High-frequency Pol/So guided waves in the oceanic lithosphere: II—heterogeneity and attenuation

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SUMMARY

In the western Pacific, high-frequency seismic energy is carried to very great distances from the source. The Po and So phases with observed seismic velocities characteristic of the mantle lithosphere have complex and elongated waveforms that are well explained by a model of stochastic heterogeneity. However, in the eastern part of the Pacific Basin equivalent paths show muted Po and weak, or missing, So. Once established, it is hard to eliminate such guided Po and So energy in the mantle lithosphere by purely structural effects. Even sharp changes in lithospheric thickness or complex transitions at fracture zones only weaken the mantle ducted wave trains, but Po and So remain distinct. In contrast, the effect of attenuation is much more severe and can lead to suppression of the So phase to below the noise level after passage of a few hundred kilometres. The differing characteristics of Po and So across the Pacific can therefore be related directly to the thermal state via the enhanced attenuation in hotter regions, such as the spreading ridges and backarc regions.

Key words: Guided waves; Seismic attenuation; Computational seismology; Wave scattering and diffraction; Pacific Ocean.

1 INTRODUCTION

In Paper I (Kennett & Furumura 2013), we described the characteristics of the propagation of the high-frequency mantle phases Po and So. These oceanic Pn and Sn phases can be observed after propagation over many thousands of kilometres from the source, retaining high frequencies but acquiring a long and complex coda. Paper I concentrated on the way in which these characteristics can be sustained by fine-scale heterogeneity in the oceanic lithosphere that reinforces the influence of multiple P reverberations in the ocean and sediments recognized by Sereno & Orcutt (1985, 1987). A form of quasi-laminar heterogeneity with horizontal correlation lengths around 10 km and vertical correlation lengths of about 0.5 km provides a good representation for efficient propagation of the Po and So wavefield. This class of stochastic heterogeneity creates a strong scattering environment within the lithosphere that helps to sustain the Po and So phases over long distances. Propagation of So is most effective in thick old lithosphere, for example, in the northeast Pacific Plate. Amplitudes of So are reduced significantly by propagation through thinner lithosphere in the Philippine Sea Plate.

In this paper, we look at the entire Pacific Basin and map out the propagation patterns for Po and So, which have the general characteristic of much more efficient propagation in the western sector than in the east, which is much less well sampled by stations and suitable sources. There are stronger changes in the nature of So than Po. For the same frequency, S waves have a shorter wavelength than P waves, and so the So phase is more sensitive to the effects of both lateral variations in lithospheric structure and seismic attenuation. We explore the relation of the nature of the observations of Po and So and the age of the lithosphere, examining the influence of changes in lithospheric structure across fracture zones and similar features. We demonstrate that the strong diffuse scattering field created in the oceanic lithosphere is hard to destroy and it is quite difficult to explain situations where So is very much weaker than Po, except by introducing enhanced seismic attenuation for younger lithosphere and the warmer asthenosphere in the neighbourhood of spreading centres.

2 Po/So PROPAGATION PATTERNS IN THE PACIFIC

In Fig. 1, we illustrate the propagation patterns for the Po and So phases across the Pacific Basin, superimposed on the seabed topography. The extensive set of paths in Fig. 1 has been assembled from a variety of sources, including the observations at ocean bottom stations reported by Brandsdottir & Menke (1988) and Shito et al. (2013). We also include the paths presented by Kennett & Furumura (2013), supplemented by our analysis of the higher frequency character of propagation (>2 Hz) on many more paths outside the northwestern Pacific region.

In Fig. 1 we include all reported observations, including those with discordant propagation characteristics. Even in areas such as...
Figure 1. Propagation efficiency of Po and So across the Pacific Ocean, superimposed on seabed topography. Stations on land are shown with open symbols, and seabed installations with solid symbols. The main plate boundaries are marked in red.

In the northwest Pacific with normally efficient Po and So observations, there are a few cases with apparently poor propagation; we have been able to track such effects to deep events with unusual source mechanisms so that radiation updip is inefficient. In other situations, for example, for events near the Gorda ridge off the coast of California, a slight change in source position to the far side of the ridge is sufficient to significantly weaken the observed So phase.

For much of the Pacific, the distribution of stations is largely dictated by the availability of suitable islands, which is denser in the western part of the Pacific than in the eastern. Ocean-bottom stations are used on the Philippine Sea Plate and in the northwest Pacific. We have also used the temporary station H2O deployed on the old telephone cable between Hawaii and the mainland of the United States (Butler 2003). This station provides important coverage in a zone where no islands are present.

Events large enough to be recorded at large distances are not too common. Although there have been significant temporary deployments on both islands and ocean bottom seismometers around French Polynesia, and also ocean bottom seismometers around the Hawaii islands, we have not been able to capture more than a few events in the relevant time periods when the experiments were being conducted. We fortunately do have enough events to study the directional dependence of the Po and So paths in the Pacific.

