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Anisotropy-revealed change in hydration along the Alaska subduction zone

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ABSTRACT

Megathrust earthquake behavior in subduction zones is controlled by a variety of factors including the hydration state of the subducting slab. Increased hydration reduces the occurrence of great, damaging earthquakes by diminishing the strength of the material along the interface between tectonic plates. Understanding variations in hydration in subductions zones is necessary for properly assessing the overall hazard posed by each region. Fortunately, seismic anisotropy is strongly dependent upon hydration of the subducting crust and lithosphere. I present shear-wave splitting measurements that illuminate changes in anisotropy, and therefore hydration, of the subducting Pacific plate beneath the Alaska subduction zone (northern Pacific Ocean). Variations in shear-wave splitting directly correlate to changes in the behavior of great, megathrust earthquakes. My measurements show that the Shumagin seismic gap is characterized by a hydrated subducting slab, explaining the long-term lack of great earthquakes. Observations in the immediately adjacent Semidi segment, which experiences great events regularly, indicate a far less hydrated slab. These results are driven by the preferential alignment of paleo-spreading fabrics of the Pacific plate. Where fabrics are more closely aligned with the orientation of the trench, outer-rise faulting and plate hydration is enhanced. These results highlight the importance of changes in preexisting slab structures and subsequent hydration in the production of great, damaging earthquakes.

INTRODUCTION

The Alaska-Aleutians subduction zone (northern Pacific Ocean) represents the most tectonically and seismically active convergent margin in North America. Seismicity in this subduction zone operates at a variety of spatial and temporal scales, including an abundance of great (M >8), damaging megathrust earthquakes (e.g., Davies et al., 1981; Fournier and Freymueller, 2007). The character and number of seismic events along the length of the subduction zone, however, are highly variable. The Shumagin seismic gap, for example, has not experienced a great megathrust earthquake for the past ~150 yr, while the immediately adjacent Semidi segment ruptures every ~50–75 yr (Fig. 1) (Davies et al., 1981). The Shumagin gap and Semidi segment also exhibit differences in outer-rise and intermediate-depth seismicity, with the Semidi segment experiencing fewer events in both cases (Fig. S1 in the Supplemental Material[1]). While the change in seismic behavior is abrupt, the tectonic characteristics of each region vary minimally between the two areas: the age of the subducting Pacific plate ranges from ca. 50 Ma to ca. 55 Ma (Müller et al., 2008), the slab dip is uniform (Lallemand et al., 2005), the convergence direction is consistent (DeMets et al., 2010), and the upper North American plate is of similar composition (Plafker et al., 1994).

The direction of paleo-spreading, and therefore orientations of tectonic fabrics and preexisting structures, of the incoming Pacific plate is the only feature that shows a sharp along-strike change (Fig. 1). Entrapment of the Kula plate ca. 55 Ma to ca. 40 Ma forced a deviation in the motion of the Pacific plate resulting in an abrupt rotation of the orientation of paleo-spreading near the Semidi-Shumagin boundary (Lonsdale, 1988). Linear fabrics near the Shumagin gap are aligned nearly parallel to the orientation of the trench (within ~10° to ~25°), while fabrics near the Semidi segment are nearly trench perpendicular (~70° from the trench). Changes in seismic behavior have previously been associated with this rotation in paleo-spreading (Shillington et al., 2015). Variable outer-rise seismicity and interplate coupling via differences in slab hydration show the strongest associations with the change in tectonic fabrics (Shillington et al., 2015). Constraining slab hydration is particularly important because it has far-reaching effects. Hydration state plays a role in the prevalence of intermediate-depth earthquakes and variable seismic anisotropy, and greatly impacts the behavior of megathrust earthquakes (e.g., Wada et al., 2008; Shiomi and Park, 2008).

The region surrounding the Shumagin gap and the Semidi segment are of great scientific interest, and it was the target of the recent U.S. National Science Foundation GeoPRISMS–supported Alaska Amphibious Community Seismic Experiment (AACSE) (Abers, 2018; Barcheck et al., 2020). The AACSE was a community-driven amphibious seismic experiment that crossed the plate boundary and included ocean-bottom seismometers (OBSs) on the Pacific and the North American plates as well as land-based stations on Alaskan islands. The AACSE represents significant community investment and resulted in a truly unique data set allowing us to examine both the subduction system as well as the unperturbed incoming Pacific plate. I present shear-wave splitting measurements at AACSE stations that show a sharp change in behavior associated with the boundary between the Shumagin gap and the Semidi segment (Fig. 1; Figs. S2–S4).

