Faulting and hydration of the Juan de Fuca plate system

Mladen R. Nedimović, DelWayne R. Bohnenstiehl, Suzanne M. Carbotte, J. Pablo Canales, Robert P. Dziak

1. Introduction

Oceanic plates carry physically and chemically bound water into subduction zones (e.g., Peacock, 1990; Meade and Jeanloz, 1991; Moore and Vrolijk, 1992; Ranero et al., 2003). As the subducting oceanic plates descend, the pressure and temperature rise with the increasing depth, the water stored in the plates is gradually released through a series of dehydration reactions (e.g., Meade and Jeanloz, 1991; Kirby et al., 1996; Peacock, 2001; Hacker et al., 2003a,b). This free water is believed to strongly affect a number of processes important to natural hazard studies. The released water promotes faulting, seismic reactivation of the normal fault systems formed at the spreading center. Imaged reactivations within the sedimentary layering are typically linked to larger offset scarps in the basement topography, suggesting reactivation of the normal fault systems formed at the spreading center. Imaged reactions within the gabbroic igneous crust indicate swelling fault dips at depth. These reactions require local alteration to produce an impedance contrast, indicating that the imaged fault structures provide pathways for fluid transport and hydration. As the depth extent of imaged faulting within this young and sediment insulated oceanic plate is primarily limited to approximately Moho depths, fault-controlled hydration appears to be largely restricted to crustal levels. If dehydration embrittlement is an important mechanism for triggering intermediate-depth earthquakes within the subducting slab, then the limited occurrence rate and magnitude of intraslab seismicity at the Cascadia margin may in part be explained by the limited amount of water imbedded into the uppermost oceanic mantle prior to subduction. The distribution of submarine earthquakes within the Juan de Fuca plate system indicates that propagator wake areas are likely to be more faulted and therefore more hydrated than other parts of this plate system. However, being largely restricted to crustal levels, this localized increase in hydration generally does not appear to have a measurable effect on the intraslab seismicity along most of the subducted propagator wakes at the Cascadia margin. © 2009 Elsevier B.V. All rights reserved.

Keywords: Juan de Fuca plate system; seismic reflection imaging; faulting; hydration; earthquakes

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Abstract

Multichannel seismic observations provide the first direct images of crustal scale normal faults within the Juan de Fuca plate system and indicate that brittle deformation extends up to ~200 km seaward of the Cascadia trench. Within the sedimentary layering steeply dipping faults are identified by stratigraphic offsets, with maximum throws of 110±10 m found near the trench. Fault throws diminish both upslope and seaward from the trench. Long-term throw rates are estimated to be 13±2 mm/yr. Faulted offsets within the sedimentary layering are typically linked to larger offset scarpas in the basement topography, suggesting reactivation of the normal fault systems formed at the spreading center. Imaged reactions within the gabbroic igneous crust indicate swelling fault dips at depth. These reactions require local alteration to produce an impedance contrast, indicating that the imaged fault structures provide pathways for fluid transport and hydration. As the depth extent of imaged faulting within this young and sediment insulated oceanic plate is primarily limited to approximately Moho depths, fault-controlled hydration appears to be largely restricted to crustal levels. If dehydration embrittlement is an important mechanism for triggering intermediate-depth earthquakes within the subducting slab, then the limited occurrence rate and magnitude of intraslab seismicity at the Cascadia margin may in part be explained by the limited amount of water imbedded into the uppermost oceanic mantle prior to subduction. The distribution of submarine earthquakes within the Juan de Fuca plate system indicates that propagator wake areas are likely to be more faulted and therefore more hydrated than other parts of this plate system. However, being largely restricted to crustal levels, this localized increase in hydration generally does not appear to have a measurable effect on the intraslab seismicity along most of the subducted propagator wakes at the Cascadia margin. © 2009 Elsevier B.V. All rights reserved.

