New Crystal Preferred Orientation of Amphibole Experimentally Found in Simple Shear

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Abstract The crystal preferred orientation (CPO) of amphibole has a large effect on seismic anisotropy in the crust. Previous studies have reported four CPO types (I–IV) of amphibole, but the genesis of type IV CPO, which is characterized by [100] axes aligned in a girdle subnormal to the shear direction, remains unknown. In this study, shear deformation experiments on amphibolite were conducted to find the origin of type IV CPO at high pressure (0.5 GPa) and temperature (500–700 °C). The type IV CPO was found under high shear strain (γ > 3.0), and the sample exhibited grains in a range of sizes but generally smaller than the grain size of samples with lower shear strain. The seismic anisotropy of type IV CPO is lower than that of types I–III. The weak seismic anisotropy of highly deformed amphibole could explain weak seismic anisotropy observed in the middle crust.

Plain Language Summary Amphibolite is one of the major constituent rocks of the middle to lower crust and amphibole is a major constituent mineral of amphibolite. The crystal preferred orientation (CPO) of amphibole has a large effect on seismic anisotropy in the crust. In many previous studies on natural amphibolites, four amphibole CPO types (types I–IV) were observed. Types I, II, and III CPOs were found in previous deformation experiments at a pressure of 1 GPa, but the genesis of type IV CPO is unknown. In this study, shear deformation experiments on amphibolite were conducted at high pressure (0.5 GPa) and temperature (500–700 °C) to find the origin of the type IV CPO. We found the type IV CPO of amphibole, for the first time, through deformation experiments under high shear strain (shear strain > 3.0), where the sample showed a wide range of grain size and/or small grain size. The type IV CPO of amphibole shows smaller seismic anisotropy than those of other amphibole CPO types. Our result shows that even highly deformed amphibolites can exhibit weak seismic anisotropy. This weak seismic anisotropy of amphibole may be important to interpret the regional low seismic anisotropy in the middle crust.

1. Introduction

Seismic anisotropy observed worldwide is a powerful tool for studying the internal structure of the Earth. In the past, there have been many studies on the seismic anisotropy of mantle origin. Recently, increasing numbers of studies have been conducted on seismic anisotropy in the crust (Bonnin et al., 2010; Huang et al., 2011; Kern et al., 2016; Ozacar & Zandt, 2009; Wenning et al., 2016). Fluid-saturated cracks (Crankin, 1981) and crystal preferred orientation (CPO) of minerals (Almqvist & Mainprice, 2017) have been considered as the causes of seismic anisotropy in the crust. However, at pressures above 200–250 MPa, most microcracks are closed (Ji et al., 2013), leading to a negligible effect on seismic anisotropy at middle and lower crust depths. Therefore, to understand seismic anisotropy in the crust, studying CPOs of the minerals in crustal rocks is necessary. It is well known from field (Burg et al., 2005; Rutter et al., 2007) and drilling studies (Gorbatschevich et al., 2002; Kern & Schmidt, 1990) that amphibolite is one of the major constituent rocks of the middle to lower crust. Amphibole, the major constituent mineral of amphibolite, is elastically anisotropic (Aleksandrov & Ryzhova, 1961) and has a significant effect on seismic anisotropy in the crust (Mainprice & Nicolas, 1989; Moschetti et al., 2010; Siegesmund et al., 1989; Tatham et al., 2008; Weiss et al., 1999). Therefore, a study of its CPO is important for understanding seismic anisotropy in the crust and subduction zones (Ji et al., 2013; Jung, 2017). However, previous research on this topic is mostly based on samples taken from outcrops in the field and the mechanism of CPO formation in amphibole is poorly understood.

In a recent experimental study, the CPO of amphibole was classified into four types, and three among them (types I, II, and III) (Figure 1a) were discovered to have formed depending on the temperature and...
Figure 1. (a) Schematic diagram of four types of amphibole CPO (modified after Ko & Jung, 2015). The blue line indicates the shear plane, and the blue arrows indicate the shear direction. (b) Representative pole figures of amphibole with increasing shear strain, which were experimentally found at high pressure (0.5 GPa) and temperatures (500–700 °C). The pole figures are presented in an equal-area net and lower hemisphere. A half-scatter width of 15° was used. The color bars indicate the density of data points with a linear scale. The white line indicates the shear plane, and the blue arrows represent the shear direction. N = number of measurements; γ = shear strain.
differential stress at a pressure of 1 GPa (Ko & Jung, 2015). Type I CPO, the most commonly found type in nature (e.g., Aspiroz et al., 2007; Barruol & Kern, 1996; Berger & Stünitz, 1996; Getsinger et al., 2013; Getsinger & Hirth, 2014; Ji et al., 1993; Kern et al., 2001; Mainprice & Nicolas, 1989; Pearce et al., 2011; Siegesmund et al., 1989), is characterized by [100] axes aligned subnormal to the shear plane and [001] axes aligned subparallel to the shear direction (Figure 1a). Type II CPO is characterized by [100] axes aligned subnormal to the shear plane and (010) poles aligned subparallel to the shear direction (Figure 1a). Type III CPO is characterized by [100] axes aligned subnormal to the shear plane and both (010) poles and [001] axes forming a girdle on the shear plane (Figure 1a). CPO types II and III are less common than type I or IV in nature (e.g., Aspiroz et al., 2007; Cao et al., 2010).