Shear-wave splitting is an ideal tool for studying tectonic structures and fabrics as well as the dynamics in a subduction zone (Long and Silver, 2009). Observations of seismic anisotropy, such as measurements of shear-wave splitting, provide direct constraints on patterns of deformation (Karato et al., 2008) and give insights into

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[1]Supplemental Material. Supplemental Tables S1 (individual split measurements), S2 (individual null measurements), and S3 (ocean-bottom station orientations), along with Figures S1–S6 (plots of seismicity in the AACSE region, individual splitting results, particle motions, examples of splitting measurements, station orientations, and earthquakes used in this study). Please visit https://doi.org/10.1130/GEOL.S.14582757 to access the supplemental material, and contact editing@geosociety.org with any questions.

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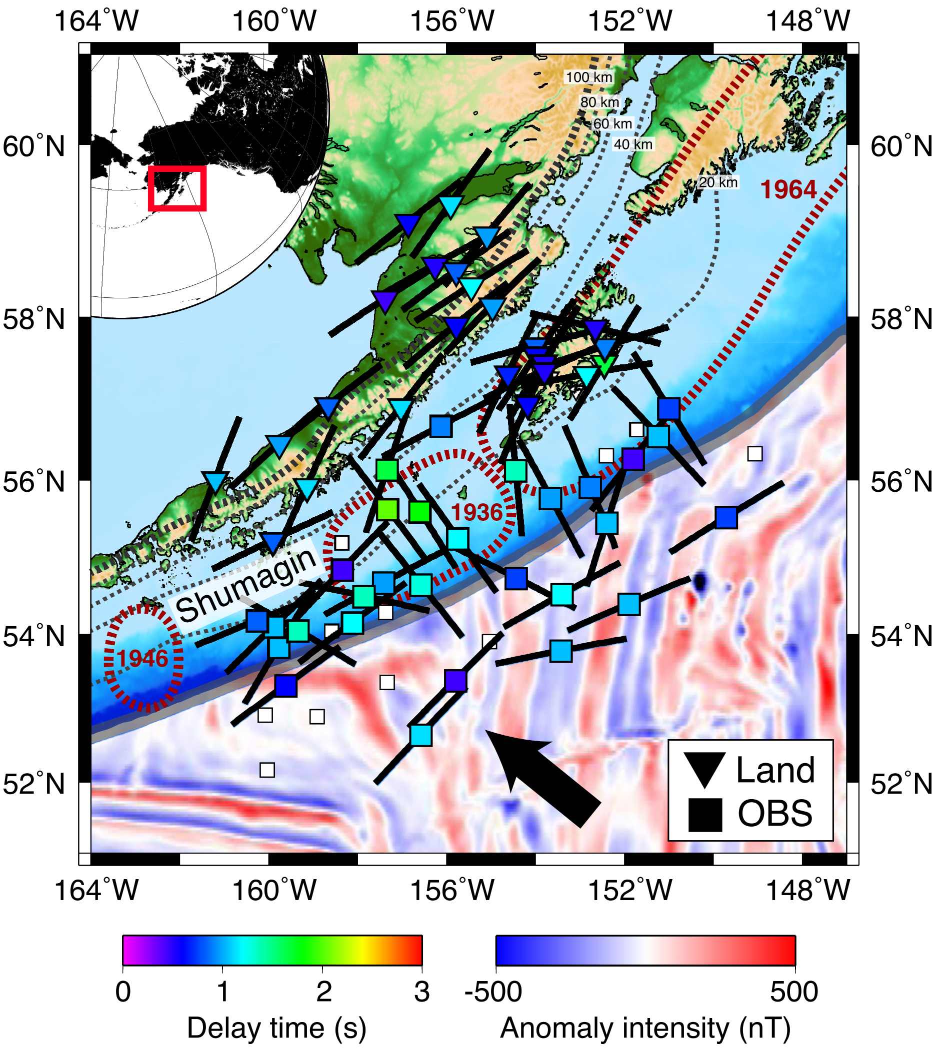

