystals, polysynthetic growth twinning with {110} planes is also frequently developed in lawsonite (Fig. 3b–f), whereas the intra-crystalline plasticity features, such as deformation twinning and undulatory extinction, are only locally observed (Fig. 3b). Although the lawsonite morphology in normal- and abnormal-type samples is overall similar, two distinctive differences may still exist. First, lawsonite crystals in the normal-type samples are mostly columnar in shape and appear to have a large aspect ratio ($\alpha > 2$) (Figs. 2a–e and 3a–c). In contrast, the abnormal-type samples tend to have more short-columnar or lozenge-shaped lawsonite crystals with a small aspect ratio ($\alpha < 2$) (Figs. 2h–l and 3d–f). Second, the polysynthetic twinning planes in lawsonite are always aligning at high-angle to the foliation in normal-type samples (Fig. 3a–c), whereas lawsonite grains tend to exhibit their growth twinning planes at relatively low angles to foliation in some domains of abnormal-type samples (Fig. 3e and f).

Fig. 3. Photomicrographs showing the enlarged textures of (a–c) normal- and (d–f) abnormal-type samples. Yellow dashed lines mark the foliations of specimens. Red solid lines denote the orientations of polysynthetic twinning planes in the thin sections. Red-edged-and-yellow-filled triangles indicate the planes of deformation twinning. All images were taken from XZ-plane thin sections under cross-polarized light. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
4. Crystal preferred orientations (CPOs)

To analyze the CPOs (or fabrics) of major constituent minerals in blueschist and eclogite, finely polished and ultra-thinly carbon-coated thin sections from XZ plane (X:lineation, Z:foliation) of a sample were prepared. The CPO was measured using an electron back-scattered diffraction (EBSD) system (installed on a JEOL-6380 SEM) housed at the School of Earth and Environment Sciences, Seoul National University. The working conditions of this EBSD system were 20 kV acceleration voltage, 15 mm working distance, and a spot size of 60, all of which were kept constant during all analysis. The EBSD patterns (i.e. Kikuchi patterns) were acquired and indexed manually using the Oxford HKL Channel 5 program in the manner of one point per grain. This procedure avoids the potential misindexing caused by crystal pseudo-symmetry, and the non-indexing resulting from overlapping diffraction patterns of neighboring grains at grain-boundary areas using automated EBSD analysis. The EBSD data were presented in pole figures using the HKL Channel 5 Mabmbo software.

The strength of mineral CPOs was quantified using both the M- and J-index. The misorientation index (M-index) describes the degree of difference by which a measured mineral fabric deviates from a theoretically random fabric (Skemer et al., 2005). The M-index has a value ranging from 0' (random fabric) to '1' (single crystal fabric), and can be calculated using either MTEx toolbox in MATLAB (Bachmann et al., 2010; Hielescher and Schaben, 2008; Mainprice et al., 2011) (software is available at the website: http://mtex-toolbox.github.io/) or the MS Excel spreadsheets we developed. In contrast, the J-index is a volume-averaged integral of the squared orientation distribution function (ODF) (Bunge, 1982). Theoretically, it ranges from 1' to infinity, corresponding to intensification of orientation from random to a single crystal fabric. Practically, the value of J-index depends inversely on given values of kernel half-width, and can also be calculated using MTEx toolbox in MATLAB. In our calculation, a 'de la Vallée Poussin' kernel with a half-width of 10° was applied. Because most blueschists and eclogites are dominated by the mineral assemblage of Lws ± Gln ± Omp, only the CPOs of these three minerals are shown below.

4.1. CPO of lawsonite

As described above, the blueschists and eclogites can be classified into three groups based on the types of lawsonite fabric. The normal-type fabric of lawsonite is characterized by a prominent concentration of [001] axes (with or without girdles) perpendicular to foliation, and a foliation-parallel girdle of [010] axes with their maxima aligning close to lineation (Fig. 4a–e). The [100] axes show weak and inconsistent preferred orientations among different samples. In contrast, the abnormal-type lawsonite fabric displays an obvious clustering of [001] axes parallel to lineation, and a girdle dispersion of [100] axes perpendicular to lineation, with or without their maxima aligning at high angle to foliation (Fig. 4h–k). Intriguingly, we also found a transitional lawsonite fabric, in which [001] axes have two main concentrations aligning normal to foliation and parallel to lineation. Besides, the transitional-type fabric also displays girdle-and-point patterns of [010] and [100] axes that resemble those normal- and abnormal-type fabrics, respectively (Fig. 4g). This transitional lawsonite fabric was also recently found in one Lws-eclogite from the same locality featured in the study by Whitney et al. (2014).

4.2. CPO of glaucophane

Regardless of lawsonite fabric types, glaucophane presents an axial fabric pattern (i.e. axial-[001] or L-type), which has a strong point maximum of [001] axes parallel to lineation and girdle patterns of [100] axes, and (010) poles sub-normal to lineation (Fig. 4a–c, e, f and h–k) in all samples. Even though their maxima are weak, [100] axes and (010) poles tend to align normal to foliation in most samples. Similar to lawsonite, glaucophane also shows strong orthorhombic distributions of principle axes in the Lws-blueschist reported by Teyssier et al. (2010) (Fig. 4i). Except for the relatively stronger fabric in the only transitional-type sample (M-index = 0.19, J-index = 7.7), glaucophane exhibited no significant difference in fabric strength between normal- (M-index = 0.08–0.15, J-index = 3.2–5.2) and abnormal-type (M-index = 0.12–0.16, J-index = 3.5–6.1) samples (Fig. 5b and Table 1), nor between blueschists and eclogites (Fig. 5b and Table 1). Owing to the strong clusterings of principal axes, the glaucophane fabric was thought to be much stronger in the sample studied by Teyssier et al. (2010).