Unlike the other three types of CPO, type IV CPO of amphibole is characterized by [100] axes forming a girdle subnormal to the shear direction and [001] axes aligned subparallel to the shear direction (Figure 1a). CPO type IV is commonly observed in nature (e.g., Aspiroz et al., 2007; Imon et al., 2004; Ji et al., 2013; Lamarque et al., 2016; Llana-Fúnez & Brown, 2012; Tatham et al., 2008) but has not been found in previous experimental studies (e.g., Getsinger & Hirth, 2014; Ko & Jung, 2015). In previous studies on natural amphibolites, dislocation creep accommodated by subgrain rotation dynamic recrystallization (Aspiroz et al., 2007) and cataclastic deformation by rigid-body rotation in cataclastically flowing fine-grained matrix (Imon et al., 2004) have been pointed to as causes of the formation of the type IV CPO; however, this mechanism remains controversial. It has been noted in several previous studies that type IV CPO in amphibolite was observed in field samples corresponding to pressures of 0.5–0.7 GPa (e.g., Aspiroz et al., 2007; Imon et al., 2004; Ji et al., 2013; Tatham et al., 2008). Therefore, in this study, we conducted shear deformation experiments on amphibolite at a pressure of 0.5 GPa, which is lower than the pressure used in the previous experimental study (Ko & Jung, 2015). We studied the CPO development of amphibole at 0.5 GPa pressure and 500–700 °C temperatures with increasing shear strain to understand the exact conditions required for the development of type IV CPO of amphibole. In addition, we report the seismic signature of the type IV CPO of amphibole.

2. Methods

Our starting material was a natural amphibolite collected in Yeoncheon, Korea, same as that used by Ko and Jung (2015). The sample was massive and composed of hornblende (68%), anorthite (23%), biotite (5%), titanite (3%), and ilmenite (1%). The chemical composition of hornblende was $K_{1.18}Na_{0.61}Ca_{1.9}Mg_{2.2}Mn_{0.03}Fe_{2.0}Ti_{1.9}Al_{1.58}Si_{6.4}Al_{1.6}(OH)_{2}$, which is classified as ferro-pargasite. The average grain size of amphibole was 20 μm (Figure S1 in the supporting information), and its CPO in the starting material was almost random (Ko & Jung, 2015).

The sample of amphibolite was deformed at 0.5 GPa pressure and 500–700 °C temperature range by using a modified Griggs apparatus at the School of Earth and Environmental Sciences, Seoul National University, Korea, with the experimental procedures being similar to the previous experimental study (Ko & Jung, 2015). The CPO of amphibole was measured by electron backscattered diffraction (EBSD) using the HKL system with Channel 5 software at the School of Earth and Environmental Sciences, Seoul National University, Korea. The CPOs of amphibole were plotted using the MATLAB toolbox MTEX (Bachmann et al., 2010). The EBSD mapping conditions were 2 μm step size, 20 kV acceleration voltage, and 25 mm working distance on samples tilted at 70°. Seismic velocity and anisotropy were calculated using the measured CPO of the deformed amphibole, and the density and elastic constants of amphibole (Brown & Abramson, 2016), using the Voigt-Reuss-Hill averaging scheme. Detailed experimental procedures, methods of measurement of CPO, and calculation of seismic anisotropy are described in Text S1 and S2.

3. Results

3.1. Microstructures

The representative deformed amphibolites produced after conducting the experiments are shown in Figure 2. In the sample deformed at low shear strain (Figure 2a), the grains of amphibole and plagioclase were elongated and had rotated depending on the shear strain. But, most of grains were fractured with a grain size of maximum 10 μm. Some small faults were visible and strain localization was rarely observed. In the sample deformed at high shear strain (Figure 2b), most grains were highly elongated with the grain size ranging from several micrometers to several hundred nanometers. Microfractures were still visible,
and deformation was highly localized. Some of the large amphibole cores (grain size ~10 μm) with a round shape had remained in the deformed layer, but their proportion had decreased compared with the samples with low shear strain.

