Final report on EQC Project BIE 08/549 – Quantifying the hazard from New Zealand's shallow intraslab earthquakes

by Martin Reyners, Donna Eberhart-Phillips and John Ristau

GNS Science, Lower Hutt

March 2010

TECHNICAL ABSTRACT

We investigate the habitat of large intraslab earthquakes shallower than 50 km in the shallow part of the Hikurangi subduction zone in New Zealand by relocating such earthquake sequences which occurred during the period 1942-2008, using a new three-dimensional seismic velocity model. Three of the largest intraslab earthquakes coincided in space and time with large earthquakes in the overlying plate or significant slow slip at the plate interface. We find that faults get larger with increasing depth (and increasing seismic velocity) below the plate interface. We also find that average stress drops, as estimated from aftershock zone dimensions, decrease with increasing depth below the plate interface. Given that fault slip inversions suggest high stress drops for deeper intraslab events, our results suggest a model where these earthquakes involve rupture of a localized asperity (the locus of dehydration embrittlement) on an otherwise weak, reactivated fault. This model explains why aftershocks for such events are sparse, and die out very quickly.

We also use the distribution of these larger intraslab earthquakes to test a model derived from small earthquakes that suggests that intraslab seismicity may be modulated by the state of coupling of the overlying plate interface. The spatial distribution of the larger intraslab earthquakes appears consistent with this model. An important seismic hazard implication of this is that there may be a time-dependence of large intraslab events related to plate coupling. If a large rupture on the strongly coupled part of the plate interface allows the egress of fluid from the subducted slab, this may stimulate previously suppressed intraslab earthquakes.

LAYMAN'S ABSTRACT

One of the major challenges in modelling seismic hazard is how to deal with hidden faults – that is, those with no surface expression. This is especially so in subduction zones, where earthquake faulting can occur not only in the overlying plate and at the plate interface, but also within the lower subducted plate. In recent years, there has been a growing appreciation that faults in the subducted plate can contribute significantly to the seismic hazard in the shallow parts of subduction zones. Because the shallow part of the Hikurangi subduction zone underlies or is close to the east coast of the North Island of New Zealand, it is important to quantify the hazard that such faults pose to population centres in this region.

Here we use new results on the three-dimensional structure of the Hikurangi subduction zone determined from seismic tomography (the earthquake wave equivalent of a medical CAT scan) to better define larger faults in the crust of the subducted Pacific plate. We look at faults that moved in eight large earthquakes, from the magnitude 6.8 Wairarapa earthquake in August 1942 through to the magnitude 5.5 Hastings earthquake in August 2008. We find that faults in the subducted plate get larger with increasing depth below the plate interface. These larger faults were formed when the subducted plate began to bend at the offshore trench. The faults initiates at rough spots on the fault where a geochemical process known as dehydration embrittlement takes place. This model explains why aftershocks for such events are sparse, and die out very quickly.

Our modelling of these faults in the subducted plate provides an explanation for the type of shaking that earthquakes on the faults produce at the surface. In addition, the distribution of these larger earthquakes in the subducted plate is consistent with a model derived from small earthquakes that suggests that seismicity in the subducted plate may be modulated by the state of locking of the overlying plate interface. In other words, this study has given us a better understanding of how, why and where larger earthquakes will occur in the subducted plate at the Hikurangi subduction zone. It provides important new information for refining seismic hazard models in this region.

RESULTS

The results of this project have been summarized in a paper, as requested by EQC. This paper was submitted to the international journal *Earth, Planets and Space* on 17 March 2010. A copy of the submitted manuscript follows.

The habitat of large shallow intraslab earthquakes in New Zealand

Martin Reyners¹, Donna Eberhart-Phillips^{1,2}, and John Ristau¹

¹GNS Science, Lower Hutt, New Zealand ²University of California Davis, USA

Abstract

We investigate the habitat of large intraslab earthquakes shallower than 50 km in the shallow part of the Hikurangi subduction zone in New Zealand by relocating such earthquake sequences which occurred during the period 1942-2008, using a new three-dimensional seismic velocity model. Three of the largest intraslab earthquakes coincided in space and time with large earthquakes in the overlying plate or significant slow slip at the plate interface. We find that faults get larger with increasing depth (and increasing seismic velocity) below the plate interface. We also find that average stress drops, as estimated from aftershock zone dimensions, decrease with increasing depth below the plate interface. Given that fault slip inversions suggest high stress drops for deeper intraslab events, our results suggest a model where these earthquakes involve rupture of a localized asperity (the locus of dehydration embrittlement) on an otherwise weak, reactivated fault. This model explains why aftershocks for such events are sparse, and die out very quickly. We also use the distribution of these larger intraslab earthquakes to test a model derived from small earthquakes that suggests that intraslab seismicity may be modulated by the state of coupling of the overlying plate interface.