4.3. CPO of omphacite

As shown in Fig. 4, omphacite in both normal- and abnormal-type samples, displays lineation-parallel points of [001] axes, and complete or incomplete lineation-perpendicular girdles of [010] and (1 1 0) poles (Fig. 4a, b, d, e, h and k). This omphacite fabric can be termed L-type (Helmsaeted et al., 1972) or axial-[001] fabric. In contrast, the transitional-type samples present an orthorhombic omphacite pattern, in which [001] axes and (010) poles are strongly concentrated parallel to lineation and perpendicular to foliation, respectively (Fig. 4f and g). This omphacite fabric is generally referred to as SL-type (Helmsaeted et al., 1972). As shown in Fig. 5a and Table 1, the omphacite fabric strength is weak and indistinguishable between normal- and abnormal-type samples (M-index = 0.07–0.21, J-index = 2.4–6.2), whereas the transitional-type samples have relatively stronger fabric (M-index = 0.30–0.32, J-index = 7.5–9.5). Regarding rock type, the only two blueschist samples, appear to have slightly higher J-index and similar M-index values relative to the eclogite samples (Fig. 5c and Table 1).

5. Rock seismic properties

The seismic properties (i.e. anisotropy and velocity) of a natural rock can be calculated from the seismic properties of all its constituting minerals. To achieve this calculation, one needs to know the mineral-specific parameters, including single-crystal elasticity ($C_{ij}$), mineral density, orientations of individual grains (available from EBSD analysis), and mineral modal abundances. By integrating the single-crystal elastic stiffness of all mineral grains over their individual orientations with a certain averaging scheme (e.g., Vogt, Reuss, VRH, and Geometric), a rock macroscopic elastic tensor $<C_{ij}>$ can be obtained. The rock density can be estimated from the averaged mineral densities weighted by their volume fractions. The elastic tensor of a polycrystalline rock generally has all its 21 $C_{ij}$ non-zero, and thus resembles a crystal with triclinic symmetry. To obtain the seismic velocities (i.e. Vp, Vs1, and Vs2) for a given propagation direction in a triclinic-mineral-like rock, the Christoffel equation needs to be solved. Repeatedly solving the Christoffel equation for all propagation directions in the whole 3D space, the 3-D seismic properties of a rock can be constructed. More practically, this complicated calculation process can be conveniently completed using the petro-physical software originally developed by Mainprice (1990) [latest version available at the website: ]
In this study, the elastic stiffness of glaucophane and omphacite were taken from the work of Bezacier et al. (2010) and Bhagat et al. (1992), respectively. A modified elastic stiffness of lawsonite was used [after Sinogeikin et al. (2000), taken from Cao et al. (2014)], which corrects the confusion of lawsonite [100]–[010] axes designation used in EBSD analysis (i.e. Libowitzky and Armbruster, 1995), and single-crystal elastic stiffness (i.e. Baur, 1978). The elastic stiffness of eclogitic garnet (Cao et al., 2013) has a chemical

![Fig. 4. CPOs of lawsonite, glaucophane, and omphacite in studied blueschist and eclogite samples, classified based on lawsonite fabric types: (a–e) normal type, (f and g) transitional type, (h–i) abnormal type. Pole figures were constructed using equal area and lower hemisphere projection and contoured with a half-width of 20° and cluster size of 5°. E–W and N–S are lineation and foliation-normal directions, respectively. Figure (l) was adopted from Teyssier et al. (2010), without showing explicit half width and cluster size.](image-url)
composition similar to the garnet in Lws-eclogites (Davis and Whitney, 2008). The elastic stiffness of all these single crystals correspond to those values under ambient conditions. Except for one sample that had a non-trivial amount of garnet (T20208, Grt ~12 vol.%), the dominant mineral assemblage of Lws ± Gln ± Omp (normalized to 100 vol.%) was used to calculate whole-rock seismic properties (Table 2).

5.1. Lawsonite aggregates

Because the seismic anisotropy of lawsonite single-crystal is characterized by the fastest and slowest P-wave velocities traveling along the [001] and <110> axes, respectively, and by similar moderate velocities along the [100] and [010] axes (Cao et al., 2014), the orientation of fast [001] axes tends to have first-order control over the seismic anisotropy pattern of lawsonite aggregate. The normal-type samples that have maxima of [001] axes aligning perpendicular to foliation thus yield the fastest Vp directions sub-normal to foliation, and slow Vp directions sub-parallel to foliation, as well as foliation-sub-perpendicular polarization directions of fast S-wave (when seismic waves propagate within moderate angles to foliation) (Figs. 6a, b and S1a–e). Because lawsonite [001] axes have relatively stronger concentration perpendicular to foliation than parallel to lineation, transitional-type samples exhibit a pattern of seismic anisotropy similar to those of normal-type samples (Fig. 4f and g). However, unlike those
normal-type samples, transitional-type present more oblique girdles of slow Vp to foliation (Figs. 6c, d and S1f and g). In contrast, abnormal-type samples, transitional-type present more oblique girdle perpendicular to lineation (Figs. 6e–g and S1h–k). Different from showing the fastest Vp parallel to the lineation, and slow Vp girdles abnormal-type samples produces a seismic anisotropy pattern containing the fastest and slowest P-wave velocities parallel to both lineation and foliation. The polarization pattern of the fast S-wave is complex for omphacite aggregates: it often shows multiple high intensities at ~45° to both lineation and foliation. The polarization directions tend to be parallel to foliation at the high S-wave splitting (i.e. AVs) intensity regions. In a similar manner, except that transitional-type samples appear to have relatively stronger seismic anisotropies (AVp = 4.1%, max. AVs = 2.5–3.2%), no significant differences in seismic anisotropy intensities between normal- (AVp = 2.0–3.7%, max. AVs = 1.5–3.2%) and abnormal-type (AVp = 3.1–3.7%, max. AVs = 1.4–2.0%) samples (Fig. 9c and Table 2), or between blueschist and omphacite (Fig. 9c’ and Table 2) were revealed. The seismic anisotropies of omphacite aggregates were much lower than those of the lawsonite and glaucophane aggregates (Table 2).