1. Introduction

Significant effort has therefore been directed toward understanding dehydration processes during subduction, with particular emphasis on the influence these processes may have on the depth-distribution of intraslab seismicity (Meade and Jeanloz, 1991; Kirby et al., 1996). To fully evaluate the importance of slab dehydration, however, it also is necessary to constrain the amount of water bound in the slab when it is subducted at the trench (Ranero et al., 2003). We focus our effort on determining the penetration depth and relative volume extent of oceanic slab dehydration offshore Cascadia margin. For this purpose, we process ~1500 km of ridge-flank multi-channel seismic (MCS) data collected in 2002 during the EW0207 cruise and compile a database of seismic reflection profiles from all earlier crustal scale MCS surveys (streamers 2.4 km or longer) across the Juan de Fuca plate system. The spatial distribution of the MCS lines examined is shown in Fig. 1, along with magnetic isochrones (Wilson, 2002) and the locations...
of Cascadia margin earthquakes believed to be spatially restricted to the Juan de Fuca plate and subducting slab (Fox et al., 1994; McCrory et al., 2004).

2. Study area

The study area shown in Fig. 1, located offshore western North America, encompasses the Juan de Fuca ridge and plate system (Explorer, Juan de Fuca and Gorda ridges and plates), Cascadia deformation front, Nootka fault, and Sovanco and Blanco fracture zones. The Juan de Fuca ridge system, a NNE-oriented intermediate-rate spreading center, is located at the boundary between the Pacific plate and the Juan de Fuca plate system. The full spreading rate along the Juan de Fuca ridge is 56 mm/yr, and 56 mm/yr and less along the Explorer and Gorda ridges (e.g., Wilson, 1993). The Cascadia deformation front marks the surface trace of the interface between the Juan de Fuca and North America plates. The Nootka fault is the boundary between the Explorer and the Juan de Fuca plates, and the Juan de Fuca ridge system, a NNE-oriented intermediate-rate spreading center, is located at the boundary between the Pacific plate and the Juan de Fuca plate system. The full spreading rate along the Juan de Fuca ridge is 56 mm/yr, and 56 mm/yr and less along the Explorer and Gorda ridges (e.g., Wilson, 1993). The Cascadia deformation front marks the surface trace of the interface between the Juan de Fuca and North America plates. The Nootka fault is the boundary between the Explorer and the Juan de Fuca plates, and the Juan de Fuca ridge system, a NNE-oriented intermediate-rate spreading center, is located at the boundary between the Pacific plate and the Juan de Fuca plate system. The full spreading rate along the Juan de Fuca ridge is 56 mm/yr, and 56 mm/yr and less along the Explorer and Gorda ridges (e.g., Wilson, 1993). The Cascadia deformation front marks the surface trace of the interface between the Juan de Fuca and North America plates. The Nootka fault is the boundary between the Explorer and the Juan de Fuca plates, and
Blanco and Sovanco fracture zones separate parts of the Juan de Fuca plate system from the Pacific plate. Both the western and eastern flanks of the Juan de Fuca ridge system are crossed by propagator wakes but otherwise show prominent differences indicating that they are evolving in a markedly different way due to distinct sedimentary and volcanic histories. Seamounts, which are found primarily on the Pacific plate, occur as isolated edifices and in chains, several of which lie close to and intersect the Juan de Fuca ridge axis (Davis and Karsten, 1986). Sediments covering the eastern Juan de Fuca ridge flank are up to a few kilometers thick at the northern Cascadia subduction deformation front and thin toward the ridge axis and southward away from the dominant source of terrigenous sediment (Nedimović et al., 2008). The western Juan de Fuca ridge flank is more sparsely sedimented, although sediment cover generally increases to the north where significant sediment accumulation is confined to mini-basins between large basement outcrops. The enhanced accumulation of sediment on the eastern flank is in large part caused by the morphology of the Juan de Fuca ridge, with its cooling and subsiding flanks forming basin-like depositional environments and its elevated axial region acting as a barrier that inhibits the transport of terrigenous sediment to the western flank.