Figure 1. Station-averaged shear-wave splitting at Alaska Amphibious Community Seismic Experiment (AACSE) ocean-bottom seismometer (OBS; squares) and land (triangles) stations. Fast splitting directions are shown as black bars, and delay times are denoted by the color of stations. Stations without splitting measurements are shown in white. Slab contours (dotted lines) are from the Slab2 model (Hayes et al., 2018). Magnetic anomalies on the Pacific plate (blue to red shading; Maus et al., 2009) demonstrate change in paleo-spreading direction. Large arrow shows motion of the Pacific plate (DeMets et al., 2010). Generalized rupture zones of recent great earthquakes are highlighted (red dashed ellipses), labeled with the year (CE) of rupture (Davies et al., 1981). The Shumagin seismic gap is highlighted. The Semidi segment encompasses the region east of the Shumagin gap with large earthquake rupture zones.

structures and hydration state of subducting slabs via variations in the fast direction of anisotropy. My observations show variable Pacific plate tectonic fabrics and preexisting structures play a significant role in slab hydration and the development of seismic anisotropy. These results highlight the influence of hydration and serpentinization on the behavior of the plate interface and help us better understand the factors controlling megathrust earthquake behavior.

DATA AND METHODS

AACSE stations used in this study include 75 broadband OBS instruments and 30 land-based broadband seismometers that were deployed for as long as 15 months between 2018 and 2019. I measured shear-wave splitting of SKS, SKKS, and PKS phases at all of the AACSE stations from earthquakes of $M_w > 5.8$ located 90° to 140° away from each instrument (Fig. S6) using the SplitLab software package (Wüstefeld et al., 2008).

Individual waveforms had their means removed, were detrended, and were bandpass filtered to retain energy between 8 s and 25 s. SplitLab employs two simultaneous shear-wave splitting methodologies: the rotation correlation (Vinnik and Kind, 1993), and the transverse-component minimization (Silver and Chan, 1991) methods. Final reporting of shear-wave splitting measurements (Tables S1 and S2) is from the transverse-component minimization method. Individual splitting measurements must have agreement between both methods. Average errors in fast directions and delay times are ~21° and ~0.4 s, respectively, for the transverse-component minimization and ~27° and ~0.6 s, respectively, for the rotation correlation methods. While errors calculated using the Silver and Chan (1991) methodology may be underestimated in certain situations (Walsh et al., 2013), both methods here show well-resolved measurements. Null shear-wave splitting measurements were based on the linearity of uncorrected particle motions (Wüstefeld and Bokelmann, 2007). In total, I recorded 136 split and 114 null measurements across the AACSE.

Unlike land-based stations, OBS instruments do not have known orientations (Lynner and Bodmer, 2017). Prior to any shear-wave splitting analyses, I determined station orientations using Rayleigh wave (Braunmiller et al., 2020) and P wave (Doran and Laske, 2017) polarization analyses. Orientations calculated from surface waves are better resolved than those from P waves (Fig. S5), so the choice of orientation was based on the Rayleigh wave orientations. Orientations from both methods are provided in Table S3.

RESULTS

AACSE shear-wave splitting results can be broken down into three distinct regions: (1) stations that sample the mantle wedge (the region above the subducting slab and below the overriding plate), (2) stations sitting on the Pacific plate, and (3) stations on the North American plate that are <~30 km above the subducting slab surface (Fig. 2). This last group is sensitive to the interface between the North American and Pacific plates. While the down-dip limit of the interplate contact along the margin is imprecisely known, the ~30 km boundary is consistent with typical upper-plate crustal thicknesses. I have chosen ~30 km based on the behavior of the shear-wave splitting measurements, but this boundary may need to be reevaluated in future studies.

Splitting at stations that sample the mantle wedge is oriented roughly parallel to the trench (Figs. 1 and 2). This pattern persists for both OBS and land stations and encompasses nearly all instruments that sit >~30 km above the slab. Stations located on the Pacific plate also exhibit largely trench-parallel orientations with the exception of those very near the trench. Pacific stations that sit within ~40 km of the trench on the outer rise and those on the North American plate between 0 km and 30 km above the slab (subsequently called outer rise and shallow North American plate [OSNAP] stations) show an abrupt change in splitting along strike from trench-perpendicular orientations at eastern stations to generally trench-parallel orientations at western stations (Figs. 1 and 2). The rapid rotation of fast splitting directions occurs at the boundary between the Semidi segment and the Shumagin gap and is of a similar lateral abruptness.