5.3. Omphacite aggregates

Different from lawsonite and glaucophane, the single-crystal of omphacite has the fastest and the slowest Vp directions propagating about 20–30° east (towards [100] direction) and west (towards [100] direction) from the [001] axis on the [010] plane, respectively (e.g., Abalos et al., 2011). Except for the two samples that show remarkable components of fast Vp at high angle to lineation (Figs. 8b, e and S3d, g), most samples present a seismic anisotropy pattern containing the fastest and slowest P-wave velocities parallel to lineation, and normal to foliation, respectively (Figs. 8a, c, d, f and S3a–c, e, f, h). The polarization pattern of the fast S-wave splitting (i.e. AVs) intensity regions. In a similar manner, except that transitional-type samples appear to have relatively stronger seismic anisotropies (AVp = 4.1%, max. AVs = 2.5–3.2%), no significant differences in seismic anisotropy intensities between normal- (AVp = 2.0–3.7%, max. AVs = 1.5–3.2%) and abnormal-type (AVp = 3.1–3.7%, max. AVs = 1.4–2.0%) samples (Fig. 9c and Table 2), or between blueschist and eclogite (Fig. 9c’ and Table 2) were revealed. The seismic anisotropies of omphacite aggregates were much lower than those of the lawsonite and glaucophane aggregates (Table 2).

5.4. Whole rocks

The calculated whole-rock seismic anisotropies of blueschists and eclogites in this study were shown in Figs. 10 and S4. In both blueschist and eclogite, the P-wave anisotropy was characterized by the fastest and slow P-wave velocities aligning sub-parallel and sub-normal to lineation, respectively (Figs. 10 and S4). However, the S-wave polarization patterns were different among samples. One normal-type (Figs. 10b and S4c) and one transitional-type (Figs. 10c and S4f) blueschists had foliation-parallel polarization directions, whereas the other four normal-type (Figs. 10a and S4a, b, d, e) and one transitional-type (Figs. 10d and S4g) eclogites presented foliation-sub-normal fast polarization directions (when

### Table 1

<table>
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<tr>
<th>Sample</th>
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<th>Lawsonite fabric types</th>
<th>Lawsonite</th>
<th>Glaucophane</th>
<th>Omphacite</th>
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<td>4.04</td>
<td>0.106</td>
</tr>
<tr>
<td>T2023</td>
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<td>3.19</td>
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<tr>
<td>T2025</td>
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<td>1.52</td>
<td>0.038</td>
<td>5.18</td>
<td>0.149</td>
</tr>
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<td>1.84</td>
<td>0.039</td>
<td>5.18</td>
<td>0.149</td>
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<td>4.68</td>
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<td>T2030</td>
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<td>0.191</td>
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<td>0.083</td>
<td>7.66</td>
<td>0.193</td>
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<td>LBS</td>
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<td>1.56</td>
<td>0.036</td>
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<td>0.133</td>
</tr>
<tr>
<td>T2022</td>
<td>LBS</td>
<td>Abnormal</td>
<td>1.73</td>
<td>0.045</td>
<td>3.54</td>
<td>0.118</td>
</tr>
<tr>
<td>T2024</td>
<td>LBS</td>
<td>Abnormal</td>
<td>2.30</td>
<td>0.073</td>
<td>4.76</td>
<td>0.156</td>
</tr>
<tr>
<td>T2007</td>
<td>LEC layer</td>
<td>Abnormal</td>
<td>1.67</td>
<td>0.039</td>
<td>6.09</td>
<td>0.156</td>
</tr>
</tbody>
</table>

**Notes:**
- LBS: lawsonite blueschist; LEC: lawsonite eclogite.
- Whole-rock fabric strength was averaged mineral fabric strength weighted by their volume proportions (see Table 2, Cao et al. (2014) and Kim et al. (2013a,b)).
- The volume proportion of garnet was considered. Because the garnet fabric is nearly random, its J-index and M-index were assumed to be 1 and 0, respectively.
- J-index were recalculated using ‘de la Vallée Poussin’ kernel half width of 10°.
- The volume proportion of fabric strength of plagioclase was considered. The J-index and M-index of plagioclase were 2.62 and 0.062, respectively.
- Data adopted from Kim et al. (2013a,b) Diablo Range, California.
- J-index were calculated using Gaussian half-width of 10° and Super-J program (D. Kim, personal communication).

