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

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ABSTRACT

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 glaucophane) 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 et al., 1996; Tsujimori and Ernst, 2014; Tsujimori et al., 2006).

In contrast to the large number of studies on the petrological and geochemical characteristics of blueschist and eclogite, only a few recent studies have addressed the seismic properties (i.e. velocities and anisotropies) of natural blueschist [e.g., Ep-blueschist: Bezacier et al. (2010), Cao et al. (2013) and Kim et al. (2013a); Lws-blueschist: Cao et al. (2014), Fujimoto et al. (2010) and Kim et al. (2013a)] and eclogites [e.g., Ep/Gln-eclogite: Cao et al. (2013) 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 glaucophane (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; Sinogeikin 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., glaucophane, 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 (LVLs) in the uppermost subducting slab can be attributed to the existence of hydrous phases (e.g., glaucophane, 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 LVLs).

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 Izmir-Ankara-Erzincan suture zone in NW Turkey (Fig. 1a). It is one of the largest and best-exposed HP-LT 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 mélange 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. Halilbağı, Okçu, Karacaören, and Kertek) with decreasing peak P–T values from north to south (Fig. 1b). The Halilbağı 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 ($P = 1.4$–1.6 GPa and $T = 425$–550 °C) to the blueschist from the Halilbağı 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 Halilbağı Belt. About ten samples that display obvious foliation or compositional layering were selected for petrographic observation and mineral fabric analysis.