Subduction factory
2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions?

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[1] New thermal-petrologic models of subduction zones are used to test the hypothesis that intermediate-depth intraslab earthquakes are linked to metamorphic dehydration reactions in the subducting oceanic crust and mantle. We show that there is a correlation between the patterns of intermediate-depth seismicity and the locations of predicted hydrous minerals: Earthquakes occur in subducting slabs where dehydration is expected, and they are absent from parts of slabs predicted to be anhydrous. We propose that a subducting oceanic plate can consist of four petrologically and seismically distinct layers: (1) hydrated, fine-grained basaltic upper crust dehydrating under equilibrium conditions and producing earthquakes facilitated by dehydration embrittlement; (2) coarse-grained, locally hydrated gabbroic lower crust that produces some earthquakes during dehydration but transforms chiefly aseismically to eclogite at depths beyond equilibrium; (3) locally hydrated uppermost mantle dehydrating under equilibrium conditions and producing earthquakes; and (4) anhydrous mantle lithosphere transforming sluggishly and aseismically to denser minerals. Fluid generated through dehydration reactions can move via at least three distinct flow paths: percolation through local, transient, reaction-generated high-permeability zones; flow through mode I cracks produced by the local stress state; and postseismic flow through fault zones. *INDEX TERMS:* 7218 Seismology: Lithosphere and upper mantle; 7230 Seismology: Seismicity and seismotectonics; 8123 Tectonophysics: Dynamics, seismotectonics; 8135 Tectonophysics: Evolution of the Earth: Hydrothermal systems (8424); 3660 Mineralogy and Petrology: Metamorphic petrology; *KEYWORDS:* subduction, seismicity, intermediate-depth earthquakes, dehydration, transformation

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1. Introduction

[2] The links among seismicity, slab metamorphism, and arc volcanism in the subduction factory remain poorly established. This paper argues that intermediate-depth earthquakes only occur where hydrous minerals are predicted to be present, implying a causal link between dehydration reactions and seismicity: dehydration alone is not sufficient for generating an earthquake. The companion paper by *Hacker et al.* [2003] outlines the computational foundation on which this paper is built.

1.1. Characteristics of Intermediate-Depth Seismicity

[3] *Gutenberg and Richter* [1954] defined intermediate-depth earthquakes as those in the ~70–300 km depth range of subducting slabs, but for the purposes of this paper, we include any intraslab event shallower than 300 km and downdip from the thrust zone. Such earthquakes are frequent and damaging in some subduction zones (e.g., the M_S = 7.8 El Salvador earthquake of 13 January 2001, which killed >1200 people), such that understanding and predicting their distribution is an issue of societal as well as scientific relevance. Intermediate-depth earthquakes have a number of defining features worldwide.

1. They tend to occur within the uppermost few kilometers of subducting slabs [*Abers*, 1992; *Kirby*, 1995], but they also can lie in a secondary plane of seismicity that may be as much as 40 km below the slab surface [*Yoshii*, 1979]. The provocative suggestion that intermediate-depth events nearest the top of the subducting Nazca plate actually occur in the slab mantle [*ANCORP Working Group*, 1999] stands in direct contrast to this, but also disagrees with the results shown by *Bock et al.* [2000] and *Yuan et al.* [2000] for the same slab 300 km farther south.
2. Their abundance shows a marked onset at depths of 30–70 km and then decreases exponentially with increasing depth [*Frohlich*, 1989; *Kirby et al.*, 1996].
3. They occur by shear failure and exhibit double-couple focal mechanisms, perhaps occasionally accompanied by a compensated linear vector dipole component but no resolvable isotropic component [*Frohlich*, 1989].

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4. They have many fewer aftershocks than shallow (<40 km) events and slightly fewer aftershocks than deep events (>400 km) [*Frohlich*, 1987]. Source durations also appear to decrease with increasing depth, although it is unclear if this reflects changes in stress drop or elastic parameters [*Vidale and Houston*, 1993; *Campus and Das*, 2000].

1.2. Slab Stress State

[4] Our understanding of slab stress state is incomplete. *Isacks and Molnar* [1969] postulated that shallowly penetrating slabs should be in downdip tension as a result of negative buoyancy with respect to the asthenosphere, and deep slabs should be in downdip compression as a result of resistance from the lower mantle; they also noted that some slabs (e.g., those now known to have double seismic zones) have stress states not readily explained by this simple model. Intermediate-depth seismicity has also been explained as the result of unbending of the slab following bending at the outer rise [*Isacks and Barazangi*, 1977], but slab seismicity is not restricted to parts of the slab that are undergoing changes in curvature. *Fujita and Kanamori* [1981] showed that all relatively slowly subducting old plates exhibit intermediate-depth earthquakes with downdip *T* axes, but many other slabs that are either young or rapidly subducting also exhibit downdip *T* axes. Slabs with intermediate-depth earthquakes exhibiting downdip *P* axes also span a wide range of subduction rates and ages, but only the slab beneath Peru is both young and fast. Slab stress state should be influenced by the volume changes of phase transformations. *Kirby et al.* [1996], building on suggestions of *McGarr* [1977] and *Pennington* [1983], proposed that eclogitization places the subducting crust in tension and the underlying mantle in compression; however, most subducting slabs with double seismic zones show a zone of downdip *P* axes overlying a zone of downdip *T* axes.

1.3. Double Seismic Zones

[5] Intermediate-depth events in some subduction zones occur in two distinct layers, forming an upper seismic zone and a lower seismic zone separated vertically by an aseismic or weakly seismic zone up to 40 km thick (Figure 1). Examples include Tohoku [*Hasegawa et al.*, 1978], Mariana [*Samowitz and Forsyth*, 1981], Tonga [*Kawakatsu*, 1986], northern Kurile [*Gorbatov et al.*, 1994; *Kao and Chen*, 1994], Alaska Peninsula [*Abers*, 1992], northern Chile(?) [*Comte and Suárez*, 1994], central Chile(?) [*Araujo and Suarez*, 1994], New Britain [*McGuire and Weins*, 1995], New Zealand [*Robinson*, 1986], and Mexico [*Pardo and Suarez*, 1995]. As with single seismic zones, the upper seismic zones occur in the uppermost part of the subducting slab [*Kirby*, 1995; *Abers*, 1996], so the lower zone must lie within the subducting mantle lithosphere. The best known lower seismic zones (beneath Tohoku, the Kurile Islands, and Kamchatka) begin at depths of 30–60 km and extend to ~180 km depth, where they may merge with the upper seismic zone. Other double seismic zones, such as those beneath Chile and Mexico, are less well defined.

[6] *Fujita and Kanamori* [1981] suggested that double seismic zones occur in slabs where the stress state is neither strongly compressional or tensional: in mostly old and rapidly subducting, and therefore cold, slabs. This observation appears to be correct for subducting slabs beneath Tohoku, the Mariana Islands, Tonga, and the northern Kurile Islands, which show downdip *P* axes in the upper seismic zone and downdip *T* axes in the lower seismic zone. Slabs that do not behave in this way include those beneath the Alaska Peninsula and New Zealand, which exhibit downdip *T* axes in both seismic zones, those beneath Mexico and northern Chile which have an upper seismic zone with downdip *T* axes and a poorly resolved lower seismic zone with downdip *P* axes, and those such as Ryukyu where the stress state changes along strike. Thus, while part of Fujita and Kanamori's suggestion seems to hold, most of the variation in stress states of slabs is not well understood.

1.4. Low-Velocity Layers

[7] Seismological studies of some relatively cold subducting slabs have revealed the presence of an anomalous low-velocity layer to depths of 100–250 km. The layers lie at the top of the downgoing plate and probably contain the zone of intermediate-depth seismicity (or the upper plane of double seismic zones). Analysis of the dispersion of seismic body waves reveals that slabs beneath Alaska, the central Aleutians, the northern Kuriles, northern Japan, and the Marianas include a layer that appears to be 2–8 km thick and 5–8% slower than the surrounding mantle [*Abers and Sarker*, 1996; *Abers*, 2000]. Similar results have been obtained from analyzing the move out of *P-S* converted phases in Japan and elsewhere [*Matsuzawa et al.*, 1986; *Helffrich and Abers*, 1997]. Finally, receiver functions show evidence for a low-velocity layer 5–20 km thick at the top of slab beneath Cascadia [*Cassidy and Ellis*, 1993], the Andes [*Bock et al.*, 2000; *Yuan et al.*, 2000], Kamchatka [*Yuan et al.*, 1999], and Alaska [*Abers et al.*, 2002]. These low-velocity layers appear to be subducted crust and are generally interpreted as either hydrous blueschist or as basalt and gabbro persisting metastably within the eclogite stability field [*Helffrich*, 1996]. One exception has been found by analyzing signals from Tonga earthquakes recorded in New Zealand, which show high-frequency precursors suggestive of a thin high-velocity layer atop the subducting Tonga slab [*Ansell and Gubbins*, 1986]. Where best resolved, these low-velocity layers appear to coincide with the uppermost zone of intermediate-depth seismicity [*Zhao et al.*, 1992] although there is some suggestion that seismicity steps into the underlying mantle with increasing depth of subduction [*Yuan et al.*, 2000]. To our knowledge, no intermediate-depth earthquakes have been reliably located above these low-velocity layers.

2. Hypotheses For Intermediate-Depth Seismicity

[8] In parallel with the uncertainty about the hypotheses regarding the macroscopic (plate scale) phenomenology of intermediate-depth earthquakes, we also lack a consensus view of the microscale (grain-scale) to mesoscale (rupture-scale) processes responsible for intermediate-depth seismicity. Three major hypotheses have been advanced to explain this issue: transformational faulting, ductile shear instability and dehydration embrittlement.

2.1. Transformational Faulting

[9] Uncertainty about whether ordinary brittle failure and frictional sliding can cause earthquakes at depths >100 km led *Kao and Liu* [1995] to propose that intermediate-depth

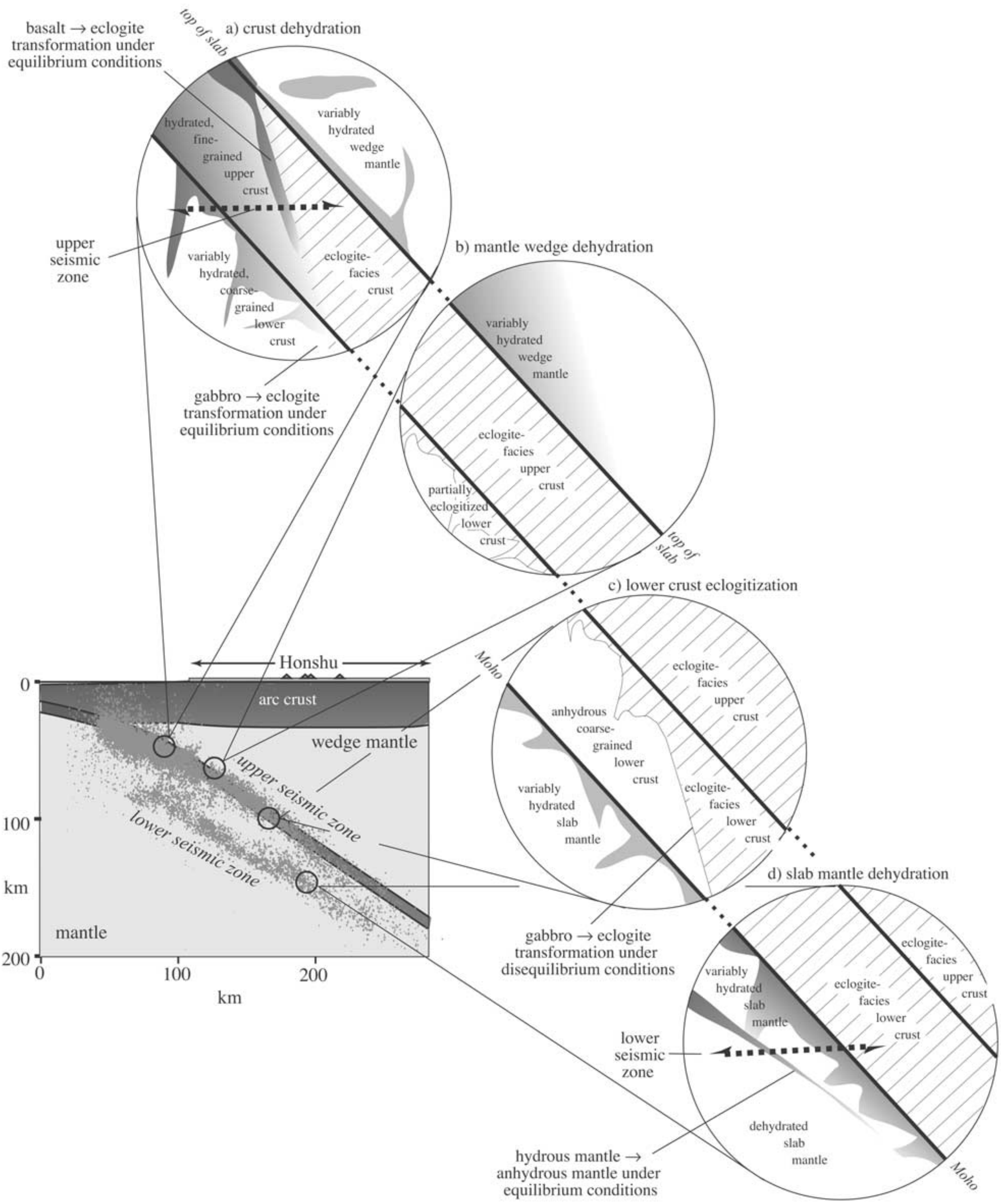

Figure 1. Schematic (not to scale) illustration of subducting crust, showing transformation from hydrated basalt and gabbro → eclogite under equilibrium conditions and kinetically overstepped transformation from anhydrous gabbro → eclogite. No horizontal or vertical scale is implied. In reality, the boundary between upper and lower crust is not sharp, the transformation from basalt or gabbro → eclogite involves many intermediate mineralogical changes, and grain size and hydration state are variable throughout the crust. The subduction zone cross section from Tohoku (true scale) shows a double seismic zone (data of *Igarashi et al.* [2001]).