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Fig. 6. Seismic anisotropies of lawsonite aggregates in representative samples, classified based on lawsonite fabric type: (a and b) normal type; (c and d) transitional type; (e–g) abnormal type. Data were presented in the lower hemisphere using equal area projection. E–W and N–S represent the lineation and foliation-normal directions, respectively.
Seismic waves propagate within moderate angles to foliation. In contrast, fast S-waves tended to polarize sub-parallel to foliation in all abnormal-type samples (three blueschists and one eclogite) (Figs. 10e–g and S4h–k). Unlike the mono-mineralic aggregates, striking differences in the intensities of whole-rock seismic anisotropy were observed (Figs. 9d and d’, Table 2). The normal-type samples had overall lower seismic anisotropies than abnormal-type samples, whereas transitional-type samples were between them (Fig. 9d). From the viewpoint of rock type, the seismic anisotropies were much stronger in blueschist.
Fig. 8. Seismic anisotropies of omphacite aggregates in representative samples, classified based on lawsonite fabric type: (a and b) normal type; (c and d) transitional type; (e and f) abnormal type. Data were presented in the lower hemisphere using equal area projection. E–W and N–S represent the lineation and foliation-normal directions, respectively.
Fig. 9. P-wave (AVp) and maximum S-wave polarization (max. AVs) anisotropies of mono-mineral aggregates of lawsonite (a, a’), glaucophane (b, b’), and omphacite (c, c’), in the studied samples. The seismic anisotropies of whole rock (d, d’) are also compiled. The data were classified based on lawsonite fabric type (a–d) and rock type (a’–d’).
Fig. 10. Seismic properties of representative blueschists and eclogites, classified based on lawsonite fabric type: (a and b) normal type; (c and d) transitional type; (e–g) abnormal type. Data were presented in the lower-hemisphere using equal-area projection. E–W and N–S represent the lineation and foliation-normal directions, respectively.
(AVp = 8.3–11.9%, max. AVs = 4.4–8.0%) than in eclogite (AVp = 2.6–4.5%, max. AVs = 2.8–4.4%) (Fig. 9d).

6. Discussion

6.1. Genesis of mineral fabrics

6.1.1. Developing conditions of mineral fabrics

Based on previous elaborate studies of the structural petrology of high-pressure rocks, the non-folded penetrative foliation, compositional layering and mineral stretching lineation in lawsonite-bearing blueschist and eclogite (e.g., our samples, see Fig. 2) from the Halilbaği Belt, are thought to represent the first stage of deformation (i.e., D1, deformation) which occurred mostly at the early stage of exhumation (i.e. slightly post-tectonic to peak pressures along an anticyclonically P–T path with a cold geothermal gradient of ~5 °C/km) (Davis and Whitney, 2008; Davis, 2011). This stage of deformation might have caused the development of mineral fabrics in our samples (Fig. 4). In fact, because of the intensive overprinting of exhumation-related deformation processes, naturally occurring high-pressure rocks (except for xenoliths) are often difficult to preserve in their original deformation texture that was formed during subduction. This fact may thus limit the implication for seismic properties of the oceanic crust that is undergoing subduction from the viewpoint of natural samples. However, because deformation of rocks occurs along the thin slab interface (i.e. subduction channel) where P–T, stress and fluid conditions might not vary significantly (in case of the Halilbaği Belt, the P–T deformation conditions during burial and uplift are similar, as indicated by the “pinched” anticyclonically P–T trajectories of Lws-bearing blueschist and eclogite; see Davis and Whitney (2008)) and simple shear is dominant across a given profile of the subduction channel, the high-pressure rocks are likely to experience the same deformation geometry and to be deformed by similar deformation mechanisms during both subduction and exhumation. In this context, the subduction-related deformation is thus expected to produce similar deformation textures (mineral fabrics) to those formed during exhumation.

6.1.2. Normal- and abnormal-type lawsonite fabrics

Because of sub-euhedral to euhedral morphology, lack of intra-crystalline plasticity, and the foliation-parallel tendency of the long axis alignment of lawsonite crystals (Figs. 2 and 3), rigid-body rotation is considered to be the dominant deformation mechanism resulting in both shape and crystal preferred orientations of lawsonite in both normal- and abnormal-type samples (Cao et al., 2014; Kim et al., 2013a; Teyssier et al., 2010). Theoretically, the mineral fabric developed by rigid-body rotation depends on the shape of rigid particle and the geometry of deformation (e.g., Gay, 1968; Masuda et al., 1995). Therefore, in the case of normal-type lawsonite fabric, the major foliation-normal and lineation-parallel alignments of respective [001] and [100] axes (Fig. 4a–e) can be approximately explained by the ideal rhombic-plate morphology of a lawsonite crystal under simple shear (Cao et al., 2014). The shortest lawsonite [001] axis tends to orient parallel to the shortening direction (i.e. foliation-normal) due to compres- sion (e.g., Gay, 1968; Passchier, 1987; Piazolo et al., 2002), whereas the intermediate-length [100] axis has a larger probability than the longest [001] axis to align parallel to flow direction (approximate to lineation) in a simplified 2D flow matrix (Cao et al., 2014). As the name ‘normal type’ implies, this lawsonite fabric has been widely found in Lws-blueschist from different localities [e.g., North Qilian mountain, NW China reported by Cao et al. (2014); Diablo Range, California reported by Kim et al. (2013a); Kurosegawa Belt, SW Japan reported by Fujimoto et al. (2010)], as well as in one Lws-Omp-bearing quartzite from the same locality as the study by Whitney et al. (2014).