3. Reflection imaging

Summary information and corresponding references that describe the MCS data used in this study are provided in Table 1. The prestack processing strategy adopted for the EW0207 MCS data consisted of: standard straight-line CMP bin geometry; F-K and bandwidth (2–7–100–125 Hz) filtering to remove the low frequency cable noise; amplitude correction for geometrical spreading; surface consistent minimum phase predictive deconvolution to balance the spectrum and remove short period multiples; surface consistent amplitude correction to correct for anomalous shot and receiver-group amplitudes not related to wave propagation; trace editing; velocity analysis using the velocity spectrum method; normal moveout and dip moveout corrections to align signal for stacking; and CMP mute to remove overly stretched data. Crossdip moveout correction (Nedimović et al., 2003b) was not required because streamer feathering was small (<10°) and structural crossdip negligible. The pre-existing zones of weakness. Fault offsets gradually diminish within the Juan de Fuca plate system that extend all the way through the sediments and crust to about the Moho discontinuity. The imaged pre-existing zones of weakness. Fault offsets gradually diminish within the Juan de Fuca plate system that extend all the way through the sediments and crust to about the Moho discontinuity. The imaged

<table>
<thead>
<tr>
<th>Project name &amp; year</th>
<th>Profiles used in this study</th>
<th>Streamer length &amp; type</th>
<th>Channels: number &amp; spacing</th>
<th>Airgun array &amp; volume</th>
<th>Shot spacing</th>
<th>Record length &amp; sample rate</th>
<th>CMP spacing &amp; fold</th>
<th>References</th>
</tr>
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<tr>
<td>Juan de Fuca, EW0207 (2002)</td>
<td>17, 3-1, 18-20-8, 34-35, 37, 31, 87-79-78a, 86</td>
<td>6 km, digital</td>
<td>480, 12.5 m</td>
<td>10-element, 49.2 L</td>
<td>37.5 s</td>
<td>10.24 s, 2 ms</td>
<td>6.25 m, 80</td>
<td>Nedimović et al. (2005)</td>
</tr>
<tr>
<td>Canadian Frontier Geoscience Project (1985)</td>
<td>1, 2, 4, 7, 9</td>
<td>3 km, analogue</td>
<td>120, 25 m</td>
<td>108.3 L</td>
<td>50 m</td>
<td>16 s, 4 ms</td>
<td>12.5 m, 30</td>
<td>Calvert and Clowes (1991) Calvert (1996)</td>
</tr>
<tr>
<td>ODP Leg 146 site survey, Vancouver Island (1989)</td>
<td>15</td>
<td>3.6 km, 144, 25 m</td>
<td>128.2 L</td>
<td>50 m</td>
<td>16 s, 4 ms</td>
<td>12.5 m, 36</td>
<td>MacKay et al. (2002)</td>
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<tr>
<td>ODP Leg 146 site survey, offshore Oregon (1989)</td>
<td>8, 24, 33</td>
<td>3.6 km, 144, 25 m</td>
<td>128.2 L</td>
<td>25 m</td>
<td>8 s, 4 ms</td>
<td>12.5 m, 72</td>
<td>MacKay et al. (1992) Flueh et al. (1998)</td>
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<td>Orwell Project, SOONE SO108 (1996)</td>
<td>102, 107, 109</td>
<td>2.4 km, 48, 50 m</td>
<td>87.4 L</td>
<td>50 m</td>
<td>16 s, 4 ms</td>
<td>25 m, 24</td>
<td>Calvert and Clowes (1991)</td>
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<tr>
<td>Gorda Rise, EW9413 (1994)</td>
<td>1226</td>
<td>4 km, digital</td>
<td>160, 25 m</td>
<td>20-element, 137.5 L</td>
<td>50 m</td>
<td>12 s, 2 ms</td>
<td>12.5 m, 40</td>
<td>Calvert and Clowes (1991) Calvert (1996)</td>
</tr>
<tr>
<td>Cape Blanco, EW9414 (1994)</td>
<td>5, 6, 7</td>
<td>4 km, digital</td>
<td>160, 25 m</td>
<td>10-element, 49.2 L</td>
<td>50 m</td>
<td>14 s, 2 ms</td>
<td>12.5 m, 40</td>
<td>Brocher et al. (1995)</td>
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<td>Mendocino Triple Junction, EW9407 (1994)</td>
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<td>4 km, digital</td>
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<td>10-element, 49.2 L</td>
<td>50 m</td>
<td>14 s, 2 ms</td>
<td>12.5 m, 40</td>
<td>Calvert and Clowes (1991)</td>
</tr>
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</table>

cannot conclude whether the lack of visible faulting within the topmost sediments (Fig. 3) is due to the limited image resolution, or due to the absence of recent dip slip displacement on these structures.