The main concentration of paths with efficient long-range propagation of Po and So lie in the western Pacific on the Pacific Plate. Efficient propagation of Po and So occurs for extraordinarily long distances up to 55°, exceeding even the ranges reported by Walker & Sutton (1971). On the younger Philippine Sea Plate, clear Po and So phases are seen at distances up to a few hundred kilometres, but are rarely visible for much longer paths. We have limited coverage of the Nazca Plate, but some evidence of efficient Po and So propagation away from the East Pacific Rise.
Direct propagation from shallower events in the various subduction zones to island stations generally show efficient high-frequency propagation with clear $P_o$, $S_o$ phases. However, where paths traverse backarc environments, such as the Lau Basin (west of the Tonga arc), there is dramatic loss of high frequencies in the hot and attenuative structure and little is left to propagate through the main Pacific Plate. The coverage of the eastern Pacific is more sparse than elsewhere. The configuration of stations and suitable sources means that we mostly have to look at observations at long ranges, and by the nature of the propagation through thinner lithosphere there is often very little in the way of high-frequency energy to be seen.

Notable topographic features do not, by themselves, act as barriers to $P_o$ and $S_o$ propagation, but may diminish the efficiency of such propagation (see the Appendix). Indeed the major island chains can act as conduits for guided energy (Maupin 1992) as, for example, in propagation to MIDW on Midway Island from events near Hawaii. Paths which cross the mid-ocean ridge with thinned, or absent, lithosphere lose $S_o$, and often lose $P_o$ as well.

The energy in the lithosphere is travelling nearly horizontal and so the radial ($R$) and transverse ($T$) components of ground motion are more developed than the vertical ($Z$) (see Fig. 3). There is often no distinct peak for the $P$ wave on the vertical component ($Z$), rather a similar maximum amplitude for the interval between the peak on the radial component ($R$) and that on the transverse component ($T$). The presence of significant $P$-wave energy on the transverse component ($T$), arriving a little delayed compared to the radial component ($R$) is an indicator of a strong scattering environment in 3-D. The behaviour of the vertical component ($Z$) is consistent with multiple arrivals of compressional waves with slight tilts from the horizontal, and a weaker scattering environment than for $S$ waves. The initial coda of $P$ is dominated by compressional energy, but acquires $S$-like characteristics later through conversion. The $P$ wavefield is reinforced by energy reverberating in the ocean, but loss can occur by conversion to $S$. The converted $S$ waves travel at steep angles that are able to escape from the lithosphere and extract energy from the $P$ wavefield. This process helps to explain the observations of higher apparent $Q_t$ than $Q_p$ for the $P_o$ and $S_o$ phases (e.g. Walker et al. 1983) that are hard to reconcile with normal intrinsic attenuation (Jackson 2007).

3 $P_oS_o$ CHARACTER IN THE NORTHEAST PACIFIC

The northwestern Pacific generally supports very efficient propagation of both $P_o$ and $S_o$ phases across the old oceanic lithosphere of the Pacific Plate (>100 Ma). The situation is rather different, however, in the northeast of the Pacific Basin (Fig. 2) where there are considerable variations in the age of the oceanic lithosphere across major fracture zones. There are a limited number of stations on the Hawaiian chain and on islands to the west, but to the east we have to rely on the seafloor Hawaii-2 Observatory ($H_2O$), and events along the plate boundary of North America.

The $H_2O$ station was established on the seafloor between Hawaii and California in 1998 using the former ocean-bottom telephone cable Hawaii-2 from Hawaii to the US mainland for power supply and telemetry (Butler 2003), and operated until 2003. The station lies on the seafloor between the Murray and Molokai fracture zones, on lithosphere which is somewhat younger than across the fracture zones to north and south. As can be seen in Fig. 2, there is strong directionality in the propagation characteristics of $P_o$ and $S_o$ at the $H_2O$ station. This behaviour was first noted by Butler & Duennebier (2000), and recordings of subsequent events reinforce their results (see Supporting Information).

A few volcanic earthquakes near Hawaii show well developed $P_o$ and $S_o$ phases at $H_2O$, but from other directions $S_o$ is weak or even suppressed below the noise level. The contrast in the character of the records is illustrated in Fig. 3, where we compare seismograms and frequency–time analysis for an event from Hawaii recorded at $H_2O$ with an event from the northern California coast that lies in young crust just to the north of the Mendocino fracture zone. The event and stations locations are shown in Fig. 2.

The propagation path from Hawaii to $H_2O$ crosses the multi-stranded Molokai fracture zone obliquely, but still produces a large amplitude $S_o$ phase in the frequency band above 3 Hz (Fig. 3a). In contrast, the larger event from the US coast with an almost opposite azimuth shows a dominant $P_o$ phase and little discernible $S_o$ (Fig. 3b). The rate of decay of the $P_o$ coda is also larger than for the Hawaiian event.

The strong contrasts in lithospheric age and consequent lithospheric thickness in the northeast Pacific Basin suggest that such structures might be capable of suppressing $S_o$. However, as we shall see in the next section, the $P$ and $S$ wavefield in the stochastic lithospheric waveguide is very robust to structural changes in the lithosphere, but much more strongly affected by attenuation contrasts imposed by thermal variations.

4 INFLUENCE OF STRUCTURE AND ATTENUATION ON $P_oS_o$ CHARACTERISTICS

In Paper I (Kennett & Furumura 2013) we demonstrated the way in which quasi-laminar heterogeneity in the mantle lithosphere serves to reinforce the effects of multiples in the water and sediments to produce complex high-frequency arrivals with long coda. The multiply-scattered waves propagating through the oceanic lithosphere in the form of $P_o$ and $S_o$ and their coda are restricted to a limited range of horizontal slownesses, and the wave trains are elongated by near surface reverberation and ‘whispering gallery’ effects in the lithosphere (Menke & Richards 1980). The scattered energy pervades the lithosphere, channelled forwards by the quasi-laminar nature of the heterogeneity. Once this multiply-scattered wavefield is established, it is hard to remove because of its diffusive character (see, e.g. Sato et al. 2012). This enables high-frequency energy to be ducted to very large distances.