However, this interpretation appears problematic for the gene-
sis of abnormal-type lawsonite fabric. In the context of rigid-body rotation of lawsonite porphyroclasts under simple shear, the preferred alignments of respective [001] and [100] axes parallel and perpendicular to lineation in this study (Fig. 4h–k), are contradic-
tory to the prediction for an ideal morphology of lawsonite crystal. To solve this contradiction, this abnormal-type fabric requires an unusual lawsonite shape in which its short axis is parallel to the [100] direction and long axis is parallel to the [001] direction. The mechanism for generating this uniquely shaped lawsonite is not clear but may be manifold. One hypothesis involves the activation of multiple cleavages in an ideal lawsonite crystal. The activation of perfect cleavages along [010] planes and imperfect cleavages along {110} planes could section an elongated rhombic-plate lawsonite crystal into a short prismatic shape that has long [001], and short [100] and [010] axes (Fig. 5). This mechanism is consistent with the morphology of abnormal-type lawsonite crystals, which are mostly short-columnar or lozenge-shaped, with aspect ratios ~2. This assumes that extensive fracturing occurred perpendicular to the [001] basal plane (Figs. 2h–l and 3d–f); and is also supported by more frequent orientations of polysynthetic {110} twin planes at low angles to foliation (Fig. 3e and f). However, it is noted that several irregularities may exist to challenge this explanation. For example, the perfect [001] cleavages need to be inhibited to produce lawsonite grains with longest length along the [001] axis. However, the reasons for the inactivation of perfect lawsonite [001] cleavages are unknown. The reasons why fracturing only occurred along the cleavages of lawsonite in abnormal-type rather than normal-type samples are also not clear. A simple explanation might be attributed to lower P–T condition or higher stress (favoring brittle behaviors, e.g., fracturing, of a material) under which abnormal-type samples were deformed in comparison to their normal-type counterparts. However, precise determination of deformation P–T conditions and stress values might not be straightforward because (1) large inconsistency of P–T estimates could exist between deformation and metamorphic (i.e. chemical/phase equilibrium) conditions—the deformation condition is generally inferred from the metamorphic P–T condition, assuming that deformation is coeval with and facilitates the completion of metamorphic reactions; (2) an effective piezometer for determining stress in the high-pressure meta-
morphic rocks is still lacking. In any case, both normal- and abnormal-type lawsonite fabrics are not considered to be controlled by the rock types, since they are present in both blueschist and eclogite (Fig. 4). If we can assume that the Lws-bearing blueschist and eclogite represent lower and higher P–T conditions, respectively (Davis and Whitney, 2006), then the occurrence of normal- and abnormal-type lawsonite fabrics is not likely to be related to the deformation P–T conditions. However, it should be noted that the spatially coexisting Lws-bearing blueschist and eclogite layers in a single hand specimen (e.g., samples T2021 and T2024) could also indicate similar deformation conditions for both blueschist and eclogite layers in those samples (Davis and Whitney, 2008). This abnormal-type lawsonite fabric has only been reported independently by Teyssier et al. (2010) in one Lws-blueschist (rock texture fairly similar to our samples) from the same locality as in this study. However, their lawsonite fabric was more orthohombic and stronger than our samples, as suggested by extremely strong framework-axes-parallel clusterings of [100], [010] and [001] axes (Fig. 4i). The cause of this difference is not known, perhaps owing to the use of lower half-width and cluster size, or a smaller area analyzed by EBSD mapping in their study.

Therefore, to resolve these issues and explore other possible mechanisms that might be responsible for the genesis of
abnormal-type lawsonite fabric, one needs to do further research on the textures of lawsonite grains (e.g., aspect ratio, grain size, and intra-crystalline texture) to reconstruct their 3D shapes in the specimen, as well as to examine their relationships with corresponding fabrics. In addition, despite the lack of adequacy to determine deformation P–T conditions, the acquisition of precise metamorphic P–T conditions for Lws-bearing blueschists and eclogites may still be helpful to investigate the relationship between lawsonite fabric types and deformation P–T conditions.

6.1.3. Fabrics of glaucophane and omphacite

Both glaucophane and omphacite occur in matrix, and present prominent preferred orientations of their crystal shapes (Figs. 2 and 3) and principal crystallographic axes (Fig. 4). These mineral fabrics could be formed by combined deformation mechanisms of dislocation creep, rigid-body rotation, and anisotropic crystal growth, though their fine-grained characteristic might suggest less contribution by anisotropic crystal growth. As described earlier, glaucophane displays an axial fabric pattern (i.e. axial-[001] or L-type) in this study, which has also been observed in garnet-rich eclogite and blueschist (Bezacier et al., 2010; Cao et al., 2013) and Lws-rich eclogite and blueschist (Cao et al., 2014). These characteristics of glaucophane fabric thus imply that the orientation of glaucophane crystals is dispersed owing to porphyroclast (e.g., garnet and lawsonite) induced deformation of local foliation. Similarly, most omphacite also exhibits L-type or axial-[001] fabric in this study. This type of fabric has also been found in the eclogite from many other localities (e.g., Bascou et al., 2002; Engvik et al., 2007; Kurz et al., 2004; Wang et al., 2009). Different from the classical argument that omphacite L-type fabric is caused by trans-tensional or constrictional deformation geometry (Bascou et al., 2002; Kurz, 2005), the L-type fabric of omphacite is also likely the result of the orientation-dispersing effect of porphyroclast. In fact, the SL-type fabric of omphacite observed in transitional-type samples indicates that the deformation regime is simple shear dominant (Bascou et al., 2002; Zhang et al., 2006), which has been evidenced in both natural and experimental samples (e.g., Bascou et al., 2001; Cao et al., 2011, 2013; Mauler et al., 2001; Wang et al., 2010; Zhang et al., 2006).

6.2. Factors controlling the variations of rock seismic properties

In general, the seismic anisotropies of a natural rock are mainly controlled by three factors: (1) mineral species and their abundances (i.e. rock types), (2) consistency of orientation or alignment of the individual mineral grains (i.e. fabric strength), and (3) interactions (constructive or destructive effects) between different mineral fabrics. Owing to their complicated roles, the contributions of these three factors on the variations of seismic anisotropies are difficult to separate and quantify. However, their relative importance may still be qualitatively inferred via comparisons of samples between different categories. For example, comparing lithologically distinct and texturally similar samples could help to investigate how rock type affects the rock seismic anisotropies (Factor 1), whereas lithologically alike and texturally distinct samples could give hints about how seismic anisotropies are affected by rock texture (Factor 2 and 3).

