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Tears or thinning? Subduction structures in the Pacific plate beneath the Japanese Islands

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ABSTRACT

The nature of a subduction zone at depth is affected by the evolution of its tectonic system, and the geometry of the trench line can change over time due to slab roll-back or the arrival of a distinctive feature with the incoming oceanic lithosphere. The configuration of the plate has to accommodate such changes with buckling, thinning or the formation of tears depending on the rate of influx to the trench. Tomographic imaging is commonly used to recognise the presence of such tears through marked reductions in wavespeed anomalies in localised zones. A good example is provided by Pacific plate subduction beneath the Japanese Islands. A horizontal tear in the plate below 300 km depth can be recognised at the southern end of the Izu-Bonin arc associated with the change in slab morphology to the much steeper Mariana arc. Beneath southern Honshu a break in the fast wavespeeds associated with the Pacific plate has been described as a tear based on the evidence of converted phases from the edge of the zone and tensional focal mechanisms for seismic events in the tear zone. In the north, close to the Hokkaido bend in the subduction zone, the reduction in the shear wavespeed anomaly is just as dramatic, but here the characteristics of high frequency guided waves from deep earthquakes indicate continuity of slab material with thinning of the slab. The thinned slab has less wavespeed contrast within the affected cells and so appears in the tomographic images as a weakened anomaly. The various modes of slab deformation represent different ways in which the subducted material accommodates the strains imposed by the evolution of the geometry of the subduction scenario. Not all significant reductions in wavespeed anomalies represent tears and thus it is important that such interpretations be checked against the characteristics of wave propagation through the zone.

1. Introduction

A number of recent studies of subduction zones using seismic tomography have revealed the complexity of processes operating in subduction that can disrupt the subducted plate. Horizontal tears have been suggested in the Indonesian arc (Widiyantoro and van der Hilst, 1996), and in the southern part of the Izu-Bonin arc (Miller et al., 2005) associated with the attempted subduction of the Marcus-Necker ridge. Vertical tears have been documented in the Mediterranean (Wortel and Spakman, 2000; Spakman and Wortel, 2004) and in the Mariana arc (Miller et al., 2006). A number of different processes have been invoked to lead to the disruption of the subducting plate including rapid roll-back of the trench (Rosenbaum et al., 2008), interaction of subducting plate and a hot spot (Devaille and Lees, 2004; Sigloch et al., 2008) and flattening of subduction into a stagnant slab in the transition zone (Obayashi et al., 2009). The oceanic plate entering the trench is far from homogeneous and carries with it variations in age associated with the generation of the oceanic lithosphere, as well as features such as chains of sea mounts. Modifications of the physical property of the subducting material can provide a locus for incipient tears. Alternatively a process of trench roll-back can impose severe strain on a plate so that it breaks along lines of internal weaknesses (Rosenbaum et al., 2008). Where a plate is broken at shallow levels, there is an opportunity for asthenospheric material to well up through the tear with a major modification of the geochemical signal in lavas erupted from volcanoes above the subduction zone, (e.g., Gasparon et al., 2009).

Commonly the interpretation of a slab tear is based on modifications of the wavespeed anomaly in a tomographic model for the subduction zone, which may also be supported by evidence from seismicity patterns and earthquake focal mechanisms. Changes in the amplitude of a fast wavespeed anomaly can be associated with differences in patterns of sampling and by the geometrical configuration of the subducted plate relative to a cellular "voxel"

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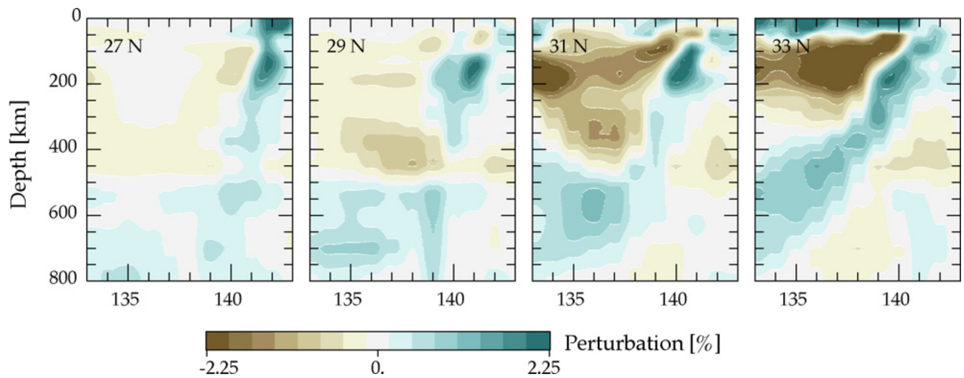

