Sn propagation in the Western United States from common midpoint stacks of USArray data

J. S. Buehler and P. M. Shearer

Received 14 August 2013; revised 19 November 2013; accepted 22 November 2013.

[1] The regional seismic phase Sn propagates horizontally in the uppermost mantle and is sensitive to variations in mantle lid thickness, temperature, and melt. Sn is therefore often used as an indicator for physical properties of the lithosphere. It has previously been noticed that Sn is not observed at many stations in the Western United States and Sn seems especially highly attenuated for paths across the Basin and Range. Here we apply stacking methods to USArray data to identify highly attenuating regions in the uppermost mantle and increase the spatial resolution of the Sn propagation image. We find evidence for Sn propagation at short ranges in the central Great Basin and the northeastern part of the Colorado Plateau, both regions where lithospheric stability and thickness is debated, and observe strong Sn attenuation around the perimeter of the central Great Basin. Citation: Buehler, J. S., and P. M. Shearer (2013), Sn propagation in the Western United States from common midpoint stacks of USArray data, Geophys. Res. Lett., 40, doi:10.1002/2013GL057680.

1. Introduction

[2] We investigate high-frequency propagation of the regional phase Sn in the Western United States. Sn propagates horizontally in the uppermost mantle just below the Moho and is often modeled as a head wave. Sn has been used for velocity and attenuation studies focused on the uppermost mantle [e.g., Diaz et al., 2013; Goek et al., 2003; Pei et al., 2007]. However, Sn has been observed to travel to teleseismic distances across oceanic paths and is more broadly defined as a channel wave that travels in the mantle lid above the low-velocity zone of the upper mantle [Molnar and Oliver, 1969; Stephens and Isacks, 1977]. A waveguide can be formed if the shear wave velocity increases with depth from the Moho to the top of the low-velocity zone. Several factors influence the propagation of Sn, not only the upper mantle shear wave velocity gradient [Stephens and Isacks, 1977] but also the thickness and thermal state of the lithosphere [Beghoul et al., 1993]. Therefore, studies of Sn propagation can be used to help constrain regional tectonic models [e.g., Barron and Priestley, 2009; Beghoul et al., 1993; Calvert et al., 2000; Ni and Barazangi, 1983].

[3] Starting with the USArray station deployment, great efforts have been made to investigate and image lithospheric structure below the Western United States with various data sets and new methods to better understand the tectonic evolution of the continent. Tomographic images from body and surface wave data show very heterogeneous velocity structure in the upper mantle in the Western United States [e.g., Lin et al., 2011; Obrebski et al., 2011; Schmandt and Humphreys, 2010]. Prominent local low-velocity anomalies imaged below the Snake River Plain and the southwestern Colorado Plateau likely reflect higher temperatures due to volcanism. Waves that travel horizontally in the uppermost mantle will be strongly affected by these lateral anomalies. Higher temperatures should also increase seismic attenuation, which will affect Sn more than the P wave analog, Pn, as S wave mantle attenuation is observed to be stronger than P wave attenuation. Generally, Sn traverses well through stable continental regions but is attenuated in more tectonically active regions and Beghoul et al. [1993] concluded in their study on regional phase propagation that Sn does not propagate across the majority of the Western United States. However, Beghoul et al. [1993] also did not observe Sn for paths that cross below the relatively stable Colorado Plateau (Figure 1).

[4] In regions where the mantle lid is thin or missing, as for example through delamination processes that cause local upwelling of the asthenosphere, a process that may explain the elevation of the Colorado Plateau [e.g., Levander et al., 2011], Sn will be strongly attenuated by the hotter material. Studies showed that the lithosphere is relatively thin for large portions of the Western United States: Goes and van der Lee [2002] estimated the lithosphere to be as thin as 50 km below the Basin and Range Province. Beghoul et al. [1993] estimated the mantle lid thickness to be about 20–40 km below the same region (adding a 20–30 km thick crust to compare to lithospheric thickness) and found no evidence for Sn in seismograms for paths that cross the Great Basin. However, more recent tomographic studies that profit from the USArray station network show finer-scale structure and possible drip features in the Great Basin that could locally increase lithospheric thickness [West et al., 2009].

[5] In this study we use the dense USArray transportable network to investigate the propagation of the Sn phase. Previous research showed that at large scales Sn is strongly attenuated in regions west of the Great Plains [Beghoul et al., 1993] (Figure 1). However, we find that there are a number of Sn picks in the database of the Array Network Facility (ANF) for stations west of the Great Plains, and an initial time term analysis with these picks showed that they are viable for tomography, as they produce similar large-scale features as Pn tomography maps. Many of these Sn picks have relatively short epicentral distances (< 6°), suggesting...
that the regions of $Sn$ blockage are similar in scale to the velocity structures observed in the upper mantle.