In the case of the blueschist and eclogite samples from Turkey, the order of importance of these three factors can be inferred as below. The most striking contrast of seismic anisotropies is presented by rock type (Factor 1), in which blueschists display consistently greater anisotropies than eclogites (Fig. 9d). The transitional-type samples have comparatively stronger mineral fabrics (Fig. 5a–c) and seismic anisotropies of mono-mineralic aggregates (Fig. 9a–c), than do those of normal- and abnormal-type samples. The highest and lowest whole-rock seismic anisotropy of P-wave (AWP) were observed in transitional-type blueschist and eclogite, respectively (Fig. 9d). These results thus imply a first-order effect for rock type and a minor role for mineral fabric strength (Factor 2) on the variations of whole-rock seismic anisotropies. Except for the transitional-type samples, no significant differences in mineral fabric strength were observed between normal- and abnormal-type samples (Fig. 5a–c), or between blueschists and eclogites (Fig. 5a–c). The observed similarities in mineral fabric strength should predict indistinguishable whole-rock seismic anisotropies between normal- and abnormal-type samples, and between blueschists and eclogites, assuming that mineral fabric strength is the main determinant of the variation of seismic anisotropy. However, this prediction is obviously contradictory to the observations (Fig. 9d and d’), and corroborates the minor role of fabric strength. Excluding one abnormal-type eclogite (sample T2024 eclogite layer) that has similar seismic anisotropies to both normal- and transitional-type eclogites, the other three abnormal-type blueschists exhibit the highest maximum AVs among the studied samples (Fig. 9d and d’). This indicates the significant effect of lawsonite fabric types on the variations of seismic anisotropies (Factor 3). Taken together, these four lines of evidence suggest that the variations of seismic anisotropies in our studied samples are mainly controlled by the rock type (Factor 1), secondarily determined by lawsonite fabric type (Factor 3), and in a minor way affected by mineral fabric strength (Factor 2).

The dominant role of rock type on the variation of seismic anisotropies can be mainly attributed to the high abundances of glaucophane and omphacite in Lws-bearing blueschist and eclogite, respectively, as well as to the distinctive intensities of seismic anisotropies of their mono-mineralic aggregates (AWP : Gln &gt; Lws &gt; Omp; max AVs : Gln &gt; Lws &gt; Omp; see Fig. 9 and Table 2). Owing to similar patterns of seismic anisotropy between abnormal-type lawsonite, glaucophane, and omphacite aggregates (Figs. 6–8, S1h–k, S2f–i and S3g, h), the abnormal-type lawsonite fabric contributes constructively to the whole-rock seismic anisotropies. In contrast, the normal-type lawsonite fabric plays a destructive role and weakens the whole-rock seismic anisotropies, due to its opposite seismic anisotropy pattern relative to glaucophane and omphacite aggregates (Figs. 6–8, S1a–e, S2a–d and S3a–d). This destructive behavior of normal-type lawsonite aggregate has also been inferred in other reported Lws-blueschist samples (Cao et al., 2014; Fujimoto et al., 2010; Kim et al., 2013a). Besides, the interaction between different mineral fabrics is not solely independent: it also relies on the relative modal abundances of these minerals. For example, because of the lack of glaucophane, the normal-type eclogites show foliation-sub-normal polarization directions of fast S-wave (when seismic waves propagate within moderate angles to foliation) caused by normal-type lawsonite fabric (Figs. 10a and S4a, b, d, e). However, owing to the dominance of glaucophane, one normal-type blueschist instead presents foliation-parallel polarization directions of fast S-wave (Figs. 10b and S4c).

The seismic anisotropies of various types of blueschist and eclogite from other localities were also compared with this study (Fig. 11). Similarly, the most striking feature is also characterized by rock type (Fig. 11b). Because of strong mineral fabrics and constructive role of epidote fabric on rock seismic anisotropies (Cao et al., 2014; Fujimoto et al., 2010; Kim et al., 2013a), Ep-blueschist has the largest seismic anisotropies (especially maximum AVs). These anisotropies become smaller in the Lws-blueschist, due to either weaker mineral fabric strength, or to destructive role of normal-type lawsonite fabric on rock seismic anisotropies. Owing to the high abundance of weakly anisotropic minerals (garnet and omphacite), all eclogites display contrasting smaller seismic anisotropies than do blueschists. An increasing
amount of highly anisotropic hydrous minerals (e.g., glaucophane, lawsonite, and epidote) from dry eclogite to Lws-eclogite and Ep/Gln-eclogite (referred to Table 2 and relevant references for hydrous mineral abundance) can thus account for the increasing intensities of their seismic anisotropies. The greater seismic anisotropies in Ep/Gln-eclogite than in Lws-eclogite are attributed to more abundant hydrous phases and constructive role of epidote fabric on rock seismic anisotropies in Ep/Gln-eclogite, though some Lws-eclogite samples have stronger mineral fabrics (Fig. 11b).