Key words: Intraslab earthquake, dehydration embrittlement, asperity, New Zealand

1. Introduction

One of the major challenges in modelling seismic hazard is how to deal with hidden faults – those with no surface expression. This is especially so in subduction zones, where earthquake faulting can occur not only in the overlying plate and at the plate interface, but also within the subducted lithospheric slab itself. In recent years, there has been a growing appreciation that such intraslab events can contribute significantly to the seismic hazard in the shallow parts of subduction zones. For example, in the Cascadia subduction zone the hazard posed by large intraslab earthquakes is nearly equal to that from other seismic sources for timescales relevant to retrofitting (Ichinose *et al.*, 2006).

Because the shallow part of the Hikurangi subduction zone underlies or is close to the east coast of the North Island of New Zealand (Fig. 1), it is important to quantify the hazard that shallow intraslab earthquakes pose to population centres in this region. This shallow subduction zone has the advantage that we have good control on seismicity from land-based seismographs. In recent years we have exploited this advantage to derive detailed three-dimensional (3-D) tomographic models for physical properties in different regions of the subduction zone, including seismic velocities (Vp and Vp/Vs) and seismic attenuation (Qp) (e.g. Eberhart-Phillips *et al.*, 2005, 2008; Reyners *et al.*, 1999, 2006). To understand the subduction zone as a whole, these regional seismic velocity models have now been stitched together to produce a nationwide 3-D seismic velocity model (Eberhart-Phillips *et al.*, in prep.).

What this compilation emphasizes is the unusual nature of the subducted Hikurangi Plateau crust, with Vp > 8.5 km/sec at relatively shallow depth in the subducted slab (Figs. 2, 3). The Hikurangi Plateau was formed as part of the largest oceanic plateau on Earth, the Ontong Java Plateau, ca. 122 Ma ago (Neal et al., 1997). At ca. 120 Ma ago, the Hikurangi and Manihiki plateaux rifted from Ontong Java, and the Hikurangi Plateau arrived at its present position after later rifting from the Manihiki Plateau (Taylor, 2006). Seismic reflection and sonobuoy wide-angle reflection/refraction measurements indicate that the crustal structure of the Ontong Java Plateau resembles that of normal Pacific oceanic crust, but each layer is abnormally thickened by up to a factor of five (Furumoto et al., 1976; Hussong et al., 1979). As a result, the crustal thickness of the plateau ranges from 35-42 km. On the central and western parts of the plateau, lower crustal Vp is rather high at 7.6-7.7 km/s, consistent with the lower crust lying within the granulite stability field. Also, unusually high sub-Moho Vp of 8.4-8.6 km/s has been detected in the northwest and southwest portions of the plateau (Neal et al., 1997), suggesting the onset of eclogitisation of the lowermost crust. Deformation can markedly enhance the rates of equilibration, as well as greatly facilitating the access of fluids, so it may be that collision of the plateau with a continental margin will further trigger the transformation to eclogite and promote subduction (Saunders et al., 1996).

So the extensive regions of Vp > 8.5 km/sec that we image in the subducted plate along the shallow part of the Hikurangi subduction zone are consistent with Hikurangi Plateau subduction, with extensive eclogitisation of its lower crust. This produces a very strong gradient in Vp within the subducted crust. Here we investigate what this structure means for seismogenesis. We do this by relocating larger intraslab earthquake sequences, using the new 3-D nationwide seismic velocity model, and relating them to Vp in the rupture zone. We also test a model derived from small earthquakes that suggests that intraslab seismicity may be modulated by the state of coupling of the overlying plate interface (Reyners and Eberhart-Phillips, 2009).

2. Large shallow intraslab earthquakes in the Hikurangi subduction zone

We have relocated large shallow (depth less than 50 km) intraslab earthquake sequences which occurred during the period 1942 – 2008. The relocations were done using the 3-D nationwide seismic velocity model and the 3-D inversion code, run in a mode for single event locations with fixed velocity. As we are also interested in the relationship between these large events and background seismicity, we have also relocated background seismicity occurring during the period 2001 January – 2009 June using the same method. Background events during the period 2007 May – 2008 June are not included, as final phase readings for earthquakes during this period are not yet available. As accurate earthquake depths are important in determining in which plate the events are occurring, we only retain background events for which the distance to the nearest seismograph is less than twice the earthquake depth. This means that we exclude some shallow events in offshore areas. Both the relocated large intraplate earthquake sequences and relocated background seismicity are more clustered and have more reliable depths than in previous studies using 1-D models. Importantly, both seismicity distributions can now be directly related to the 3-D seismic velocity structure.

Details of the relocated large intraslab events are given in Table 1, and locations and focal mechanisms are shown in Fig. 1. Mechanisms range from normal to strike-slip. Further details on the individual events follow:

2008 Hastings earthquake: This relatively small M_w 5.5 event produced a rich aftershock sequence, which was well recorded by the recently upgraded GeoNet seismograph network. The relocated aftershocks form a tight cluster 5 km across.