[6] We apply stacking methods, similar to those employed locally in active source studies, on a regional scale using both earthquakes and quarry blasts, and measure the $Sn$ amplitudes of these stacks at various locations. This allows us to map overall $Sn$ propagation efficiency over large regions and image highly attenuating regions but without the need to inspect individual seismograms or the complications of formal attenuation modeling. We find evidence in our stacks for transmission of $Sn$ below the northwestern portion of the Colorado Plateau, and in the center of the Great Basin, areas that coincide with regions of higher seismic velocities. As expected, we find $Sn$ to be highly attenuated in the belt associated with recent volcanism and high heat flow that surrounds the central portion of the Great Basin and includes the Cascades back-arc, the Snake River Plain, and the southwestern margin of the Colorado Plateau.

2. Methods

[7] $Sn$ is often emergent, buried by $P$ wave coda, and hard to see by eye in individual seismograms. Stacking methods can greatly enhance such weak arrivals [e.g., Richards-Dinger and Shearer, 1997]. Common midpoint stacks are typically applied in seismic reflection experiments, but a similar approach can be used with refracted arrivals to obtain information on average seismic properties within a certain region [Behm et al., 2007]. Here we stack seismograms that have the midpoint of their ray paths within a common two-dimensional cell. We then measure $Sn$ amplitudes in these stacks to investigate variations in propagation efficiency or blockage at the various locations of the common midpoint cells.

[8] We downloaded waveforms from the ANF for about 8000 earthquakes and quarry blasts for broadband channels that have at least 10 $Pn$ or $Sn$ picks remaining after applying a similar space-time windowing procedure to that described in Buehler and Shearer [2010]. The ray paths for the stacks span ranges from 1.8° to 12°. We did not remove the instrument response since all the USArray transportable array stations are equipped with very similar instruments. We rotate the raw horizontal velocity seismograms into radial and transverse components using the epicenter location provided by the ANF and filter the waveforms between 0.8 and 4 Hz to remove microseisms and high-frequency noise.

[9] We proceed in similar fashion to that described in Behm et al. [2007]: We shift an equal area square cell with a width of 1.6° in increments of 0.8° across the Western United States. At each location, we find the event and station combinations that have their range midpoint within the window. Figure 2 shows an example for a common midpoint cell in the Great Basin. We stack all traces that satisfy this condition and that have a minimum signal-to-noise ratio of 2.5 for the first-arriving $Pn$ phase on the vertical component. Since we cannot expect waveform coherency for the earthquakes from various ranges and azimuths around the common midpoint cell we find that stacking the short-term average to long-term average (STA/LTA) function of the waveforms works well [Astiz et al., 1996]. We use 1 and 10 s for the short- and long-term windows, respectively. For stacking we use 0.25° for the range bin size and 0.5 s for the time bins (see supporting information).

[10] Similar to Behm et al. [2007], we find that the traces collected in individual distance bins stack with greater coherency if we align the $Sn$ arrivals by means of a reduction velocity. For each stack, we find the average uppermost mantle $Pn$ velocity and crustal thickness from our tomography [Buehler and Shearer, 2010] within the common midpoint cell. From this information we estimate an average slowness and intercept time for $Sn$ at that location, assuming constant crustal velocity and $Vp/Vs$ in the uppermost mantle. We then adjust the timing of the seismograms according to these parameters, in order for $Sn$ to align at approximately zero time. We found that a more sophisticated approach with individual station and event time terms does not increase coherency and that the 0.5 s time bins are large enough to counteract small misalignments.

[11] Working with STA/LTA functions of seismograms is convenient, as the process functions as automatic gain control and often nicely enhances the appearance of individual phases. However, the shape of the waveforms is not conserved, and STA/LTA functions might bias the results, as more impulsive arrivals could map into a higher amplitude in the stacks. Therefore, we also produce common midpoint stacks using the envelope function of the seismograms for comparison (Figure 2b). We then use both the STA/LTA and the envelope stacks to measure the $Sn$ amplitude. To properly capture the $Sn$ signal strength we measure the mean amplitudes in a 10 s window that starts 4 s before the estimated $Sn$ arrival time for the bins between a range of 3.25° and 4°. At certain locations $Sn$ appears stronger at greater ranges, so we therefore also shift the amplitude-measuring window along the range axis in 0.25° increments and...
measuring the maximum signal at any range between 3.25° and 8°. This reduces the localization and makes interpretation more difficult but indicates the general visibility of Sn in a stack more clearly. Often Sn appears stronger at shorter ranges, but here we risk that the Sn phase amplitude is contaminated by energy of crustal Lg. However, since energy transfer between Sn and the crustal phase can occur, especially at continental margins [Isacks and Stephens, 1975] and possibly continental plateaus, we separately measure the mean amplitude of Lg using a similar window. We normalize both the measured Sn and Lg amplitudes with the mean amplitude of a window in the P coda.