3.2. CPOs of Amphibole

Three types of amphibole CPOs were observed after the deformation experiments at $P = 0.5$ GPa and $T = 500–700^\circ$C (types I + II, II, and IV; Figure 1b). The CPO development of amphibole corresponded with the magnitude of the shear strain. At low shear strain ($\gamma \leq 2.1$), type II and mixed type I + II CPOs were observed (Figure 1b). In sample JH117, type II CPO was observed at the lowest experimental temperature (500 °C; Figure 1b). In sample JH157, a mixed CPO of types I and II was observed at the intermediate temperature (600 °C; Figure 1b). This mixed CPO displayed [100] axes of amphibole aligned subnormal to the shear plane and [001] axes aligned subnormal and subparallel to the shear direction. At high shear strain ($\gamma \geq 3.0$), the type IV CPO was found at temperatures of 500, 600, and 700 °C (Figure 1b). The CPOs of all other samples have been shown in supporting information Figure S2. A sample with shear strain $\gamma \sim 2.5$ showed a mixed CPO type I + II, with weak girdles of (110) poles and [100] axes (JH104). The CPOs of other two samples (JH165 and JH168), deformed at high strain ($\gamma \sim 3.7$ and 3.1, respectively), are similar to the type IV CPO, but their (110) poles and [100] axes are distributed as a relatively weak girdle subnormal to the shear direction. Following deformation experiments, the Kikuchi bands of plagioclase and biotite were too weak to measure CPO, and the amount of ilmenite and titanite was too small to plot pole figures with meaningful information.

3.3. Seismic Velocity and Anisotropy

Seismic velocity and anisotropy for each representative CPO type of amphibole are shown in Figure 3a. In all samples, the slowest velocity of the $P$ wave was aligned subnormal to the shear direction (white small circle in Figure 3a), and the fastest $P$ wave velocity was aligned subparallel or subnormal to the shear direction (black square in Figure 3a). The type II CPO showed the strongest $P$ wave anisotropy (12.5%) and the maximum $S$ wave anisotropy (10.7%). The mixed type I + II CPO showed a $P$ wave anisotropy and a maximum $S$ wave anisotropy of 5.7–10% and 5.1–7.9%, respectively. The samples with type IV CPO showed a weak $P$ wave anisotropy (4.0–7.3%) and the weakest maximum $S$ wave anisotropy (2.7–4.8%) (Table 1). For horizontal flow (Figure 3a), the $P$ wave velocity and $S$ wave anisotropy for vertically propagating seismic waves are very low. The polarization direction of the fast $S$ wave for the horizontal flow of amphibole was aligned subparallel to the shear direction (Figure 3a). We also calculated the effect of the dipping angle of the flow on seismic anisotropy of amphibole and the polarization direction of the fast $S$ wave (Figure 3b). If the dipping angle of the flow was larger than 30°, the $P$ wave velocity and $S$ wave anisotropy for vertically propagating seismic wave (at the center of the stereonet in Figure 3b) increased, and the polarization directions of the fast $S$ wave for vertically propagating seismic wave were aligned subnormal to the shear direction (Figures 3b, S5, and S6).
Figure 3. (a) Seismic velocities and anisotropy of hornblende for the representative CPOs in the case of horizontal flow. (b) Seismic velocities and anisotropy of hornblende for the flow dipping at 45° assuming a 2-D corner flow model. The X direction represents the shear direction and Z direction represents direction normal to the shear plane. The white bar at the center of the $V_{S1}$ polarization diagram represents the polarization direction of the fast shear wave, which is propagating vertically. $V_p$ = velocity of $P$ wave; $AV_s$ = anisotropy of $S$ wave; $V_{S1}$ polarization = polarization direction of the fast shear wave ($V_{S1}$).
4. Discussion

4.1. Microstructures

All the deformed samples showed that amphibole, plagioclase, ilmenite, and titanite were elongated on a macroscopic scale. However, on a microscopic scale, fractures were visible inside the grains (Figure 2). Some large amphibole cores still remained in the highly deformed layer. In some amphibole cores, intracrystalline microfractures had propagated into fine grains. These macroscopically ductile but microscopically brittle deformations indicate that cataclastic flow was the dominant amphibolite deformation mechanism in this study. This observation has been suggested in many previous studies (Allison & Tour, 1977; Babaie & La Tour, 1994; Hacker & Christie, 1990; Imon et al., 2004; Ko & Jung, 2015; Nyman et al., 1992).

4.2. CPOs of Amphibole

By conducting deformation experiments on amphibole in simple shear at high pressure (0.5 GPa) and temperatures (500–700 °C), we found that the development of type IV CPO of amphibole was dependent on the magnitude of the shear strain. In our study, the type IV CPO was observed under high shear strain ($\gamma > 3.0$). In samples deformed under high shear strain, a mixture of coarse-grained and fine-grained amphiboles was observed (Figure 2b). For example, the fine-grained amphiboles in sample JH132 exhibited the distribution of [100] axes as a weak girdle subnormal to the shear direction with the maximum concentration near the center of the pole figure (Figure S3). In contrast, the coarse-grained amphiboles exhibited the alignment of [100] axes subnormal to the shear plane (Figure S3). This finding indicates that the girdle distribution of [100] axes of amphibole shown in the type IV CPO was produced due to a mixture of the alignments of [100] axes with different grain sizes.