earthquakes in lower seismic zones might be caused by transformational faulting. Transformational faulting, a process by which a phase transformation propagates along a planar fault-like feature at seismic velocities [*Kirby*, 1987] or by which a fault plane forms by the coalesence of weaker reaction products [*Green and Burnley*, 1989] and requires that reaction kinetics be sluggish enough [*Bridgman*, 1945] that rupture-scale areas of the metastable mineral exist. Transformational faulting has been demonstrated for at least three solid-solid reactions under laboratory conditions: $\alpha \rightarrow \gamma$ Mg_2GeO_4 [*Green and Burnley*, 1989], ice I $\rightarrow$ ice II [*Kirby et al.*, 1991], and $\alpha \rightarrow \beta$ $(Mg, Fe)_2SiO_4$ [*Green et al.*, 1990]; all these reactions are polymorphic and relatively exothermic. At least three other polymorphic reactions: calcite $\rightarrow$ aragonite [*Hacker and Kirby*, 1993], quartz $\rightarrow$ coesite [*Tullis*, 1971; *Griggs*, 1972], and $CdTiO_3$ ilmenite $\rightarrow$ perovskite [*Green and Zhou*, 1996], do not exhibit transformational faulting under laboratory conditions, probably because they are only weakly exothermic or endothermic [*Green and Zhou*, 1996]. Moreover, nonpolymorphic solid-solid transformations, such as albite $\rightarrow$ jadeite + quartz [*Hacker et al.*, 1993], can never be associated with transformational faulting because such reactions require diffusion over timescales exceeding earthquake rupture periods. For this reason, the suggestion that the transformation of aluminous enstatite $\rightarrow$ garnet + enstatite is responsible for lower seismic zone activity [e.g., *Kao and Liu*, 1995] is implausible. There is no possibility that the lower seismic zone of intermediate-depth events is the result of transformational faulting because the only other major constituent of the mantle lithosphere, olivine, is thermodynamically stable at depths <410 km. Similarly, most of the solid-state reactions (e.g., albite $\rightarrow$ jadeite + quartz) involved in the metamorphism of basalt and gabbro to eclogite are not polymorphic, so transformational faulting is not a viable earthquake mechanism in the subducting oceanic crust.

2.2. Plastic or Melt Shear Instabilities

[10] Some evidence suggests that a high-temperature process may allow runaway shear failure that is sufficiently rapid to generate earthquakes. While discussion of these processes has been concentrated on deep earthquakes, similar arguments should apply at intermediate depths. One possibility is that a localized shear instability generates heat faster than dissipation by conduction, leading to melting along failure planes and allowing runaway slip at relatively low shear stresses [*Ogawa*, 1987]. This mechanism has been invoked to explain rupture properties of the 1994 Bolivian deep earthquake [*Kanamori et al.*, 1998]. However, it is unknown whether shear strain rates are high enough or shear zones are narrow enough for this process to occur in slabs. Even without melting, other forms of strain softening may allow plastic shear to propagate catastrophically, thus generating earthquakes [*Hobbs and Ord*, 1988]. Such mechanisms should be relatively independent of normal stress, although it is unclear whether rocks at mantle conditions behave in this way. In summary, it is possible that some form of nonbrittle instability may produce intermediate-depth earthquakes, but to date no experimental or field evidence has confirmed that these processes take place within the Earth.

2.3. Dehydration Embrittlement

[11] Fluid pressure can strongly influence the mechanical behavior of rocks; such fluid can come from in situ dehydration or be externally derived. It has been observed experimentally in numerous systems (e.g., amphibolite [*Hacker and Christie*, 1990], chlorite [*Murrell and Ismail*, 1976], gypsum [*Ko et al.*, 1997], serpentine [*Rutter and Brodie*, 1988], and tremolite [*Kirby*, 1987]) that rocks undergo sudden weakening and embrittlement (a change from ductile to brittle behavior) during their dehydration under conditions wherein the permeability is insufficient to relieve increasing fluid pressure. The embrittlement is independent of whether the same rock exhibits stable or unstable (“stick-slip”) sliding in the presence of an externally derived fluid. For example, in their classic experimental study of serpentinite, *Raleigh and Paterson* [1965] reported that dehydration during deformation led to shear fracturing accompanied by a sudden stress drop. These experimental observations imply that dehydration in subducting slabs could cause seismicity. *Connolly* [1997] and *Hacker* [1997] have emphasized that even reactions with a negative total volume change can lead to elevated fluid pressures over the timescale at which the rock can creep or become sealed.

[12] As an outgrowth of these early experiments on dehydration embrittlement, and because at that time the oceanic crust was thought to be composed of serpentinized peridotite, *Raleigh* [1967] suggested that serpentine dehydration causes subduction zone earthquakes. Subsequently it was realized that the oceanic crust is instead mafic, and this idea fell into disfavor. This general idea was resurrected, however, most comprehensively by *Green and Houston* [1995] and *Kirby* [1995], who suggested that intermediate-depth earthquakes are the result of dehydration reactions in general. Improved seismic imaging and earthquake locations show that the main zone of intermediate-depth earthquakes lies at the top of the subducting plate, not within its cold interior [e.g., *Matsuzawa et al.*, 1986; *Ekstrom and Engdahl*, 1989; *Abers*, 1992], and *Kirby et al.* [1996] emphasized that the top of the slab is precisely where hydrous minerals should be most abundant as a result of ocean-ridge hydrothermal alteration or hydration during faulting at the outer rise. Moreover, *Jiao et al.* [2000] showed that earthquakes down to 450 km depth in the Tonga subduction zone occur along faults whose asymmetry matches the faults inferred for outer rise events, suggesting that the intermediate-depth earthquakes occur along faults formed prior to subduction. *Seno and Yamanaka* [1996] suggested that the lower plane of double seismic zones may be caused by serpentine dehydration and noted that most subduction zones exhibiting double seismic zones also have outer rise earthquakes with deep (several tens of kilometers) thrust focal mechanisms. *Peacock* [2001] suggested that faulting associated with outer rise earthquakes promotes local hydration (serpentinization) of the incoming slab mantle and demonstrated that subsequent subduction yields slab pressure-temperature paths that intersect antigorite (serpentine) dehydration reactions, supporting *Seno and Yamanaka*’s [1996] hypothesis.

3. Evaluation of the Hypothesis

[13] The purpose of this study is to test the general hypothesis that intermediate-depth slab earthquakes are

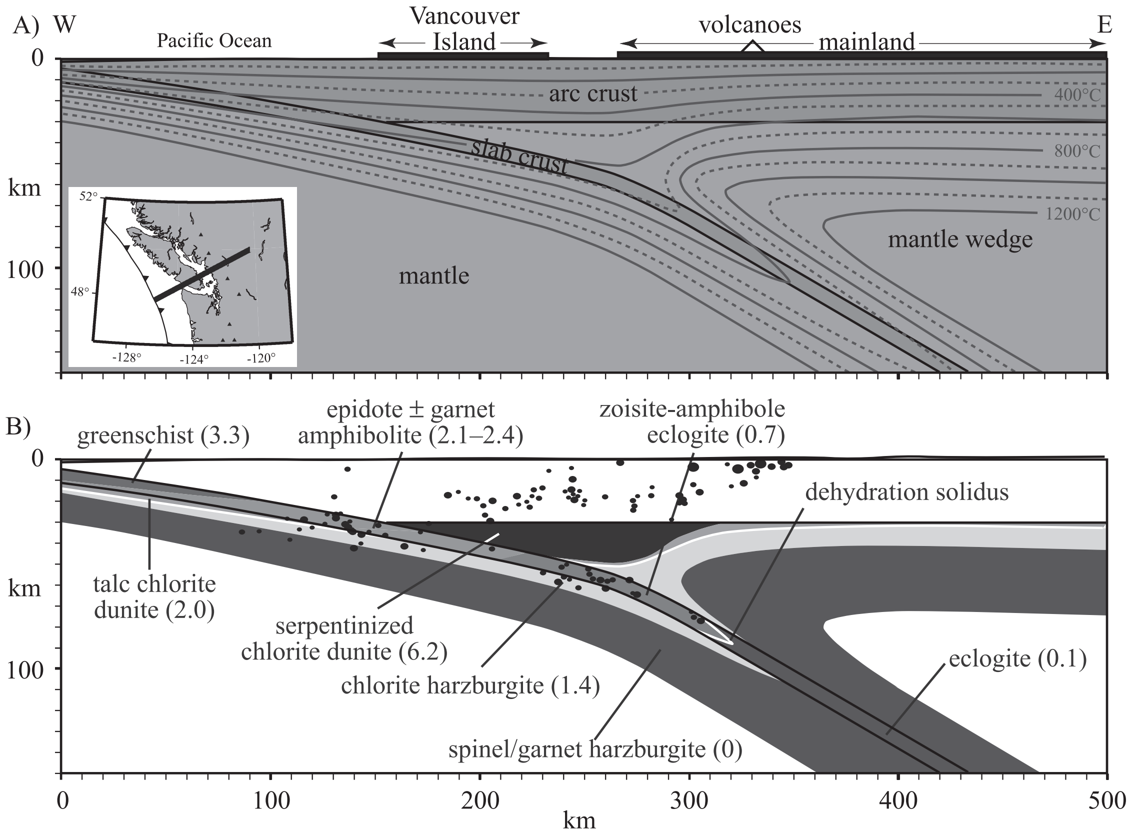

Figure 2. Correlation between seismicity and phase transformations in the Cascadia subduction zone. (a) Transect through southern Vancouver Island; thermal model calculated in this study. (b) Metamorphic facies calculated following *Hacker et al.* [2003]. Seismicity from *Rogers* [1998], which was taken from within 50 km of the transect from a combination of Washington and Canadian regional network catalogs for events between 1980 and 1991 having magnitude >1.0 and formal depth uncertainty <3 km. See color version of this figure at back of this issue.

related to dehydration reactions. Our knowledge of kinetics, however, permits a more detailed hypothesis to be formulated. Numerous experimental studies and field studies (summarized by *Hacker* [1996]) demonstrate that while dehydration reactions are not kinetically hindered [*Walther and Wood*, 1984; *Jové and Hacker*, 1997] and run to completion at conditions close to equilibrium in the Earth, solid-solid phase transformations can be remarkably sluggish in the absence of free H_2O, particularly in coarse-grained rocks. This is of salient importance for subduction zones, where the upper oceanic crust, composed of glassy and fine-grained, more extensively hydrated rocks, overlies a coarse-grained, only locally hydrated lower crust and uppermost mantle (Figure 1) [*Hacker*, 1996; *Tucholke et al.*, 1998].

[14] We predict that (1) Earthquakes in subduction zones with only single seismic zones correspond spatially to dehydration reactions in the crust and/or the uppermost mantle. (2) Upper seismic zones of double seismic zones correspond spatially to dehydration of the crust. (3) Lower seismic zones of double seismic zones correspond spatially to dehydration of the mantle. (4) Seismic gaps between double seismic zones correspond spatially to the thermally cold core of the slab. (5) Aseismic mantle below the zone(s) of active seismicity is anhydrous. We make these specific tests by comparing the predicted metamorphic phase relationships [*Hacker et al.*, 2003] with observed seismicity in the subducting slabs beneath Vancouver Island (Cascadia), SW Japan (Nankai), central Costa Rica, and NE Japan (Tohoku) (Figures 2–5). In particular, we expect to see, within the uncertainties of the method outlined in section 4, that seismicity occurs within rocks predicted to contain hydrous phases and not in rocks predicted to be anhydrous. Because all subducting rocks undergo heating and most phase changes in mafic rocks are continuous, dehydration is expected to be ongoing in all H_2O-saturated rocks; that is, dehydration is not restricted to facies transitions and neither are earthquakes expected to be. The means by which we calculated phase relationships are detailed by *Hacker et al.* [2003].

[15] We also apply a statistical test to evaluate whether seismicity is consistent with intraslab earthquakes being confined to the subducted crust, by examining the distribution of hypocenters normal to a surface defining the slab. Specifically, assume d is the observed distance of an event from the slab surface, with measurement uncertainty σ_d, and assume events are distributed uniformly over a width between $d = 0$ to $d = L$. The observed distribution of events from the slab surface (Figure 6) should be a convolution of the probability density function of d and a uniform distribution from 0 to L. That observed distribution should have a variance $\sigma_T^2 = \sigma_d^2 + L^2/12$, the last term being the variance

