B-type olivine fabric and mantle wedge serpentinization beneath the Ryukyu arc

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[1] Subduction is a fundamental Earth process, yet many aspects of subduction systems remain to be fully understood. Here we present anisotropic receiver function (RF) analysis to characterize the structure of the mantle wedge beneath the Ryukyu subduction zone. Radial and transverse P-to-S RFs computed for eight broadband stations yield evidence for coherent P-to-SV conversions originating at the top of the subducting slab. We also observe conversions on the transverse component RFs that are consistent with the presence of multiple anisotropic layers, with structure varying significantly along strike. Forward modeling of observations at station ZMM in the center of the Ryukyu arc yields evidence for a ~6 km thick layer of strongly anisotropic material, most likely serpentinite, directly above the subducting slab and likely B-type olivine fabric in the shallow mantle wedge. Citation: McCormack, K., E. A. Wirth, and M. D. Long (2013), B-type olivine fabric and mantle wedge serpentinization beneath the Ryukyu arc, Geophys. Res. Lett., 40, doi:10.1002/grl.50369.

1. Introduction

[2] Many aspects of mantle dynamics in subduction systems remain poorly understood, including mantle flow and wedge hydration, but we have the ability to interrogate the dynamics and composition of the mantle wedge through the study of seismic anisotropy. Seismic anisotropy in the upper mantle is largely controlled by the lattice-preferred orientation of mantle minerals due to strain accumulation during mantle flow [e.g., Karato et al., 2008]. Consequently, if we can determine the orientation of anisotropy via seismologic observations, we can infer the likely flow geometry. The anisotropic characteristics of the mantle can also provide information regarding composition and degree of hydration, because hydrous minerals tend to have large intrinsic anisotropies [e.g., Mainprice and Ildefonse, 2009]. A more precise understanding of the spatial distribution of hydrous phases within subduction zone mantle wedges can yield important insights into the transportation, storage, and release of water in subduction systems.

[3] Seismic anisotropy in the mantle wedge is often interrogated through shear wave splitting of local *S* phases originating

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within the subducting slab [e.g., *Smith et al.*, 2001; *Nakajima and Hasegawa*, 2004; *Long and van der Hilst*, 2006]. Shear wave splitting is a path-integrated measurement, however, and it cannot constrain the depth distribution of anisotropy. Teleseismic receiver function analysis can provide constraints on anisotropic structure that are complementary to those obtained with shear wave splitting, such as the depth to anisotropic layers and the orientation of nonhorizontal axes of symmetry [e.g., *Park et al.*, 2004; *Shiomi and Park*, 2008; *Nikulin et al.*, 2009; *Wirth and Long*, 2012].

[4] A *P*-wave encountering a sharp impedance contrast at depth will convert to an SV-wave, which is recorded on the radial component of a receiver function (RF). A P-wave encountering a dipping interface, anisotropy, or a point scatterer will have an additional SH component of motion on the transverse component [e.g., Levin and Park, 1998; Bostock, 1998; Jones and Phinney, 1998]. Detailed analysis of transverse component RFs can distinguish among potential causes of SH motion. For example, a dipping interface yields a twolobed polarity flip (that is, two polarity reversals within the full backazimuthal range), with SH energy disappearing at backazimuths parallel to the dip of the interface [Bostock, 1998]. Alternatively, P-to-SH converted phases due to flat layers of anisotropy with a horizontal symmetry axis exhibit a four-lobed polarity flip, with SH energy disappearing at backazimuths parallel and perpendicular to the symmetry axis [Levin and Park, 1998].

[5] Previous shear wave splitting studies in Ryukyu have reported strong mantle wedge anisotropy, with delay times of ~1 s [e.g., Long and van der Hilst, 2006; Nakamura and Yamamoto, 2009]. The subducting slab beneath the stations used in these studies is relatively shallow (~40 km) [Syracuse and Abers, 2006], and accruing a shear wave splitting delay time of ~ 1 s would require the presence of strong anisotropy. Measured fast directions are predominantly trench-parallel, contrary to what would be expected for A-, C-, or E-type olivine fabric and 2-D corner flow. Many models have been proposed to explain trench-parallel fast splitting directions in the mantle wedge, including trench-parallel flow [e.g., Smith et al., 2001; Abt et al., 2009], the presence of B-type olivine fabric [e.g., Nakajima and Hasegawa, 2004; Long and van der Hilst, 2006; Kneller et al., 2008], crustal foundering [Behn et al., 2007], and the hydration of the mantle wedge to form serpentinite minerals [e.g., Katayama et al., 2009; Jung, 2011].