Type IV CPO of amphibole has been observed in previous studies of natural rocks deformed under high-strain zone and/or mylonitized shear zone in the middle crust (Imon et al., 2004; Lamarque et al., 2016; Tatham et al., 2008), fault block area (Ji et al., 1993), and plate convergence zone (Aspiroz et al., 2007; Cao et al., 2010), and these natural amphibolites showed a similar finding of a wide range of grain size distribution and/or a small grain size of amphibole in mylonitic rocks to that in our study. For example, Aspiroz et al. (2007) reported type IV amphibole CPO in the El Rellano amphibolite, showing a core-mantle structure. The grain size of the core amphibole in their study was large (400 μm to 2 cm), while the grain size of the mantle part was small (15–400 μm). In the study by Cao et al. (2010), the fine amphibole grains showed a weak girdle distribution of [100] axes, while the amphibole porphyroclasts showed strong [100] axes alignment subnormal to foliation. In the study by Imon et al. (2004), type IV CPOs of amphibole were also observed in samples with a broad spectrum of grain sizes, while type I CPO was observed in the samples with a narrower grain size spectrum. Imon et al. (2004) suggested that the type IV amphibole CPO was produced due to rigid body rotation in the cataclastically flowing fine-grained matrix during cataclastic deformation. This finding is in good agreement with the observations for our samples in this study.

The other CPO types of amphibole (type II and mixed type I + II) were found under low shear strain ($\gamma < 2.1$) in this study. In the samples with low shear strain, localized strain zones were relatively rare and the grain size of amphibole was relatively homogeneous and larger than that in the samples with high shear strain.

| Run No. | $P$ (GPa) | $T$ (°C) | Diff. $\sigma$ (MPa) | $\gamma$ | $\gamma$ (s$^{-1}$) | CPO type | $AV_p$ (%) | Max. $AV_s$ (%) |
|---------|-----------|----------|----------------------|---------|-----------------|----------|------------|----------------|
| JH 117  | 0.5       | 500 ± 30 | 400 ± 20             | 1.9 ± 0.3 | $8.8 \times 10^{-5}$ | II       | 12.5       | 10.7           |
| JH 157  | 0.5       | 590 ± 10 | 240 ± 10             | 2.1 ± 0.6 | $8.0 \times 10^{-5}$ | I + II   | 10.0       | 7.9            |
| JH 104  | 0.5       | 600 ± 35 | 370 ± 20             | 2.5 ± 1.5 | $9.0 \times 10^{-5}$ | I + II   | 5.7        | 5.1            |
| JH 165  | 0.5       | 490 ± 20 | 640 ± 60             | 3.7 ± 1.5 | $9.1 \times 10^{-5}$ | IV like  | 6.7        | 4.5            |
| JH 170  | 0.5       | 500 ± 10 | 240 ± 10             | 4.7 ± 1.6 | $1.4 \times 10^{-4}$ | IV       | 7.1        | 4.8            |
| JH 132  | 0.5       | 580 ± 20 | 130 ± 20             | 3.2 ± 1.6 | $8.5 \times 10^{-5}$ | IV       | 5.8        | 4.4            |
| JH 160  | 0.5       | 590 ± 24 | 160 ± 10             | 3.3 ± 1.5 | $1.7 \times 10^{-4}$ | IV       | 4.5        | 4.8            |
| JH 168  | 0.5       | 695 ± 15 | 230 ± 40             | 3.1 ± 1.2 | $8.7 \times 10^{-5}$ | IV like  | 4.0        | 3.0            |
| JH 124  | 0.5       | 690 ± 20 | 260 ± 30             | 3.5 ± 0.8 | $2.1 \times 10^{-4}$ | IV       | 7.3        | 4.6            |

Note. Diff. $\sigma$ = differential stress; $\gamma$ = shear strain; $\gamma$ (s$^{-1}$) = shear strain rate; $AV_p$ = anisotropy of $P$ wave velocity; Max. $AV_s$ = maximum anisotropy of $S$ wave velocity. CPO type of amphibole.
Types II and III CPOs, which are similar to mixed type I + II, have not been commonly reported in previous studies on natural rocks. In the previous studies that reported the type II or III CPO of amphibole, it was suggested that the dominant deformation mechanisms of amphibole are rigid body rotation (Aspiroz et al., 2007; Cao et al., 2010; Elyaszadeh et al., 2018; Okudaira et al., 2015) and cataclastic flow (Aspiroz et al., 2007). Here we propose a basic process for developing CPOs of amphibole at the pressure of middle crust ($P \approx 0.5$ GPa). During the early stage of deformation ($\gamma < 3.0$), the largest planes of amphibole single crystal, (110) planes, aligned subparallel to the shear plane and [100] axes aligned subnormal to the shear plane and then the longest axes of amphibole, [001] axes, aligned subparallel to the shear direction through rigid body rotation of amphibole in cataclastic flow. When the amphibole is further deformed ($\gamma > 3.0$), grain size decreases, and (110) planes and [100] axes dispersed along the direction subnormal to shear direction (type IV) by rigid body rotation during cataclastic flow.