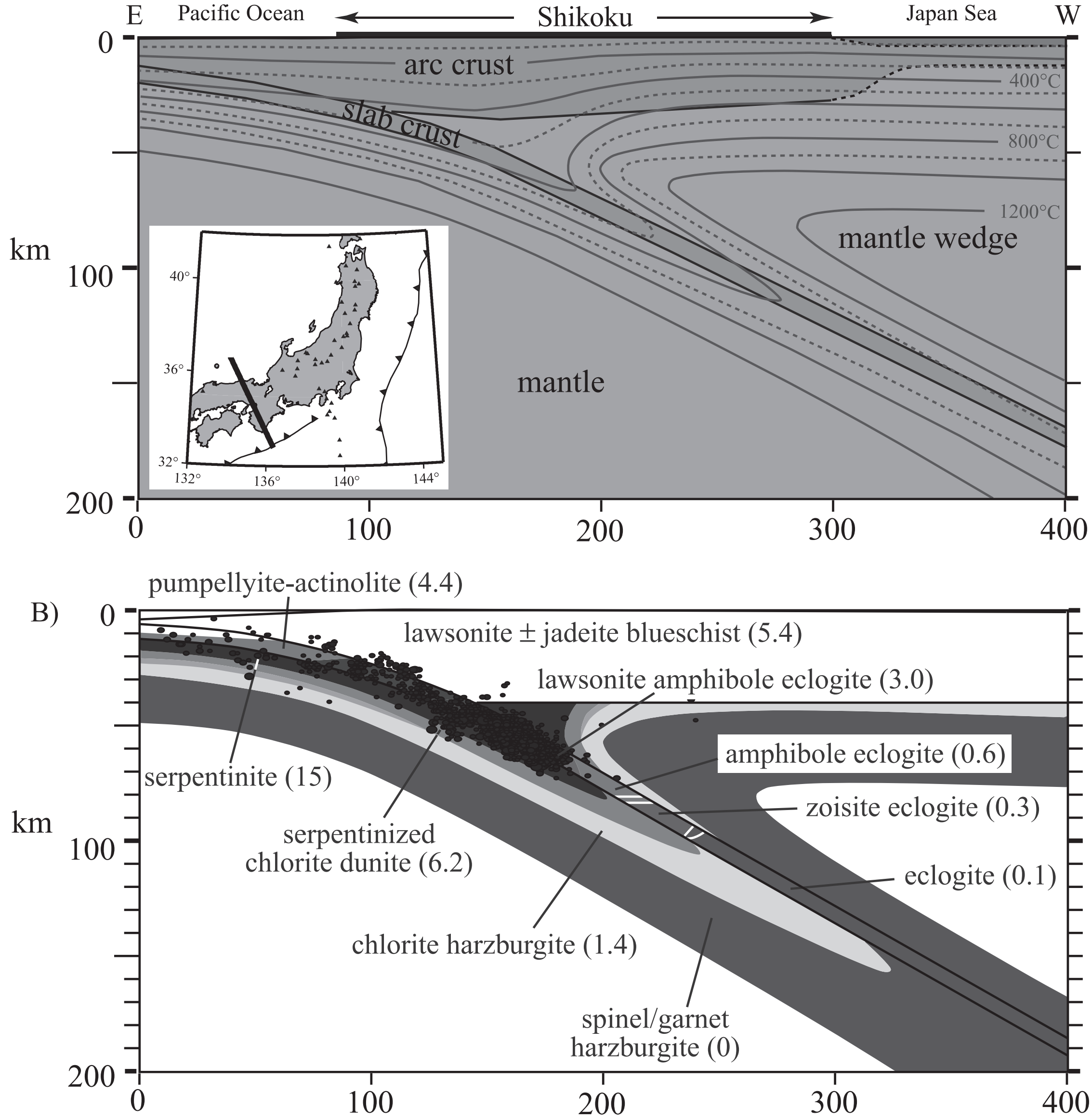

Figure 3. Correlation between seismicity and phase transformations in the Nankai subduction zone. (a) Transect through Kii Peninsula; geometry after *Zhao and Hasegawa* [1993] and *Kodaira et al.* [2000] thermal model calculated in this study. (b) Metamorphic facies calculated following *Hacker et al.* [2003]. Seismicity from an integrated database of regional network arrival times [*Cummins et al.*, 2002], projected from within 20 km of the transect, for events recorded by at least four *P* arrivals by each network. See color version of this figure at back of this issue.

of a uniform distribution. We can measure σ_T directly from the distribution of hypocenters, and in principle determine L if the hypocentral uncertainties σ_d are well known. Typically, however, catalogs report only formal uncertainties in hypocenters which can significantly underestimate actual uncertainties. So, instead, we assume L to be the thickness of a dehydration zone consistent with petrologic models (say, 7 km, the thickness of subducted oceanic crust) and predict the value of σ_d needed if all events are within that zone.

3.1. Limitations

[16] Our test of the dehydration-seismicity hypothesis is necessarily imperfect for three main reasons.

1. The thermal structures of subduction zones are not known exactly; for the Nankai and Tohoku thermal models, *Peacock and Wang* [1999] estimated uncertainties of 50–100°C for the subducted oceanic crust. Another measure of the uncertainty is given by comparing our thermal model for Nankai to *Hyndman et al.*'s [1995] model for Tonankai, only 40 km farther east. For example, in Hyndman et al.'s model the 450°C isotherm intersects the slab at a distance of 150 km from the Nankai trough whereas in our model the 450°C isotherm is not reached until 180 km.

2. Oceanic lithosphere includes a range of bulk compositions produced by igneous and metamorphic processes, yet our petrological model for oceanic crust considers only unmetasomatized MORB; in reality, the metamorphism of

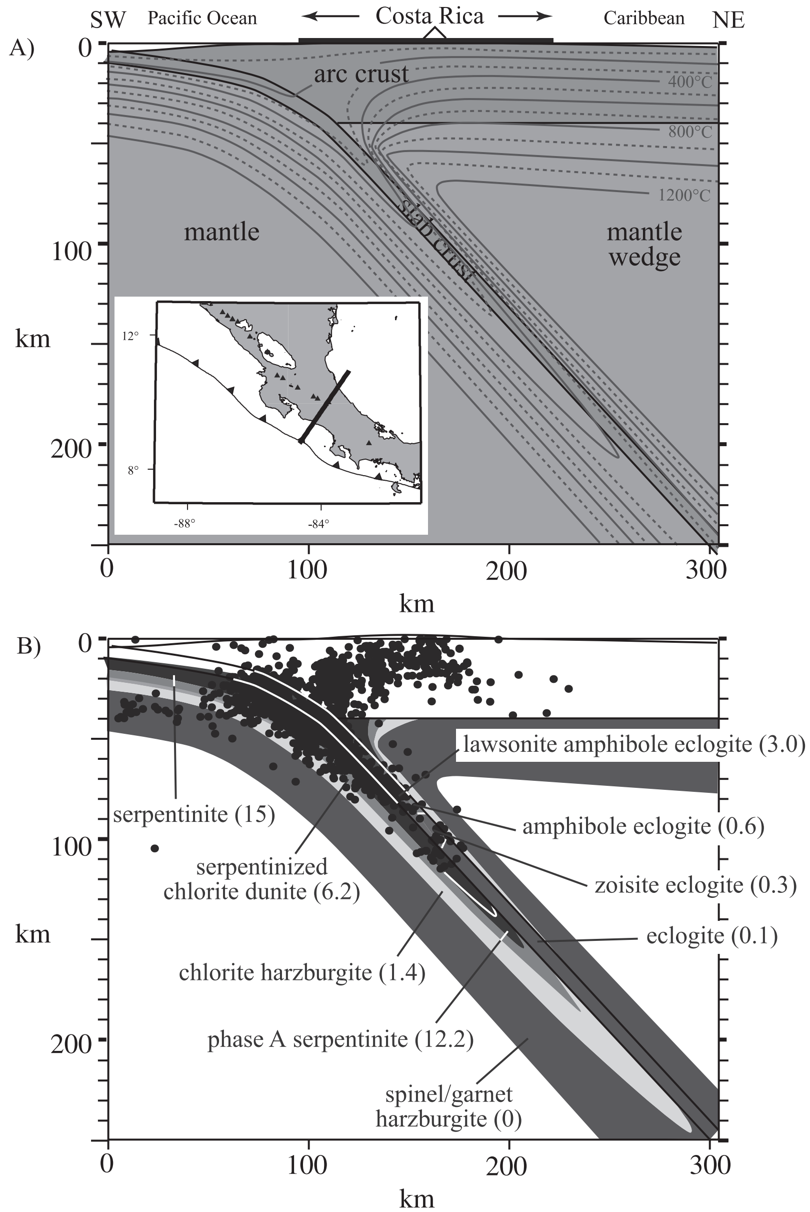

Figure 4. Correlation between seismicity and phase transformations in the Costa Rica subduction zone. (a) Transect through central Costa Rica; thermal model calculated in this study. (b) Metamorphic facies calculated following *Hacker et al.* [2003]. Seismicity of *Protti et al.* [1995] projected from 25 km either side of the section; events have horizontal and vertical formal errors less than 4 and 5 km, respectively. See color version of this figure at back of this issue.

subducting oceanic crust is more complex than we model, with the stabilization of hydrous Ca-Al silicates in particular a potentially important issue not addressed in this study. There is disagreement about the phase relations of MORB, particularly at high pressure and low temperature, but we rely on a single phase diagram.

3. We would like to know the precise locations of slab earthquakes with respect to the predicted metamorphism. Unfortunately, there are many sources of error: (1) random errors in relative hypocenters (these are given in the figure captions); (2) systematic biases introduced by incorrect velocity models (particularly problematic for events down-dip or updip past the end of the recording network); (3) projection of hypocenters along strike onto a single cross section; and (4) assuming that the location of the subducting slab is defined by the observed seismicity. The latter can be circumvented through, for example, converted phases [e.g., *Zhao et al.*, 1997], but in the majority of subduction zones, the location of the slab cannot be defined independently of the seismicity, such that one cannot assess critically whether the earthquakes at a given depth are above, within, or below the subducting crust.

3.2. Northern Cascadia

[17] In the Cascadia subduction zone (Figure 2a), the 5–9 Ma Juan de Fuca plate subducts at a rate of ~40 mm/yr, rendering it among the youngest and warmest slabs in the world [*Hyndman and Wang*, 1993]. The incoming plate has

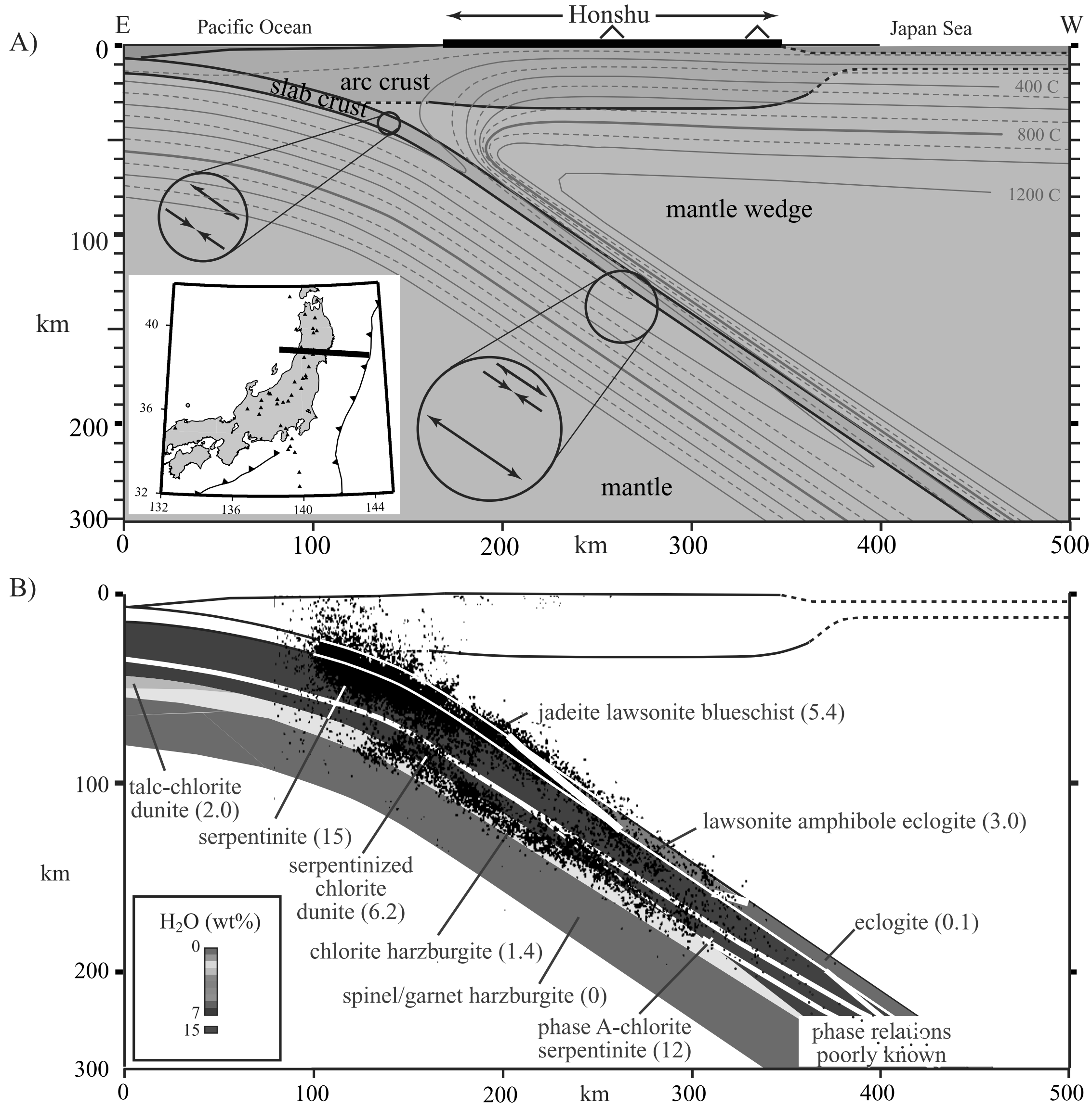

Figure 5. Correlation between seismicity and phase transformations in the Tohoku subduction zone. (a) Transect through northern Honshu; crustal thickness after *Zhao et al.* [1992], and isotherms from *Peacock and Wang* [1999]. Offset circles show stress states inferred by *Igarashi et al.* [2001]. (b) Metamorphic facies calculated following *Hacker et al.* [2003]; phase relations at $P > 5$ GPa and $T < 600°C$ are not well known. Seismicity above 200 km depth projected from 250 km north and south of the section [*Igarashi et al.*, 2001] from 1975 to 1998, following a relocation with spatially variable station corrections. Information about hypocenter uncertainties is not given, but events shown have RMS residual in arrival time of <0.3 s. Seismicity at >200 km from *Kosuga et al.* [1996] is not as well located. See color version of this figure at back of this issue.

a thick sediment blanket and upper plate volcanism is weak to moderate. We modeled the slab in the vicinity of southern Vancouver Island. Using a new thermal model and the methodology of *Hacker et al.* [2003], we calculated the equilibrium mineralogy to temperatures $\leq 1200°C$ (Figure 2b). The subducting crust is predicted to undergo a series of dehydration reactions with increasing temperature and depth, culminating in the formation of nearly anhydrous eclogite at 80–90 km depth. The subducting mantle is thermodynamically permitted to contain a thin ($\sim$5 km thick) sliver of chlorite-bearing peridotite, but otherwise is expected to be composed of anhydrous spinel- and garnet-bearing harzburgite.