Fig. 1. Vertical cross-sections across the Izu-Bonin arc from 27°N to 33°N through a *P* wavespeed model constructed using the data selected for the joint inversion of Gorbatov and Kennett (2003). The wavespeed perturbations are displayed relative to the *ak135* reference model (Kennett et al., 1995), for which cold subducted lithosphere appears fast and the surroundings slow. The uniform dip in the northernmost section is modified to the south, and there is a clear disruption of the subducted material associated with a sub-horizontal tear zone in which earthquake activity is concentrated (Miller et al., 2005).

representation. It thus is important that inferences of slab tearing be corroborated by evidence from the nature of seismic wave propagation through the zone of interest. Such features as strong converted phases can arise when there is a sharp break (Gorbatov and Kennett, 2003). If there is an actual tear it would be expected that high frequency seismic waves would be blocked even though lower frequency waves with longer wavelength might cross the tear zone.

An important example of the variability in behaviour along a single plate boundary is provided by the behaviour of the Pacific plate as it subducts beneath the Japanese Islands from the southern end of the Izu-Bonin chain to Hokkaido. In this region there is a high density of seismic stations and earthquakes that provide excellent sampling for tomographic imaging. At the southern end of the Izu-Bonin chain (26.5°N) the Ogasawara plateau is resisting subduction, and acts as a pinning point for the northern end of the near-vertical Mariana subduction zone.

There is a dramatic change in the configuration of the subducting slab in the Izu-Bonin arc with an extensive zone of stagnant slab in the transition zone extending to the west beneath the present Ryukyu arc (Miller et al., 2005). The abrupt termination of the subducted material has lead to a horizontal zone of weakness in which earthquakes are concentrated (Miller et al., 2005). This zone can be clearly seen in *P* wave tomography as, e.g., in the group of east-west sections in Fig. 1 taken from a tomographic inversion made using the dataset selected by Gorbatov and Kennett (2003). In the northernmost section there is a very clear dipping subduction zone with elevated wavespeeds, but as the southern end of the arc is approached the fast wavespeeds are disrupted. A similar effect is seen in *S* wavespeed, but the slower wavespeeds are still slightly faster than the *ak135* reference model (Kennett et al., 1995).

Beneath the main Japanese Islands (Fig. 2) there are two arc junctions. The first, just south of Tokyo, brings the Izu-Bonin arc in contact with the main Honshu arc. The second, marked by the bend in the trench line near Hokkaido, links the Honshu arc to the Kurile arc. In each case the current configuration of the trench is much shorter than in the past, based on the distribution of fast seismic wavespeeds at depth (Miller and Kennett, 2006), and so there is a volumetric discrepancy between trench influx and the situation at depth.

A localised zone of diminished wavespeed anomalies in the subducting Pacific plate beneath central Honshu has been recognised for some time, see, e.g. Miller et al. (2005). Obayashi et al. (2009) have undertaken a detailed study that correlates earthquakes with mechanisms indicating lateral tension and reflected converted phases observed on the dense Hi-net array to infer a tear in the subducting Pacific plate. The break in the *P* wavespeed anomalies in their tomographic images can be tracked from around 300 to 600 km depth. Obayashi et al. (2009) associate the tear with the bending of the Japan and Izu-Bonin segments of the subduction zone to the horizontal in the transition zone, to form a stagnant slab segment. The slight differences in arc orientation relative to the motion of the Pacific plate, mean that the directions of motion of the two slab segments differ. The differences in these motions will tend to maintain or even expand the tear against the downward motion of the Pacific plate. There has been substantial roll-back of the Pacific slab in the period from 30 to 17 Ma that is likely to have led to the laying down of slab material in the transition zone (van der Hilst and Seno, 1993). The configuration of the Pacific, Eurasian and Philippine plate triple junction has evolved significantly over the past 17 Ma with modest trench retreat to 8 Ma followed by trench advance (Miller and Kennett, 2006). The complex set of relative motions may well have helped to keep the tear active once it had formed.