[6] The goal of the work presented here is to use anisotropic RF analysis to differentiate among these competing hypotheses. We present *P*-to-*S* receiver functions for eight stations of the broadband F-net array located on the Ryukyu Islands (Figure 1). We discuss forward modeling results that determined a preferred model for mantle wedge structure beneath the central part of the Ryukyu arc, allowing us to place constraints on the depth to anisotropic layers and nonhorizontal

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Figure 1. Map of the Ryukyu arc showing the topography and location of seismic stations (red inverted triangles) used in this study. Solid black line denotes the trench location and dashed lines represent the 50 km slab contours [*Syracuse and Abers*, 2006]. The white arrow indicates the direction of absolute plate motion for the Philippine Sea plate.

anisotropic symmetry axes. Finally, we examine how these new constraints on mantle wedge structure and anisotropy yield insight into the dynamics of mantle flow and wedge hydration in the Ryukyu subduction system.

2. Data and Methods

[7] Stations used in this study (Figure 1) are part of the F-net array and are maintained by Japan's National Institute for Earth Science and Disaster Prevention. Our data processing procedures are identical to those used by Wirth and Long [2012] to examine F-net stations in northeastern Japan; we briefly summarize our methodology here. For each station, we compiled 500+ events (see Figure S1 in the auxiliary material) with magnitudes ≥ 6.0 at epicentral distances of $20-100^{\circ}$ to ensure a nearly vertical incidence angle. We used the multitaper receiver function estimator of Park and Levin [2000] to compute RFs in the frequency domain. All records were low-pass filtered at 1 Hz. At each station, we gathered and stacked individual RFs in overlapping 20° backazimuthal intervals with a 10° bin spacing and plotted them as a function of time. A zero time delay corresponds to the arrival of the direct P-wave, and a nonzero delay time represents the difference in arrival time between the direct P-wave and a P-to-S conversion at the seismic station. Positive pulses (blue) indicate a velocity increase with depth and negative pulses (red) indicate a velocity decrease with depth.

3. Results

[8] We divided the stations into three groups based on geographic location. Northern stations (TKO, TAS, and KYK) are located near the northern edge of the subducting slab, central stations (AMM, KGM, and ZMM) are located in the middle of the island arc, and southern stations (IGK and YNG) are near the southernmost edge of the subducting Philippine Sea plate, close to the island of Taiwan. Representative examples of radial and transverse receiver function gathers for each geographical region are shown in Figure 2; other stations are shown in Figures S2–S6.

[9] There are a number of features that are coherent in all or most of our radial RF gathers. Arriving ~2-3 s after the direct *P*-wave, a pulse of positive polarity (representing a sharp velocity increase with depth) can be seen across nearly the full backazimuthal range. This is likely a P-to-S conversion at the Moho of the overriding plate, and the delay time matches what we would expect for a crustal thickness of 28 km and assuming $V_P = 6.1$ km/s and $V_P/V_S = 1.7$ [Iwasaki, 1990; Kodaira et al., 1996; Nakamura and Yoshida, 2003]. We also see a positive pulse at \sim 6–8 s that exhibits considerable moveout with backazimuth. The absolute arrival time of this pulse, and its variation with backazimuth, is consistent with an interface dipping to the north or northwest, and is likely associated with a P-to-S conversion at the subducting oceanic Moho. The prominence of the conversions from these two wellestablished structures-the overriding plate Moho and the subducting oceanic Moho-lends confidence to our methods and results [Wirth and Long, 2012]. Several stations show a prominent negative pulse at ~4-6 s that precedes the positive pulse associated with conversions at the subducting oceanic Moho. Such negative pulses may be associated with the top of a low velocity layer.