[18] Seismicity in the vicinity of our cross section was characterized by *Rogers* [1998], who shows events from 1980 to 1991 with formal errors in depth <3 km. Seismicity within the subducting slab occurs from 20 to 80 km depth (Figure 2b), and while this seismicity is shallower than typical intermediate-depth events, the hypocenters and focal mechanisms of the best located earthquakes clearly show that these are intraslab events. Given the hypocenter uncertainties, it is unclear whether all these events lie within the

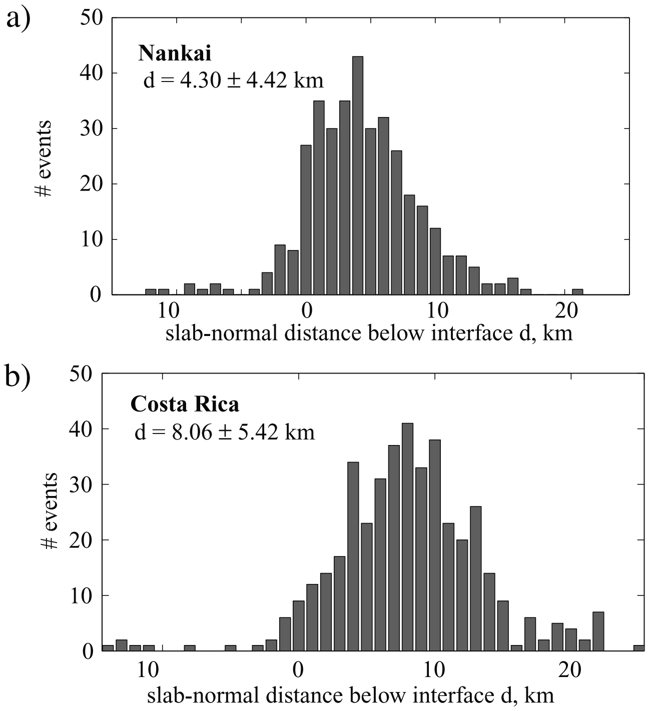

Figure 6. Histograms of event distribution versus distance from the inferred slab surface for Costa Rica and Nankai. Events are only those clearly not associated with the thrust zone (>100 km from trench) and not associated with the upper plate (>25 km or >40 km deep for Nankai or Costa Rica, respectively); other sorting parameters same as Figures 3–6. Measured parameter d is distance of each event to closest point on slab surface, its standard deviation (σ_T) reflects the thickness of seismogenic zone (L) and uncertainties in hypocenters.

subducted crust or whether some are below the slab Moho. There is a clear spatial correlation between this seismicity and the predicted dehydration reactions in the subducting crust (Figure 2b): throughout this same depth interval crystallographically bound H_2O reduces from 2.1 to 0.1 wt %. In other words, beneath southern Vancouver Island, the bulk of the seismicity occurs at depths coincident with predicted dehydration in the downgoing crust. Most of the potential mantle earthquakes appear within the portion of the slab predicted to contain chlorite-bearing harzburgite. The material flow lines of the slab cross isotherms at an acute angle, such that all parts of the slab mantle undergo heating at all depths; we suggest that chlorite dehydration is responsible for the slab mantle earthquakes.

[19] Receiver function studies have shown that a low-velocity layer, ~5 km thick, lies at the top of the subducting Cascadia slab to at least 75 km depth [*Owens et al.*, 1988; *Cassidy and Ellis*, 1993]. This layer, estimated to be 9–15% slower than the surrounding mantle, appears to be a good candidate for hydrated subducted crust at these depths. Generally, the hypocenters lack sufficient accuracy to ascertain whether the intermediate-depth earthquakes occur within the subducted crust or mantle. Beneath western Washington, south of the studied transect, refraction experiments have traced the subducting Juan de Fuca crust as a relatively low-velocity layer to 50 km depth [*Taber and Lewis*, 1986; *Parsons et al.*, 1998], below which the signal deteriorates.

[20] The Cascadia wedge mantle at depths of 60–70 km has V_P = 7.9–8.1 km/s [*Drew and Clowes*, 1990] and V_S = 4.8 km/s [*Cassidy and Ellis*, 1993], in good agreement with our calculated values for unmetamorphosed harzburgite (V_P = 8.1 km/s and V_S = 4.7 km/s at 2 GPa, 700°C). This reveals that the wedge is not significantly hydrated at these depths and implies that the slab does not contribute much H_2O to the wedge at these depths or that the H_2O is not retained in the wedge.

3.3. Nankai (SW Japan)

[21] Beneath SW Japan the Philippine Sea plate subducts at ~45 mm/yr. The regional tectonics are complex: at the northeastern end of the Nankai Trough the Izu-Bonin arc is colliding with the Amurian plate, at the southwestern end of the Trough the Kyushu-Palau Ridge remnant arc is subducting, and in the center of the Trough the fossil Shikoku Basin spreading ridge is subducting; these features are nearly parallel to the plate convergence direction such that they undergo only slow arc-parallel migration [*Hibbard and Karig*, 1990]. The dip of the subducting slab and the maximum depth of subduction zone seismicity are at a minimum at the center of the Nankai Trough where the 15 Ma fossil Shikoku Basin spreading ridge is subducting; northeast and southwest of this, where the subducting lithosphere is older, the slab is steeper and seismicity extends to greater depth [*Nakamura et al.*, 1997].

[22] We modeled the thermal structure of the subducting Philippine Sea plate beneath the Kii Peninsula. The seismicity pattern suggests the presence of complex contortions or tears in the slab, so our thermal model only applies to a narrow segment of the subduction zone. The predicted thermal structure is slightly cooler than Cascadia, and volcanism is also weak (Figure 3a). Seismicity occurs near the top of the slab down to depths of ~70 km (Figure 3b). Like Cascadia, there is a correlation between this seismicity and our predicted metamorphic phase relations for the slab, which, in particular, indicate a transition from hydrous rocks (e.g., blueschist and zoisite eclogite) to anhydrous eclogite at ~80 km depth. Unfortunately, owing to the complexity of the slab at Nankai, it is difficult to tell whether the earthquakes are confined to the subducted crust: the seismicity is distributed normal to the slab in a Gaussian manner with a standard deviation of σ_T = 4.4 km (one sigma standard deviation), consistent with a 7-km-thick seismic zone (the thickness of the crust) and location errors of 3.9 km (Figure 6a). While this is roughly double the median standard error for depth among the earthquakes plotted, formal errors typically underestimate actual hypocenter uncertainties significantly [e.g., *Pavlis*, 1986]. Alternatively, the earthquakes could be distributed over a zone up to 15 km wide, provided actual depth errors are ≤1.3 km.

[23] Like Cascadia, seismological evidence suggests that the subducting crust persists as a low-velocity layer to the depths at which most intraslab earthquakes occur. *Hori et al.* [1985] showed that a low-velocity layer, resembling subducted Philippine Plate crust, can be seen in eastern Nankai as deep as 60 km. *Ohkura* [2000] made similar observations

near Shikoku. This layer is roughly 14% slower than the surrounding mantle, at wave speeds consistent with gabbro persisting at these depths [*Hacker et al.*, 2003].

3.4. Costa Rica

[24] The Cocos plate subducts beneath central Costa Rica along the Middle America Trench at a rate of 87 mm/yr [*DeMets et al.*, 1994]. We constructed our thermal-petrological model (Figure 4a) through central Costa Rica (Puerto Quepos) where the incoming Cocos plate is 18 Ma [*Barckhausen et al.*, 2001]. The subducting plate dips at $\sim 10°$ to about 40 km depth [*Sallares et al.*, 2001], beyond which point earthquake hypocenters suggest that it steepens to $\sim 45°$ [*Protti et al.*, 1995]. Central Costa Rica had voluminous Cenozoic arc volcanism [*Johnston and Thorkelson*, 1997] with a gap during the Pliocene [*Suárez et al.*, 1995].

[25] Along the Central America subduction zone, the maximum depth of slab seismicity decreases southward from ~200 km beneath Nicaragua to ~60 km beneath southern Costa Rica [*Protti et al.*, 1995]. For our model of central Costa Rica the hypocenters lie at the center of the Costa Rica seismic networks and are among the best constrained in Central America; we utilize the relocations of *Protti et al.* [1995]. Here, subduction earthquakes extend to ~115 km depth, although much of the seismicity does not extend deeper than ~80 km (Figure 4b). Hydrous minerals are predicted to be stable in the crust to depths of ~105 km at the transition to eclogite, with the bulk of the dehydration occurring within the lawsonite amphibole eclogite stability field.

[26] We estimate that the distribution of hypocenters has a variance $\sigma_T = 5.4$ km (5.1 km for events within 10 km of the cross section) and appears roughly Gaussian, as expected were it to arise from hypocentral error (Figure 6b). If these events were produced from within a zone 7 km wide, the hypocenters must have uncertainties $\sigma_d = 5.0$ km (4.7 km for events within 10 km of the cross section). This uncertainty estimate compares favorably to the maximum formal error in depth of 5 km quoted for these data [*Protti et al.*, 1995]. If any of these earthquakes are located within the slab mantle, they could result from serpentine or chlorite breakdown; the fact that they do not continue to depths of 200 km or more may be taken as a failure of the presently defined dehydration-seismicity hypothesis or as an indication that they occur only in the subducting crust.

3.5. Tohoku (NE Japan)

[27] Beneath Tohoku (NE Japan), the 130 Ma Pacific Plate subducts at 91 mm/yr; the calculated thermal structure is among the coldest on the planet (Figure 5a). Intraslab seismicity forms a double seismic zone, traditionally described as having an upper zone in downdip tension and a lower zone in downdip compression [*Hasegawa et al.*, 1978]. The separation between the two zones continues down to depths of ~160 km. The lower seismic zone is 30–40 km deeper into the slab and extends from ~70 to ~300 km depth. *Igarashi et al.* [2001] showed, through relocations and redetermination of focal mechanisms, that the upper zone is complex. While events with downdip *P* axes dominate the upper zone, earthquakes in a thin region at the top of the slab and downdip from the thrust zone have *P* axes normal to the downdip direction (faulting is strike-slip or normal in slab-centered coordinates). This small-scale variability of mechanisms and inferred stresses within the upper 10 km of the downgoing plate cannot be explained by plate-scale bending. Instead, *Igarashi et al.* [2001] modified *Kirby*'s [1995] model of phase changes driving shear stresses to argue that this stress state arises from densification reactions in the uppermost crust that place the uppermost crust in tension and the remainder of the crust in compression. While we support this general reasoning, we note that the densification reactions might well be driven by greater H_2O content and finer grain size rather than temperature alone.

[28] Extensive analysis of regional earthquakes beneath Tohoku has led to several lines of evidence supporting the existence of a low-velocity channel at the top of the subducted plate, commonly accepted to be the oceanic crust. *Matsuzawa et al.* [1986] utilized record sections of large-amplitude *P-S* and *S-P* converted phases to show that (1) a sharp interface must exist immediately above the upper plane of seismicity, and (2) *P* velocities, in a 5–10 km thick layer below that plane are 6–12% slower than those of surrounding mantle. These phases were best recorded for propagation between 60 and 150 km depth. *Zhao et al.* [1997] extended this data set to map out the slab surface through northern Honshu, confirming that the surface defines the uppermost bound to seismicity. *Gubbins et al.* [1994] noticed that the dispersed signals reported by *Iidaka and Mizoue* [1991] could be explained as a consequence of a low-velocity waveguide here. This notion was quantified by *Abers* [2000], who utilized dispersion properties of regional *P* and *S* waves to define a 3–8 km thick layer with wave speeds 6 ± 2% slower than the surrounding mantle. These velocities are not slow enough to represent metastable gabbro but they rule out a fully eclogitized crust at 60–150 km depths [*Helffrich*, 1996], and are consistent with the lawsonite amphibolite eclogite expected at these conditions [*Hacker et al.*, 2003].

[29] Seismicity in both the upper and lower seismic zones beneath Tohoku occurs where we predict hydrous minerals are stable in the slab. Earthquakes in the upper zone occur almost universally within 10 km of the upper surface of the slab [*Igarashi et al.*, 2001, Figure 11], and may all occur in the crust (the hypocenters in Figure 5a are too imprecisely located to evaluate this). Their abundance falls off markedly with depth (Figure 5b), paralleling the predicted downdip reduction in crystallographically bound H_2O content from 5.4 wt% (blueschists) to 3.0 wt% (lawsonite amphibole eclogite) to 0.1 wt% (eclogite). There are virtually no recorded earthquakes in the nearly anhydrous eclogite field. Earthquakes in the lower zone occur chiefly within the portion of the subducting mantle that we predict is a serpentine- or chlorite-bearing harzburgite. Thus, like the warm subduction zones, the implication is that the earthquakes in the upper seismic zone occur as a result of dehydration in the crust, and those in the lower seismic zone are the result of dehydration in the mantle.