There is always some natural attrition of the higher frequencies of seismic phases through the effect of geometrical spreading and progressive loss to attenuation, and so it is not surprising that only a few really long paths show clear $P_o$ and $S_o$ phases. Nevertheless, in the western Pacific we have a large number of paths of well over a thousand kilometres for which $P_o$ and $S_o$ are very clear, but few such paths in the eastern Pacific (Fig. 1). The relative propagation characteristics between these regions cannot be explained with simple structural effects.

The northeastern part of the Pacific shows major fracture zones separating lithosphere of different ages with the potential for jumps in lithospheric thickness across these localized transitions. Further the mid-ocean ridge system plays a major role in the central to southern part of the eastern Pacific, and here the effects of lithospheric thickening and cooling with age are important.

We have undertaken a wide range of simulations of the behaviour of the guided wavefield in the presence of major contrasts in the lithosphere, using large-scale finite-difference calculations carried
to high frequencies. We build on the models examined in Paper I, and employ lithospheric models incorporating stochastic heterogeneity with much longer horizontal correlation length than vertical. Propagation of $P$ and $S$ in this class of stochastic waveguide is very robust and little affected by significant changes in structure in the lithosphere. We find that features such as transition between two distinct lithospheric segments with different thickness can serve to weaken but not suppress $S_o$ waves. Only by invoking enhanced attenuation linked to thermal structures is it possible to suppress $S_o$ while retaining $P_o$. The strongest attenuation associated with structure near the ocean ridges can eliminate the high-frequency guided waves as observable features.

4.1 Finite-difference simulations and reference structure

As in Paper I, we undertake simulations of seismic wave propagation in heterogeneous structures with a 2-D finite-difference method (FDM). The 2-D model used for the simulation covers a region of 1200 km horizontally and 168 km in depth, discretized with a uniform grid interval of 0.04 km in both directions. We use models with quasi-laminar stochastic heterogeneity in the mantle, and various transitions in lithosphere character. Earth flattening is applied to the model of $P$- and $S$-wave speed ($V_p$, $V_s$) in order to include the effect of the sphericity of the Earth in a cartesian-coordinate system, so that the model can be used with conventional rectangular FDM grid.

A double-couple line source with dip $45^\circ$ fault mechanism is placed at a depth of 33 km. However, the multiple scattering of the seismic wavefield in the stochastic heterogeneous structure rapidly renders the simulations insensitive to the details of the focal mechanism of the source. The seismic source-slip function is a pseudo-delta function, which radiates seismic waves with a maximum frequency of 10 Hz.

We again employed the full boundary conditions at the free surface air/liquid interface (Okamoto & Takenaka 2005), and forced zero-tangential-stress at the fluid/solid interface (see Maeda & Furumura 2013 for details). To suppress artificial reflections from the edges of the model we used a 10-grid point Perfectly Matched Layer technique (Marcinkovich & Olsen 2003; Moczo et al. 2007).
Figure 3. Character of events at H2O station, rotated three-component seismograms and frequency–time analysis: (a) Hawaiian event with significant So; (b) dominant Po from northern California event. For clarity the amplitudes of the vertical component (Z) are enhanced by a factor of two.

In order to achieve long-distance propagation at high frequencies (10 Hz) we have employed a parallel implementation of the FDM with a staggered-grid configuration (fourth-order accuracy in space and second-order accuracy in time; Furumura & Chen 2004). As we saw in Fig. 3 most of the Po and So energy is confined to the 2–8 Hz band for which the grid size (0.04 km) of the finite-difference calculation satisfies the requirements for four gridpoints per minimum wavelength in the finite-difference calculation even for the low-velocity sedimentary layer (Vs = 1.154 km s\(^{-1}\)). Tests with a more accurate (eighth-order finite-difference) scheme indicate no significant impact from numerical dispersion for the present calculation at the very highest frequencies (10 Hz) even for a propagation distance of 1000 km. The simulations used 16 nodes (64 CPUs) of the Earth Simulator supercomputer at the Japan Agency for Marine-Earth Science and Technology.

As demonstrated in Paper I, we can produce a good representation of the character of the high-frequency propagation of Po and So in a model with fine-scale heterogeneity superimposed on a stratified background. Reverberations in the ocean and the basal sediments also play an important role in continuously reinforcing the complex wavefield in the stochastic waveguide in the lithosphere. Such fine-scale heterogeneity is embedded in the FDM simulations in this paper, using a von Karman distribution for the heterogeneity with a horizontal correlation length of 10 km in the lithosphere and 5 km in the asthenosphere, with a vertical correlation length of 0.5 km in each case. The amplitude of wave speed variation is normally set at 2 per cent. The asthenosphere model is similar to that advocated by Kawakatsu et al. (2009). The crust has a dyke-like structure with correlations lengths of 0.25 km in the horizontal direction and 5 km in the vertical direction. The Q\(_p\) in the oceanic lithosphere is set to 2000, and in the asthenosphere below to 450. In all the simulations later we have set Q\(_p\) = 2Q\(_s\), unless otherwise stated.