2007 Gisborne earthquake: This $M_w 6.6$ event caused structural damage in the city of Gisborne, where peak ground accelerations of around 0.2g were recorded. Details of preliminary studies of the earthquake have been summarized by Francois-Holden *et al.* (2008). While the offshore area where the earthquake occurred is outside the best resolved part of the nationwide 3-D seismic velocity model (Fig. 2), the model in that region is still reasonable due to linking of nodes during the inversion. The earthquake produced sparse but widespread aftershocks (Fig. 2), resulting in an aftershock zone of over 500 km². In contrast, inversion of strong motion data from 12 GeoNet sites suggests that the main slip pulse occurred over a much smaller 6 x 10 km² area, where the maximum slip reached 6.5 m and a stress drop of 17 MPa is indicated. The earthquake was followed by a slow slip event on the subduction interface, which started on the same day as the earthquake. The downdip edge of the southern half of the slow slip region abutted the aftershock zone. The slow slip lasted about 57 days with faster moment release early on and then tailing off. The average slip was about 120 mm over an area of 2450 km², equivalent to $M_w 6.7$.

2005 Upper Hutt earthquake: This small M_w 5.3 intraslab event is included here because a special study by Reyners and Bannister (2007) has provided insight into the environment in which it occurred. The event was preceded by an earthquake swarm nine months earlier. Double-difference relocation indicates that the swarm represents incremental slip on adjacent patches of the same fault. The subsequent 2005 event occurred on a separate, deeper fault, sub-parallel to that of the swarm, but separated from it by about 1 km. This suggests a rapid decrease in mechanical damage in the slab with depth below the plate interface.

1993 Ormond earthquake: This M_w 6.2 event also caused structural damage in the Gisborne region, with a maximum recorded peak ground acceleration of 0.26g. A special study of the aftershock sequence of this earthquake has been carried out by Reyners *et al.* (1998), using data from portable seismographs deployed immediately after the mainshock. Like the 2007 Gisborne earthquake, the aftershock zone is rather large (Fig. 2). Also, aftershocks in the deeper part of the subducted Hikurangi Plateau crust decayed exceptionally rapidly compared with those near the plate interface. Focal mechanisms of aftershocks near the plate interface indicate that compression along strike dominates over slab pull, and that the down-dip stress has a similar magnitude to the vertical stress. This suggests that, at least after the Ormond earthquake, the tectonic stress coupled across the plate interface is rather low. This finding is consistent with recent estimates of the slip rate deficit at the plate interface in this region (Fig. 1).

1990 Weber earthquake: This M_w 6.2 event caused relatively minor damage in the rural epicentral region. It was followed some three months later by an M_w 6.4 earthquake in the overlying plate, with a nearly coincident epicentre. Both these earthquake sequences have been studied in detail by Robinson (1994, 2003) using data from both permanent and portable seismographs. The first event involved a mix of normal and strike-slip faulting in the subducted Hikurangi Plateau (Fig. 1), while the second involved a mix of thrusting and strike-slip motion in the overlying Australian plate. There was no seismicity at the plate interface between these earthquake sequences. The coincidence of these two events in space and time is suggestive of a 'fault-valve' episode involving upward migration of fluids (e.g. Sibson, 2007),

with such fluids crossing the plate interface. Coupling at the plate interface is moderately weak in this region (Fig. 1). So these two earthquakes appear consistent with the model of Reyners and Eberhart-Phillips (2009) that coupling is weak where fluid can cross the plate interface.

1985 Tiniroto earthquake: This M_w 5.9 earthquake sequence has previously been studied by Bannister *et al.* (1989), using the joint hypocentre determination method for locating aftershocks recorded on portable seismographs. Aftershocks relocated using the new 3-D nationwide seismic velocity model reveal an even tighter aftershock distribution, and confirm that the earthquake involved normal motion on a high-angle fault in the subducted Hikurangi Plateau (Fig 1).

1977 Cape Campbell earthquake: This M_w 6.0 earthquake had a sparse aftershock sequence, with only two aftershocks (M_L 4.7, 3.5) recorded on the permanent seismograph network in the 24 hours following the mainshock. While this sequence is insufficient to define an aftershock zone, the distribution of relocated earthquakes suggests updip directivity on the low angle plane of the normal faulting focal mechanism (Fig 1).

1942 Wairarapa earthquake: This M_w 6.8 earthquake was preceded by an M_w 6.9-7.2 event five weeks earlier on June 24. Both these earthquakes strongly shook the southern North Island, causing widespread moderate to severe damage (Downes et al., 2001). Relocation using the nationwide 3-D model results in well-determined hypocentres for both earthquake sequences (Fig. 3). This contrasts with previous hypocentre determinations using a 1-D model, where depths had to be restricted (Downes et al., 2001). This suggests that neglect of crustal heterogeneity, rather than sparse station spacing alone, has been a major impediment in getting good hypocentres for these early events. Both mainshocks were preceded by foreshocks – the June mainshock by an M_L 5.3 event three hours earlier at 9 km depth in the eventual aftershock zone, and the August mainshock by an M_w 5.6 foreshock in the top of the subducted plate eight hours earlier and 50 km to the northeast. Our relocations confirm that the June sequence was restricted to the overlying Australian plate, and the August sequence was restricted to the subducted Hikurangi Plateau crust, with no indication of significant activity at the intervening plate interface. The coincidence of these two events in space and time suggests similarities with the 1990 Weber earthquakes, except that this time the event in the overlying plate happened first. Aftershocks for the August event were sparse, with only two locatable events (M_L 4.4, 4.5) in the following five days. Again, we cannot define an aftershock zone for this intraslab event, but the distribution of relocated earthquakes suggests that the mainshock involved motion on the high angle plane of the normal faulting focal mechanism (Fig 1).