Intriguingly, the normal-type Lws-blueschist (black triangle and square) reported in the work of Cao et al. (2014) and Kim et al. (2013a) exhibits remarkably stronger mineral fabrics and seismic anisotropies than the normal- and transitional-type Lws-blueschist in this study. Even benefiting from constructive role of abnormal-type lawsonite fabric on rock seismic anisotropies, the abnormal-type Lws-blueschist still exhibits weaker seismic anisotropies (especially AVp) than their previously reported normal-type counterpart (Fig. 11). These results thus suggest that the mineral fabric strength is probably the main factor that accounts for

Table 2
Calculated seismic properties of monomineralic aggregates and whole rocks at ambient condition.

| Sample  | Rock type | Lawsonite fabric type | Mineral volume proportions (vol.%)
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Lws</td>
<td>Gln</td>
</tr>
<tr>
<td>T2007 LEC</td>
<td>Normal</td>
<td>33</td>
<td>30</td>
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<tr>
<td>T2008 LEC</td>
<td>Normal</td>
<td>40</td>
<td>20</td>
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<td>T2023 LEC</td>
<td>Normal</td>
<td>23</td>
<td>77</td>
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<tr>
<td>T2016 LBS</td>
<td>Normal</td>
<td>16</td>
<td>84</td>
</tr>
<tr>
<td>T2025 LBS</td>
<td>Normal</td>
<td>17</td>
<td>60</td>
</tr>
<tr>
<td>T2021 LBS</td>
<td>Transitional</td>
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<td>T2004 LBS</td>
<td>Abnormal</td>
<td>42</td>
<td>48</td>
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<td>T2022 LBS</td>
<td>Abnormal</td>
<td>38</td>
<td>62</td>
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<tr>
<td>T2024 LBS</td>
<td>Abnormal</td>
<td>42</td>
<td>58</td>
</tr>
</tbody>
</table>

* LBS: lawsonite blueschist; LEC: lawsonite eclogite.
* Normalized volume proportions of major constituent minerals used for calculating whole-rock seismic properties. The volume proportions were estimated by calculating the area percentages of these minerals in a thin section, then normalized them to 100 vol.%.
* Ave Vp = (max Vp + min Vp) / 2.
* Ave Vs = (max Vs1 + min Vs1 + max Vs2 + min Vs2) / 4.
* The seismic anisotropy of garnet aggregate (the only sample having non-ignorable amount of garnet) was calculated but not shown.
the variations of seismic anisotropies in Lws-blueschist across different localities.

In contrast to seismic anisotropies that are affected by all three of the factors discussed above, the isotropic seismic velocities (i.e., Vp and Vs) only depend on rock type (Factor 1). To better illustrate the relationship between rock type and rock velocity, we compiled average whole-rock seismic velocities (approximate to isotropic velocities) of various types of blueschists and eclogites in this and previous studies (Fig. 12b). Owing to the enrichment of high-velocity minerals (omphacite and garnet), eclogite overall has significantly higher Vp and Vs than blueschist. Moreover, Lws-bearing blueschist and eclogite display higher Vs but lower Vs than Ep-bearing blueschist and eclogite, because Vp and Vs of isotropic lawsonite aggregate are higher and lower than those of isotropic epidote aggregates, respectively. The variation of average rock seismic velocities among various types of blueschist and eclogite, could be explained by varying mineral species and abundances of glaucophane, lawsonite, epidote, omphacite, and garnet. The higher Vp and lower Vs in abnormal-type compared to normal- and transitional-type samples (Fig. 12a) can be ascribed to relatively higher modal abundance of lawsonite in abnormal-type samples (Table 2 and Fig. S6).

6.3. Implications for the seismic properties of subducting oceanic crust

Before extrapolating the seismic properties calculated from natural blueschist and eclogite to those of deep-seated oceanic crust in subduction zones, several uncertainties need to be addressed. In this study, there are mainly three sources of uncertainties. For calculating the seismic properties of most samples, we used the normalized modal proportions of dominant mineral assemblage of Lws ± Gln ± Omp. The neglect of other minor minerals, especially relatively abundant garnet and phengite, would inadvertently cause unfavorable uncertainties. The degree of this uncertainty is hard to estimate, but their influence to the final outcome may not be that significant, because the total volume proportion of these minor minerals is less than 10 vol.%, and there is a strong canceling effect on seismic properties between garnet (high velocities and low anisotropies) and phengite (low velocities and high anisotropies).

The mineral fabrics were measured using one-point-per-grain manual EBSD acquisition, instead of one-point-per-pixel automated EBSD mapping, which is more representative of the bulk-rock properties. The difference between these two EBSD analysis methods is mainly presented in regard to the fabric strength, as the former method tends to yield slightly weaker fabric than the latter method, especially when grain-size distribution is rather heterogeneous in specimens. Therefore, it is expected that the seismic anisotropies calculated for our samples might be slightly stronger in the normal- and transitional-type samples, and weaker in the abnormal-type samples, owing to potentially slightly weaker lawsonite fabrics resulting from the heterogeneous grain size of lawsonite.

The seismic properties of our samples were calculated using the single-crystal elastic stiffness under ambient conditions, which unavoidably causes uncertainty when directly applying the calculated results to mantle-depth conditions. In the case of seismic velocities, the exact influences of pressure and temperature on our studied samples are unknown. However, it is generally suggested that, for most blueschist and eclogite compositions, pressure and temperature effects tend to compensate to depths of ~100 km, before pressure effects dominate, leading to increasing velocities with depths along a subduction geotherm (e.g., Chantel et al., 2012; Hacker et al., 2003a; Reynard and Bass, 2014). Moreover, because of the similar trends of pressure and temperature effects on the seismic velocities of various rock types (e.g., blueschist, eclogite, and peridotite), these P–T effects induced uncertainty can be further minimized or even ignored, especially when the in-situ seismic velocities contrasts between different types of rock at depth are considered. In contrast, noticeable P–T effects may exist on seismic anisotropies. Because the seismic anisotropies of single-crystal such as glaucophane and lawsonite may decrease significantly with increasing pressure or temperature (Chantel et al., 2012; Mookherjee and Bezacier, 2012; Reynard