In Fig. 4 we consider two reference cases, presenting a record section of radial component seismograms and a set of snapshots, where the P wavefield is shown in red, and the S wavefield in green. The first case (Fig. 4a) represents old oceanic lithosphere with a thickness of 100 km, and the second (Fig. 4b) younger lithosphere with a thickness of 50 km. Both So and Po are more strongly developed in the thicker lithosphere, with a slower rate of decay with distance. The general character of the high-frequency arrivals travelling through the oceanic lithosphere is similar in each case, with the dominant energy in the first 30 s of each phase and then a gentle decay into an elongated coda. Reducing Q\(_s\) to 500 for the thicker lithosphere has a comparable effect to reducing the thickness of the lithosphere (see Supporting Information). However, a similar reduction of Q\(_s\) to 200 in the asthenosphere has much less influence on the nature of the So phase, when the thickness of the lithosphere (100 km) is large enough to retain the high-frequency ducted waves.

4.2 The influence of strong lateral variations in structure

In a purely stratified structure, the lithospheric wavefield is composed of a ‘whispering gallery’ superposition of multiply-reflected diving waves turned back by the modest wave speed gradient in the lithosphere. The patterns of multiple reflections are reinforced by the reverberations in the ocean and sediments to give complex wave trains (e.g. Sereno & Orcutt 1987). Nevertheless, this class of multiply-reflected wavefield is vulnerable to rapid horizontal changes in lithospheric structure. Once part of the multiply-reflected field is lost, for example, by transmission into the asthenosphere at a sudden change of lithospheric thickness, it cannot be regenerated.
In contrast, in a stochastic waveguide the wavefield is both more complex and more robust. The variations in wave speed in the lithosphere create an environment with horizontally elongated features relative to the wavelengths of the high-frequency waves, and link to locally strong vertical gradients. Energy is ducted through the multiple channels of lowered seismic velocity at near grazing incidence. As can be seen from the snapshots for the reference structures (Fig. 4), the wavefield in the lithosphere is strongly scattered, with multifold interactions with structure. In consequence, the wavefield lies in the diffusive scattering regime (Sato et al. 2012) where it is self-healing and resilient to changes in wave speed structure, but still sensitive to variations in attenuation.

A characteristic feature of the northeast Pacific, where So tends to be weak, is the presence of a suite of fracture zones with sharp jumps in age, and hence lithospheric thickness. As can be seen from Fig. 5, even a major change in lithospheric thickness from 100 to 50 km, whether sharp or extended over a 100-km transition, has only a modest impact on the amplitudes of Po and So, and none on the character of the seismograms. We find a similar behaviour with lithospheric thickening, where initially the Po and So phases are less well developed in the thinner lithosphere (cf. Fig. 4b). After the transition to thicker lithosphere, there is some tendency for Po to become more pronounced with range, building on the trapped P-wave energy in the ocean and sediments. So remains strong, and after the thickening the diffuse S wavefield expands to fill the entire lithosphere. Compared with the reference case for thick lithosphere (Fig. 4a) the amplitudes of the So phases passing across the lithospheric transition are reduced by about 25 per cent at ranges near 1000 km. Even multiple passage through such simple structures would have only a modest impact on the efficiency of propagation of So. If a transform fault juxtaposes lithospheres of very different age and attenuation structure then transition into younger more attenuative lithosphere can lead to a more significant reduction in the amplitudes of the guided phases Po and So (see Supporting Information).

Studies of oceanic transform faults have revealed complex structures with localized crustal low-velocity zones (see, e.g. Van Avendonk et al. 1998, 2001). It is likely that such complexity is preserved in fracture zones once the material has moved away from the spreading ridge. Further, many fracture zones show multistranded structures, so that waves in the lithosphere will encounter multiple transitions in quick succession. We have therefore constructed models with localized zones of lowered velocity (10 per cent reduction in shear wave speed) and enhanced attenuation (Q reduced to 200) associated with fracture zones, with separate realizations of the stochastic heterogeneity field on the two sides of the transition. Such complex lithospheric transitions introduce only a modest reduction in the efficiency of propagation of Po and So (Fig. 6), even for an unrealistically wide zone of modified properties. The short residence of the P and S waves in one or more complex zones is not sufficient to disrupt the robust wavefield. Even a source close to a fracture zone is able to overcome the local barrier, and set up a clear stochastic guided field with no more than a 50 per cent reduction in Po and So amplitude.

For the high frequencies observed in Po and So, we are restricted to 2-D simulations of the wave propagation and so cannot represent oblique propagation through a fracture zone structure directly. Propagation away from the perpendicular direction will extend the effective width of the fracture zone structures and so enhance local energy loss through the influence of structural change and attenuation.

As we have seen in the reference calculations, Po and So are less well developed when generated in a thinner stochastic lithosphere.
What then is the influence on the wavefield of structural gradients in lithospheric properties or attenuation?