Details of these relocated earthquakes are summarized in Table 1. In determining rupture length and area, we have assumed that the aftershock zone gives a good representation of the rupture zone. The only event for which we have a preliminary source inversion (the 2007 Gisborne earthquake; Francois-Holden *et al.*, 2008), suggests that this assumption is reasonable. Also, detailed study of the source processes of large intraslab earthquakes elsewhere suggests that the spatial extent of the rupture area is broadly consistent with the aftershock area (e.g. Okada and Hasegawa, 2003). Aspect ratios of the resulting ruptures average 1.3, and we have assumed circular rupture in estimating the average stress drop across each rupture. Plots of M_w and average stress drop against Vp at the centroid of the aftershock zones are shown in Fig 4. As Vp increases with depth from the plate interface D (Figs. 2, 3), plots of M_w and average stress drop against D are similar.

3. Discussion

Figure 4a shows a clear trend of M_w increasing as Vp increases with depth in the subducted Hikurangi Plateau crust. In other words, faults get larger with depth from the plate interface. This result expands on those of Wang *et al.* (2004) and Smith *et al.* (2004), which found that larger events tend to occur deeper within the slab. Numerical modelling of strain associated with plate bending at the outer rise suggests a similar trend. For example, Faccenda *et al.* (2009) show that these high strains become localized on larger and more widely spaced faults deeper in the slab. Evidence for the creation of such large faults comes from large outer rise events such as the M_w 8.1 Kuril earthquake of 13 January 2007, which involved extensional faulting to ~29 km depth within the Pacific slab (Lay *et al.*, 2009). It is presumably these larger faults that are reactivated by larger earthquakes such as the Gisborne, Ormond and Wairarapa events.

In contrast to M_w , average stress drop decreases as Vp increases with depth in the subducted Hikurangi Plateau crust (Fig. 4b). At first glance, this result appears inconsistent with the common observation that intraslab events have high stress drops. For example, from a global survey Choy and Kirby (2004) find that the average apparent stress of intraslab normal-fault earthquakes is considerably higher than that of interplate thrust-fault earthquakes. These authors suggest that this reflects the fact that intraslab faults are less mature, having accumulated less slip during their lifetime. Our results suggest an alternative explanation, namely that of very high stress drop asperities on larger faults. For example, while aftershocks of the Gisborne earthquake rupture zone suggest a total rupture area of about 572 km², strong motion inversion suggests that most slip occurred on a 60 km² patch which generated a stress drop of 17 MPa (Francois-Holden *et al.*, 2008). This finding is consistent with the suggestion of Ichinose *et al.* (2006) that deeper intraslab earthquakes have a significantly smaller combined area of asperities than those compiled for shallower strike-slip earthquakes of the same seismic moment.

Furthermore, the fact that average stress drop decreases as faults get larger with depth in the subducted Hikurangi Plateau crust suggests that there is some constraint on asperity size. We can understand this in terms of fluid processes within the subducted crust. It is now generally accepted that deeper seismicity within subducted slabs is due to dehydration embrittlement (e.g. Kirby *et al.*, 1996; Peacock, 2001). Deep faulting at the outer rise sets up conditions for downward pumping of fluids, which then react with the crust and mantle surrounding the faults and are stored in the form of hydrous minerals (Faccenda *et al.*, 2009). With increasing pressure and temperature upon subduction these hydrous minerals dehydrate. As water in its free form is highly incompressible, it exerts a counter pressure on the surrounding rocks, allowing them to behave in a brittle mode. Given that the pressure and temperature conditions conducive to dehydration are unlikely to exist everywhere at the same time on a large hydrated fault in the subducted crust, dehydration embrittlement is likely to be a localized process.

So what will be the frictional state of the rest of the fault? If dehydration has already occurred, pore pressures will be high, resulting in a weak fault. If dehydration has not yet occurred, the fault will still be serpentinized, which again suggests a weak fault (e.g. Hilairet *et al.*, 2007). So a viable model of the deeper faults in the subducted Hikurangi Plateau crust is that of an isolated asperity of limited size on an otherwise weak fault. As such an asperity carries the large shear load resulting from the increased confining pressure at depth, this logically leads

to higher static stress drop when it fails. And when it fails, rupture propagates into the surrounding weaker portions of the fault. If these lie in the conditionally stable frictional field, the rupture will die out smoothly. This provides an explanation for why these deeper intraslab earthquakes produce sparse aftershock sequences of short duration.