To resolve this, we first estimate the maximum long-term fault-throw rates for the study area and then compare them with the recent sedimentation rates. Maximum fault throws of 110 ± 10 m are observed offshore Oregon, just west from the trench along the ODP Leg 146 line 8. The shortest distance seaward from this fault toward the onset of faulting is 200 ± 20 km, and the half spreading rate is 28 mm/yr (e.g., Wilson, 1993). This information yields a maximum long-term throw rate of 15 ± 2 mm/kyr. We also estimate the same parameters along the 2002 Juan de Fuca survey transect 17-3-1 offshore Vancouver Island/Olympic Peninsula that spatially coincides with the Endeavour ODP/IODP drilling transect, and for which there is a wealth of information about the sedimentation rates. Maximum identified throw along this profile is 20 ± 2 m; trench-normal distance between the maximum throw fault and the seaward onset of faulting is 50 ± 5 km; and the half spreading rate is also 28 mm/yr. These data yield a maximum long-term throw rate of 11 ± 2 mm/kyr. The two calculated long-term throw rates agree within the error limits and combined give an average long-term throw rate for the imaged normal faults along the Juan de Fuca plate of 13 ± 2 mm/kyr. This long-term throw-rate estimate is more than 25 times smaller than the rapid average sedimentation rate of ~336 mm/kyr obtained for the time-stratigraphic period A characterizing the past 90 kyr along the Endeavour ODP/IODP drilling transect (Underwood et al., 2005). The topmost sediments accumulated during the time-stratigraphic period A have an average thickness of some 30 m while the estimated cumulative fault throw during this period is 1.17 ± 0.18 m, less than the resolution threshold for our images. This suggests that plate-deforming processes have remained active during most recent geologic time with the resulting normal faulting displacing the whole sediment column.

Fault throws show no reversals in slip direction and gradually increase both downsection, from younger to older sediments, and toward the trench with increasing crustal age. Observations of compaction-induced sediment folding without faulting at places where there are large offsets in the basement structure (e.g., Fig. 3 at ~125 km; Fig. 4 at ~85 km; Figs. 5 and 6 at ~120 km) suggests that the sediment rupture is not caused by compaction, but rather by movement of basement fault systems. Particularly supportive of this interpretation is the Fig. 4 reflection image of the section of transect 17-3-1 showing significant sediment accumulation on the western Endeavour ridge flank. Folding of sedimentary strata due to differential compaction over the rough igneous basement is present throughout the mini-basins but no faulting can be observed despite the large, up to a few hundred meters high steps in the basement structure. These mini-basins extend to more than 110 km west from the Endeavour ridge axis, significantly farther than the distance east from the Juan de Fuca ridge axis (55–110 km) at which the seaward limit of faulting is observed on all transects (Figs. 1–3, 6). Moreover, sediment thickness in the mini-basins over the western Endeavour ridge flank (Fig. 4) is twice that on the eastern Endeavour flank at the seaward limit of faulting (Fig. 2), further indicating that the faulting is caused by movement of basement fault systems and not differential compaction. However, faulting in the sediments where there are only small offsets in the basement implies that faulting does not in all cases occur at the pre-existing planes of weakness formed at the Juan de Fuca ridge system.

The growth-fault interpretation is in general in agreement with the existing lithospheric stress models for the Juan de Fuca plate system (Wang et al., 1997). Nevertheless, the intraplate stress regime for the Juan de Fuca plate system is known to be complex, with variable distribution of compressive and tensile stresses, and it is possible that many of the described faults may have also experienced transcurrent motion. Based on reflection images of the sediments (MacKay et al., 1992; Gulick et al., 1998), and from earthquake studies and high-resolution images of the seafloor (Chaytor et al., 2004), strike-slip and normal faulting have both been suggested for the Gorda and southern part of the Juan de Fuca plate. Our images are 2D and sparsely distributed thus providing no constraints on transcurrent motion along the imaged faults.