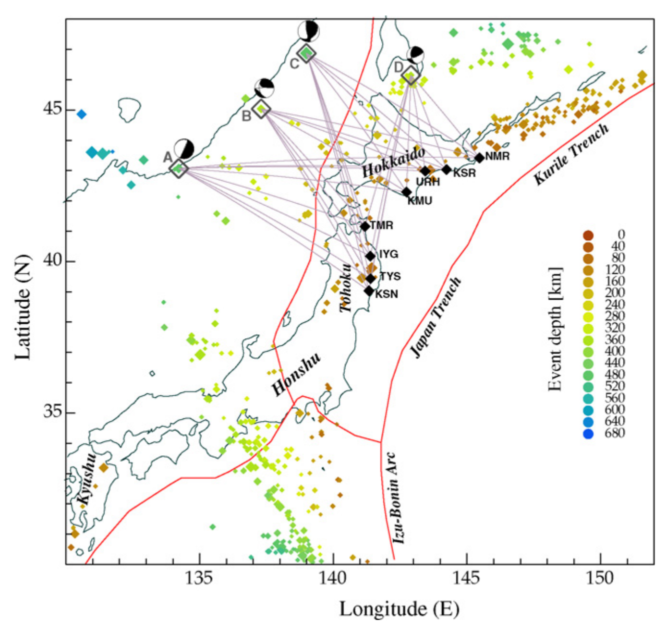

Fig. 2. The configuration of the main Japanese Islands and the major plate boundaries. Recent seismicity (1997–) with events of JMA magnitude 4.5 or greater is displayed with colour coding for depth and symbol size graded by magnitude. Four deep earthquakes (A–D) are indicated, with the focal mechanisms displayed beside the location symbols. The seismograms from these events at the marked set of broadband stations from F-net are analysed in Figs. 4 and 5. The great circle paths between the sources and broadband stations are indicated in light grey.

In addition to the slab tear beneath central Honshu, there is marked reduction in the wavespeed anomalies in the Pacific slab related to the Hokkaido corner between 300 and 500 km depth (see, e.g., Miller et al., 2005 using the tomographic model of Gorbatov and Kennett, 2003). The present configuration of the Pacific plate has been established by the retreat of the Japan arc since the mid-Miocene at a faster rate than along the Kurile arc where subduction is oblique (Miller and Kennett, 2006). The Japan and Kurile arc segments started to collide around 11 Ma. Ongoing collision is expressed in the uplift of the Hidaka Mountains in Hokkaido, and the major thrust earthquakes that continue to occur off-shore of southeastern Hokkaido. The subducting slab has a steeper dip (around 50°) beneath the Kurile arc, and there is a transition to a more gentle dip of around 35° for the Japan arc, with a complex slab geometry in this transitional zone (Miller et al., 2006). The tomographic imaging suggests that the subducting slab is somewhat thinner along the Kurile arc than beneath northern Honshu, but some slab thickening may accompany the arc collision.

The configuration of seismicity near the Hokkaido bend is consistent with an abrupt change in the dip of the slab leading to a relatively sharp crease in the upper surface of the subduction zone. This configuration is largely supported by the interpretation of the tomographic images. Recent seismicity is concentrated along the crease line, and in a further linear trend slightly further north. In each case the earthquakes extend to considerable depth within the slab. Obayashi et al. (2009) note that they see a slab gap in their *P* wave tomographic images near 42.5°N, 132°E, which lies at the end of the crease line. The earthquake focal mechanisms in this region indicate tensional axes parallel to slab-strike; this may well be a zone when a slab tear is in progress (Obayashi et al., 2009).

The deep earthquakes in the Pacific slab commonly produce high frequency wave arrivals at fore-arc stations along the eastern Japanese seaboard (Furumura and Kennett, 2005) that have been guided to the surface in the plate. The variation in the character of the seismograms at the fore-arc stations provides another means of mapping out variations in the nature of the subducting plate. As we shall see there is a close correspondence between changes in the seismograms and the zone of reduced tomographic contrast that suggests slab thinning rather than a major tear in the slab at the Hokkaido bend.