In Fig. 7, we show the impact of gentle gradients in the level of heterogeneity, and in $Q_s$, on the nature of $P_o$ and $S_o$. With a lowered lithospheric $Q_s$ of 500 (compared to 2000 in the reference calculations) we can already reduce the amplitude of $S_o$ compared to $P_o$. The reduction is enhanced by steadily reducing the level of heterogeneity with range. With less internal variation in the lithosphere, the leakage of $P_o$ and $S_o$ into the asthenosphere is enhanced. In a similar way an increase in attenuation with range (with a progressive reduction of $Q_s$ from 500 to 100) has the effect of steadily suppressing the stochastic wavefield with $S_o$ diminished relative to $P_o$. The reference seismograms from Fig. 4(a) are plotted behind the record sections in green to allow comparison.
Both attenuation and heterogeneity level are likely to be linked to the thermal state, with hotter areas having both lower $Q_s$ and less well-developed heterogeneity and thereby producing a strong reduction in the strength of the $So$ phase.

In simulations with propagation in the opposite sense of gradient, from weaker to stronger heterogeneity or from stronger to weaker attenuation, there is strong effect from the source zone. With a weaker heterogeneity level the guided phases are smaller. As such waves pass into a zone of stronger heterogeneity, the $P$ reverberations in the ocean and sediments help to build the guided energy, but couple more effectively into $Po$ than $So$. A source in a zone of low $Q_s$ generates much less high-frequency energy, and these components cannot be restored once lost.

In Fig. 8, we present a comparison of the synthetic seismograms for a range of simulations in different 2-D models, with bandpass filtering with corners at 2 and 8 Hz. We compare the radial component seismograms for epicentral distances of 960 km from Figs 4–7 and related calculations. In all cases the records bear the strong imprint of reverberations in the water and shallow sediment structure. The two cases with a sharp step in lithosphere thickness (b), (c) show very similar character to the reference case for thick lithosphere (a), but we do see a slight reduction in the efficiency of $Po$ and $So$ propagation. In comparison the reference case of a 50-km-thick lithosphere (d) displays somewhat reduced $Po$ and $So$. When the lithospheric $Q_s$ is reduced to 500, in case (e), $So$ is moderately diminished. The effect of gradients in either heterogeneity (f) or decreasing $Q_s$ (g), lead to a striking reduction in the size of the high-frequency guided phases.

Fig. 9 displays a comparison of simulated radial component seismograms and corresponding frequency–time analysis for the thicker (100 km) and thinner (50 km) lithosphere reference structures, and the case with increased attenuation in the 50-km-thick lithosphere. For the low attenuation lithospheric structures, significant high-frequency energy (>6 Hz) persists for more than a minute in the $So$ coda. The progressive decay of the coda envelope is not accompanied by a loss of the high-frequency energy, indeed the relative proportion of the higher frequencies tends to increase with time along the coda. Such effects are frequently seen for very efficient propagation of $So$, and have probably contributed to the unusual $Q_s$ properties reported for such paths (Walker et al. 1983).

4.3 Near ridge-crest structure

The lithosphere near a spreading ridge will be thinned and hot, so that passage of $Po$ and $So$ will be impeded. In Fig. 10 we show a simplified structure for the neighbourhood of a mid-ocean ridge, with thinned lithosphere and enhanced asthenospheric attenuation. We have used $Q_s$ of 200 in the asthenosphere for these high-frequency waves. This value is somewhat higher than is characteristic for the frequency range of surface waves (<0.03 Hz) for which, for example, Cara (1981) has $Q_s$ of 80, but is consistent with a modest frequency dependence of attenuation.

An initially well-developed set of $Po$ and $So$ waves are nearly extinguished by the time that they have passed the ridge. The first effect of the thinning lithosphere is to concentrate the $Po$ and $So$ energy near the surface so that their onsets are more marked (Fig. 10a). Subsequently, wave energy is lost from the lithosphere and the coda becomes more prominent. Loss of guided energy is most pronounced in the immediate neighbourhood of the ridge.

A source placed at the ridge in the same structure is able to overcome the effects of attenuation and produce weak $Po$ and $So$ that are able to become stabilized in the thicker lithosphere away from the ridge (Fig. 10b). For a fast-spreading ridge like the East Pacific Rise, the zone of thinned lithosphere will be wide and consequently the influence of local attenuation will be enhanced for near ridge crest events.
Figure 8. Comparison of synthetic radial component seismograms for epicentral distance 960 km in various structures: (a) reference model, 100 km lithosphere; (b) with sharp reduction in lithosphere thickness from 100 to 50 km; (c) with sharp increase in lithospheric thickness from 50 to 100 km; (d) reference model, 50 km lithosphere (e) with increased attenuation $Q_s = 500$; (f) with graded heterogeneity (2 per cent to 0.5 per cent); (g) with graded attenuation ($Q_s$ decreasing from 500 to 100). In (b), (c) the reference seismogram for the 100 km lithosphere (a) is plotted beneath in green. For (e)–(g) the reference seismogram for the 50 km lithosphere (d) is plotted beneath in cyan.

Decreasing the $Q_s$ throughout the asthenosphere to 80 has the effect of enhancing the suppression of $S_0$ and $P_0$, in propagation towards and away from the ridge. The amplitudes after propagation through about 1000 km are reduced by approximately a half compared with the results shown in Fig. 10. Thus enhanced asthenospheric attenuation near the ocean ridge can be a significant contributor to the suppression of the lithospheric phases.