Crustal faulting within young oceanic plates is in most cases inferred from offsets observed at the igneous basement or within the overlying sediments, as shown in Fig. 3. Fig. 2 is exceptional because it shows reflections from the fault planes that can be identified within the lower half of the image, or the lower two-thirds of the igneous oceanic crust assuming average crustal velocities. The deep faulting projects to offsets in the igneous basement and sediments indicating that the faults transect the whole crust. This suggests that the imaged faults are listric—too steep to be imaged in the shallow-most crust, and sloping gently enough to be imaged at greater depth.
Crustal reflections can potentially also be caused by varying mineralogical content (e.g., of plagioclase) inherited from axial igneous processes; however, the geometry of the boundary between crustal zones of different mineralogical content is unlikely to both a) be identical to that caused by normal faulting and b) spatially correlate with the position of basement scarps and faulting in the sediments. Furthermore, the sharp changes in crustal mineralogical content needed to produce imageable reflections are not common in nature, at least not in our study area where images of the oceanic crust are void of any reflectivity excluding the top of the igneous crust and Moho events, and the small number of fault-related steeply dipping events discussed in this work.

The imaged fault reflections are not migration or other artefacts because their geometrical shape does not resemble that of migration ‘smiles’, they extend over a very long distance through the sections, and they project onto the displaced sediments. Moreover, the seismic sections formed using data collected during the 2002 Juan de Fuca cruise are of high signal-to-noise ratio (Nedimović et al., 2005) and are generally void of seismic noise that could be misinterpreted as fault reflections. Primary multiples are very strong and limit the depth to which the obtained images can be interpreted. In Fig. 2, primary multiples arrive at about 7 s two-way traveltime. We show this section to 6.4 s two-way traveltime because the deeper portion to 7 s is affected by primary multiples migration noise.

The observed fault reflections returning from within the mostly gabbroic oceanic crust and mostly peridotitic uppermost mantle are possible only if the rocks along the fault surfaces are altered to produce an acoustic impedance contrast. As these alteration products require the availability of seawater, this indicates that the extensional faults along the Juan de Fuca plate system are conduits for fluids and that their observed depth extent in the reflection images should constrain the local depth limit of plate hydration. The depth of imageable fault penetration correlates well with the 500 – 600 °C isotherm and is approximately coincident with the location of the Moho reflection (Fig. 2). At greater depths and therefore greater temperatures, serpentinization, the most important hydration mechanism for peridotites, becomes a marginal process (Ulmer and Trommsdorff, 1995). The lowest Juan de Fuca plate temperatures are expected along the Oregon Margin (8 – 10 Ma crust); however, due to the increasing accumulation of an insulating and heat producing sediment layer, thermal models predict that Moho temperatures will remain high (450 – 500 °C) as the plate enters the trench (Hyndman

Fig. 3. Seismic reflection images showing normal faulting within the sediments at the eastern end of transect 34-32. Also visible in the sections are the igneous basement reflection and the layer 2A-2B event that is believed to mark the location of the upper crustal interface between the extrusives and sheeted dikes. (a) An 80 km-long section of transect 34-32 (see Fig. 1 for location) depicting the gradual westward transition from faulted to not faulted sediments. The white dashed box in (a) outlines the location of the detailed image of faulting shown in depth in (b). Conversion from twtt to depth was done along vertical rays using interval velocities. The discontinuity marked by a vertical white line in (b) at the distance of ~129 km is at the location where lines 34 and 32 were merged.
and Wang, 1993, 1995; Wang et al., 1995). Therefore, it appears that prior to subduction only the uppermost Juan de Fuca mantle can become hydrated by peridotite “corrosion” to serpentinite, despite the pervasive extensional faulting imaged seaward of the trench (Figs. 2 and 3).

After subduction, increased pressure may cause the antigorite stability region to initially increase as the slab starts to descend (e.g., Wada et al., 2008). Provided fault systems maintain permeability, free water within the plate could facilitate additional and deeper serpentinization of the mantle rocks during this time. This process is expected to be common to all slabs; however, its extent cannot be assessed readily from reflection imaging. Dehydration occurs during later stages of subduction in response to slab warming.