How do these intraslab earthquakes relate to coupling at the plate interface? Recently Reyners and Eberhart-Phillips (2009) have proposed a model where plate coupling is controlled by the ability of fluid to cross the plate interface. When the plate interface is impermeable, plate coupling is strong and the resulting fluid overpressures in the subducted plate impede dehydration reactions (Miller *et al.*, 2003; Perrillat *et al.*, 2005). This will result in the suppression of deeper intraslab earthquakes. So if this model is correct, larger intraslab earthquakes should only occur in regions where the plate interface is relatively uncoupled. This seems to be the case in the shallow part of the Hikurangi subduction zone, where larger intraslab events generally occur beneath uncoupled parts of the plate interface, or on the edge of more strongly coupled parts (Fig.1). But there are two exceptions – the 2005 Upper Hutt and 1942 Wairarapa earthquakes.

Both these events occurred after perturbations to the strongly coupled part of the plate interface in the southern North Island. The Upper Hutt earthquake (and the nearby earthquake swarm nine months earlier) was most likely triggered by slow slip on the plate interface further downdip (Revners and Bannister, 2007). Also, the occurrence of the M_w 6.9-7.2 strikeslip event in the overlying plate five weeks before and directly above the Wairarapa intraslab event may have changed fluid conditions at the plate interface. These Wairarapa earthquake sequences are located at the updip edge of a strong, relatively impermeable Permian-Triassic geological terrane which is thought to control strong plate coupling in the southern North Island (Reyners and Eberhart-Phillips, 2009). They occur near the updip limit of highly clustered small earthquake activity in the top of the subducted plate (Fig. 3), which is interpreted as an overpressured, fluid-rich region beneath the terrane. So the larger intraslab earthquakes relocated in this study are not inconsistent the idea that plate coupling may modulate the occurrence of such events. An implication of the 1942 Wairarapa earthquake sequences is that there might be a time-dependence of large intraslab events related to plate coupling. If a large rupture on the strongly coupled part of the plate interface allows the egress of fluid from the subducted slab, this may stimulate previously suppressed intraslab earthquakes.

Does the distribution of background seismicity give us any clues about where large intraslab events might occur? For example, from a detailed study of the 2003 M 7.1 intraslab earthquake of Miyagi in northeastern Japan, Sakoda *et al.* (2004) have suggested that high background seismicity in the uppermost mantle of the subducted slab may correspond to a region where rupture within the subducted crust can extend more easily, causing large intraslab events. We do not seem to see this same pattern of high background seismicity in the rupture zones of large earthquakes in the much thicker crust of the subducted Hikurangi Plateau. Rather, the most consistent feature that we see is that large intraslab events seem to occur near the edges of regions of high background seismicity in the uppermost subducted crust, as demonstrated by the Hastings, Gisborne, Ormond, Cape Campbell and Wairarapa earthquakes. This observation appears consistent with the model of Reyners and Eberhart-Phillips (2009), which suggests that clustering of background seismicity is largely controlled by the state of coupling of the overlying plate interface. When the plate interface is strongly coupled, fluid cannot cross the interface. This promotes clustered seismicity in the top of the slab, and suppresses the deeper dehydration embrittlement which leads to larger intraslab earthquakes. The edges of this clustered seismicity in the top of the slab presumably indicate regions where fluid can again cross the interface, allowing deeper dehydration embrittlement and larger intraslab earthquakes.

Our conceptual model of faulting within the subducted crust of the Hikurangi Plateau beneath the eastern North Island resulting from this study is shown in Fig. 5. This is a first step in better quantifying the hazard of shallow intraslab earthquakes in the New Zealand probabilistic seismic hazard model. It will need to be tested by further studies of earthquakes large and small. Whether this model also works in subduction zones where oceanic crust of normal thickness is being subducted also warrants further investigation.

Acknowledgments

Funding for this work was provided by the New Zealand Earthquake Commission (EQC) and the Marsden Fund administered by the Royal Society of New Zealand. Stephen Bannister and Bill Fry provided useful comments on the manuscript.

Figures

1. Map of the Hikurangi subduction zone showing focal mechanisms of the large historical intraslab earthquakes relocated in this study. Beachballs are labelled with the earthquake name as in Table 1, with the depth in km marked and the preferred fault plane from the distribution of aftershocks shown in bold. Focal mechanisms are from Doser and Webb (2003), Webb and Anderson (1998), and more recent regional moment tensor analysis (Ristau, 2008). Dashed lines are depth to the plate interface (labelled in km), and shading denotes the slip deficit rate at the plate interface (both from Wallace *et al.* 2009). The arrow shows the velocity of the Pacific plate relative to the Australian plate (DeMets *et al.*, 1994).

2. Map and depth section down the dip of the subducted plate of the relocated 2007 M_w 6.6 Gisborne (magenta pluses) and 1993 M_w 6.2 Ormond (orange diamonds) earthquake sequences in the northern Hikurangi subduction zone. The mainshock and first day of aftershocks are shown of each sequence. The P-wave seismic velocity (Vp) along section A-B from the 3-D model of Eberhart-Phillips *et al.* (in prep.) is shown, together with background seismicity during the period 2001 January – 2009 June relocated with this model. The dashed white line on the Vp section encloses the region where Vp resolution is the best.