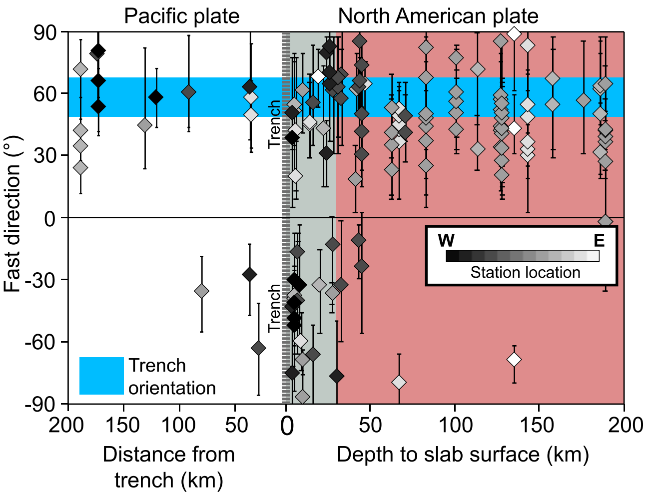

Figure 2. Individual fast shear-wave splitting measurements with associated 2σ errors plotted relative to depth to the surface of the subducting slab. Stations on the Pacific plate are plotted at their distance from trench. Measurements are shaded by longitude. Mantle wedge (red) and outer-rise and shallow North American plate (OSNAP; gray) regions are shaded. Orientation of trench is shown in blue.

DISCUSSION

Splitting beneath both the Pacific plate and mantle wedge regions can be explained by trench-parallel asthenospheric flow (Long and Silver, 2009; Long and Wirth, 2013). Mantle material beneath many subducting slabs (the sub-slab mantle) shows similar trench-parallel orientations (Lynner and Long, 2014). Splitting directions in mantle wedges are typically more complex, but trench-parallel orientations are globally prevalent (Long and Wirth, 2013). Previous measurements in the AACSE region are sparse (Venereau et al., 2019; McPherson et al., 2020), but those that sample the mantle wedge agree well with our results (Fig. S2). Trench-parallel shear-wave splitting in the sub-slab mantle and mantle wedge is likely driven by slab-aligned mantle flow. Many geodynamic models show trench-parallel flow is excited by slab rollback forcing material around slab edges (Faccenda and Capitanio, 2012), such as at the edge of the Pacific slab beneath central Alaska. Furthermore, numerical models aimed specifically at mimicking the Alaska-Aleutians subduction zone have suggested three-dimensional (3-D) toroidal flow exists around the edge of the subducting Pacific slab, consistent with my results (Jadamec and Billen, 2012).

The rotation from broadly trench-perpendicular fast splitting orientations at eastern OSNAP stations to nearly trench-parallel splitting at western OSNAP stations correlates nicely with the change in Pacific plate paleo-spreading direction and the boundary between the Semidi segment and the Shumagin gap (Fig. 1). OSNAP stations with trench-parallel splitting exist where the Pacific plate fabrics are nearly parallel (within ~20° of trench parallel) to the strike of the trench. Where plate fabrics are more trench perpendicular, in the eastern portion of the Alaska-Aleutians subduction zone, OSNAP stations exhibit trench-perpendicular fast splitting directions. Trench-perpendicular splitting is expected for non-hydrated lithosphere the age of the subducting slab (Lynner and Long, 2014). Eastern OSNAP splitting, therefore, likely reflects two-dimensional entrainment of the subjacent mantle following the motion of the Pacific plate. As the slab moves along, it entrains sub-slab mantle material creating plate motion–aligned fast directions. This is consistent with previous source-side splitting measurements in this region (Lynner and Long, 2014). This scenario remains compatible with the trench-parallel flow farther from the slab seen at Pacific plate stations. When 3-D toroidal flow is excited around a slab edge, a layer of mantle coupled to the motion of the subducting slab exists that isolates the slab from the region of trench-parallel flow (e.g., Faccenda and Capitanio, 2012).