### 4.3. Implications for Seismic Velocity and Seismic Anisotropy

The velocities of $P$ waves ($V_p$) and the fastest $S$ waves ($V_{s1}$) passing through the [100] axes of hornblende are 6.10 and 3.40 km/s, respectively (Ko & Jung, 2015; Weiss et al., 1999), which are 85% ($V_p$), 78% ($V_{s1}$) and 77% ($V_p$), 79% ($V_{s1}$) of the velocities through [010] axes and [001] axes of hornblende, respectively. Therefore, the orientation of the [100] axes of hornblende, whose seismic velocities are significantly slower than those of other axes, is critically important in determining seismic anisotropy of hornblende. While the [100] axes of the CPO types I, II, and III of amphibole were aligned subnormal to the shear plane (Ko & Jung, 2015), the [100] axes of the type IV CPO were distributed as a girdle subnormal to the shear direction.

The seismic velocities and anisotropy of the representative samples in this study are shown in Figure 3. The samples showing type IV CPO produced $P$ wave anisotropies of 4.0–7.3% and maximum $S$ wave anisotropies of 2.7–4.8% (Figure 3a and Table 1). These seismic anisotropies are much lower than those of type II and mixed type I + II CPOs (Figure 3a) and many other crustal rocks (e.g., Almqvist & Mainprice, 2017; Ji et al., 2015). Our data indicate that the type IV CPO of hornblende, which is produced in a high-strain zone in the midcrust ($P \approx 0.5$ GPa), will induce a weak seismic anisotropy. In fact, in many previous studies, this weak seismic anisotropy was observed in the midcrust (about 5- to 20-km depths), while strong seismic anisotropy was observed in the lower crust (Lamarque et al., 2016; Ozacar & Zandt, 2004; Savage, 1998; Sherrington et al., 2004). For example, Lamarque et al. (2016) reported a weak seismic anisotropy in the crust under the Mertz shear zone, East-Antarctica. Although they attributed this weak anisotropy to low contents of amphibole and biotite, some amphibolite facies samples in their study showed high proportion of amphibole (up to 55%). Our finding of type IV CPO could be invoked to explain this weak seismic anisotropy in the shear zone.

The polarization directions of the fast $S$ waves ($V_{s1}$) for horizontal flow (Figure 3a) are subparallel to the shear direction but are mostly aligned subnormal to the shear direction if the flow dips at an angle of 30° (Figure S5) or more (Figures 3b and S6). This $V_{s1}$ polarization direction, which is aligned subnormal to the shear direction, can contribute to the trench-parallel seismic anisotropy of $S$ wave in the subduction zones observed in the world (Eberhart-Phillips & Reyners, 2009; Huang et al., 2011; Long, 2013; Wölbern et al., 2014). Similar results for $S$ wave anisotropy were reported for the types I, II, and III CPOs of hornblende based on the deformation experiments of amphibolite at a pressure of 1 GPa (Ko & Jung, 2015), which corresponds to a depth of approximately 30 km. In this study, we showed that the type IV CPO of amphibole can also produce a similar trench-parallel seismic anisotropy at the midcrust depth ($P = 0.5$ GPa), which indicates that all the CPO types of hornblende found to date ($P = 0.5$–1.0 GPa) show a trench-parallel seismic anisotropy. This observation verifies the suggestion of Ko and Jung (2015) that amphibole produces significant delay times with trench-parallel seismic anisotropy in subduction zones.

The other minerals in amphibolite, such as plagioclase, mica, and other major minerals in crustal rocks, such as quartz and alkali feldspar, should also be considered to investigate seismic features in the crust. Although plagioclase, alkali feldspar, and quartz are very abundant in the crust (Almqvist & Mainprice, 2017; McLennan & Taylor, 1999; Nesbitt & Young, 1984; Ronov, 1967), they showed very weak seismic anisotropy in previous studies due to their weak CPO strength (Tatham et al., 2008). Mica and clay minerals are elastically very anisotropic minerals in the crust (Almqvist & Mainprice, 2017). Although they are scarce in the middle to lower crust, they can strongly influence seismic anisotropy (Almqvist & Mainprice, 2017;
Lloyd et al., 2009; Lloyd et al., 2011; Mahan, 2006; Meissner et al., 2006; Shapiro et al., 2004). It is reported that [001] axes of mica are usually aligned normal to foliation and/or shear plane (e.g., Ji et al., 2015). This CPO of mica induces the lowest direction of $V_p$ and $AV_s$ aligned normal to the foliation, which is similar case for the types I, II, and III CPOs of amphibole. Thus, if mica is considered in amphibolite, seismic anisotropy ($AV_p$ and $AV_s$) will be slightly larger, but the directional components of seismic waves (directions of the fastest/slowest $P$ waves and the maximum/minimum $AV_s$) would be similar to that of amphibole alone.