2. Tomographic imaging of the Pacific slab beneath Japan

We build on the regional seismic tomography of Gorbatov and Kennett (2003) with joint inversion for bulk-sound speed and shear wavespeed using *P* and *S* arrival times from common source-receiver pairs, supplemented by a *P* wave model derived from the same data (Miller et al., 2006). The arrival times were extracted from an updated version of the EHB catalogue (Engdahl et al., 1998) with the *ak135* model (Kennett et al., 1995) as reference, yielding a total of 900,000 ray paths. The regional model is represented with a 19-layer model using 0.5° × 0.5° cells in the uppermost man-

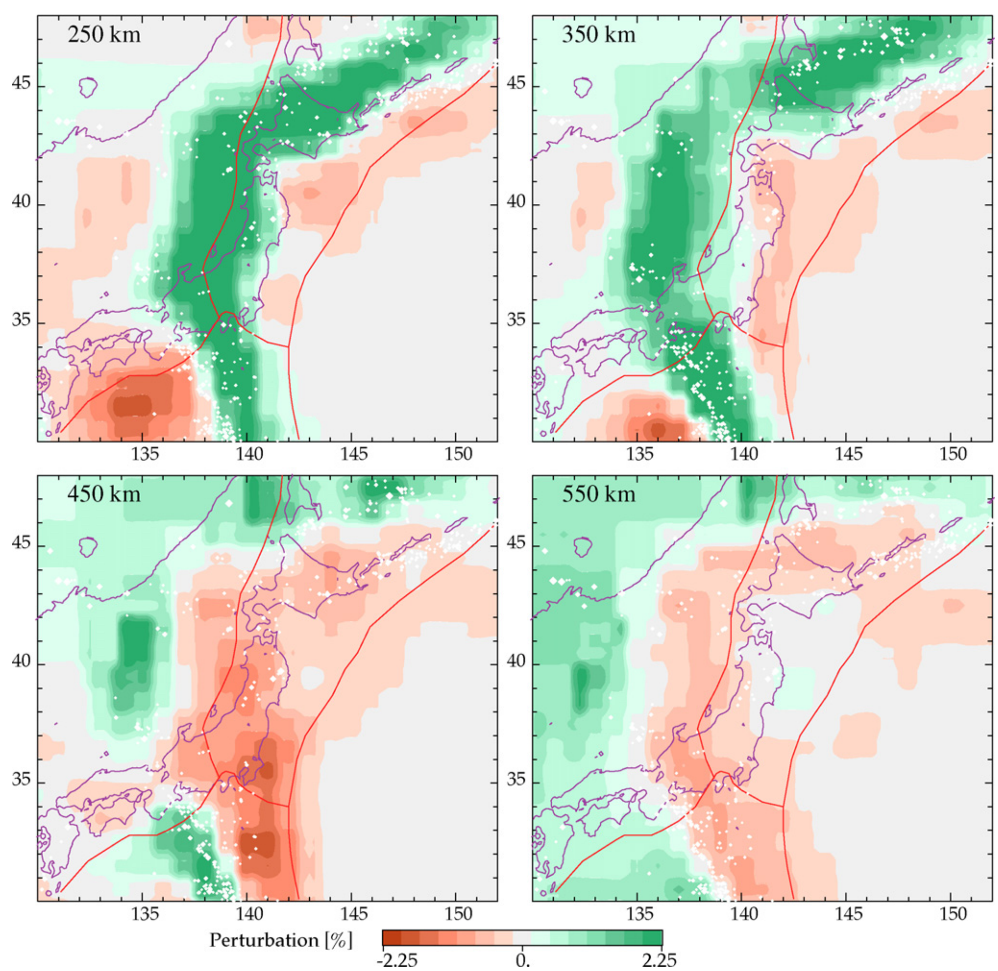

Fig. 3. Map views of depth slices through the shear wavespeed tomographic model (Gorbatov and Kennett, 2003) for nominal depths of (a) 250 km, (b) 350 km, (c) 450 km, (d) 550 km, with recent seismicity superimposed with white symbols. The wavespeed perturbations are displayed relative to the *ak135* reference model (Kennett et al., 1995), for which cold subducted lithosphere appears fast and the surroundings slow. The continuous plate at 250 km breaks up into distinct pieces associated with the individual arcs at greater depth. The influence of the coarser cellular parameterisation at depth can also be seen.

tle, $1^\circ \times 1^\circ$ cells in the transition zone and lower mantle down to 1500 km. In sparsely sampled zones well away from the subduction zones $2^\circ \times 2^\circ$ were employed. The detailed regional model is embedded in a 16-layer global model with $5^\circ \times 5^\circ$ cells that compensates for the structure outside the region of interest. The first stage is separate *P* and *S* inversions with iterated 3D ray tracing to improve the representation of gradients and strong variations in wavespeed. This pair of independent inversion is followed by a second-stage joint inversion for bulk-sound speed and shear wavespeed using the ray paths through the *P* and *S* models.

The density of path coverage in the vicinity of the Japanese Islands is very high (see, e.g., Fig. 3 in Miller et al., 2006), with the result that expected resolution is good at the 100 km scale needed to represent subduction zone structure. The use of 3D ray tracing sharpens the contrasts and definition of the subducted plate structure.