3. Map and depth section down the dip of the subducted plate of the relocated 1942 June (magenta diamonds) and 1942 August (green squares) Wairarapa earthquake sequences in the southern Hikurangi subduction zone. For the June sequence, an M_L 5.3 foreshock which occurred at 9 km depth three hours before the M_w 6.9-7.2 mainshock, and first day of well-located aftershocks are shown. For the August sequence, an M_w 5.6 foreshock in the top of the subducted plate eight hours before and 50 km northeast of the M_w 6.8 mainshock is shown, together with two well-located aftershocks in the following five days. The P-wave seismic velocity along section A-B from the 3-D model of Eberhart-Phillips *et al.* (in prep.) is shown, together with background seismicity during the period 2001 January – 2009 June relocated with this model. The dashed white line on the Vp section is the lower limit of the region where Vp resolution is the best.

4. Plots of P-wave velocity (Vp) at the centroid of the aftershock zone against Mw (a), and average stress drop derived from aftershock zone dimensions (b). Intraslab earthquakes are labelled as in Table 1. As Vp increases with depth from the plate interface D, plots of M_w and average stress drop against D are similar.

5. Conceptual model of faulting within the subducted crust of the Hikurangi Plateau beneath the eastern North Island. The zigzag pattern denotes a strongly coupled portion of the plate interface, and high stress drop portions of larger faults deeper within the subducted plateau, which are interpreted as regions of dehydration embrittlement. Dashed faults are those beneath the strongly coupled portion of the plate interface on which dehydration embrittlement, and hence large earthquakes, may be suppressed. The shading indicates increasing seismic velocities with depth in the plateau. See text for details.

Table 1. List of large intraslab earthquakes relocated in this study. M_w determinations are from Doser and Webb (2003), Webb and Anderson (1998) and Ristau (2008). Rupture length (L) and area (A) are determined from the relocated aftershock zones, with ND indicating that there were insufficient well-located aftershocks to determine a rupture area. D in slab refers to the distance of the centroid of the aftershock zone from the plate interface, and Vp is the P-wave velocity at this centroid. Average $\Delta \sigma$ is the average stress drop assuming a circular rupture.

References

- Bannister, S. C., B. J. Perin, and T. H. Webb, Normal faulting through subducted oceanic crust; the 19 July 1985 earthquake of Hawke's Bay, New Zealand, *Tectonophysics*, 162, 303-313, 1989.
- Choy, G. L. and S. H. Kirby, Apparent stress, fault maturity and seismic hazard for normalfault earthquakes at subduction zones, *Geophys. J. Int.*, **159**, 991-1012, 2004.
- DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, 21, 2191-2194, 1994.
- Doser, D. I. and T. H. Webb, Source parameters of large historical (1917-1961) earthquakes, North Island, New Zealand, *Geophys. J. Int.*, **152**, 795-832, 2003.
- Downes, G. L., D. J. Dowrick, R. J. Van Dissen, J. J. Taber, G. T. Hancox, and E. G. C. Smith, The 1942 Wairarapa, New Zealand, earthquakes; analysis of observational and instrumental data, *Bull. N. Z. National Soc. Earthquake Engineering*, 34, 125-157, 2001.
- Eberhart-Phillips, D., M. Reyners, S. Bannister, M. Chadwick, and S. Ellis, Setting up a versatile 3-D seismic velocity model for New Zealand, *Seismol. Res. Lett.*, in prep.
- Eberhart-Phillips, D., M. Reyners, M. Chadwick, and J.-M. Chiu, Crustal heterogeneity and subduction processes: 3-D Vp, Vp/Vs and Q in the southern North Island, New Zealand, *Geophys. J. Int.*, **162**, 270-288, 2005.
- Eberhart-Phillips, D., M. Reyners, M. Chadwick, and G. Stuart, Three-dimensional attenuation structure of the Hikurangi subduction zone in the central North Island, New Zealand, *Geophys. J. Int.*, **174**, 418-434, 2008.
- Faccenda, M., T. V. Gerya, and L. Burlini, Deep slab hydration induced by bending-related variations in tectonic pressure, *Nature Geoscience*, **2**, 790-793, 2009.