[12] This simple waveform-stacking approach is unable to return high-resolution attenuation images as for example produced by Phillips and Stead [2008] for USArray Lg. Attenuation tomography for Sn is difficult since the phase is generally only well approximated as a head wave that travels horizontally right below the Moho at short ranges [e.g., Sereno, 1989]. At longer ranges, Pn and Sn generally evolve into turning waves and modeling them as pure head waves with a horizontal uppermost mantle path will introduce errors. The ranges over which this transition occurs depend on the velocity gradient in the mantle lid and on the crustal thickness [Sereno, 1989]. The type of head wave that is observed up to teleseismic distances is typically described as a sum of whispering gallery or interference waves which travel in the mantle lid between the Moho and the low-velocity zone of the upper mantle [e.g., Menke and Richards, 1980]. Attenuation behavior of such waves is generally quite complicated and different from the behavior of pure head waves, and the amplitudes will depend on the velocity gradient in the uppermost mantle [Hill, 1973; Braile and Smith, 1975]. Because of these complications, we do not attempt to formally model the Sn attenuation but try to determine the broad variations of the propagation efficiency. The method we apply allows us to process a large number of seismic observations from USArray and improves our view of Sn propagation efficiency in the Western United States.

3. Results

[13] Figure 3 displays the measured stack amplitudes, and Figure 4 shows corresponding stacks for various locations for the transverse components. Images for the radial component are not displayed but look similar. The results from the STA/LTA and envelope stacks show similar features although the structures in the envelope map are less distinct (compare Figure 3a with Figure 3c). This is to be expected as the STA/LTA filter is more sensitive to changes in the shape and amplitude of the signal. Note that strong P arrivals are visible on the transverse component as a result of this filter sensitivity. Measuring amplitudes with just one range window at 3.25° and 4° seems to capture the characteristics of the stacks well, except for a few regions, as for example north of the Colorado Plateau, where Sn is visible more clearly at larger distances (Figure 3b).

[14] Similar to observations of seismic velocities, the Sn amplitude structure is quite heterogeneous. As in Rodgers et al. [1997], the measured Sn amplitudes are typically lower in regions of low Pn velocities. We find the most distinctive zone without evidence for Sn propagation in the back-arc of the Cascade Range, a region with recent volcanism.
Figure 3. (a) Measured Sn amplitudes at a range of 3.25 to 4° in STA/LTA stacks normalized by the mean amplitude of the P coda. Blue colors indicate regions of strong Sn signal; red colors show regions that greatly attenuate Sn. Regions without colored circles do not have enough data after processing. (b) same as Figure 3a, but the maximum amplitudes of all range windows are plotted. (c) Measured Sn amplitudes at a range of 3.25 to 4° in envelope stacks normalized by the mean amplitude of the P coda. (d) Pn velocities from tomography for comparison. Measured Sn amplitudes are typically lower in regions of low Pn velocities.

Similarly, we do not observe Sn in stacks across the Snake River Plain and the current location of the Yellowstone hotspot, regions of low Pn velocities (Figure 3d, updated model from Buehler and Shearer [2010]) and very low shear velocities [Schmandt and Humphreys, 2010]. These observations could indicate zones of partial melt in the uppermost mantle. To the north of the Snake River Plain and Yellowstone the character of the stacks changes abruptly and Sn is clearly visible in the stacks. We also find clear Sn arrivals in the region of the Columbia Plateau, where recent receiver function analysis showed a local increase in the depth of the lithosphere-asthenosphere boundary [Kumar et al., 2012].

[15] We do not observe Sn in the transition zone between the Great Basin and the Colorado Plateau. The Basin and Range Province is associated with high heat flow [e.g., Lachenbruch, 1978] that is generally related to strong Sn attenuation [Molnar and Oliver, 1969]. Yet interestingly we see a region of Sn propagation in the center of the Great Basin, in the broad region of a previously imaged higher-velocity body interpreted as a lithospheric drip [West et al., 2009], and close to the low heat flow anomaly in southwestern Nevada [Lachenbruch, 1978]. West et al. [2009] explain that the downwelling would locally increase the thickness of the lithosphere and potentially reduce its thickness around the periphery of the Great Basin. It is a current understanding that the mantle lid of lithosphere needs to be sufficiently thick in order for Sn to propagate. However, at the relatively short epicentral distances over which we measure the amplitudes the phase should propagate near the top of the mantle similar to a pure head wave. Still, the stacks show a clear Sn strand to a range of about 6° (Figure 4, stack 3) before the phase fades, supporting the existence of a locally colder and possibly thicker lithosphere.