5. Comparisons and implications

The only other convergent margin with both seismic reflection evidence for the depth extent of faulting and thermal modelling results is the Middle America subduction zone (Ranero et al., 2003; Harris and Wang, 2002). Normal faulting offshore Middle America margin covers a narrower swath of seafloor (~60 km) but is more pronounced than offshore Cascadia margin where the faulted area is wider (100–250 km). The width of the faulted area offshore Middle America appears consistent with the 40–75 km wide area estimated from lower resolution single-channel seismic and sidescan images from the outer-rise region of other subduction zones (e.g., Masson, 1991). The anomalously wide zone documented on the Juan de Fuca plate may indicate that the stress field within this small plate is not controlled solely by plate bending, but includes contributions from thermal contraction and basal shear, as well as ridge and transform push (Wang et al., 1997). Fault fabric inherited from crustal accretion at the ridge also has relatively little time to heal and may therefore be reactivated even under small differential stresses found at a great distance from the trench. Alternatively, the faulting offshore Middle America margin (and elsewhere) may start at a greater distance from the trench than observed, but the combination of slower sedimentation rates and few available high quality MCS reflection images makes it impossible to resolve faults with throws smaller than ~10–20 m with the existing data. Faults are imaged to depths of ~6–7 km within the Juan de Fuca plate system. Although there are currently no seismic reflection constraints on the depth extent of alteration along fault planes within the oldest portions of the plate near the Cascadia margin, thermal modelling (Hyndman and Wang, 1993, 1995; Wang et al., 1995) indicates that serpentinitization should extend no more than a few kilometers into slab mantle. At the Middle America trench, however, faults are imaged to depths of ~20–22 km, some 15 km into the upper mantle. Like at the Cascadia margin, the depth of imageable fault penetration at the Middle America trench correlates well with the 500–600 °C isotherm from thermal models. The Middle America outer-rise fault density gradually increases toward the trench reaching ~8 faults per 5 km. Fault density at the Cascadia margin, although variable, is comparatively low across the faulted area with ~1–2 faults per 5 km trench-normal distance. While fault throws at the Middle America trench can reach ~500 m, those adjacent to the Cascadia trench exhibit maximum offsets of only ~110 m. These differences in fault density, fault throws, and imageable depth of fault penetration suggest that the amount of water bound in the...
The maximum depth of intraslab seismicity is well known to correlate with slab thermal parameter, the product of slab age and subduction rate (Kirby et al., 1996). This is commonly interpreted to reflect the temperature-dependent locus of dehydration within metamorphosed oceanic crust and serpentinitized slab mantle (Raleigh and Paterson, 1965; Peacock, 2001; Hacker et al., 2003a,b). However, MCS observations also show that the dense and deep-cutting faulting of the older (14–24 Ma), colder and thicker (50–55 km) downgoing Cocos plate at the Middle America trench provides a mechanism to embed into the oceanic plate a volume of water much greater than that for the young (4–10 Ma), warm and thin (30–35 km) Juan de Fuca plate. This enhanced availability of water may create an environment more prone to brittle failure once the dehydration processes start. Moreover, water bound within the Cascadia slab is mostly contained within the hydrous crustal mineral phases, rather than serpentinitized mantle peridotite, which remains stable at higher temperatures (greater depths) within the slab (Yamasaki and Seno, 2003; Hacker et al., 2003b). Deep fault penetration into the Cocos plate at the Middle America trench also creates pre-existing zones of weakness with larger surface area relative to those at the Cascadia margin, leading to higher potential for larger magnitude intraslab earthquakes.

In addition to the low frequency of intraslab earthquakes beneath Cascadia, relative to Middle America, we note that the sparse seismicity of the slab is clustered tightly within the northern and southern portions of the plate (Fig. 1). The uniform thickness and structure of Juan de Fuca crust formed along the spreading center (Nedimović et al., 2005) suggests that these clusters may be caused by anomalous hydration of the lithospheric plate as it ages and/or by larger intraslab differential stresses. In this regard, the northward migration of the Mendocino Triple Junction and the accompanying retreat of the slab (Furlong and Schwartz, 2004) may create anomalous stress conditions along the southern margin of the plate. The Mendocino transform zone also may be cooled more rapidly than the rest of the plate due to a thermal boundary effect (e.g., Louden and Forsyth, 1976) caused by juxtaposition of the old and cold Pacific plate and the young and warm Gorda plate, allowing deeper and more extensive hydration along this long-lived fault zone. Further facilitating hydration of the oceanic plate in this area are two sets of crossing faults observed in reflection profiles (Gulick et al., 2001). The internally deforming and fragmenting southern Gorda plate is rotating clockwise toward the