- Francois-Holden, C., and 10 others, The Mw 6.6 Gisborne earthquake of 2007: preliminary records and general source characterisation, *Bull. N. Z. Soc. Earthquake Engineering*, 41, 266-277, 2008.
- Furumoto, A. S., J. P. Webb, M. E. Odegard, and D. M. Hussong, Seismic studies on the Ontong Java Plateau, 1970, *Tectonophysics*, 34, 71-90, 1976.
- Hilairet, N., and 6 others, High-pressure creep of serpentine, interseismic deformation, and initiation of subduction, *Science*, **318**, 1910-1913, 2007.
- Hussong, D. M., L. K. Wipperman, and L. W. Kroenke, The crustal structure of the Ontong Java and Manihiki oceanic plateaus, J. Geophys. Res., 84, 6003-6010, 1979.
- Ichinose, G. A., H. K. Thio, and P. G. Somerville, Moment tensor and rupture model for the 1949 Olympia, Washington, earthquake and scaling relations for Cascadia and global intraslab earthquakes, *Bull. Seismol. Soc. Am.*, **96**, 1029-1037, 2006.
- Kirby, S. H., E. R. Engdahl, and R. P. Denlinger, Intermediate-depth intraslab earthquakes and arc volcanism as physical expressions of crustal and uppermost mantle metamorphism in subducting slabs, *Geophysical Monograph*, **96**, 195-214, 1996.
- Lay, T., H. Kanamori, C. J. Ammon, A. R. Hutko, K. Furlong, and L. Rivera, The 2006 -2007 Kuril Islands great earthquake sequence, J. Geophys. Res., 114, B11308, doi:10.1029/2008JB006280, 2009.
- Miller, S. A., W. van der Zee, D. L. Olgaard, and J. A. D. Connolly, A fluid-pressure feedback model of dehydration reactions: experiments, modelling, and application to subduction zones, *Tectonophysics*, **370**, 241-251, 2003.
- Neal, C. R., J. J. Mahoney, L.W. Kroenke, R. A. Duncan, and M. G. Petterson, The Ontong Java Plateau, *Geophysical Monograph*, **100**, 183-216, 1997.
- Okada, T., and A. Hasegawa, The M7.1 May 26, 2003 off-shore Miyagi Prefecture earthquake in northeast Japan; source process and aftershock distribution of an intraslab event, *Earth Planets Space*, **55**, 731-739, 2003.
- Peacock, S. M., Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle? *Geology*, **29**, 299-302, 2001.
- Perrillat, J-P., I. Daniel, K. T. Koga, B. Reynard, H. Cardon, and W. A. Crichton, Kinetics of antigorite dehydration: a real-time X-ray diffraction study, *Earth Planet. Sci. Lett.*, 236, 899-913, 2005.
- Reyners, M., and S. Bannister, Earthquakes triggered by slow slip at the plate interface in the Hikurangi subduction zone, New Zealand, *Geophys. Res. Lett.*, **34**, L14305, doi:10.1029/2007GL030511, 2007.
- Reyners, M., and D. Eberhart-Phillips, Small earthquakes provide insight into plate coupling and fluid distribution in the Hikurangi subduction zone, New Zealand, *Earth Planet. Sci. Lett.*, **282**, 299-305, 2009.
- Reyners, M., D. Eberhart-Phillips, and G. Stuart, A three-dimensional image of shallow subduction: crustal structure of the Raukumara Peninsula, New Zealand, *Geophys. J. Int.*, **137**, 873-890, 1999.
- Reyners, M., D. Eberhart-Phillips, G. Stuart, and Y. Nishimura, Imaging subduction from the trench to 300 km depth beneath the central North Island, New Zealand, with Vp and Vp/Vs, *Geophys. J. Int.*, **165**, 565-583, 2006.
- Reyners, M., P. McGinty, and K. Gledhill, The Ormond, New Zealand, earthquake of 1993 August 10: rupture in the mantle of the subducted Pacific plate, N. Z. J. Geol. Geophys., 41, 179-185, 1998.
- Ristau, J., Implementation of routine regional moment tensor analysis in New Zealand, *Seismol. Res. Lett.*, **79**, 400-415, 2008.
- Robinson, R., Shallow subduction tectonics and fault interaction; the Weber, New Zealand, earthquake sequence of 1990-1992, *J. Geophys. Res.*, **99**, 9663-9679, 1994.

- Robinson, R., Fault interactions and subduction tectonics: a re-examination of the Weber, New Zealand, earthquake sequence of 1990, *Geophys. J. Int.*, **154**, 745-753, 2003.
- Sakoda, K., T. Okada, J. Suganomata, and A. Hasegawa, Upper plane seismicity of the double seismic zone beneath NE Japan and May 26, 2003, M7.1 off Miyagi earthquake, *Zisin*, 57, 187-198, 2004.
- Saunders, A. D., J. Tarney, A. C. Kerr, and R. W. Kent, The formation and fate of large oceanic igneous provinces, *Lithos*, **37**, 81-95, 1996.
- Sibson, R. H., An episode of fault-valve behaviour during compressional inversion? -- The 2004 MJ6.8 Mid-Niigata Prefecture, Japan, earthquake sequence, *Earth Planet. Sci. Lett.*, **257**, 188-199, 2007.
- Smith, A. J., P. R. Cummins, T. Baba, S. Kodaira, Y. Kaneda, and H. Yamaguchi, Intra-plate seismicity in the subducting Philippine Sea Plate, southwest Japan: magnitude-depth correlations, *Phys. Earth Planet. Int.*, 145, 179-202, 2004.
- Taylor, B., The single largest oceanic plateau; Ontong Java-Manihiki-Hikurangi, *Earth Planet. Sci. Lett.*, **241**, 372-380, 2006.
- Wallace, L. M., and 21 others, Characterizing the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand, Geochem. Geophys. Geosyst., Q10006, doi:10.1029/2009GC002610, 2009.
- Wang, K., J. F. Cassidy, I. Wada, and A. J. Smith, Effects of metamorphic crustal densification on earthquake size in warm slabs, *Geophys. Res. Lett.*, **31**, L01605, doi:10.1029/2003GL018644, 2004.
- Webb, T. H. and H. Anderson, Focal mechanisms of large earthquakes in the North Island of New Zealand: slip partitioning at an oblique active margin, *Geophys. J. Int.*, 134, 40-86, 1998.