[16] The previous study by Beghoul et al. [1993] showed that Sn does not propagate across the Colorado Plateau. They argued that the absence of Sn indicates a thin mantle lid since the Pn velocities below the central Colorado Plateau are relatively high, and therefore, Sn attenuation is likely not caused by thermal effects. Their study used WWSSN stations, and the ray paths were between 3 and 16°. Since the station network was much sparser pre-USArray, many of the Sn paths analyzed traveled across the entire Colorado Plateau. In our study, we observe Sn at shorter ranges for some parts of the Colorado Plateau, and the strength of the amplitudes in the stacks change from the northeastern section to the southwestern part. Our stacks that sample the southwestern...
part of the Plateau do not show evidence for $Sn$, roughly for the same area as USArray uppermost mantle tomographies show low shear velocities. However, stacks from ray paths that mostly sample the northeastern part of the Colorado Plateau, generally associated with faster upper mantle velocities, show a low-energy $Sn$ strand arriving slightly later than the time estimated from the $Pn$ Moho depth model (Figure 4, stack 5). This suggests that $Sn$ is strongly attenuated when it travels across the likely warmer western and southern margins of the Colorado Plateau, where Schmandt and Humphreys [2010] show very low shear velocities at 90 km depth, and that a thin lithosphere is not necessarily the primary reason for $Sn$ attenuation. This is in agreement with recent mapping of the asthenosphere-lithosphere boundary (LAB) below the Western United States with receiver functions [Kumar et al., 2012; Levander and Miller, 2012], which generally show a thicker lithosphere below the Colorado Plateau compared to the adjacent Basin and Range Province. 

Kumar et al. [2012] find boundary depths up to 140 km below the Colorado Plateau. The estimates by Levander and Miller [2012] are lower at ~90 km but still significantly deeper compared to their measured LAB depth of ~65 km below the Basin and Range. In addition, Obrebski et al. [2011] noted that their observation of high shear velocities might be consistent with a stable and relatively thick lithosphere for the northeastern part of the Colorado Plateau.

Fig. 4. Images of individual STA/LTA common mid-point transverse component stacks at various locations. Number or letter in the top left corner of each stack corresponds to the number/letter in the map on the top. Stacks 1–6 show $Sn$, but $Sn$ is attenuated in stacks A–F.

Fig. 5. Measured Lg amplitudes in STA/LTA stacks normalized by the mean amplitude of the $P$ coda.
In addition, we do not find anomalous Lg amplitudes for the Colorado Plateau that would suggest any significant energy transfer from the uppermost mantle into the crust. Similar to Phillips and Stead [2008], we observe that Lg, in contrast to Sn, generally propagates well in the Snake River Plain.

4. Summary

[18] We examine the propagation of Sn in the Western United States. The dense USArray station coverage allows us to experiment with methods that are conventionally used in active source studies at local scales. Common midpoint stacking analysis shows that Sn is highly attenuated across smaller and more localized regions than previously assumed, mostly where the paths cross the perimeter of the Great Basin. We find that the regions with high Sn attenuation correlate with volcanism and previously imaged low-velocity anomalies in the uppermost mantle. These observations are in agreement with local zones of partially molten uppermost mantle material. We find Sn arrivals along the coast of California, Oregon, and Washington, in the central Great Basin, in the northeastern part of the Colorado Plateau, and the Columbia Plateau. The structure of the Sn propagation efficiency below the Colorado Plateau is nonuniform, and the signal strength increases from southwest to northeast. This is in agreement with a potentially intact and thicker lithosphere in the northeastern part of the Colorado Plateau, as previously suggested as an explanation for the higher body wave velocities in this region, but more localized measurements are needed for more conclusive interpretations.

[19] Acknowledgments. We thank Luciana Astiz for discussions and assistance with the Antelope system and Tom Hearn and two anonymous reviewers for their constructive comments. This research was supported by grant EAR-0950391 from the National Science Foundation.

[20] The Editor thanks Thomas Hearn and an anonymous reviewer for their assistance in reviewing this paper.

References


Kumar, P., Xiao Yuan, R. Kind, and J. Mechie (2012), The lithosphere-asthenosphere boundary observed with USArray receiver functions, Solid Earth, 3, 149–159.