![Fig. 12. Average seismic velocities (Vp and Vs) of blueschists and eclogites, classified based on lawsonite fabric type (a) and rock type (b). Error bars indicate anisotropies. The additional data of normal-type Lws-blueschist (black and white triangles) are from Cao et al. (2014) and Kim et al. (2013a). Ep-blueschist (blue circle and square) are from Bezacier et al. (2010), Cao et al. (2013) and Kim et al. (2013a). Ep/Gln-eclogites (magenta circle and square) are from Bezacier et al. (2010) and Cao et al. (2013). Dry eclogites (red circle) were from Bascou et al. (2001); Lws-eclogites (cyan circle) are from Chantel et al. (2012); Peridotites are from Pera et al. (2003). The background of this figure was modified after Reynard and Bass (2014). All seismic velocities were estimated at ambient condition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)
and Bass, 2014; Schilling et al., 2003), weaker seismic anisotropies than those calculated using ambient single-crystal elasticities, would be expected for those deep-seated blueschist and eclogite. Consequently, we consider that the seismic properties calculated for the samples in this study may approximately represent those of blueschist and eclogite in a deeply subducted oceanic crust (depth < 100 km).

Previous inferences on the intrinsic seismic anisotropy (induced by mineral fabrics) of subducting oceanic crust are mostly from the studies on natural blueschist and eclogite (e.g., Abalos et al., 2011; Cao et al., 2013, 2014; Fujimoto et al., 2010; Kim et al., 2013a; Sun et al., 2012). These studies estimated fairly high seismic anisotropies for most deformed Ep-blueschist and normal-type Lws-blueschist (AVp > 15% and maximum AVs > 8%). These values have recently been favored to explain the highly anisotropic region (AVs ~ 10–14%) at 40–70 km depth across the Cascadia subduction zone (Piana Agostinetti and Miller, 2014). However, the seismic anisotropies of the deformed Lws-blueschist in this study are obviously smaller (AVp ~ 8–12% and max. AVs ~ 4–8%) than in previous reports (Fig. 11). This is probably due to weaker mineral fabrics or degree of deformation (see previous discussion section). The exact reason for the weaker mineral fabrics in Turkey Lws-blueschist is unknown. One possibility may be related to the fabric-weakening effect caused by large amounts of lawsonite porphyroclasts. Alternatively, these weaker mineral fabrics could possibly be attributed to more intense strain partitioning between meta-basaltic and meta-sedimentary rocks (smaller strain tends to be accommodated by stronger meta-basaltic rocks). These conditions would be present because the Svišhrivša Massif represents a subducted continental margin rather than typical oceanic crust. Even so, the MORR-like composition of these HP meta-basaltic rocks may still contain some information about rheological and seismic properties that may have some similarities to a subducted oceanic crust. Nevertheless, if these weaker mineral fabrics of Lws-blueschist can be taken as a common characteristic for a typical subducting oceanic crust, then it implies that the seismic anisotropies of subducting ocean crust might be over-represented and overestimated based on those deformed blueschist samples in previous studies. These seismic anisotropies (maximum AVs ~ 4–8%) will induce small delay times (~0.1 s) within the delay time range (0.03–0.3 s) for a 7-km thick, blueschist-dominated subducting oceanic crust with a high subduction angle (~40–60°) (Cao et al., 2014).

As another important component of subducting oceanic crust, the seismic anisotropies of natural lawsonite-bearing eclogite have not been addressed hitherto. As the first attempt to address this issue, we found that Lws-eclogite still presents much smaller seismic anisotropies than Ep/Gln-eclogite, in spite of fairly strong mineral fabrics in some Lws-eclogite samples (Fig. 11b). These results thus suggest that about 70% and 40% drops (for respective AVp and maximum AVs) are expected when the oceanic crust transforms from Lws-blueschist to Lws-eclogite during subduction. In addition, Lws-eclogite has significantly higher velocities than Lws-blueschist, but both of these have remarkably lower velocities than Lws-eclogite (Fig. 12). In a similar manner, we can estimate that variations of about ~7% to ~3% in Vp contrasts, and of about ~8% to ~6% in Vs contrasts (relative to mantle peridotite) can be predicted for the Lws-blueschist to Lws-eclogite transformation with increasing depth. These results further corroborate the important roles of Lws-bearing blueschist and eclogite on interpreting the existence and gradual weakening or diminishing of low-velocity layers in subducting oceanic crust with depth, until lawsonite is no longer stable (~250 km depth) (e.g., Abers, 2000, 2005; Chantel et al., 2012; Lin et al., 1999; Nakajima et al., 2009; Reynard and Bass, 2014).

Acknowledgements

H.J. thanks Prof. Gültekin Topuz for his kind help in the field at Svišhrivša in Turkey. The authors also thank Prof. David Mainprice for his fruitful discussions on the genesis of lawsonite fabric, as well as for generously providing his Unicef careware and MTEX toolbox in MATLAB, which greatly helped us analyze rock textures and calculate seismic properties. Special thanks also go to two anonymous reviewers for their helpful comments, which significantly improved the quality of our manuscript. We also thank Yoonhae Ha for preparing the thin sections, and Dr. Daeyeong Kim for giving us the raw EBSD data for those of his samples that were used in this study. This research was supported by the Mid-career Researcher Program through an NRF grant to H.J. funded by the MEST (NRF 2010-0015027, 2015R1A2A1A1052305) and a BK21+ postdoctoral fellowship to Y.C. in Korea.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pepi.2015.10.003.

References


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