A further likely consequence of the hotter thermal regime near the mid-ocean ridge is that the level of heterogeneity in the lithosphere is diminished. We illustrate the effect of such a change in Fig. 11 from a heterogeneity level of 0.5 per cent at the ridge crest to 2 per cent when the lithosphere reaches full thickness (50 km). We have used a constant attenuation structure in Fig. 11 to isolate the effect of the heterogeneity change. The change in heterogeneity coupled to the increasing thickness of the lithosphere produces a significant effect on the efficiency of $S_0$ propagation for sources at the ridge when compared with the reference case for 50 km lithosphere displayed in Fig. 4(b). For propagation to the ridge the effect is quite modest in comparison.

These simulations illustrate the complexity of the processes that can influence the nature of the propagation of the $P_0$ and $S_0$ phases in the regions around the mid-ocean ridges. The hotter environment certainly will enhance the attenuation of seismic waves and can also influence the heterogeneity structure. The observations (Fig. 1) suggest that there are strong effects for paths both to and from the ridges as well as for paths crossing the mid-ocean ridges, so that attenuation is most likely the dominant factor.

4.4 H$_2$O simulations

In the simulations mentioned above we have looked at the effect of contrasts in lithospheric structure individually. We now turn to the events illustrated in Fig. 3, and undertake simulations for propagation to the H$_2$O site building in the full range of complexity in the lithosphere. We are restricted to 2-D simulation and so have taken profiles along the great circle paths from the events in Hawaii and northern California to H$_2$O (Fig. 12). In each case we build in the seabed topography from the SRTM30_PLUS model (Becker et al. 2009) with a 30 arc-second resolution (roughly 1 km), and lithospheric thickness based on the estimate of the age of the plate. We also incorporate reduced shear wave speed and $Q_s$ in the fracture zones, as in Fig. 6. For each profile we have incorporated stochastic heterogeneity in the lithosphere and make long-range FDM simulations for full high-frequency seismograms.

Along profile $a$–$a'$ from Hawaii to H$_2$O, the $P_0$ and $S_0$ waves have to cross the Molokai fracture zone obliquely, and encounter progressive thinning of the lithosphere. As expected, the crossing of the fracture zone does not have a pronounced effect on the lithospheric waves, but there is some loss as the lithosphere continues to thin. Nevertheless, at the H$_2$O location in Fig. 12(b) we see clear $S_0$ and $P_0$ wave trains comparable to those in Fig. 3(a).

For propagation from the northern California coast to H$_2$O along profile $b$–$b'$, the initial part of the path is on very young thin crust. The waves then encounter the Pioneer fracture zone, and after 1400 km the Murray fracture zone. We have incorporated lowered $Q_s$ of 500 in the lithosphere and 200 in the asthenosphere to represent the effect of the younger, and warmer structure along this path.
The combination of the steady change in structure along the path with the enhanced attenuation is able to suppress $S_o$ while leaving perceptible $P_o$ (Fig. 12d), as observed in the records in Fig. 3(b). Even if we reduce the lithospheric attenuation ($Q_s = 1000$) as in Fig. 12(c) the transitions in structure near the source play a large role in reducing $S_o$ to the point where it is barely visible in the simulation. The excitation of the $T$-phase in the simulations is much larger for the shallower northern California coast event than for that in Hawaii. This $T$-phase represents energy that has spent most of its path as acoustic waves in the ocean. Stronger radiation into the ocean will mean that less energy is available for ducting through the lithosphere, and contribute to the suppression of the $P_o$ and $S_o$ phases.

With the 2-D FDM modelling of the paths to $H_2O$ using stochastic waveguide models, we have been able to reproduce the character of the seismograms for both the paths shown in Fig. 3 very well. The closest correspondence with the observations comes with the introduction of enhanced attenuation for younger lithosphere, since the structural effects alone are barely adequate to suppress the ducted phases.

5 DISCUSSION

The characteristics of efficient propagation of the $P_o$ and $S_o$ phases are the transmission of high-frequency seismic waves in the oceanic lithosphere at mantle wave speeds, accompanied by a long coda with comparable energy on the orthogonal components of horizontal motion. These features indicate that the waves are associated with strong, multiple scattering in the lithosphere. The character of the $P_o$ and $S_o$ wave trains can be well represented by propagation with multiple scattering through quasi-lamellar heterogeneity associated with a von Karman distribution with much longer horizontal correlation length (around 10 km) than in the vertical direction (0.5 km). This configuration produces a stochastic wavefield that is robust and
Figure 10. The impact of structure near a mid-ocean ridge on $P_o$ and $S_o$ propagation including variations in lithospheric thickness and attenuation: (a) propagation to the mid-ocean ridge from a source at 32 km depth in 50-km-thick lithosphere; (b) propagation from the mid-ocean ridge for a source at 20 km depth. The seismograms for the 50 km lithosphere reference case in Fig. 4(b) are indicated in cyan for comparison.

Figure 11. The impact of structure near a mid-ocean ridge on $P_o$ and $S_o$ propagation including variations in lithospheric thickness and level of heterogeneity with fixed attenuation structure: (a) propagation to the mid-ocean ridge from a source at 32 km depth in 50 km thick lithosphere; (b) propagation from the mid-ocean ridge for a source at 20 km depth. The seismograms for the 50 km lithosphere reference case in Fig. 4(b) are indicated in cyan for comparison.

Insensitive to significant changes in lithospheric structure. The presence of island chains and other seafloor edifices are likely to modify the wave speed heterogeneity, and internal contrasts will lead to energy loss to the asthenosphere. Nevertheless, such features are not sufficient to suppress the $P_o$ and $S_o$ phases.