[10] Transverse component RFs, except for station TKO (the northernmost station), exhibit generally similar patterns within individual geographic regions in the time interval between ~4–7 s (when we would expect to see arrivals from structure at or immediately above the slab interface). For instance, the three central stations (AMM, KGM, and ZMM; Figures 2, 3 and S4–S5) all have similar features on the transverse component between ~4–7 s, including a clear polarity reversal at ~6 s and a backazimuth of ~150° due to the dip of the downgoing slab. The two southernmost stations (YNG and IGK; Figures 2 and S6) have more complex transverse components, but still show a clear polarity reversal at ~6 s for backazimuths aligned with the updip direction of the slab (~180°). Conversions associated with shallower features exhibit much more along-strike variability.

4. Forward Modeling

[11] Visual inspection of our receiver function gathers can provide helpful insight, but we can place more quantitative constraints on mantle wedge properties by comparing synthetic RFs to actual data. We generated synthetic seismograms using the RAYSUM wave propagation code that allows for both dipping interfaces and anisotropic structure [Frederiksen and Bostock, 2000], initially using one representative slowness value (Figure S7) to test synthetic models, but ultimately applying the actual station-event geometry to the synthetic data set. We focused on creating a best-fit model for wedge structure beneath central Ryukyu station ZMM (Figure 3), due to its coherent P-to-S conversions on both horizontal components and its location in the central part of the subduction zone, away from the slab edge. Due to potential problems arising from forward modeling with steep interfaces documented by Frederiksen and Bostock [2000], we use a dip of 25° in our forward modeling. In reality, the dip of the subducting slab is closer to ~40-45° [Syracuse and Abers, 2006]. We focus

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Figure 2. Receiver function backazimuthal gathers for northern station TAS, central station KGM, and southern station IGK. RFs are binned and stacked by backazimuth (vertical axis) and plotted as a function of time (horizontal axis), with zero time delay representing the arrival of the direct *P*-wave. The green curves represent the estimated arrival time of a *P*-to-*S* conversion at the top of the subducting slab beneath each station. For station TAS, this corresponds to an interface at 65 km depth with a strike of 190° and a 55 dip°; for station KGM, an interface at 40 km depth with a strike of 210° and a 45° dip; for station IGK, an interface at 45 km depth with a strike of 230° and a 45° dip.

on matching receiver function features that can be attributed to structure in the mantle wedge, and therefore do not focus on crustal structure or structure in the subducting oceanic plate. We also emphasize that one of the most reliable inferences from anisotropic receiver function analysis is the orientation of the anisotropic symmetry axis, as transverse component polarity reversals due to anisotropy are not subject to tradeoffs with parameters such as layer thickness and isotropic velocities. However, we note that the strength of anisotropy is more difficult to constrain (auxiliary material). Although a full waveform inversion would be ideal, the complexity of the data makes such an approach difficult, and instead we focus on constraining a few parameters using forward modeling.

[12] We started with a simple, isotropic four-layer model (overriding plate, wedge mantle, subducting oceanic crust, and subducting oceanic lithosphere), and added additional layers and/or anisotropy only when required to match major features in the data. Our trial-and-error modeling procedure closely follows that used by *Wirth and Long* [2012]. While our starting isotropic model matched the radial component receiver functions well, we were unable to match features on the transverse component data that arrive between 3–6 s.



Figure 3. Receiver function backazimuthal gathers computed for station ZMM using actual data (left) and synthetic seismograms (right). Synthetic seismograms were generated from the model shown in Figure 4 and Table 1. RFs are plotted as described in Figure 2. We focus on matching *P*-to-*S* conversions arriving between 2–8 s (unshaded). Colored symbols denote transverse component features that are replicated by our synthetic model (i.e., polarity flip at ~5 s and 130°, yellow triangle; convergence of positive pulses at ~4 s and ~230°, orange star; polarity flip at ~5.5 s and ~310°, blue star). Estimated arrival curves (green) are for a *P*-to-*S* conversion from an interface at 45 km depth with a strike of 210° and a dip of 45°.