Fig. 3 shows four depth slices through the *S* wavespeed model that illustrate the disruption of the continuous slab into a set of isolated patches of enhanced wavespeed as the depth increases. The elements of the Kurile, Japanese and Izu-Bonin arcs have clearly defined orientations recognisable through the zones of highest wavespeeds. The transitional zone between the arc segments below 350 km is marked by reduced wavespeeds. The southern zone beneath central Honshu corresponds to the tear identified by Obayashi et al. (2009) from their *P* wave tomography, using a somewhat different dataset. There is close correspondence in the definition of the tear between the different studies, but the contrasts in wavespeed are somewhat larger in the shear wavespeed images in Fig. 3. The presence of tensional earthquake mechanisms in the zone of lower wavespeed and distinct *P* to *S* converted phases point to a tear in the subducting Pacific plate (Obayashi et al., 2009).

In the north, behind the Hokkaido bend, the transitional zone between the Honshu and Kurile arcs is just as distinct but more extended. This zone can also be seen distinctly in the vertical sections presented in Fig. 4 of Obayashi et al. (2009). There is slightly lower ray path coverage in the northeast of the displayed region compared with the south, but this cannot produce the selective suppression of the wavespeed anomaly seen in Fig. 3. The reduction in wavespeed is just as large as in the south, and the images are suggestive of another tear in the plate. Indeed there are distinctive patterns of focal mechanisms for seismic events along the flanks of the transitional zone, but not with tensional behaviour.

However, a suppression of a tomographic signal does not by itself require the presence of a slab tear. We have to remember the nature of tomographic imaging using a representation based on voxels, which imposes volume averaging of wavespeed anomalies over cells. If we have a thinner plate with only part of the slab occupying particular cells, then the apparent wavespeed anomaly in the cell will be reduced. When the source and station distribution is favourable, we can distinguish between the case of a break in the slab and a continuous but thinned slab by examining the characteristics of seismic waves transmitted through the transitional region.

3. Seismic wave propagation from deep earthquakes

Deep earthquakes near Hokkaido are characterised by large amplitude high frequency arrivals with sustained coda at fore-arc stations along the Japanese coast (Furumura and Kennett, 2005). The detailed character of these arrivals depends on the position of the source in the subduction zone and can be exploited to examine the nature of the subduction zone itself. The subducted material has higher velocities than its surroundings and so would be expected to act as an anti-waveguide and to shed high frequency energy. Some component of trapping will occur in the lower velocity region at the top of the slab associated with the former oceanic crust but this mechanism is not available for deep events. It is however possible to sustain strong high frequency energy from events as deep as