On all paths the propagation of $P_o$ and $S_o$ will be subject to geometrical spreading, and the effects of intrinsic attenuation. Yet, in the western Pacific, high-frequency energy travels for thousands of kilometres through old lithosphere, which must therefore have very high $Q_s$. 
Figure 12 Simulations of propagation to the H\textsubscript{2}O site in the NE Pacific. The calculations have been made for 2-D profiles from events in Hawaii and northern California to the H\textsubscript{2}O site as indicated in the upper map (a). The remaining panels show the evolution of the seismic wavefield from each source with the seismogram at the H\textsubscript{2}O site indicated in orange. Despite crossing the Molokai fracture zone both Po and So are distinct for the path from Hawaii (b). For the path from northern California to H\textsubscript{2}O, the combination of young, thin and attenuative ($Q_s = 500$) lithosphere and the crossing of the Pioneer and Murray fracture zones ($Q_s = 200$; 10 wave speed) leaves almost no energy in $S_s$ and little in $P_o$ (d), and $S_o$ is still largely suppressed if less attenuation ($Q_s = 1000$) is imposed (c). The excitation of the $T$-phase, comprising acoustic energy in the ocean, is much more efficient for the northern California event, and will drain energy from the lithospheric wavefield.
Figure 12 (Continued.)
The contrasts in the efficiency of propagation of Po and So between the western and eastern Pacific is striking (Figs 1 and 13). Interaction of the mantle guided waves with multiple fracture zones can diminish the size of So compared to Po, but from our modelling studies is not sufficient to suppress the phase. However, we can achieve more rapid loss of So than Po though the action of attenuation. Enhanced intrinsic attenuation can be expected for younger lithosphere where temperatures are hotter, with the strongest effects near the spreading ridge crest (as demonstrated in Fig. 10).

In Fig. 13, we plot the propagation efficiency of Po and So as a function of path, superimposed on the age distribution for the oceanic lithosphere (Müller et al. 2008). We see that efficient So propagation is concentrated in the areas of older lithosphere, or for short paths on younger material. Most longer paths associated with weak So in the western Pacific pass through backarc zones, for example, the Lau Basin behind the Tonga arc, before entering the Pacific Plate. The high-frequency S will be lost in this hot and highly attenuative environment, and cannot be regenerated on the rest of the path.
In the eastern Pacific we find that some ridge crest events produce recognizable, but weak, \( Po \) and \( So \) at some stations, yet at others the signals drop below the noise level and are not detected. Paths which cross spreading ridge segments may sometimes preserve weak \( Po \), but generally both \( Po \) and \( So \) are suppressed.

Because the dominant influence on intrinsic attenuation is thermal (Jackson 2007), the thermal state of the lithosphere is more important for the efficiency of high-frequency propagation than the actual age. The studies of Ritzwoller et al. (2004) and Maggi et al. (2006) using surface wave tomography have mapped out the variations in shear wave speed across the Pacific. In a number of locations these results indicate equivalent thermal ages differing from that expected from the age of lithosphere formation. In particular, the area around the H2O station shows lower than expected shear wave speeds at lithospheric depths, extending to the east. Enhanced attenuation in this region would help to explain the strong directivity in the character of \( Po \) and \( So \) observed at this seabed station, with suppression of the \( So \) phases from sources to the east (Figs 2 and 3).

For the areas around the Pacific Basin, Molnar & Oliver (1969) defined the poor \( So \) propagation in the young Philippine Sea Plate, and pointed out the suppression of \( So \) through backarc regions in the Aleutians and Marianas. Nearly all paths across the young Gorda Plate off Cascadia to near coastal stations, show poor \( So \), and this phase is largely eliminated for paths crossing the Gorda ridge, off the coast of northern California. These additional results confirm the major role played by attenuation even for short paths.

6 CONCLUSIONS

Our results confirm that high-frequency \( Po \) and \( So \) propagation occurs across most of the Pacific Plate with most efficient transmission in the older, colder areas. We are able to match the character of the propagation well with a heterogeneous lithospheric mantle with much longer horizontal than vertical correlation distances. The behaviour is consistent with heterogeneity being introduced into the oceanic lithosphere at the time of its formation and then being translated with plate motion, with consequent cooling and reduced seismic attenuation. As we have seen the strong attenuation environment in the neighborhood of the ridge is a barrier to investigating the detailed character of the heterogeneity near its likely source using high-frequency seismic waves.

In this paper and in Paper I we have studied the guiding of high-frequency waves in the oceanic lithosphere, using a model of quasi-laminar stochastic heterogeneity. Subducted slabs also have the capacity to duct high-frequency energy from deep events, with most notable effects seen in old slabs, for example, Japan (Furumura & Kennett 2005), Indonesia (Kennett & Furumura 2008) and Italy (Sun et al. 2014), but also for younger slabs in southwestern Japan (Furumura & Kennett 2008) and Taiwan (Chen et al. 2013). This guided energy too can be explained with a similar model of heterogeneity. In the stress and thermal states prevailing in the subducted slab, it is difficult to achieve slab-parallel alignment (Sun et al. 2014), and therefore the heterogeneity must be imported with the incoming oceanic lithosphere. The successful modelling of Shito et al. (2013) of \( Po \) and \( So \) arrivals from deep events in the subducted Pacific Plate recorded at ocean bottom seismometers, using the same heterogeneity structure in both the subduction zone and the oceanic lithosphere provides strong support to a common origin of the heterogeneity, as also proposed by Sun et al. (2014).