4. A Petrologic-Kinetic Model for Intermediate-Depth Seismicity

[30] The correlation between the intermediate-depth seismicity and the predicted crystallographically bound H_2O

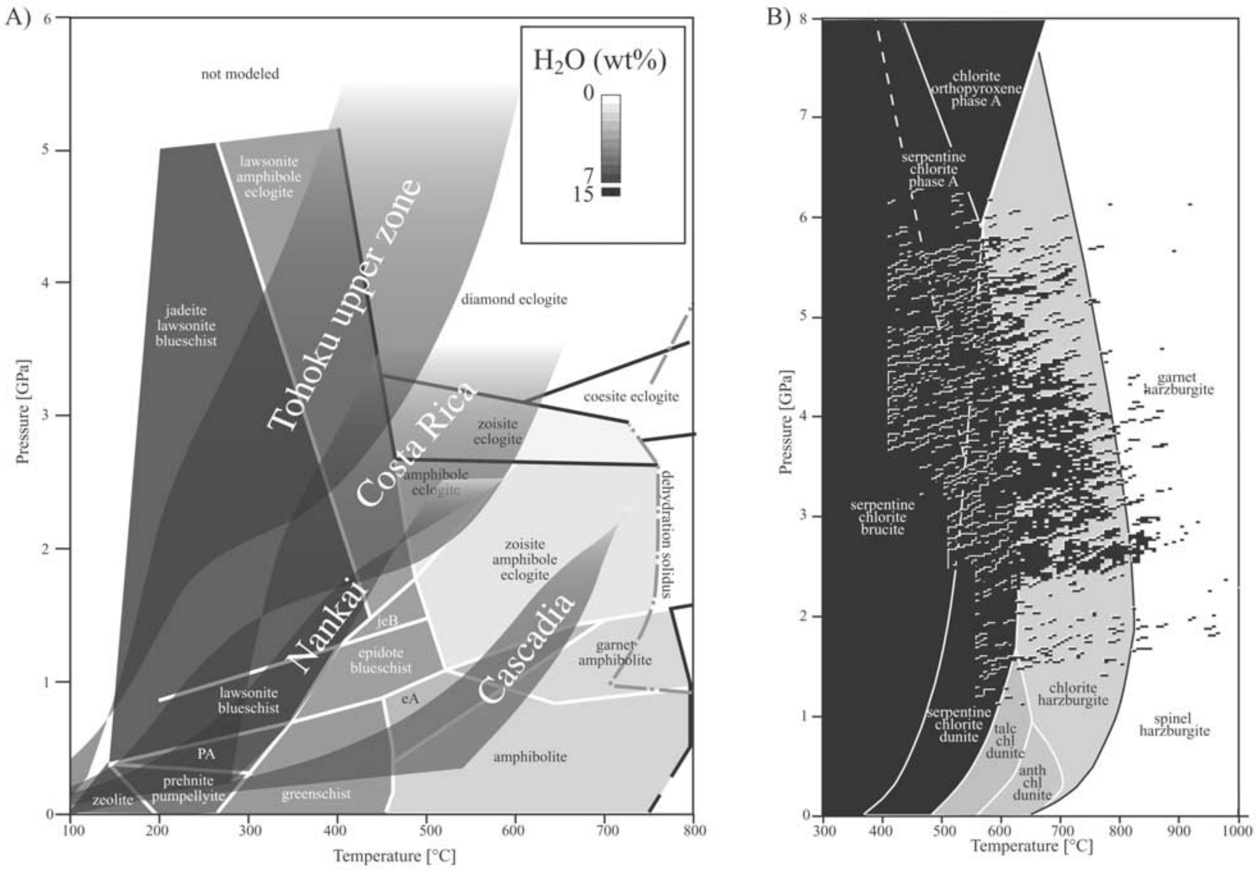

Figure 7. (a) Metamorphic facies and maximum H_2O contents for mid-ocean-ridge basalt [*Hacker et al.*, 2003] and slab crust PT regimes corresponding to depths of intermediate-depth earthquakes. (b) Metamorphic facies and H_2O contents for harzburgite [*Hacker et al.*, 2003] and intermediate-depth earthquakes in the lower seismic zone beneath Tohoku. PA, prehnite-actinolite; eA, epidote amphibolite; eB, epidote blueschist; jeB, jadeite-epidote blueschist.

content of subducting slabs is especially striking in pressure-temperature space. Figure 7 shows seismicity for the four subduction zones discussed above superimposed onto our petrogenetic grids for mafic rock and harzburgite [*Hacker et al.*, 2003]. The seismicity occurs chiefly in rocks predicted to contain abundant hydrous phases and is absent or less abundant in rocks predicted to contain anhydrous phases or only trace hydrous phases. Moreover, there is no single temperature or pressure at which seismicity stops, as might be expected if seismicity were a temperature- or pressure-mediated mechanical property. The correlation is not perfect, indicating either a failure of the hypothesis or uncertainty in thermal modeling, petrological modeling, or earthquake locations.

[31] The observation of a spatial correlation between hydration state and seismicity leads to a model for the mineralogy, phase transformations, and seismicity of subducting slabs in which the downgoing plate consists of four petrologically and seismically distinct layers (Figure 8).

1. The hydrated, glassy and fine-grained basaltic upper crust is dehydrating under equilibrium conditions and producing earthquakes driven by dehydration embrittlement; earthquakes in this layer are restricted to rocks with hydrous minerals. Once the rocks have transformed to nearly anhydrous eclogite, seismicity in this layer stops.

2. The coarse-grained gabbroic lower crust is generally anhydrous but contains local areas of substantial hydration produced either at mid-ocean spreading centers [e.g., *Tucholke et al.*, 1998] or during bending at the outer rise [*Kirby et al.*, 1996; *Peacock*, 2001]. Hydrous rocks in this layer undergo dehydration under equilibrium conditions and produce earthquakes, but the bulk of the gabbro layer transforms aseismically to eclogite at depths well beyond equilibrium because of the kinetic hindrance of solid-solid transformations and the reduced hydration state. Seismicity in upper seismic zones thus receives some contributions from the lower crust but comes dominantly from the upper crust. Because the thermal gradient in the upper seismic zone is inverted in most subduction zones, and therefore the potential for dehydration increases upward, the seismicity begins at the top of the slab and then descends slowly toward the slab Moho with increasing subduction depth.

3. The uppermost mantle is locally hydrated down to depths of ~40 km in cold slabs as a result of bending at the outer rise; it could also be hydrated by H_2O supplied from dehydration reactions at greater depth (see below). The hydrous portions dehydrate under equilibrium conditions and produce earthquakes. Because the temperature in the lower seismic zone increases downward, and therefore the potential for dehydration increases downward, the seismi-

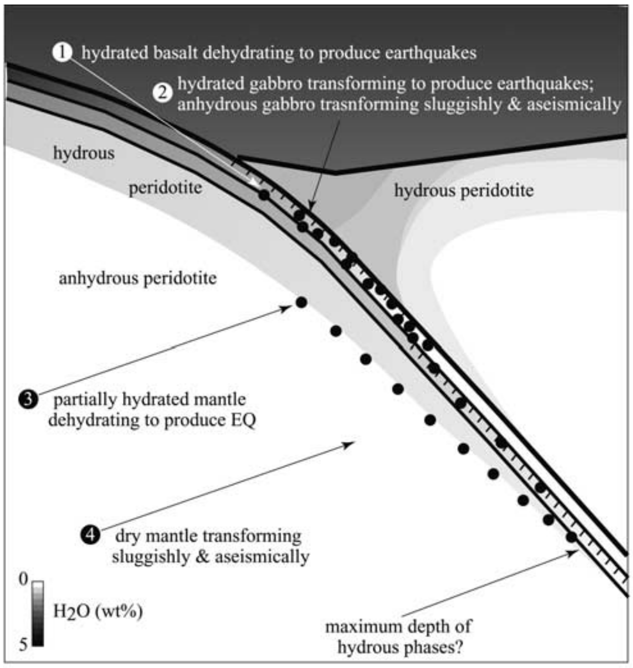

Figure 8. Ideal, relatively cold end-member subduction zone. Solid and open circles indicate earthquakes induced by dehydration. Numbers 1–4 correspond to discussion in text.

city begins at modest depth in the slab and then ascends slowly toward the slab Moho with increasing subduction depth.

4. The remaining, anhydrous mantle transforms sluggishly and aseismically from spinel- to garnet-bearing assemblages.

[32] This hypothesis explains several important features of intermediate-depth seismicity: (1) the earthquakes occur at locations in the slab that correspond to predicted dehydration reactions; (2) the observed low-velocity waveguides that persist to depths greater than the equilibrium transformation of gabbro → eclogite exist because equilibrium transformation occurs in the upper crust, while the coarse, dry lower crusts persists metastably to greater depth; (3) the upper and lower zones of double seismic zones result from dehydration reactions in the crust and mantle, respectively; and (4) the gap between the upper and lower zones of double seismic zones reflects slower and/or later reaction in the cold core of the slab.

4.1. Issues Outstanding

[33] While the observed locations of intermediate-depth seismicity correlate with the predicted H_2O content of subducting slabs, understanding why some portions of slabs that are predicted to contain hydrous minerals do not generate earthquakes will be an important step forward. Moreover, although petrological models [e.g., *Peacock*, 1993] and seismological observations [*Kamiya and Kobayashi*, 2000] indicate that hydrous minerals are stable in some mantle wedges, and these minerals must undergo partial or complete dehydration if dragged to higher temperatures and pressures, why are mantle wedges seismically inactive? One possibility is that hydrous rocks in mantle wedges are not dragged down and do not dehydrate.

4.2. Further Tests of the Hypothesis

[34] Several additional tests of our hypothesis are possible.

1. The crystallographically bound H_2O contents of mafic rocks (Figure 7a) dictate that the downdip limit of upper seismic zones should be near-isothermal in cold subduction zones and near-isobaric in warm subduction zones (this contrasts with the behavior expected if a temperature-dependent rheological property, such as the onset of creep, controlled seismicity).

2. Seismicity should be proportional to the amount of crystallographically bound H_2O. Thus more extensively hydrated crust (e.g., crust from slowly spreading ridges [*Karson*, 1998]) should have more earthquakes. Sections of subducting lithosphere with abundant fine-grained, glassy rocks should have more earthquakes. Plates that undergo more extreme bending, and thus hydration, at outer rises might have more earthquakes.

3. The vertical separation between the upper and lower seismic zones should be correlated to plate age, given equal opportunity for hydration prior to subduction, because older plates have thicker zones where hydrous mantle minerals are stable. For example, even the warm Cascadia slab might have a lower seismic zone within the uppermost mantle that is distinct from seismicity in the crust.

4. The dehydration reactions for basalt/gabbro and harzburgite do not coincide over much of PT space (Figure 7), such that some subduction zones should have upper and lower seismic zones that remain distinct and terminate at different depths.

5. The petrological and kinetic difference between the upper and lower crust means that the low-velocity waveguide observed within subducting slabs begins in the upper crust and migrates into the lower crust with increasing subduction depth. At depths <30 km the hydrated upper crust is slower (V_P = 6.5–6.7 km/s) than the relatively anhydrous lower crust (~7.0 km/s) [*Hacker et al.*, 2003]. At greater depths, the hydrated upper crust densifies under equilibrium conditions to blueschist (V_P = 7.3–7.9 km/s) and eclogite ($V_P \geq$ 8.4 km/s), quickly surpassing the relatively low-velocity metastable gabbro ($V_P \leq$ 7.3 km/s) [*Hacker*, 1996].

[35] Finally, except for the slabs where double seismic zones are present, it remains unclear whether earthquakes are confined to the subducting crust or lie within both the crust and mantle. Part of the difficulty is that, except at Tohoku and Cascadia, the location of the slab has not been determined independently from the seismicity. Further, given our knowledge of hypocentral errors it is difficult to rule out the possibility of a "thin" belt of seismicity in most slabs.

4.3. Fluid Flow Associated With Dehydration Reactions and Seismicity

[36] If our hypothesis of where and why H_2O is generated in slabs is generally correct, the next step is to understand the subsequent path and transport mechanism(s) of the H_2O (Figure 9). Does the evolved H_2O move upward into the mantle wedge or into the overlying part of the slab? Does it move up the dip of the slab? Does it hydrate rocks with

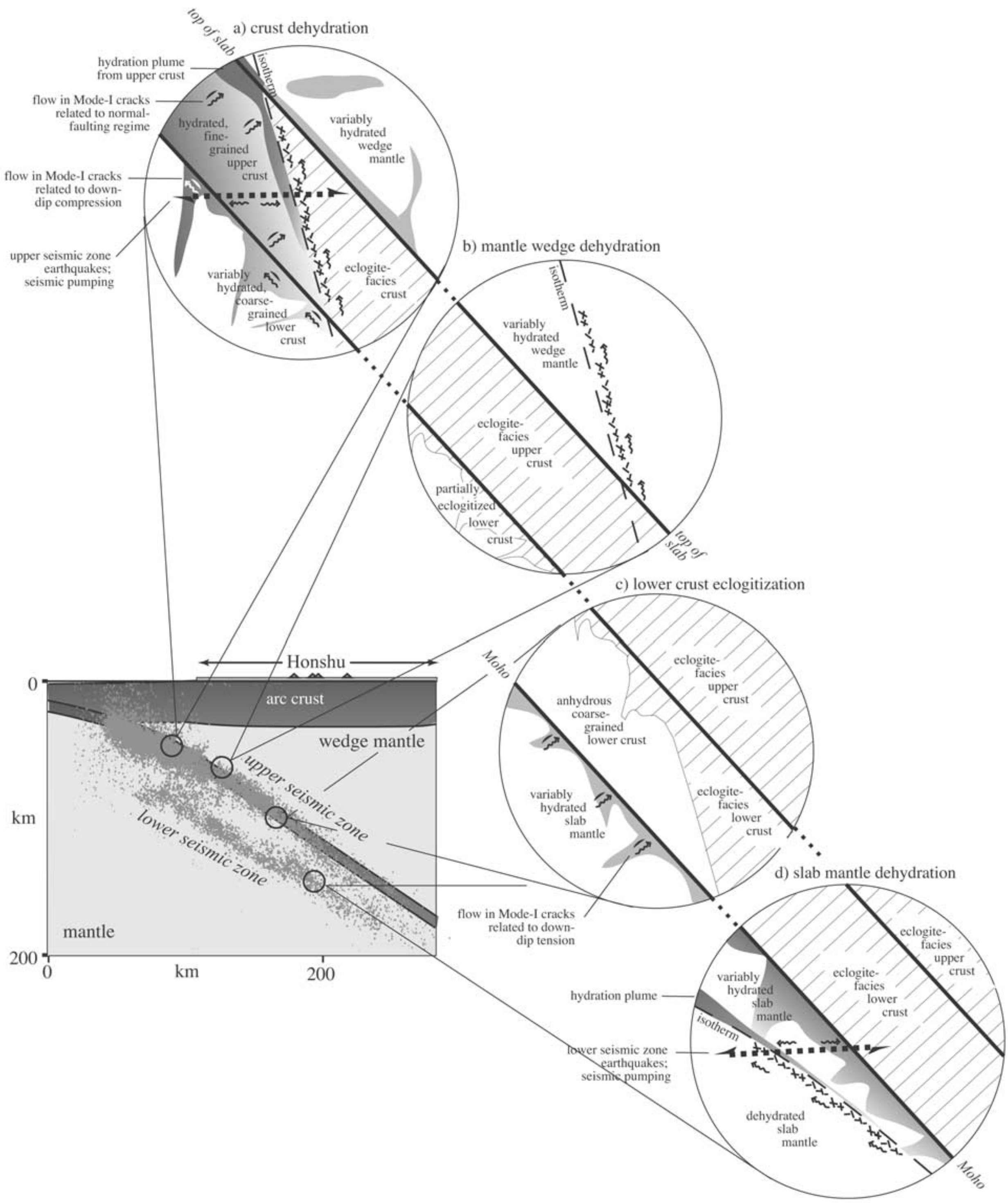

Figure 9. Model for fluid flow in subducting slabs. Upper crust is assumed to be completely hydrated. Mantle and lower crust are assumed to be incompletely hydrated. Depths >70 km where the uppermost earthquakes are normal faulting events. Isotherm shown applies to depth shallower than onset of influence of wedge convection; at deeper levels, coldest part of slab lies 5–20 km beneath the top of the slab. Large dashed arrows indicate earthquakes; small arrows show fluid flow; and crosses indicate reaction zones with microearthquakes, densification, and high permeability. Gray scale shows schematic H_2O content.

which it comes in contact? Under what circumstances does the H_2O move by advection in pores or in crystals, by porous flow through pores or cracks, or by flow in conduits such as faults? Figure 9 shows potential interactions among dehydration, earthquakes, stress state, fluid flow, and hydration. There are at least three distinct fluid-flow paths.