We added a layer of anisotropy in the wedge mantle with a trench-parallel fast symmetry axis, as inferred from previous studies [e.g., Long and van der Hilst, 2006; Nakamura and Yamamoto, 2009]. Although this feature improved the fit, we were unable to identify a combination of anisotropy parameters for the wedge mantle portion of our model that allowed us to reproduce all the transverse component features. However, the addition of a 6 km thick super-slab layer with strong anisotropy (10%) and a slow axis of symmetry oriented perpendicular to the slab interface provided a good fit to the observations (Figure 3). In particular, this layer correctly predicts the Ps phase polarities at ~4 s and a backazimuth of 0° and 360° , and transverse component features at ~5–7 s. To correctly match the transverse component polarity reversal at ~4 s and a backazimuth of 240°, our model required an additional thin (3 km) anisotropic layer just below the overriding plate Moho with weaker anisotropy (4%) and a roughly trenchparallel fast axis. The emergence of this negative pulse at ~ 4 s and 240° on the transverse component is enhanced by the addition of 8% anisotropy with a roughly trench-parallel fast axis to the central portion of the mantle wedge (layer UM2). While the presence of UM2 does not dramatically alter the resulting synthetic receiver functions, its presence does improve the overall fit to the data. A cartoon sketch of our preferred model is shown in Figure 4.

[13] To assess the robustness of our preferred model, we carried out sensitivity tests to explore how much the parameters in each layer could be perturbed before features in the synthetic RFs no longer matched the data (auxiliary material Figures S8–S10). We found that in general, variations of more than $\sim 10-20^{\circ}$ in the orientation of the symmetry axis or $\sim 4\%$ changes in anisotropy strength degraded the fit to important features in the data. One exception is that if

we allow the uppermost mantle wedge layer to be isotropic (keeping all other model parameters the same) the quality of the fit is similar, so anisotropy in the uppermost wedge layer is not strongly required by the data. A change of more than ~ 2 km in the thicknesses of the layers, especially the layer directly above the slab, has significant adverse effects



Figure 4. Cross-section of our preferred model for station ZMM. Arrows and crosses represent the orientation of the anisotropic symmetry axes, with the latter indicating (nearly) trench-parallel alignment. Model parameters are given in Table 1. Mantle wedge layers are designated UM1-3. We interpret UM1 and UM2 as B-type olivine fabric in the shallow wedge and UM3 as a thin layer of serpentinized mantle above the subducting slab.

Preferred model									
Layer	Thickness (m)	V_P (m/s)	V_S (m/s)	ρ (kg/m ³)	% anisotropy	Trend (°)	Plunge (°)	Strike (°)	Dip (°)
Crust	28000	6700	3900	2800	_	_	_	_	_
UM1	3000	7600	4250	3000	4	40	0	_	_
UM2	9000	7600	4250	3000	8	50	0	220	25
UM3	6000	7800	4200	3200	-10	130	70	220	25
Subducting crust	7000	7300	4050	2900	-6	310	30	220	25
Subducting lithospheric mantle	60000	7900	4500	3200	_	_	_	220	25
	Halfspace	8000	4500	3300	-	_	-	220	25

Table 1. Model Parameters Used to Generate Synthetic Receiver Functions Shown in Figure 3^a

^aModel sketch is shown in Figure 4. Many parameters were held constant or varied very little during the forward modeling process (regular font); parameters that were varied significantly are bolded.

A positive or negative percent anisotropy refers to a fast or slow axis of symmetry, respectively.

Trend refers to the azimuth from north of the anisotropic symmetry axis.

Plunge refers to the dip of the anisotropic symmetry axis, downward from horizontal.

Strike refers to the layer's upper interface, relative to north.

Dip refers to the layer's upper interface, downward from horizontal.

on the quality of the model (auxiliary material). We also experimented with implementing a fast axis of hexagonal symmetry in the superslab layer and were unable to identify any fast axis orientation that fits the observations (most notably the transverse component polarity flips at \sim 3 s at backazimuths of 210° and 300°, and a polarity flip at \sim 4 s at a backazimuth of 240°), suggesting that anisotropy with a slow axis of symmetry is required.

5. Discussion

[14] Our preferred model has important implications for wedge structure and dynamics beneath the central Ryukyu arc. For instance, our model requires a 6 km thick anisotropic layer directly above the slab with a slow symmetry axis and strong $(10 \pm 4\%)$ anisotropy to match the major features seen in actual receiver function data (UM3, Figure 4). Upper mantle anisotropy is usually attributed to the lattice preferred orientation of olivine and is commonly approximated with a fast axis of hexagonal symmetry. Fine-scale horizontal layers or aligned cracks may result in a slow axis of hexagonal symmetry, but it is unclear as to what mechanism would produce these features in the mantle wedge. Our preferred explanation is that a layer of wedge mantle above the subducting slab has undergone serpentinization. Dehydration of the subducting slab and the ensuing hydration of the overlying mantle peridotite may result in serpentinization of wedge material [e.g., Reynard et al., 2007]. The serpentinite stability field requires relatively cool temperatures [e.g., Ulmer and *Trommsdorff*, 1995], and therefore serpentinite may be stable in a layer directly overlying the subducting slab [e.g., Katayama et al., 2009; Bezacier et al., 2013; Saiga et al., 2013] or in the cool corner of the mantle wedge [e.g., Kneller et al., 2008].