The environment near the mid-ocean ridge with melt-rich asthenosphere provides opportunities for near-horizontal penetration of melts into the growing oceanic lithosphere, with preservation of heterogeneity on cooling. Sun et al. (2014) discuss a number of mechanisms that might help to preserve such heterogeneity. As noted in Paper I, our preferred class of lithosphere heterogeneity has a strong resemblance to a frozen version of the mille-feuille model proposed by Kawakatsu et al. (2009) for asthenospheric structure including melt pods beneath the Philippine Sea Plate. The heterogeneous structure with quasi-laminar structure would be compatible with lithospheric growth by underplating from below, which would be expected to be most important near the ridge crest.

For a fast spreading ridge, such as the East Pacific Rise, with a spreading rate of 10 cm yr\(^{-1}\), the characteristic horizontal correlation length of \( 10 \) km, for wave speed heterogeneity in the lithosphere, would be generated in \( 10^5 \) yr. In contrast at a slow spreading ridge, such as the mid-Atlantic ridge, only \( 1 \) km of new crust would be produced in the same interval. The vertical scale of processes will be similar in the two situations, but we can expect considerable differences in the aspect ratio of the heterogeneities generated in the near-ridge area. The fast-spreading ridge would show the 20:1 horizontal to vertical correlation length ratio we have used in our simulations. Whereas for a slower spreading ridge, with more episodic crust formation, the correlation ratio would be more like 2:1. We have shown in Paper I that such near isotropic heterogeneity is capable of producing high-frequency guided waves, but with less efficiency than with a quasi-laminar configuration, so that \( Po \) and \( So \) would not be sustained for very long distances (see also Supporting Information). Further, the stability of the stochastic wavefield to variations in structure reduces significantly as the horizontal correlation length decreases, so the impact of changes in lithospheric properties will be greater for lithosphere generated by slower spreading processes.

We would expect the ridge crest processes to impose their own scales on the 3-D pattern of heterogeneity. For a fast-spreading ridge we would expect a most elongation of the correlation length parallel to the magnetic lineations, which would induce a component of anisotropy to the character of \( Po \) and \( So \). For slow spreading ridges, the along-ridge scale length is likely to be dictated by the character of the episodic formation of new lithosphere.

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APPENDIX: INFLUENCE OF SHALLOW STRUCTURE

In Section 4 we have concentrated on the influence of major changes in the nature of the lithosphere. Nevertheless, as discussed in Paper I, the shallow structure including the ocean, seabed and sediments plays an important role in developing the character of the lithospheric wavefield through reverberations.

In Fig. 14 we illustrate the effect of modifying seafloor topography for two different situations. In the first, we impose the seabed fluctuations from the SRTM30_PLUS model (Becker et al. 2009) along the profile from Hawaii to the H2O station. This model has a resolution of 30 arc-seconds (approximately 0.5 km). In the second, we impose a random seafloor topography model with horizontal correlation length of 20 km and amplitude of 0.1 km (one standard deviation). The random structure has a similar large-scale response to the actual topography, but is richer in short wavelength features (Fig. A2), which are not present in the SRTM30_PLUS model.

Even modest variation in seafloor topography has the effect of modifying the character of the reverberations in the ocean and sediments. The multiple bounces of P-wave energy are less regular than in the purely stratified case, and in consequence the energy in the water column becomes extended in space and time. This results in a shift of amplitude to later in the coda and a consequent modification of the character of the Po and So arrivals. The changes in the Po and So waveforms are most evident in the case with the random topography, where the characteristic secondary P wavefront is much less distinct.
Figure A1. The influence of seabed topography on the lithospheric wavefield: (a) seabed topography from the SRTM30_PLUS model (Becker et al. 2009) along the profile from Hawaii to H2O and (b) a random topography model with horizontal correlation length of 20 km and amplitude of 0.1 km (one standard deviation). The reference seismograms from Fig. 4(a), without any topography are plotted beneath the record sections in green.

Figure A2. Power spectral density of sea-bed topography in wavenumber space. Blue line - seabed topography from the SRTM30_PLUS model along the profile from Hawaii to H2O; Red line - a random topography model with horizontal correlation length of 20 km and amplitude of 0.1 km (one standard deviation), with much richer short scale structure.

Major topographic features on the seafloor also have the potential of modifying the character of the Po and So arrivals by disturbing the local reverberation patterns. The effects seem to be most notable in propagation across, rather than along major topographic edifices. The presence of the Shatsky rise (near 35° N, 160° E), which contains large shield volcanoes, is not notable in the character of arrivals at WAKE from the Kuriles. Yet, paths which traverse this area to the central Pacific show much less efficient So propagation.

Similarly the various island chains, such as the Hawaiian, can act as locally enhanced waveguides along their length, but tend to impede perpendicular propagation.

The elevated topography of such features reflects major changes in lithospheric structure. We can therefore expect that the character of the stochastic heterogeneity will be disturbed, and so the processes that tend to sustain the scattered energy will be interrupted. The net result will be a reduction of the efficiency of the lithospheric waveguide, with potential loss of higher frequency energy.