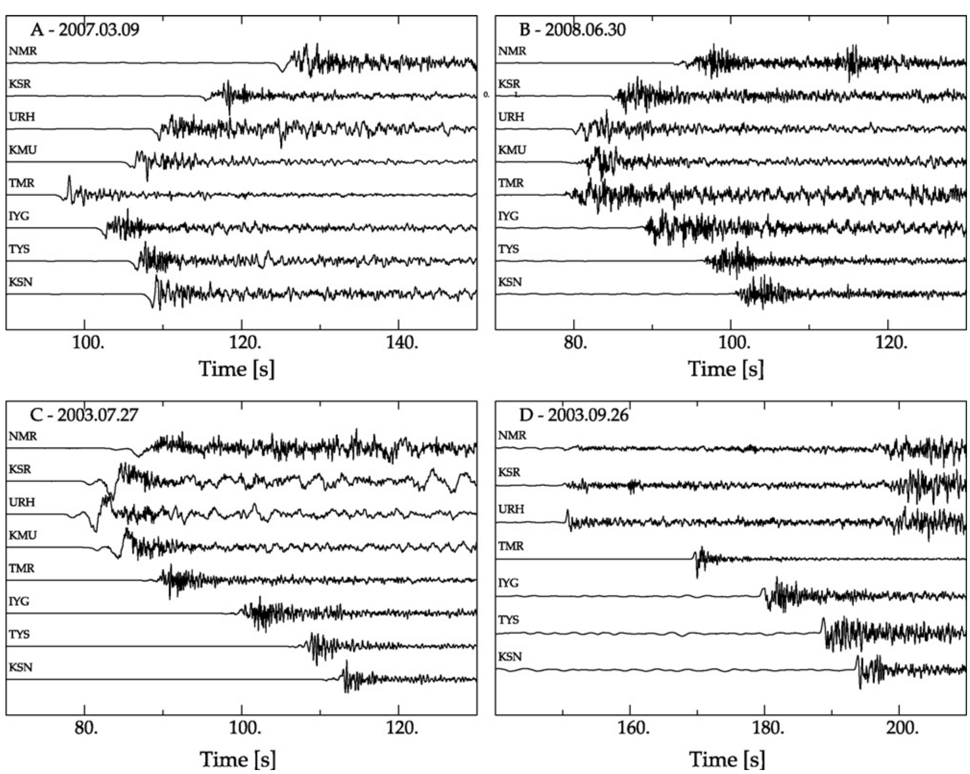

Fig. 4. Unfiltered broadband seismograms for the *P* wavetrain from the set of deep events indicated in Fig. 2 recorded at fore-arc stations on the Japanese eastern seaboard. Paths through the Kurile arc slab show a distinctive lower frequency signature with high frequencies riding on top (e.g. event C to stations NMR, KSR, URH and to some extent KMU). In contrast paths through the Honshu arc slab have strong high frequency coda (event A at stations IYG, TYS, KSN). The character changes for paths through the transition region (event B to stations KSR, URH, KMU, TMR), but the efficient transmission of seismic energy suggests continuity of the subducted lithosphere.

Table 1
Event parameters and station locations for the paths indicated in Figs. 2 and 5, for which seismograms are displayed in Fig. 4.

Event	Origin time (JST)	Mw	Latitude (E)	Longitude (N)	Depth (km)
A	2007/03/09, 12:22	6.20	134.2898	43.0145	580
B	2008/06/30, 05:53	5.80	137.4288	44.9845	420
C	2003/07/27, 15:25	7.10	139.1515	46.8177	520
D	2003/09/26, 13:44	5.30	143.1327	46.0945	400

Station	Latitude (E)	Longitude (N)	Height (m)	
NMR	43.3673	145.7379	20	Nemuro
KSR	42.9820	144.4851	18	Kushiro
URH	42.9298	143.6711	75	Urahoro
KMU	42.2391	142.9625	185	Kamikineusu
TMR	41.1016	141.3831	120	Tomari
IYG	40.1217	141.5833	427	Yamagata
TYS	39.3772	141.5932	346	TonoYamasaki
KSN	38.9762	141.5301	260	Kesennuma

600 km with a stochastic waveguide with heterogeneities that are elongated down-slab but rather narrow relative to slab thickness (Furumura and Kennett, 2005, 2008). For a thinner slab such as the Philippine plate subduction beneath Kyushu there is a shift towards lower frequency trapping compared with a thick slab such as the Pacific plate beneath Honshu (Furumura and Kennett, 2008).

The advent of broadband seismic recording has meant that the subtleties in seismic waveforms are preserved and so it is possible to exploit seismograms to examine the difference between different classes of paths. In Fig. 4 we compare the *P* wave seismograms for eight F-net stations along the eastern coast of Japan for four deep earthquakes with paths that span the Hokkaido bend (Fig. 2). These broadband seismic stations lie in the fore-arc region and commonly display high frequency arrivals from intermediate and deep events. The locations of these selected deep events, their focal mechanisms, and the propagation paths to the coastal stations are indicated in Fig. 2; the event and station parameters are given in Table 1. We see that the paths provide good coverage of the transitional region between the Honshu and Kurile arcs at the Hokkaido bend.

The F-net stations have very similar instrument characteristics and so we employ unfiltered records in the comparison of the different events in Fig. 4. We use a 60 s window for vertical motion broadband seismograms including the full *P* arrival that allows us to make useful comparisons of the character of the various seismograms, and display normalised seismograms since there is some site related variability in amplitudes.

The southernmost event A lies on the crease line in the configuration of the slab suggested by the historical seismicity. Relatively high frequency *P* wave arrivals are seen at most stations, but we note that the records at KMU and TMR show some loss of higher frequency *P* wave energy. Propagation of high frequencies for P waves is very clear to NMR, KSR and URH.

Event B lies in the midst of the transitional zone. There is a distinct change in the character of the seismograms to the central group of stations URH, KMU, TMR with a sustained coda, but somewhat less high frequency content than the stations to either side. The subtle loss of higher frequencies is what is expected from modelling studies for stochastic guided waves in a thinner plate (Furumura and Kennett, 2008).