1. Fluids may flow along high-permeability reaction zones. Rocks with hydrous minerals undergo dehydration chiefly as a result of heating, but, at high pressures, also as a result of compression. This dehydration (shown in zones parallel to isotherms in Figure 9) causes a local transient increase in fluid pressure that may enable earthquakes, but also a finite decrease in solid volume, leading to a transient high-permeability pathway that can remain open until sealed. Indeed, the tradeoffs between volume change, permeability, and creep may control the extent to which dehydration can lead to brittle behavior [*Connolly*, 1997; *Hacker*, 1997; *Wong et al.*, 1997]. Fluid generated by this means in the mantle wedge has little choice but to migrate farther into the wedge (Figure 9b). Fluid generated by dehydration in the crust should flow upward through the local high-permeability reaction zone until it encounters the interplate fault, where it could migrate up dip, leading to additional hydration of incoming upper crust, or react to hydrate the mantle hanging wall (Figure 9a). Hydrated mantle wedge might subsequently be dragged downward by viscous coupling to the slab, and dehydrated, eventually leading to arc magmatism [*Davies and Stevenson*, 1992]. Fluid generated in the slab mantle by devolatilization can move trenchward through the local high-permeability reaction zone, which dips toward the arc, creating a hydration plume within rocks containing less than their equilibrium amount of H_2O (Figure 9d). This plume could attain a steady state configuration that depends on subduction velocity and permeability.

2. Fluid may flow by hydrofracturing along mode I cracks that propagate perpendicular to the least compressive stress. *Davies* [1999] suggested that at ambient subduction zone temperatures, any fluid will soon be subjected to high pressure by ductile creep of the rock even if the permeability is high. He suggested that isolated pockets of H_2O nucleate microcracks that are then held open by fluid. Figure 9 illustrates the orientation that mode I cracks might have in the triple-planed seismic zone of Tohoku [*Kosuga et al.*, 1996; *Igarashi et al.*, 2001]. At depths >70 km, where normal-faulting earthquakes overlie dominantly downdip P axis earthquakes, most hydrofractures should be orthogonal to the slab and dip toward the trench in the uppermost crust and be parallel to the slab deeper in the crust. The lower seismic zone, with mostly downdip T axis earthquakes, should have hydrofractures primarily perpendicular to the slab. This layered variation in stress state should permit slab-normal flow of fluid in mode I cracks in the upper crust and slab mantle and updip flow in cracks in the lower crust. Fluid generated in the lower crust or slab mantle cannot leave the lower crust via mode I cracks but can escape along faults or through high-permeability reaction zones. It is important to note that mode I cracks cannot themselves explain earthquakes because intermediate-depth events show no isotropic component [*Frohlich*, 1989].

3. Fluids may flow upward by hydrofracturing along new or preexisting fractures [*Davies*, 1999]. Mode I cracks do not themselves constitute fault planes, but they can coalesce to nucleate a rupture which would then connect more H_2O-filled cracks. *Kirby* [1995] noted that the length scale for fluid migration necessary to induce faulting need not be large because preexisting faults in subducted oceanic crust contain hydrous minerals. After an earthquake, and before the fault is sealed, the dilated fault core where cataclasis was localized serves as a high-permeability corridor for fluid migration [*Sibson*, 1992]. The unusually low aftershock activity of intermediate-depth earthquakes [*Frohlich*, 1987] may support this fluid pressure embrittlement model, as the earthquake-generated permeability leads to a transient incapacity for earthquakes because of the fluid loss. The bulk of the fault planes for large events in the slab beneath Tohoku are subvertical and subhorizontal [*Kosuga et al.*, 1996], and those in the Tonga subduction zone occur along faults whose asymmetry matches the faults present in the outer rise events in the presubducted crust [*Jiao et al.*, 2000]. Thus fault-related fluid migration pathways may be dictated by presubduction fault geometries.

5. Conclusions

[37] In four subduction zones (Cascadia, Nankai, Costa Rica, and Tohoku), there is a correlation between the locations of intermediate-depth earthquakes, the depths of observed low-velocity subducted crust, and the predicted locations of hydrous minerals. This implies that dehydration reactions are linked to intermediate-depth seismicity. The strong contrast between the fine-grained, hydrous upper oceanic crust and the coarse-grained lower crust means that the two layers should be kinetically and seismically different. Specifically, transformation to eclogite, with accompanying seismicity, should occur at near-equilibrium conditions in the upper crust, while transformation of the lower crust to eclogite may be substantially inhibited and form the low-velocity waveguides observed in some subduction zones. The lower seismic zone of double seismic zones is the result of serpentine or chlorite dehydration in the slab mantle.

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References

Abers, G. A., Relationship between shallow- and intermediate-depth seismicity in the eastern Aleutian subduction zone, *Geophys. Res. Lett.*, *19*, 2019–2022, 1992.

Abers, G. A., Plate structure and the origin of double seismic zones, in *Subduction: Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 223–228, AGU, Washington, D. C., 1996.

Abers, G. A., Hydrated subducted crust at 100–250 km depth, *Earth Planet. Sci. Lett.*, *176*, 323–330, 2000.

Abers, G. A., and G. Sarker, Dispersion of regional body waves at 100–150 km depth beneath Alaska: In situ constraints on metamorphism of subducted crust, *Geophys. Res. Lett.*, *23*, 1171–1174, 1996.

Abers, G. A., J. Stachnik, S. Pozgay, D. H. Christensen, R. Hansen, and E. V. Meyers, The BEAAR facts: Sampling the Alaskan slab, wedge and mountains with a broadband experiment across the Alaska Range (BEAAR), *Seismol. Res. Lett.*, *73*, 219, 2002.

ANCORP Working Group, Seismic reflection image revealing offset of Andean subduction-zone earthquake locations into oceanic mantle, *Nature*, *397*, 341–344, 1999.

Ansell, J. H., and D. Gubbins, Anomalous high-frequency wave propagation from the Tonga-Kermadec seismic zone to New Zealand, *Geophys. J. R. Astron. Soc.*, *85*, 93–106, 1986.
Araujo, M., and G. Suarez, Geometry and state of stress of the subducted Nazca Plate beneath central Chile and Argentina; evidence from teleseismic data, *Geophys. J. Int.*, *116*, 283–303, 1994.
Barckhausen, U., C. R. Ranero, R. von Huene, S. C. Cande, and H. A. Roeser, Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models, *J. Geophys. Res.*, *106*, 19,207–19,220, 2001.
Bock, G., B. Schurr, and G. Asch, High-resolution image of the oceanic Moho in the subducting Nazca plate from *P-S* converted waves, *Geophys. Res. Lett.*, *27*, 3929–3932, 2000.
Bridgman, P. W., Polymorphic transitions and geological phenomena, *Am. J. Sci.*, *243A*, 90–97, 1945.
Campus, P., and S. Das, Comparison of the rupture and radiation characteristics of intermediate and deep earthquakes, *J. Geophys. Res.*, *105*, 6177–6189, 2000.
Cassidy, J. F., and R. M. Ellis, *S* wave velocity structure of the northern Cascadia subduction zone, *J. Geophys. Res.*, *98*, 4407–4421, 1993.
Comte, D., and G. Suárez, An inverted double seismic zone in Chile: Evidence of phase transformation in the subducted slab, *Science*, *263*, 212–215, 1994.
Connolly, J. A. D., Devolatilization-generated fluid pressure and deformation-propagated fluid flow during prograde regional metamorphism, *J. Geophys. Res.*, *102*, 18,149–18,173, 1997.
Cummins, P. R., T. Baba, A. Smith, J. Townend, and K. Uhira, An integrated focal mechanism database for Japanese earthquakes, *Seismol. Res. Lett.*, *73*, 251, 2002.
Davies, J. H., The role of hydraulic fractures and intermediate-depth earthquakes in generating subduction-zone magmatism, *Nature*, *398*, 142–145, 1999.
Davies, J. H., and D. J. Stevenson, Physical model of source region of subduction zone volcanics, *J. Geophys. Res.*, *97*, 2037–2070, 1992.
DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal time-scale of estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194, 1994.
Drew, J. J., and R. M. Clowes, A re-interpretation of the seismic structure across the active subduction zone of western Canada, *Pap. Geol. Surv. Can.*, *89–13*, 115–132, 1990.
Ekstrom, G., and E. R. Engdahl, Earthquake source parameters and stress distribution in the Adak Island region of the central Aleutian Islands, Alaska, *J. Geophys. Res.*, *94*, 15,499–15,519, 1989.
Frohlich, C., Aftershocks and temporal clustering of deep earthquakes, *J. Geophys. Res.*, *92*, 13,944–13,956, 1987.
Frohlich, C., The nature of deep-focus earthquakes, *Annu. Rev. Earth Planet. Sci.*, *17*, 227–254, 1989.
Fujita, K., and H. Kanamori, Double seismic zones and stresses of intermediate depth earthquakes, *Geophys. J. R. Astron. Soc.*, *66*, 131–156, 1981.
Gorbatov, A., G. Suarez, V. Kostoglodov, and E. Gordeev, A double-planed seismic zone in Kamchatka from local and teleseismic data, *Geophys. Res. Lett.*, *21*, 1675–1678, 1994.
Green, H. W., and P. C. Burnley, A new self-organizing, mechanism for deep-focus earthquakes, *Nature*, *341*, 733–737, 1989.
Green, H. W., and H. Houston, The mechanics of deep earthquakes, *Annu. Rev. Earth Planet.*, 169–213, 1995.
Green, H. W., and Y. Zhou, Transformation-induced faulting requires an exothermic reaction and explains the cessation of earthquakes at the base of the mantle transition zone, *Tectonophysics*, *256*, 39–56, 1996.
Green, H. W., T. E. Young, D. Walker, and C. H. Scholz, Anticrack-associated faulting at very high pressure in natural olivine, *Nature*, *348*, 720–722, 1990.
Griggs, D. T., The sinking lithosphere and the focal mechanism of deep earthquakes, in *The Nature of the Solid Earth*, edited by E. C. Robertson, pp. 361–384, McGraw-Hill, New York, 1972.
Gubbins, D., A. Barnicoat, and J. Cann, Seismological constraints on the gabbro-eclogite transition in subducted oceanic crust, *Earth Planet. Sci. Lett.*, *122*, 89–101, 1994.
Gutenberg, B., and C. F. Richter, *Seismicity of the Earth and Related Phenomena*, 310 pp., Princeton Univ.y Press, Princeton, N. J., 1954.
Hacker, B. R., Eclogite formation and the rheology, buoyancy, seismicity, and H_2O content of oceanic crust, in *Dynamics of Subduction*, edited by G. E. Bebout et al., pp. 337–246, AGU, Washington, D. C., 1996.
Hacker, B. R., Diagenesis and the fault-valve seismicity of crustal faults, *J. Geophys. Res.*, *102*, 24,459–24,467, 1997.
Hacker, B. R., and J. M. Christie, Brittle/ductile and plastic/cataclastic transitions in experimentally deformed and metamorphosed amphibolite, in *The Brittle-Ductile Transition in Rock*, *Geophys. Monogr. Ser.*, vol. 56, edited by A. G. Duba et al., pp. 127–147, AGU, Washington, D. C., 1990.
Hacker, B. R., and S. H. Kirby, High-pressure deformation of calcite marble and its transformation to aragonite under non-hydrostatic conditions, *J. Struct. Geol.*, *15*, 1207–1222, 1993.
Hacker, B. R., S. R. Bohlen, and S. H. Kirby, Albite → jadeite + quartz transformation in albitite, *Eos Trans. AGU*, *74*(430), Fall Meet. Suppl., 611, 1993.
Hacker, B. R., G. A. Abers, and S. M. Peacock, Subduction factory, 1, Theoretical mineralogy, density, seismic wave speeds, and H_2O content, *J. Geophys. Res*, doi:10.1029/2001JB001127, in press, 2003.
Hasegawa, A., N. Umino, and A. Takagi, Double-planed deep seismic zone and upper-mantle structure in the northeastern Japan Arc, *Geophys. J. R. Astron. Soc.*, *54*, 281–296, 1978.
Helffrich, G., Subducted lithospheric slab velocity structure: Observations and mineralogical inferences, in *Subduction: Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 215–222, AGU, Washington, D. C., 1996.
Helffrich, G., and G. A. Abers, Slab low-velocity layer in the eastern Aleutian subduction zone, *Geophys. J. Int.*, *130*, 640–648, 1997.
Hibbard, J. P., and D. E. Karig, Structural and magmatic responses to spreading ridge subduction: An example from southwest Japan, *Tectonics*, *9*, 207–230, 1990.
Hobbs, B. E., and A. Ord, Plastic instabilities: Implications for the origin of intermediate and deep focus earthquakes, *J. Geophys. Res.*, *93*, 10,521–10,540, 1988.
Hori, S., H. Inoue, Y. Fukao, and M. Ukawa, Seismic detection of the untransformed "basaltic" oceanic crust subducting into the mantle, *Geophys. J. R. Astron. Soc.*, *83*, 169–197, 1985.
Hyndman, R. D., and K. Wang, Thermal constraints on the zone of possible major thrust earthquake failure on the Cascadia margin, *J. Geophys. Res.*, *98*, 2039–2060, 1993.
Hyndman, R. D., K. Wang, and M. Yamano, Thermal constraints on the seismogenic portion of the southwestern Japan subduction thrust, *J. Geophys. Res.*, *100*, 15,373–15,392, 1995.
Igarashi, T., T. Matsuzawa, N. Umino, and A. Hasegawa, Spatial distribution of focal mechanisms for interplate and intraplate earthquakes associated with the subducting Pacific plate beneath the northeastern Japan arc: A tripled-planed deep seismic zone, *J. Geophys. Res.*, *106*, 2177–2191, 2001.
Iidaka, T., and M. Mizoue, *P*-wave velocity structure inside the subducting Pacific Plate beneath the Japan region, *Phys. Earth Planet. Inter.*, *66*, 203–213, 1991.
Isacks, B., and P. Molnar, Mantle earthquake mechanisms and the sinking of the lithosphere, *Nature*, *223*, 1121–1124, 1969.
Isacks, B. L., and M. Barazangi, Geometry of Benioff zones: Lateral segmentation and downwards bending of the subducted lithosphere, in *Island Arcs, Deep Sea Trenches and Back-arc Basins*, edited by M. Talwani and W. C. Pitman III, pp. 99–114, AGU, Washington, D. C., 1977.
Jiao, W., P. G. Silver, Y. Fei, and C. T. Prewitt, Do intermediate- and deep-focus earthquakes occur on preexisting weak zones? An examination of the Tonga subduction zone, *J. Geophys. Res.*, *105*, 28,125–28,138, 2000.
Johnston, S. T., and D. J. Thorkelson, Cocos-Nazca slab window beneath Central America, *Earth Planet. Sci. Lett.*, *146*, 465–474, 1997.
Jové, C., and B. R. Hacker, Experimental investigation of laumontite → wairakite + H_2O: A model diagenetic reaction, *Am. Mineral.*, *82*, 781–789, 1997.
Kamiya, S., and Y. Kobayashi, Seismological evidence for the existence of serpentinized wedge mantle, *Geophys. Res. Lett.*, *27*, 819–822, 2000.
Kanamori, H., D. L. Anderson, and T. H. Heaton, Frictional melting during the rupture of the 1994 Bolivian earthquake, *Science*, *279*, 839–842, 1998.
Kao, H., and W.-P. Chen, The double seismic zone in Kuril-Kamchatka: The tale of two overlapping single zones, *J. Geophys. Res.*, *99*, 6913–6930, 1994.
Kao, H., and L.-g. Liu, A hypothesis for the seismogenesis of a double seismic zone, *Geophys. J. Int.*, *123*, 71–84, 1995.
Karson, J., Internal structure of oceanic lithosphere: A perspective from tectonic windows, in *Faulting and Magmatism at Mid-Ocean Ridges*, *Geophys. Monogr. Ser.*, vol. 106, edited by W. R. Buck et al., pp. 177–217, AGU, Washington, D. C., 1998.
Kawakatsu, H., Downdip tensional earthquakes beneath the Tonga arc: A double seismic zone, *J. Geophys. Res.*, *91*, 6432–6440, 1986.
Kirby, S. H., Localized polymorphic phase transitions in high-pressure faults and applications to the physical mechanism of deep earthquakes, *J. Geophys. Res.*, *92*, 13,789–13,800, 1987.
Kirby, S. H., Interslab earthquakes and phase changes in subducting lithosphere, *U.S. Natl. Rep. Int. Union Geod. Geophys. 1991–1994*, *Rev. Geophys.*, *33*, 287–297, 1995.
Kirby, S. H., W. B. Durham, and L. A. Stern, Mantle phase changes and deep-earthquake faulting in subducting lithosphere, *Science*, *252*, 216–225, 1991.