5. Conclusion

The genesis of a new CPO (type IV) of amphibole was investigated by conducting shear deformation experiments on amphibolite under 0.5 GPa pressure and 500–700 °C temperatures. The type IV CPO of amphibole is characterized with [100] axes forming a girdle subnormal to the shear direction and was found under high shear strain ($\gamma > 3.0$), pressure (0.5 GPa), and temperature (500–700 °C) conditions. The girdle distribution of the [100] axes of amphibole was caused due to a wide range of grain size and/or a small grain size. On the other hand, the type II CPO was found under low shear strain ($\gamma < 3.0$) and temperature (500 °C) conditions, and the mixed CPO type I + II was found under intermediate shear strain ($\gamma \approx 2.5$) and temperature (600 °C) conditions. The type IV CPO of hornblende showed very weak seismic anisotropies of the $P$ wave ($AV_p = 4.0–7.3\%$) and maximum $S$ wave ($AV_s = 2.7–4.8\%$). However, the type II CPO of amphibole showed the strongest $P$ wave (12.5%) and maximum $S$ wave (10.7%) anisotropies. The reason for weak seismic anisotropy in the type IV CPO of amphibole compared with other CPO types is the distribution of the [100] axes of amphibole as a girdle subnormal to the shear direction. This remarkably weak seismic anisotropy of the type IV CPO of amphibole may be important for interpreting low seismic anisotropy in localized zones of the middle crust.

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References

Aleksandrov, K., & Rybsova, T. (1961). The elastic properties of rock forming minerals, pyroxenes and amphiboles. Bull. Acad. Sci. USSR Geophys. Ser., 87(1875), 1339–1344.

Allison, I., & Tour, T. E. L. (1977). Brittle deformation of hornblende in a mylonite: A direct geometrical analogue of ductile deformation by translation gliding. Canadian Journal of Earth Sciences, 14(8), 1953–1958. https://doi.org/10.1139/e77-166

Almqvist, B. S., & Mainprice, D. (2017). Seismic properties and anisotropy of the continental crust: Predictions based on mineral texture and rock microstructure. Reviews of Geophysics, 55, 367–433. https://doi.org/10.1002/2016RG000552

Aspinor, M. D., Lloyd, G., & Fernández, C. (2007). Development of lattice preferred orientation in clinoamphiboles deformed under low pressure–metamorphic conditions. A SEM/EBSD study of metabasites from the Aracena metamorphic belt (SW Spain). Journal of Structural Geology, 29(4), 629–645. https://doi.org/10.1016/j.jsg.2006.10.010

Babaei, H. A., & La Tour, T. E. (1994). Semicrystal and cataclastic deformation of hornblende-quartz rocks in a ductile shear zone. Tectonophysics, 229(1–2), 19–30. https://doi.org/10.1016/0040-1951(94)90003-5

Bachmann, F., Hielscher, R., & Schaeben, H. (2010). Texture analysis with MTEX—free and open source software toolbox, paper presented at Solid State Phenomena. Trans Tech Publ.

Barruol, G., & Kern, H. (1996). Seismic anisotropy and shear-wave splitting in lower crustal and upper-mantle rocks from the Ivrea Zone—Experimental and calculated data. Physics of the Earth and Planetary Interiors, 95(3–4), 175–194.

Berg, A., & Stünitz, H. (1996). Deformation mechanisms and reaction of hornblende: Examples from the Bergell tonalite (Central Alps). Tectonophysics, 257(2–4), 149–174. https://doi.org/10.1016/0040-1951(95)00125-5

Bonin, M., Barruol, G., & Bokelmann, G. H. (2010). Upper mantle deformation beneath the North American–Pacific plate boundary in California from SKS splitting. Journal of Geophysical Research Solid Earth, 115, B04306. https://doi.org/10.1029/2009JB006438

Brown, J. M., & Abramson, E. H. (2016). Elasticity of calcium and calcium–sodium amphiboles. Physics of the Earth and Planetary Interiors, 261, 161–171. https://doi.org/10.1016/j.pepi.2016.10.010

Burg, J.-P., Arbaret, L., Chaudhry, N., Dawood, H., Hussain, S., & Zeilinger, G. (2005). Shear strain localization from the upper mantle to crustal and upper-mantle rocks from the Ivrea Zone—Experimental and calculated data. Physics of the Earth and Planetary Interiors, 95(3–4), 175–194.

Caio, S., Liu, J., & Leiss, B. (2010). Orientation-related deformation mechanisms of naturally deformed amphibole in amphibolite mylonites from the Diancang Shan, SW Yunnan, China. Journal of structural geology, 32(5), 606–622. https://doi.org/10.1016/j.jsg.2010.03.012

Crampin, S. (1981). A review of wave motion in anisotropic and cracked elastic-media. Wave motion, 3(4), 343–391. https://doi.org/10.1016/0165-2125(81)90026-3

Eberhart-Phillips, D., & Reynolds, M. (2009). Three-dimensional distribution of seismic anisotropy in the Hikurangi subduction zone beneath the central North Island, New Zealand. Journal of Geophysical Research Solid Earth, 114(B6), B06301. https://doi.org/10.1029/2008JB005947