Westernmost OSNAP stations, in the Shumagin gap, present trench-parallel splitting orientations that cannot reflect entrainment of the sub-slab mantle which had previously been suggested in the region by source-side splitting measurements (Lynner and Long, 2014). Trench-parallel directions likely originate from increased hydration of the subducting slab. Associated with the along-strike change in tectonic fabrics is an increase in outer-rise seismicity near the Shumagin gap (Fig. S1). Outer-rise seismicity stems from increased faulting, which is the main pathway for hydration of the oceanic crust and lithosphere (Ranero et al., 2003). Increased hydration explains trench-parallel splitting directions by preferentially allowing highly anisotropic serpentine minerals, which require significant hydration (Christensen, 2004), to form in bands aligned with the trench (Faccenda et al., 2008; Healy et al., 2009). Serpentine-derived anisotropy beneath the Shumagin gap may overwhelm the entrainment signal from beneath the slab, thereby producing the observed trench-parallel splitting. This scenario leads to multiple layers of anisotropy beneath western OSNAP stations. Layered anisotropy can be modeled with sufficient back-azimuthal coverage, which is infeasible with the AACSE stations. Longer-running stations on Alaskan islands may be able to provide future constraints on the different potential anisotropic layers within the subduction zone.

The change in along-strike splitting at OSNAP stations suggests the Shumagin gap is sufficiently well hydrated to produce serpentine minerals while the Semidi segment is not. I propose that the change in OSNAP splitting can be attributed to a change in the hydration state of the subducting slab (Fig. 3). Multi-channel seismic results and the relative abundances of intermediate earthquakes further support the assertion that the slab beneath the Semidi segment is less hydrated than the slab beneath the Shumagin gap (Shillington et al., 2015). Variations in slab hydration are ultimately tied to tectonic structures of the Pacific plate. Bending stresses from the outer rise drive faulting and seismicity and follow the shape of the trench as well as preexisting tectonic structures. How the Pacific plate accommodates this bending is dependent upon the preexisting properties of the plate. At the Shumagin gap, where tectonic fabrics are oriented closely to the strike of the trench, bending stresses impact both strong and weak preexisting features, leading to enhanced faulting, seismicity, and hydration. The nearly orthogonal fabrics at the Semidi segment, conversely, allow the majority of bending stresses to be borne by stronger structures, diminishing faulting and hydration along the margin.

Faulting and hydration strongly impact megathrust earthquake behavior by altering the

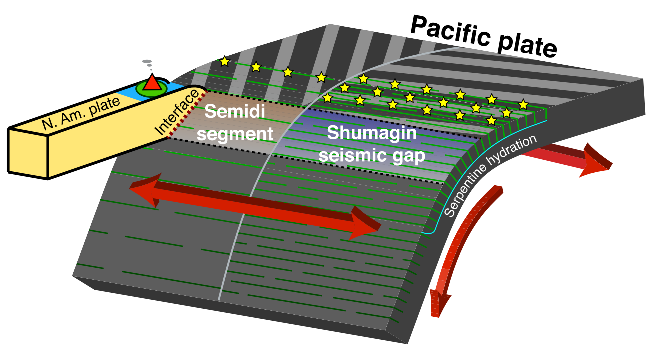

Figure 3. Schematic cartoon of the Alaska-Aleutians subduction zone. Pacific plate stations far from the trench and mantle wedge stations show trench-parallel splitting due to trench-parallel mantle flow (red arrows). Outer-rise and shallow North American plate (OSNAP) stations show changes in splitting due to variations in tectonic fabrics (shaded bands) of the Pacific plate, and the associated changes in outer-rise seismicity (stars) and hydration by serpentine minerals. The change in hydration leads to different properties of the plate interface in the Semidi segment and Shumagin seismic gap. N. Am.—North American.

properties of interplate coupling (Wada et al., 2008). Serpentine minerals are weak and can support limited accrued stresses (Christensen, 2004). While the Shumagin gap exhibits abundant interplate seismicity and several M <6.0 earthquakes, it fails to produce great megathrust events (Fournier and Freymueller, 2007). This follows predictions of enhanced subducting-plate serpentinization where decreased crustal strength along the plate interface prevents the development of sufficient stresses to yield great megathrust events. Other elements of the subduction system, such as slab sedimentation, lithology, stress-induced cracks, and changes in coupling, undoubtedly contribute to along-strike variations in great-earthquake behavior. This work, however, shows that inherited tectonic structures like paleo-spreading directions impact great megathrust earthquakes through outer-rise faulting and hydration. The shear-wave splitting results necessitate changes in hydration of the subducting slab between the relatively dry Semidi segment and the hydrated Shumagin gap. These measurements show how abrupt changes in outer-rise earthquake behavior can lead to abrupt variations in splitting directions and the prevalence of great earthquakes.

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