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**Fig. 6.** Seismic reflection image showing the approximate location of the landward onset of faulting at the eastern end of transect 87-89-73-89a (see Figs. 1 and 5 for location). The earthquake swarm shown in Fig. 5 partially overlaps the faulted section and extends further east.
Mendocino triple junction. This causes the incoming ridge fabric to be oriented at a high angle to the trench (Fig. 1). When the strike of the incoming oceanic spreading fabric forms an oblique angle (>20–30°) with the trench, a new set of trench-parallel faults is formed (Masson, 1991) providing fluid pathways into the oceanic plate in addition to those formed at the spreading center and reactivated near the trench.

In the north, intraslab stresses are influenced by interactions with the Nootka transform fault, which plunges beneath mid-western Vancouver Island (Fig. 1), and by the sharp along-strike bending of the slab beneath Olympic Peninsula. The trench bends westward in this area and, like at the southern Gorda plate, becomes oblique to the ridge tectonic fabric. Therefore, it is possible that two-directional faulting and associated enhanced plate hydration also take place in this northern locality but without new MCS data this cannot be validated.

6. Effect of propagator wakes

We also investigate the spatial relationship between the location of propagator wakes and the distribution of seismicity within both the Juan de Fuca plate system and the subducted oceanic slab at the Cascadia margin. While the smaller Explorer and Gorda plates show evidence of seismicity, and presumably active faulting, throughout much of their interior [e.g., Fox and Dziak, 1999; Dziak, 2006], earthquakes located within the Juan de Fuca plate are concentrated along a broad NE-trending propagator wake crossing the eastern Cleft ridge flank (Fig. 1). This region includes a swarm of >600 SOSUS-detected events recorded in April 2008, positioned near 44°N/128°W (Figs. 1 and 5). The affected area is located near the eastern end of our seismic transect 87–89–73–89a. Analysis of the seismic reflection image formed along this 300 km-long transect shows that the only observable faulting in this profile spans the area crossing this propagator wake (Fig. 6). These observations suggest that propagator wakes, as potential zones of plate weakness inherited from crustal accretion, may respond to increasing external stresses by brittle wakes, as potential zones of plate weakness inherited from crustal–mantle interactions. Magnetic isochrons (Fig. 1) suggest that the oceanic plate in this area may appear to spatially correlate with the largest concentration of intraslab seismicity at the Cascadia margin except, perhaps, for the anomalous area below the Olympic Peninsula.

Imaged reflections within the gabbroic igneous crust indicate swelling fault dips at depth. These reflections require local alteration to produce an impedance contrast, suggesting that these structures provide pathways for fluid transport and hydration. As the depth extent of imaged faulting within this young and sedimented oceanic plate is primarily limited to approximately Moho depths (temperatures reach 500–600 °C), fault-controlled hydration is for the most part restricted to crustal levels. Hydration of a thin layer of the uppermost mantle is most likely for sections along the trench where the coldest and anomalously faulted parts of the Juan de Fuca plate system are subducted. If dehydration embrittlement is an important mechanism for triggering intermediate-depth earthquakes within the subducting slab, then the limited occurrence rate and magnitude of intraslab seismicity at the Cascadia margin may in part be explained by the limited amount of water imbedded into the uppermost oceanic mantle prior to subduction.

The distribution of earthquakes within the Juan de Fuca plate system, including the 2008 earthquake swarm, indicates that propagator wake area is likely to be more heavily faulted and therefore more hydrated than other parts of oceanic plates. However, being mostly restricted to the crust, this additional hydration does not appear to have an effect on the distribution and magnitude of the intraslab seismicity at the Cascadia margin except, perhaps, for the anomalous area below the Olympic Peninsula.

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