Kirby, S. H., E. R. Engdahl, and R. Denlinger, Intermediate-depth intraslab earthquakes and arc volcanism as physical expressions of crustal and uppermost mantle metamorphism in subducting slabs, in *Subduction: Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 195–214, AGU, Washington, D. C., 1996.

Ko, S.-Z., D. L. Olgaard, and T.-F. Wong, Generation and maintenance of pore pressure excess in a dehydrating system, 1, Experimental and microstructural observations, *J. Geophys. Res.*, *102*, 825–839, 1997.

Kodaira, S., N. Takahashi, J. O. Park, K. Mochizuki, M. Shinohara, and S. Kimura, Western Nankai Trough seismogenic zone: Results from a wide-angle ocean bottom seismic survey, *J. Geophys. Res.*, *105*, 5887–5905, 2000.

Kosuga, M., T. Sato, A. Hasegawa, T. Matsuzawa, S. Suzuki, and Y. Motoya, Spatial distribution of intermediate-depth earthquakes with horizontal or vertical nodal planes beneath northeastern Japan, *Phys. Earth Planet. Inter.*, *93*, 63–89, 1996.

Matsuzawa, T., N. Umino, A. Hasegawa, and A. Takagi, Normal fault type events in the upper plane of the double-planed deep seismic zone beneath the northeastern Japan Arc, *J. Phys. Earth*, *34*, 85–94, 1986.

McGarr, A., Seismic moments of earthquakes beneath island arc, phase changes and subduction velocities, *J. Geophys. Res.*, *82*, 256–264, 1977.

McGuire, J. J., and D. A. Weins, A double seismic zone in New Britain and the morphology of the Solomon Plate at intermediate depth, *Geophys. Res. Lett.*, *22*, 1965–1968, 1995.

Murrell, S. A. F., and I. A. H. Ismail, The effect of decomposition of hydrous minerals on the mechanical properties of rocks at high pressures and temperatures, *Tectonophysics*, *31*, 207–258, 1976.

Nakamura, M., H. Watanabe, T. Konomi, S. Kimura, and K. Miura, Characteristics activities of subcrustal earthquakes along the outer zone of southwestern Japan, *Annu. Disaster Prev. Res. Inst. Kyoto Univ.*, *40*, B1–B21, 1997.

Ogawa, M., Shear instability in a viscoelastic material as the cause of deep focus earthquakes, *J. Geophys. Res.*, *92*, 13,801–13,810, 1987.

Ohkura, T., Structure of the upper part of the Philippine Sea plate estimated by later phases of upper mantle earthquakes in and around Shikoku, Japan, *Tectonophysics*, *321*, 17–35, 2000.

Owens, T. J., R. S. Crosson, and M. A. Hendrickson, Constraints on the subduction geometry beneath western Washington from broadband teleseismic waveform modeling, *Bull. Seismol. Soc. Am.*, *78*, 1319–1334, 1988.

Pardo, M., and G. Suarez, Shape of the subducted Rivera and Cocos plates in southern Mexico: Seismic and tectonic implications, *J. Geophys. Res.*, *100*, 12,357–12,373, 1995.

Parsons, T., A. M. Trehu, J. H. Luetgert, K. C. Miller, F. Kilbride, R. E. Wells, M. A. Fisher, E. R. Flueh, U. S. ten Brink, and N. I. Christensen, A new view into the Cascadia subduction zone and volcanic arc: Implications for earthquake hazards along the Washington margin, *Geology*, *26*, 199–202, 1998.

Pavlis, G. L., Appraising earthquake hypocenter location errors: A complete, practical approach for single-event locations, *Bull. Seismol. Soc. Am.*, *76*, 1699–1717, 1986.

Peacock, S. M., Large-scale hydration of the lithosphere above subducting slabs, *Chem. Geol.*, *108*, 49–59, 1993.

Peacock, S. M., Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle?, *Geology*, *29*, 299–302, 2001.

Peacock, S. M., and K. Wang, Seismic consequences of warm versus cool subduction metamorphism: Examples from southwest and northeast Japan, *Science*, *286*, 937–939, 1999.

Pennington, W. D., Role of shallow phase changes in the subduction of oceanic crust, *Science*, *220*, 1045–1046, 1983.

Protti, M., F. Güendel, and K. McNally, Correlation between the age of the subducting Cocos Plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica, in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, edited by P. Mann, *Spec. Pap. Geol. Soc. Am.*, *295*, 309–326, 1995.

Raleigh, C. B., Tectonic implications of serpentinite weakening, *Geophys. J. R. Astron. Soc.*, *14*, 113–118, 1967.

Raleigh, C. B., and M. S. Paterson, Experimental deformation of serpentinite and its tectonic implications, *J. Geophys. Res.*, *70*, 3965–3985, 1965.

Robinson, R., Seismicity, structure and tectonics of the Wellington region, New Zealand, *Geophys. J. R. Astron. Soc.*, *87*, 379–409, 1986.

Rogers, G. C., Earthquakes and earthquake hazards in the Vancouver area, *Bull. Geol. Surv. Can.*, *525*, 17–25, 1998.

Rutter, E. H., and K. Brodie, Experimental "syntectonic" dehydration of serpentinite under conditions of controlled pore water pressure, *J. Geophys. Res.*, *93*, 4907–4932, 1988.

Sallares, V., J. J. Danobeitia, and E. R. Flueh, Lithospheric structure of the Costa Rican isthmus: Effects of subduction zone magmatism on an oceanic plateau, *J. Geophys. Res.*, *106*, 621–643, 2001.

Samowitz, I. R., and D. W. Forsyth, Double seismic zone beneath the Mariana island arc, *J. Geophys. Res.*, *86*, 7013–7021, 1981.

Seno, T., and Y. Yamanaka, Double seismic zones, compressional deep trench-outer rise events, and superplumes, in *Subduction: Top to Bottom*, *Geophys. Monogr. Ser.*, vol. 96, edited by G. E. Bebout et al., pp. 347–355, AGU, Washington, D. C., 1996.

Sibson, R. H., Implications of fault-valve behavior for rupture nucleation and recurrence, *Tectonophysics*, *211*, 283–293, 1992.

Suárez, G., M. Pardo, J. Domínguez, and L. Ponce, The Limón, Costa Rica earthquake of April 22, 1991: Back arc thrusting and collisional tectonics in a subduction environment, *Tectonics*, *14*, 518–530, 1995.

Taber, J. J., and B. T. R. Lewis, Crustal structure of the Washington continental margin from refraction data, *Bull. Seismol. Soc. Am.*, *76*, 1011–1024, 1986.

Tucholke, B. E., J. Lin, and M. C. Kleinrock, Megamullions and mullion structure defining oceanic metamorphic core complexes on the Mid-Atlantic Ridge, *J. Geophys. Res.*, *103*, 9857–9866, 1998.

Tullis, J. A., Preferred orientations in experimentally deformed quartzites, thesis, Univ. of Calif., Los Angeles, 1971.

Vidale, J. E., and H. Houston, The depth dependence of earthquake duration and implications for rupture mechanisms, *Nature*, *365*, 45–47, 1993.

Walther, J. V., and B. J. Wood, Rate and mechanism in prograde metamorphism, *Contrib. Mineral. Petrol.*, *88*, 246–259, 1984.

Wong, T.-F., S.-Z. Ko, and D. L. Olgaard, Generation and maintenance of pore pressure excess in a dehydrating system, 2, Theoretical analysis, *J. Geophys. Res.*, *102*, 841–852, 1997.

Yoshii, T., A detailed cross-section of the deep seismic zone beneath northeastern Honshu, Japan, *Tectonophysics*, *55*, 349–360, 1979.

Yuan, H., J. Park, and V. Levin, P-to-S converted phases from subducted slabs in the northwest Pacific, *Eos Trans. AGU*, *80*(46), Fall Meet. Suppl., F720, 1999.

Yuan, X., et al., Subduction and collision processes in the central Andes constrained by converted seismic phases, *Nature*, *408*, 958–961, 2000.

Zhao, D., and A. Hasegawa, *P* wave tomographic imaging of the crust and upper mantle beneath the Japan Islands, *J. Geophys. Res.*, *98*, 4333–4353, 1993.

Zhao, D., A. Hasegawa, and S. Horiuchi, Tomographic imaging of P and S wave velocity structure beneath northwestern Japan, *J. Geophys. Res.*, *97*, 19,909–19,928, 1992.

Zhao, D., T. Matsuzawa, and A. Hasegawa, Morphology of the subducting slab boundary in the northeastern Japan arc, *Phys. Earth Planet. Inter.*, *102*, 89–104, 1997.