Event name	Label	Date	Time	Latitude	Logitude	Depth	Mw	Directivity	Rupture L	Rupture A	D in slab	Vp	Average Δσ
		(year mo da)	(hrmn)	(°S)	(°E)	(km)			(km)	(km²)	(km)	(km/s)	(MPa)
Wairarapa	WA	1942 08 01	1234	40.962	175.686	39.6	6.8	Bilateral?	~27	ND	17	9.0	ND
Cape Campbell	CC	1977 01 18	0541	41.781	174.486	41.6	6.0	Updip	~13	ND	13	8.3	ND
Tiniroto	TI	1985 07 19	1433	38.725	177.376	30.7	5.9	Downdip	11	11 x 11	9	7.5	1.6
Weber	WE	1990 02 19	0534	40.373	176.360	25.9	6.2	Downdip	12	12 x 9	8	7.2	5.5
Ormond	OR	1993 08 10	0946	38.553	177.909	46.0	6.2	Bilateral	25	30 x 15	20	8.6	0.6
Upper Hutt	UH	2005 01 20	1856	41.097	175.065	31.4	5.3	Updip	4	4 x 3	6	7.0	6.6
Gisborne	GI	2007 12 20	0755	38.902	178.457	35.5	6.6	Updip	26	22 x 26	18	8.0	1.8
Hastings	HA	2008 08 25	1125	39.652	176.754	29.3	5.5	Updip	5	5 x 5	6	7.0	4.4

Table 1. List of large intraslab earthquakes relocated in this study. M_w determinations are from Doser and Webb (2003), Webb and Anderson (1998) and Ristau (2008). Rupture length (L) and area (A) are determined from the relocated aftershock zones, with ND indicating that there were insufficient well-located aftershocks to determine a rupture area. D in slab refers to the distance of the centroid of the aftershock zone from the plate interface, and Vp is the P-wave velocity at this centroid. Average $\Delta \sigma$ is the average stress drop assuming a circular rupture.



Figure 1. Map of the Hikurangi subduction zone showing focal mechanisms of the large historical intraslab earthquakes relocated in this study. Beachballs are labelled with the earthquake name as in Table 1, with the depth in km marked and the preferred fault plane from the distribution of aftershocks shown in bold. Focal mechanisms are from Doser and Webb (2003), Webb and Anderson (1998), and more recent regional moment tensor analysis (Ristau, 2008). Dashed lines are depth to the plate interface (labelled in km), and shading denotes the slip deficit rate at the plate interface (both from Wallace *et al.* 2009). The arrow shows the velocity of the Pacific plate relative to the Australian plate (DeMets *et al.*, 1994).



Figure 2. Map and depth section down the dip of the subducted plate of the relocated 2007 Gisborne (magenta pluses) and 1993 Ormond (orange diamonds) earthquake sequences in the northern Hikurangi subduction zone. The mainshock and first day of aftershocks are shown of each sequence. The P-wave seismic velocity along section A-B from the 3-D model of Eberhart-Phillips *et al.* (in prep.) is shown, together with background seismicity during the period 2001 January – 2009 June relocated with this model. The dashed white line on the Vp section encloses the region where Vp resolution is the best.



Figure 3. Map and depth section down the dip of the subducted plate of the relocated 1942 June (magenta diamonds) and 1942 August (green squares) Wairarapa earthquake sequences in the southern Hikurangi subduction zone. For the June sequence, an M_L 5.3 foreshock which occurred at 9 km depth three hours before the M_w 6.9-7.2 mainshock, and first day of well-located aftershocks are shown. For the August sequence, an M_w 5.6 foreshock in the top of the subducted plate eight hours before and 50 km northeast of the M_w 6.8 mainshock is shown, together with two well-located aftershocks in the following five days. The P-wave seismic velocity along section A-B from the 3-D model of Eberhart-Phillips *et al.* (in prep.) is shown, together with background seismicity during the period 2001 January – 2009 June relocated with this model. The dashed white line on the Vp section is the lower limit of the region where Vp resolution is the best.



Figure 4. Plots of P-wave velocity (Vp) at the centroid of the aftershock zone against Mw (a), and average stress drop derived from aftershock zone dimensions (b). Intraslab earthquakes are labelled as in Table 1. As Vp increases with depth from the plate interface D, plots of M_w and average stress drop against D are similar.



Figure 5. Conceptual model of faulting within the subducted crust of the Hikurangi Plateau beneath the eastern North Island. The zigzag pattern denotes a strongly coupled portion of the plate interface, and high stress drop portions of larger faults deeper within the subducted plateau, which are interpreted as regions of dehydration embrittlement. Dashed faults are those beneath the strongly coupled portion of the plate interface on which dehydration embrittlement, and hence large earthquakes, may be suppressed. The shading indicates increasing seismic velocities with depth in the plateau. See text for details.