[15] We also considered alternative explanations for the highly anisotropic superslab layer in our model. Subducted sediments may provide an alternative explanation for a superslab anisotropic layer with a slow axis of symmetry [e.g., *Savage et al.*, 2007]. However, *Kodaira et al.* [1996] estimated <1 km of sediment on the downgoing plate on the oceanic side of the central Ryukyu arc; this is an unlikely explanation for our thicker superslab layer. High pore fluid pressures may play a role in the observed properties of the subducting oceanic crust [e.g., *Song and Kim*, 2012], resulting in low seismic velocities and high Poisson's ratio

[e.g., *Audet et al.*, 2009] but would not affect our interpretation of the composition of model layer UM3.

[16] Serpentinites have many defining geophysical characteristics that make them distinguishable from other mantle minerals, including strong anisotropy with a slow symmetry axis [e.g., Mainprice and Ildefonse, 2009; Bezacier et al., 2010] and a high V_P/V_S ratio [Watanabe et al., 2007]. Serpentinized mantle may exhibit low seismic velocities [Christensen, 1996], although high-temperature phases such as antigorite exhibit higher velocities than their lower-temperature counterparts (chrysotile and lizardite) [Watanabe et al., 2007]. Additionally, estimates of V_P/V_S may be complicated by the presence of anisotropy [Hacker and Abers, 2012]. The seismologic attributes of serpentinized peridotite are generally consistent with our model's superslab anisotropic layer ($10 \pm 4\%$ anisotropy with a slow symmetry axis, $V_P/V_S = 1.86$; thus, it is a likely explanation for our observations. A serpentinized layer would likely lead to high splitting delay times and trench-parallel fast splitting directions [e.g., Katayama et al., 2009; Jung, 2011], which is consistent with previous studies in Ryukyu.

[17] Our RF analysis also yields evidence for the likely presence of B-type olivine fabric in the mantle wedge (UM1 and UM2, Figure 4). At moderate stresses and temperatures, mineral physics studies suggest that A-type, C-, or E-type olivine fabric likely dominates [Karato et al., 2008]. However, under high-stress, low-temperature conditions with moderate amounts of water, B-type olivine fabric may develop. Unlike, A-, C-, or E-type fabric where the fast splitting direction corresponds to the shear direction, for B-type olivine fabric the fast direction will be perpendicular to the shear direction [Jung and Karato, 2001]. Our preferred model invokes an anisotropic mantle wedge region with a roughly horizontal fast axis of symmetry aligned parallel to the trench; this geometry is consistent with the presence of B-type olivine fabric and sluggish corner flow in the shallow wedge corner beneath Ryukyu, again consistent with previous studies [e.g., Kneller et al., 2008].

[18] Our analysis has yielded precise constraints on the geometry and strength of anisotropy in different parts of the subduction zone wedge beneath Ryukyu. We find evidence for significant variations in anisotropic structure along-strike, which are likely related to changes in mantle flow pattern and/or wedge mineralogy due to local variations in slab structure. Forward modeling of RFs suggests the likely presence of

a serpentinite layer directly above the subducting slab and B-type olivine fabric in the wedge corner. This has important implications for water transport and release in the subduction system, as it suggests that at a depth of ~40 km beneath the central part of the Ryukyu arc, dehydration of the subducting slab releases significant amounts of water that serpentinizes the mantle wedge material directly above the slab. The presence of B-type fabric in the wedge corner also requires the presence of water, likely at a level of several hundred ppm [Karato et al., 2008]. We suggest that future quantitative modeling of the thermal structure and hydrous mineral distribution of the Ryukyu subduction zone and comparison with RF observations will place tighter constraints on the relative contribution of different minerals (hydrous and anhydrous) to the observed anisotropic signal, and may shed additional light on the source of the alongstrike variations in anisotropic structure.

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