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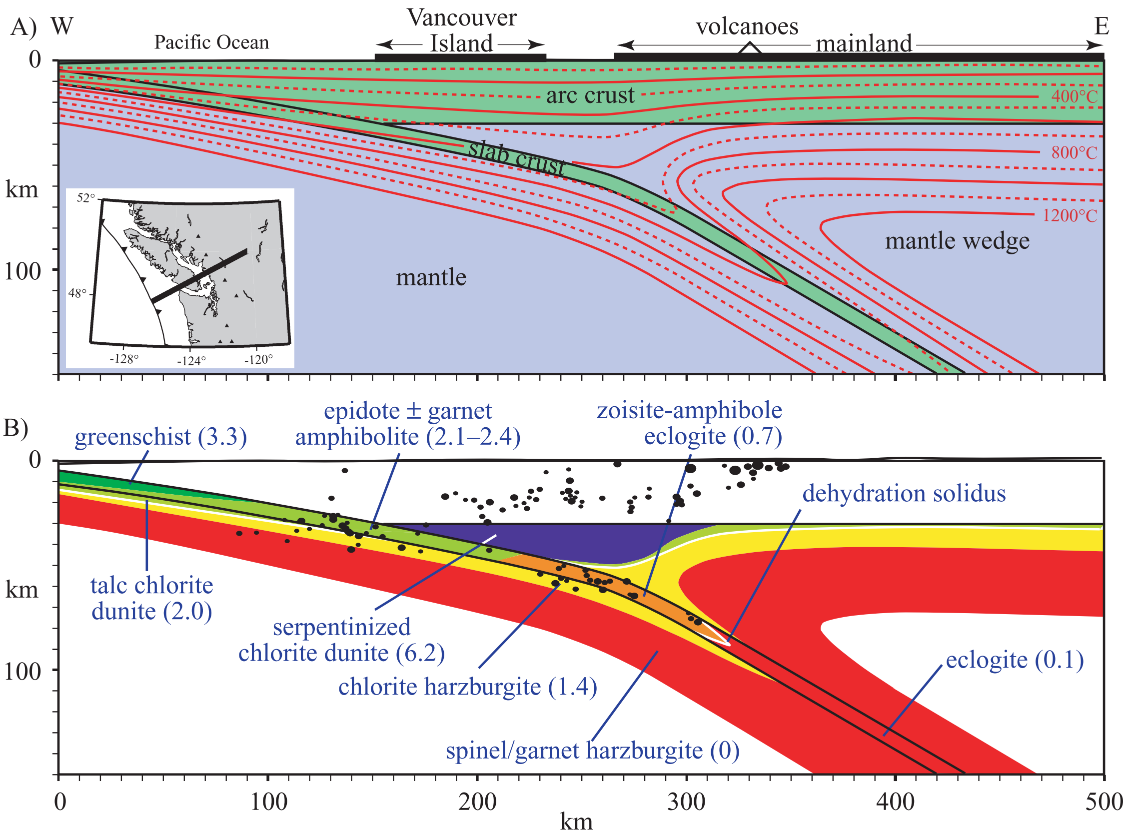

Figure 2. Correlation between seismicity and phase transformations in the Cascadia subduction zone. (a) Transect through southern Vancouver Island; thermal model calculated in this study. (b) Metamorphic facies calculated following *Hacker et al.* [2002]. Seismicity from *Rogers* [1998], which was taken from within 50 km of the transect from a combination of Washington and Canadian regional network catalogs for events between 1980 and 1991 having magnitude >1.0 and formal depth uncertainty <3 km.

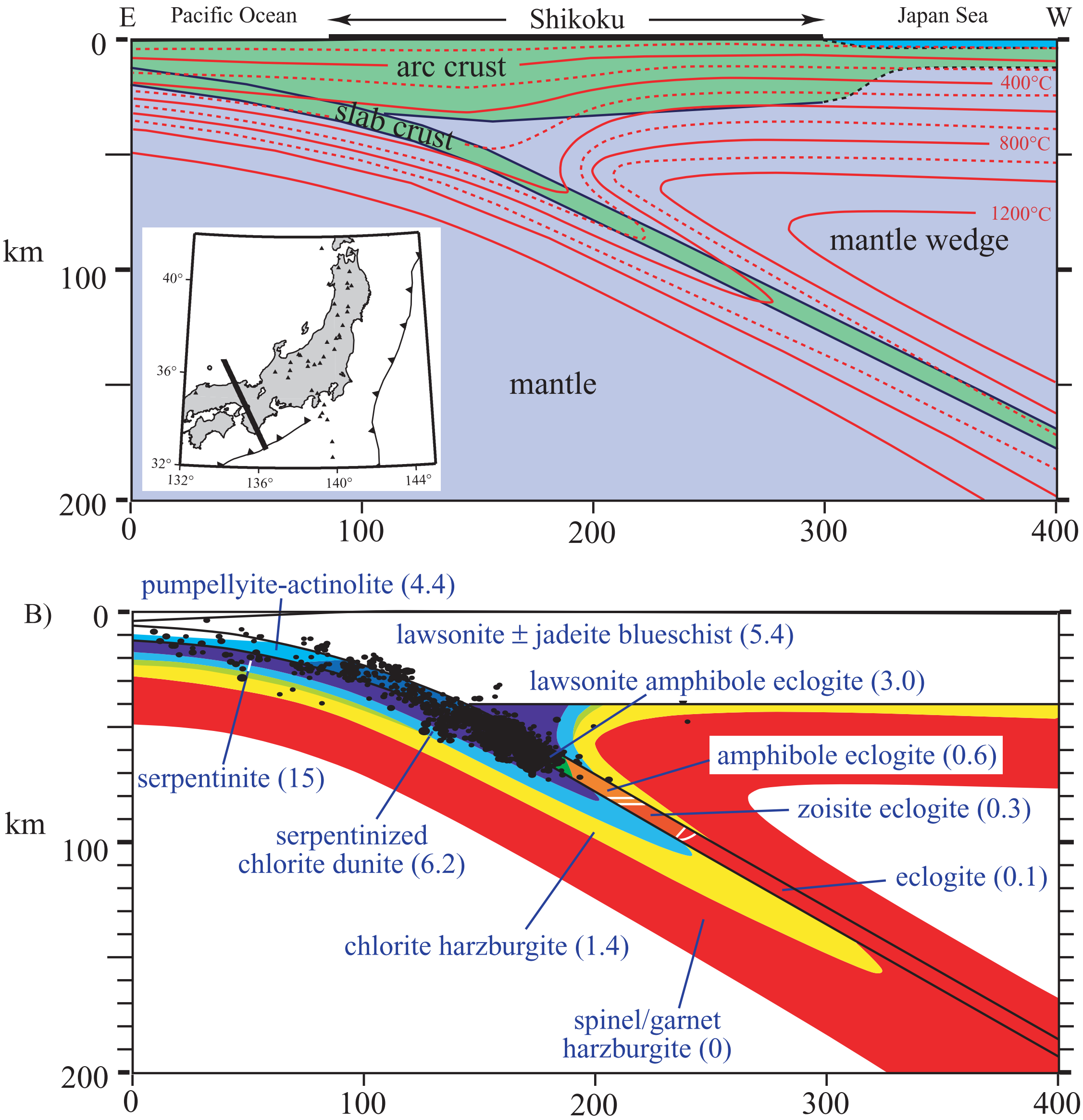

Figure 3. Correlation between seismicity and phase transformations in the Nankai subduction zone. (a) Transect through Kii Peninsula; geometry after *Zhao and Hasegawa* [1993] and *Kodaira et al.* [2000] thermal model calculated in this study. (b) Metamorphic facies calculated following *Hacker et al.* [2002]. Seismicity from an integrated database of regional network arrival times [*Cummins et al.*, 2002], projected from within 20 km of the transect, for events recorded by at least four *P* arrivals by each network.

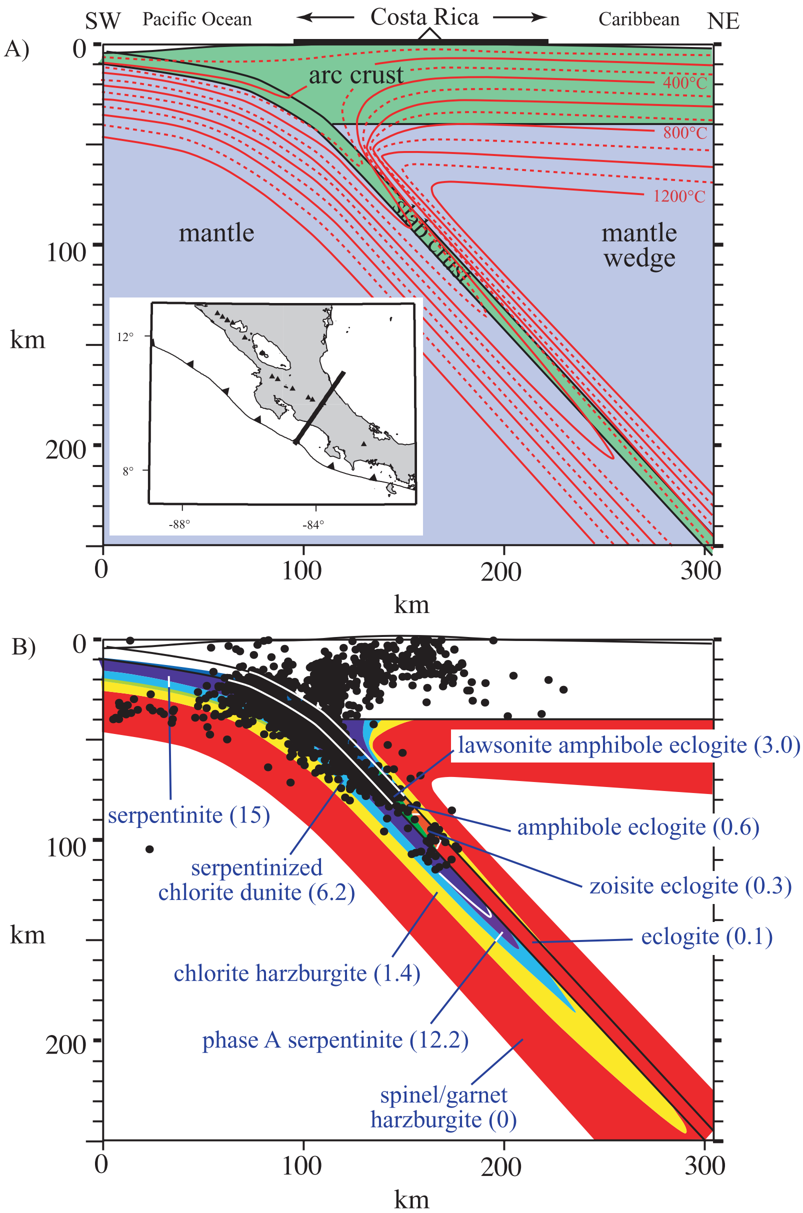

Figure 4. Correlation between seismicity and phase transformations in the Costa Rica subduction zone. (a) Transect through central Costa Rica; thermal model calculated in this study. (b) Metamorphic facies calculated following *Hacker et al.* [2002]. Seismicity of *Protti et al.* [1995] projected from 25 km either side of the section; events have horizontal and vertical formal errors less than 4 and 5 km, respectively.

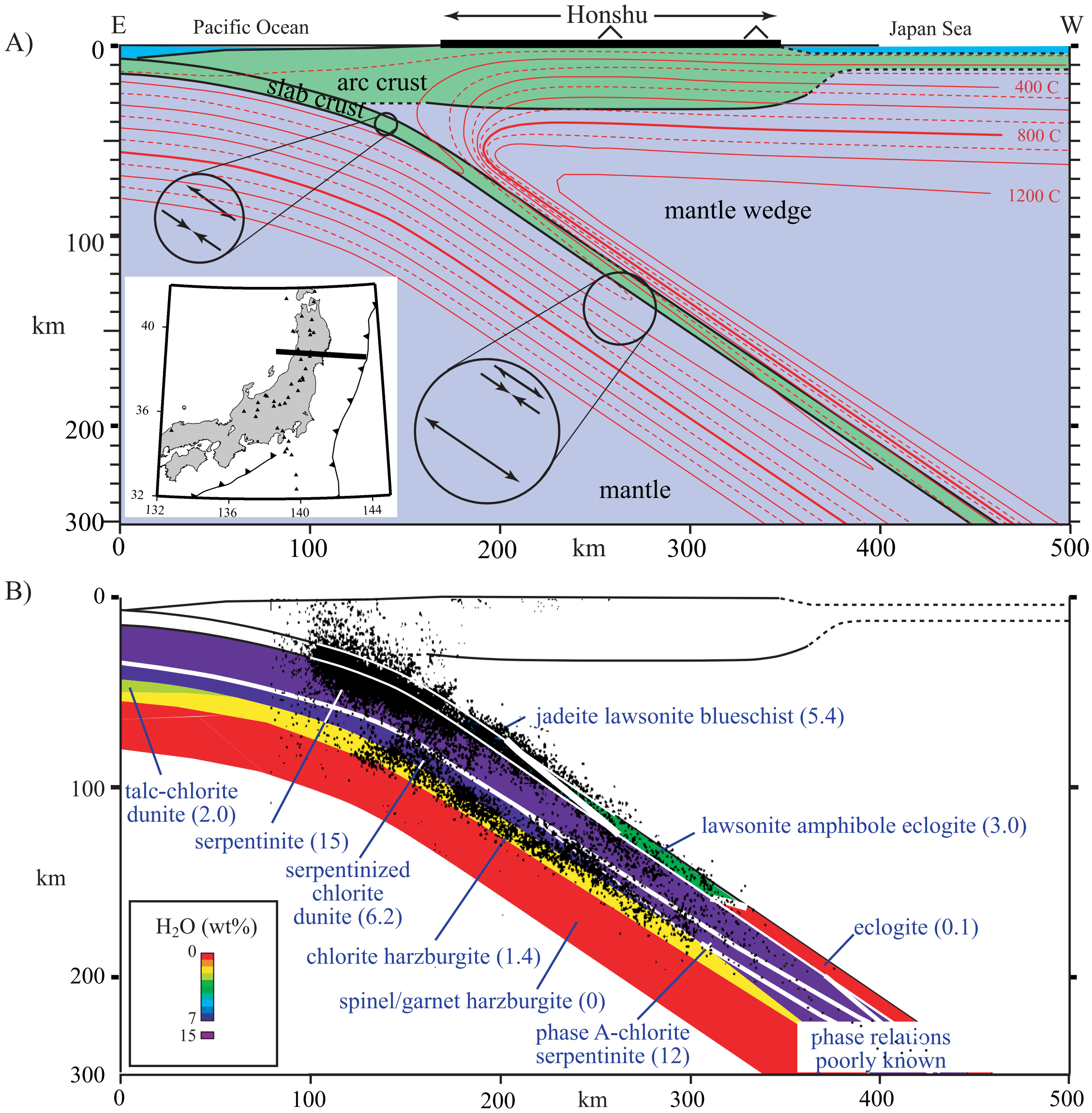

Figure 5. Correlation between seismicity and phase transformations in the Tohoku subduction zone. (a) Transect through northern Honshu; crustal thickness after *Zhao et al.* [1992], and isotherms from *Peacock and Wang* [1999]. Offset circles show stress states inferred by *Igarashi et al.* [2001]. (b) Metamorphic facies calculated following *Hacker et al.* [2002]; phase relations at $P > 5$ GPa and $T < 600$°C are not well known. Seismicity above 200 km depth projected from 250 km north and south of the section [*Igarashi et al.*, 2001] from 1975 to 1998, following a relocation with spatially variable station corrections. Information about hypocenter uncertainties is not given, but events shown have RMS residual in arrival time of <0.3 s. Seismicity at >200 km from *Kosuga et al.* [1996] is not as well located.