Elyaszadeh, R., Prior, D. J., Sarkarinejad, K., & Mansouri, H. (2018). Different slip systems controlling crystallographic preferred orientation and intracrystalline deformation of amphibole in mylonites from the Neyriz mantle diapir, Iran. Journal of Structural Geology, 107, 38–52. https://doi.org/10.1016/j.jsg.2017.11.020

Getzinger, A., & Hirth, G. (2014). Amphibole fabric formation during diffusion creep and the rheology of shear zones. Geology, 42(6), 535–538. https://doi.org/10.1130/G35327.1
Gertsinger, A., Hirth, G., Stünitz, H., & Goergen, E. (2013). Influence of water on rheology and strain localization in the lower continental crust. *Geochimica, Geophysics, Geosystems*, 14, 2247–2264. https://doi.org/10.1002/2013GC005200

Gorbachev, F., Golovataya, O., Echenko, V., Smirnov, Y. P., Kern, H., Popp, T., et al. (2002). Elastic properties of Kola overdeep borehole (SG-3) samples determined under atmospheric and in situ conditions. *Izvestiya-Physics of the Solid Earth*, 38(7), 576–584.

Hacker, B. R., & Christie, J. M. (1990). Brittle/ductile and plastic/cataclastic transitions in experimentally deformed and metamorphosed amphibolite. *Geophysical Monograph*, 56, 127–147.

Huang, Z., Zhao, D., & Wang, L. (2011). Shear wave anisotropy in the crust, mantle wedge, and subducting Pacific slab under northeast Japan. *Geochemistry, Geophysics, Geosystems*, 12(1).

Immon, R., Okudaira, T., & Kanagawa, K. (2004). Development of shape-and lattice-preferred orientations of amphibole grains during initial cataclastic deformation and subsequent deformation by dissolution–precipitation creep in amphibolites from the Ryoke metamorphic belt, SW Japan. *Journal of Structural Geology*, 26(5), 793–805.

Ji, S., Salisbury, M. H., & Hammer, S. (1993). Petrofabric, P-wave anisotropy and seismic reflectivity of high-grade tectonites. *Tectonophysics*, 222, 195–226.

Ji, S., Shao, T., Michibayashi, K., Long, C., Wang, Q., Kondo, Y., et al. (2013). A new calibration of seismic velocities, anisotropy, fabrics, and elastic moduli of amphibole-rich rocks. *Journal of Geophysical Research: Solid Earth*, 118, 4699–4728.

Ji, S., Shao, T., Michibayashi, K., Oya, S., Satsukawa, T., Wang, Q., et al. (2015). Magnitude and symmetry of seismic anisotropy in mica-and amphibole-bearing metamorphic rocks and implications for tectonic interpretation of seismic data from the northeast Tibetan Plateau. *Journal of Geophysical Research: Solid Earth*, 120(9), 6404–6430.

Jung, H. (2017). Crystal preferred orientations of olivine, orthopyroxene, serpentine, chloride, and amphibole, and implications for seismic anisotropy in subduction zones: A review. *Geosciences Journal*, 21(6), 985–1011.

Kern, H., Popp, T., Gorbachev, F., Zharikov, A., Lobanov, K., & Smirnov, Y. P. (2001). Pressure and temperature dependence of Vp and Vs in rocks from the superdeep well and from surface analogues at Kola and the nature of velocity anisotropy. *Tectonophysics*, 338(2), 113–134.

Kern, H., & Schmidt, R. (1990). Physical properties of KTB core samples at simulated in situ conditions. *Scientific Drilling*, 4(5), 217–223.

Ko, B., & Jung, H. (2015). Crystal preferred orientation of an amphibole experimentally deformed by simple shear. *Nature communications*, 6.

Kong, F., Wu, J., Liu, K. H., & Gao, S. S. (2016). Crustal anisotropy and ductile flow beneath the eastern Tibetan Plateau and adjacent areas. *Earth and Planetary Science Letters*, 442, 72–79.

Lamarque, G., Bascou, J., Maurice, C., Cottin, J.-Y., Riel, N., & Ménat, R.-P. (2016). Microstructures, deformation mechanisms and seismic properties of a Palaeoproterozoic shear zone: The Mertz shear zone. *Antarctica*, 680, 174–191.

Llana-Fáñez, S., & Brown, D. (2012). Contribution of crystallographic preferred orientation to seismic anisotropy across a surface analog of the continental Moho at Cabo Ortegal, Spain. *Geological Society of America Bulletin*, 124(9–10), 1495–1513.

Lloyd, G. E., Butler, R. W., Casey, M., & Mainprice, D. (2009). Mica, deformation fabrics and the seismic properties of the continental crust. *Earth and Planetary Science Letters*, 280(1–2), 320–328.

Lloyd, G. E., Butler, R. W. H., Casey, M., Tatham, D., & Mainprice, D. (2011). Constraints on the seismic properties of the middle and lower continental crust. *Geological Society, London, Special Publications*, 360(1), 7–32.

Long, M. D. (2013). Constraints on subduction geodynamics from seismic anisotropy. *Reviews of Geophysics*, 51, 76–112.