Event C lies to the north of the main transition zone seen in the tomographic images, and the seismograms show a rather different character. There are still high frequency *P* arrivals across the full set of stations but pronounced low frequency onsets to stations in Hokkaido (NMR, KSR, URH, KMU). The paths through the Kurile slab have a relatively high level of low frequencies throughout the records; a similar feature, though weaker, is seen for the Hokkaido stations from event D. We can see a clear evolution in the character of the *P* arrivals for the stations in Honshu (TMR, IYG, TYS, KSN) with, in each case, an extended high frequency *P* wave coda.

Event D to the south of Sakhalin is a little shallower than the other events, but provides a useful control on direct propagation through the Kurile slab to stations NMR, KSR and URH. The relatively oblique paths to the stations in Honshu show very clear propagation of high frequencies for *P* waves.

The propagation features seen in the *P* waves are also displayed for *S* waves, with some modulation from the radiation patterns imposed by the focal mechanisms, as can be seen in Fig. 5 that displays a 160 s window including both *P* and *S* arrivals. As discussed by Furumura and Kennett (2005) an initial low frequency onset followed shortly by a much higher frequency arrival is what is to be expected for stochastic guided waves trapped in a heterogeneous slab.

The paths from the set of selected events that show distinct contrasts in character are event A to KMU, TMR and event B to URH, KMU, TMR. This group of paths traverse the zone where there are reduced wavespeed anomalies as can clearly be seen when the propagation paths are superimposed on the tomographic image as in Fig. 6, where we use the depth slice at 400 km. The efficient propagation of medium to higher frequency waves with a long duration to all stations from the selected events suggests continuity of the slab, but the loss of the highest frequencies through the centre of the transitional zone would be consistent with a thinned slab.

The seismograms for the deep events show some clear path effects in such features as the time interval between the low frequency onset and the higher frequency guided wave energy indicating that a complex pattern of 3D propagation is taking place. Much more effort will be needed to unravel the full complexity of the structure in this region.

4. Discussion and conclusions

Although the tomographic images for the main Japanese Islands show distinctly lowered wavespeed in both the transitional zones between the Izu-Bonin/Honshu arcs and the Honshu/Kurile arcs only in the southern zone beneath central Honshu is there evidence of a slab tear. In the northern transitional region the efficient propagation of medium to high frequency seismic waves implies continuity of the subducted material. The seismograms are consistent with a thinned slab which would also be expected to be expressed in the tomographic images by reduced contrast since the volumetric wavespeed anomaly in any cell would be less.

Tears and other disruptions to subducted slabs have received considerable attention of late, (e.g., Sigloch et al., 2008). Yet the behaviour at the Hokkaido bend requires other modes of deformation of the slab, more like the stretching of an elastic sheet.

Interpretations of tears are generally made from tomographic images without the benefit of auxiliary seismological information. For the central Honshu tear, the presence of converted phases and distinctive focal mechanisms reinforces the interpretation. Similarly the sub-horizontal tear zone in the Southern Izu-Bonin region links to seismicity and focal mechanism patterns. In contrast the northern transitional zone at the Hokkaido bend in the trench line for the Pacific plate has similar tomographic features, but the seismological evidence points in the direction of a continuous but thinned slab.

Care must therefore be taken in the interpretation of tomographic images of subduction, particularly when images are only available for a single wavespeed, usually *P* waves. The assumptions of the tomographic approach must be borne in mind, the model is usually cellular and variations of volumetric contrast from absence of slab material or thinning shared across several cells have a very similar effect. The use of ratios of wavespeeds, e.g.,