Mahan, K. (2006). Retrograde mica in deep crustal granulites: Implications for crustal seismic anisotropy. *Geophysical research letters*, 33(24).

Mainprice, D., & Nicolas, A. (1989). Development of shape and lattice preferred orientations: Application to the seismic anisotropy of the lower crust. *Journal of Structural Geology*, 11(1–2), 175–189.

McLennen, S. M., & Taylor, S. R. (1999). Earth's continental crust. *Encyclopedia of Geochemistry*, 712.

Meissner, R., Rabbel, W., & Kern, H. (2006). Seismic laminar and anisotropy of the lower continental crust. *Tectonophysics*, 416(1–4), 81–99.

Moschetti, M., Ritzwoller, M., Lin, F., & Yang, Y. (2010). Seismic evidence for widespread western-US deep-crustal deformation caused by extension. *Nature*, 464(7290), 885–889. https://doi.org/10.1038/nature08951.

Nesbitt, H. W., & Young, G. (1984). Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. *Geochemistry, Geophysics, Geosystems*, 48(7), 1523–1534.

Nyman, M. W., Law, R. D., & Smelik, E. A. (1992). Cataclastic deformation mechanism for the development of core-mantle structures in amphibole. *Geology*, 20(5), 455–458.

Okudaira, T., Jelibe, P., Stünitz, H., & Fusselis, F. (2015). High-temperature fracturing and subsequent grain-size-sensitive creep in lower crustal gabbros: Evidence for coseismic loading followed by creep during decaying stress in the lower crust? *Journal of Geophysical Research: Solid Earth*, 120, 3139–3141.

Ozacier, A. A., & Zandt, G. (2004). Crustal seismic anisotropy in central Tibet: Implications for deformational style and flow in the crust. *Geophysical Research Letters*, 31, L23601. https://doi.org/10.1029/2004GL021096

Ozacier, A. A., & Zandt, G. (2009). Crustal structure and seismic anisotropy near the San Andreas Fault at Parkfield, California. *Geophysical Journal International*, 178(2), 1098–1104.

Pearce, M. A., Wheeler, J., & Prior, D. J. (2011). Relative strength of mafic and felsic rocks during amphibolite facies metamorphism and deformation. *Journal of Structural Geology*, 33(4), 662–675.

Ronov, A. (1967). Chemical structure of the Earth's crust. *Geokhimiya*, 11, 1285–1309.

Rutter, E., Brodie, K., James, T., & Burlini, L. (2007). Large-scale folding in the upper part of the Ireea-Verbano zone, NW Italy. *Journal of Structural Geology*, 29(1), 1–17.

Savage, M. K. (1998). Lower crustal anisotropy or dipping boundaries? Effects on receiver functions and a case study in New Zealand. *Journal of Geophysical Research Solid Earth*, 103, 15069–15087.

Shapirio, N. M., Ritzwoller, M. H., Molnar, P., & Levin, Y. (2004). Thinning and flow of Tibetan crust constrained by seismic anisotropy. *Science*, 305(5681), 233–236. https://doi.org/10.1126/science.1098276.

Sherrington, H. F., Zandt, G., & Frederiksen, A. (2004). Crustal fabric in the Tibetan Plateau based on waveform inversions for seismic anisotropy parameters. *Journal of Geophysical Research Solid Earth*, 109.

Siegesmund, S., Takeshita, T., & Kern, H. (1989). Anisotropy of Vp and Vs in an amphibolite of the deeper crust and its relationship to the mineralogical, microstructural and textural characteristics of the rock. *Tectonophysics*, 57(1–3), 25–38.

Tatham, D., Lloyd, G., Butler, R., & Casey, M. (2008). Amphibole and lower crustal seismic properties. *Earth and Planetary Science Letters*, 267(1), 118–128.
Weiss, T., Siegesmund, S., Rahbel, W., Bohlen, T., & Pohl, M. (1999). Seismic velocities and anisotropy of the lower continental crust: A review. *Seismic Exploration of the Deep Continental Crust*, 97-122.

Wenning, Q. C., Almqvist, B. S., Hedin, P., & Zappone, A. (2016). Seismic anisotropy in mid to lower orogenic crust: Insights from laboratory measurements of $V_p$ and $V_s$ in drill core from central Scandinavian Caledonides. *Tectonophysics*, 692, 14–28.

Wölbern, I., Löbl, U., & Rümpker, G. (2014). Crustal origin of trench-parallel shear-wave fast polarizations in the Central Andes. *Earth and Planetary Science Letters*, 392, 230–238.

References From Supporting Information

Birch, F. (1960). The velocity of compressional waves in rocks to 10 kilobars: 1. *Journal of Geophysical Research*, 65(4), 1083–1102. https://doi.org/10.1029/JZ065i004p01083

Mainprice, D. (1990). A FORTRAN program to calculate seismic anisotropy from the lattice preferred orientation of minerals. *Computers & Geosciences*, 16(3), 385–393.