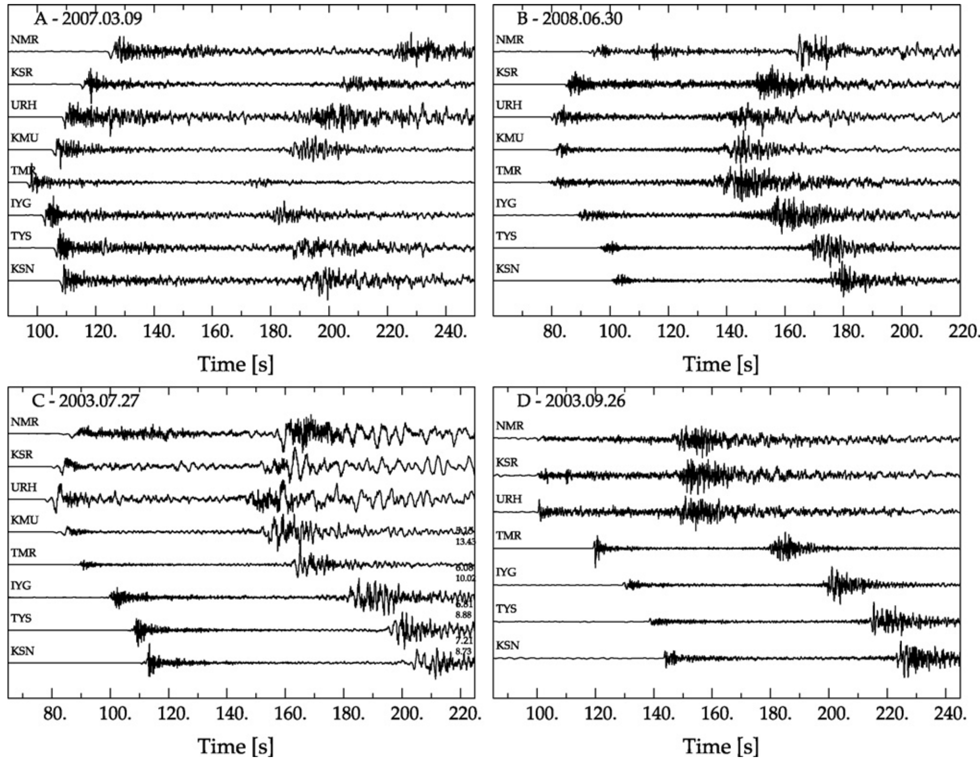

Fig. 5. Unfiltered broadband seismograms for the *P* and *S* wavetrains from the set of deep events indicated in Fig. 2 recorded at fore-arc stations on the Japanese eastern seaboard. The behaviour of the *S* waves mirrors that seen for *P* in Fig. 4, with some modulation of amplitudes due to the focal mechanisms of the deep events. Once again there is a change in character for the paths from event B to stations KSR, URH, KMU, TMR compared with the other stations, and for event A to KMU and TMR.

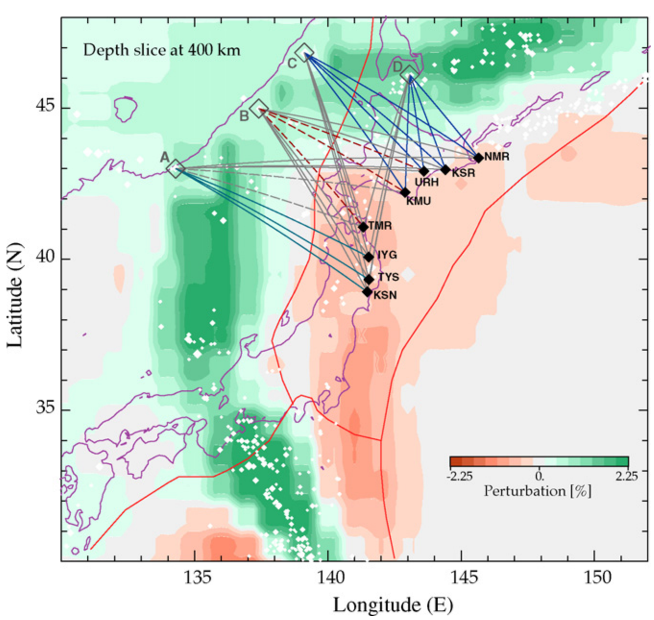

Fig. 6. Propagation paths from the four deep earthquakes in grey superimposed on the shear wavespeed tomographic image at 400 km depth. The group of distinctive seismograms from event B shown with red dashed lines correspond directly to the transitional zone between the clear subducted slabs. The reduction in the wavespeed anomalies is thus consistent with thinning of the subducted slab. The paths in the Honshu slab from event A are indicated with cyan toned lines and the paths in Kurile slab from events C,D with blue toned lines. The two paths from event A with some loss of high frequencies are indicated with long dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

between bulk-sound and shear wavespeed, provides an effective way of recognising changes in the physical properties of a subducted slab in the physical properties of a subducted slab (Miller et al., 2005; Kennett and Cummins, 2005). Such changes in physical properties in the shallow part of a subduction zone can have a significant influence on the way in which major events develop in the seismogenic zone (Kennett and Cummins, 2005).

Mere reduction in wavespeed contrast in a tomographic study should not be used as evidence for the presence of a tear in a slab unless corroborated by other classes of geophysical evidence.

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