

Evidence for both crustal and mantle earthquakes in the subducting Juan de Fuca plate

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[1] We investigate the relationship between high-precision hypocenters in the subducting Juan de Fuca plate beneath southwest British Columbia, and the velocity structure from receiver function analysis and reflection seismic data. 108 earthquakes at depths of 40 to 65 km were relocated using a double-difference algorithm to obtain precise earthquake locations. Correlation of the relocated seismicity with structural information shows a concentration of earthquakes near the top of the subducting oceanic crust, and a deeper layer of seismicity in the uppermost mantle of the subducting Juan de Fuca plate. The strong correlation of the seismicity with the structure of the subducting plate suggests that seismic failure is caused by changes in mechanical strength within the plate, supporting the hypotheses that phase transformations and thermal-petrological conditions play an important role in the seismogenesis of double-seismic zones. **INDEX TERMS:** 7209 Seismology: Earthquake dynamics and mechanics; 7218 Seismology: Lithosphere and upper mantle; 7230 Seismology: Seismicity and seismotectonics; 7220 Seismology: Oceanic crust. **Citation:** Cassidy, J. F., and F. Waldhauser, Evidence for both crustal and mantle earthquakes in the subducting Juan de Fuca plate, *Geophys. Res. Lett.*, 30(2), 1095, doi:10.1029/2002GL015511, 2003.

1. Introduction

[2] The detailed spatial relationship between intraslab hypocenters and the seismic structure of subduction zones provides crucial information regarding the physical environment of and the internal processes that take place within the subducting lithosphere. Since the primary seismic expression of subducting slabs are the Wadati Benioff Zone (WBZ) earthquakes themselves, independent data are needed to determine the location of these earthquakes within the subducting slabs. Tomographic inversion of regional and teleseismic travel times places most intermediate-depth intraslab seismicity near the tops of gross velocity anomalies caused by low slab temperature [Engdahl *et al.*, 1995, among others]. Studies of phase conversion indicate also that earthquakes locate just beneath the velocity discontinuity between the subducting oceanic crust and the overriding plate [Matsuzawa *et al.*, 1990].

[3] The interaction of the Juan de Fuca (JdF) plate and the North America plate dominates the Cascadia subduction

zone [see e.g., Hyndman *et al.*, 1990 for a review]. Seismic activity within the northern JdF plate is concentrated in two bands extending parallel to the coastline: one along the west coast of Vancouver Island at a depth of 25–35 km; and a second band extending from southern Puget Sound to the central Georgia Strait at a depth of 50–60 km. It is in this latter band that the 28 February, 2001 $M = 6.8$ Nisqually earthquake [Crosson *et al.*, 2001], and other large in-slab earthquakes have occurred (Figure 1).

[4] We relocated 108 earthquakes within this deeper cluster (Figure 1) using the double-difference (DD) algorithm of Waldhauser and Ellsworth [2000] and correlated the seismicity with nearby structural information from receiver function analysis [Cassidy, 1985] and from a deep seismic reflection profile [Clowes *et al.*, 1987]. The combined study of active and passive seismic data allows us to examine the relationship between the well-resolved seismicity and the seismic velocity structure of the subducting JdF plate.

2. Earthquake Relocation

[5] The double-difference earthquake relocation method minimizes residuals between observed and calculated travel time differences (or double-differences) for pairs of nearby earthquakes at each station that recorded both events to solve for the hypocentral separation between the events. In this way errors caused by unmodeled velocity structure are minimized without the use of station corrections. We use the program hypoDD [Waldhauser, 2001] together with P- and S-wave phase data of all deep (>40 km) earthquakes recorded in the study area (Figure 1) between 1992 and 2000 by the CNSN, and larger magnitude ($M = 4-5.5$) events that date back to 1976. From a total of 114 earthquakes, 108 events had sufficient pair-wise observations to continuously link the events together. An average of 10 observations (stations) per event pair is used, and the average distance between linked events is about 9 km. Inter-event distance and misfit weighting is applied to the data during the iterative relocation process to downweight/reject travel time differences for event pairs with large separation distance and/or large residuals, respectively. A 1-D layered velocity model obtained from the analysis of receiver functions [Cassidy, 1995] is used to predict the travel time differences and partial derivatives.

[6] Figure 2 shows a subset of the relocated slab events in cross-section. In contrast to the network locations, where the fine-scale structure of the seismicity is buried in the location uncertainties, the DD locations have the resolution required to reveal the internal structure of the JdF plate. Least squares error estimates for the DD locations average 679 m and 1042 m for horizontal and vertical direction, compared to 3134 m and 5517 m for the catalog locations, yet are consistent with errors derived from bootstrap resam-

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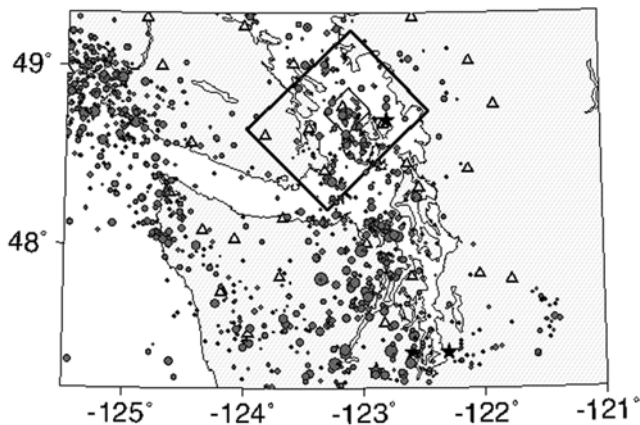


Figure 1. Earthquakes in southwest British Columbia recorded between 1976–1999 by the Canadian National Seismograph Network and the Pacific Northwest Seismic Network. Triangles represent seismograph locations. Box outlines study area. Stars denote the location of the largest ($M > 5.5$) inslab earthquakes in the region.

pling of the residual vector [see *Waldhauser and Ellsworth, 2000*]. The effect of variation in the somewhat sparse station distribution on the event locations is estimated by repeatedly relocating a subset of 24 events (those shown in Figure 2), each time subsampling the data by deleting one station at a time. The resulting mean standard deviations of changes in hypocentral location are much smaller than the errors introduced by noise in the data. The potential influence of the velocity model used (shown in Figure 3) on the relocations was investigated by considering a wide range of earth models, including ones that have the low-velocity zone associated with the crust of the JdF plate 5 km shallower and 5 km deeper, no low-velocity zone, and a simple 4 layer model used for the routine location of earthquakes in the region. The variance in the locations of the DD solutions caused by these drastic model changes (20% velocity changes) was within about 300 m horizontal and about 500 m vertical. The absolute depth of the locations obtained in this study are tied to the receiver function results by using the receiver function model for the DD locations.

3. Relocation Results and Synthesis

[7] We first compare the relocated hypocentres with the results of structural studies in the region. Figure 3 shows the superposition of the seismicity and the seismic structure

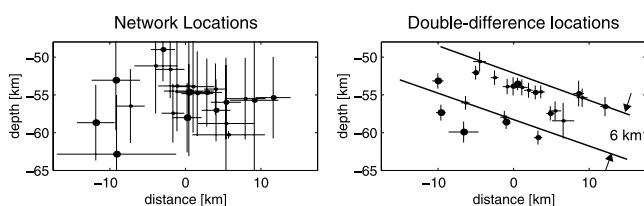


Figure 2. A comparison of initial (network) and final (DD relocated) locations of 24 earthquakes near Saturna Island (see small inset box in Figure 1). Crosses represent errors at the 90% confidence level.

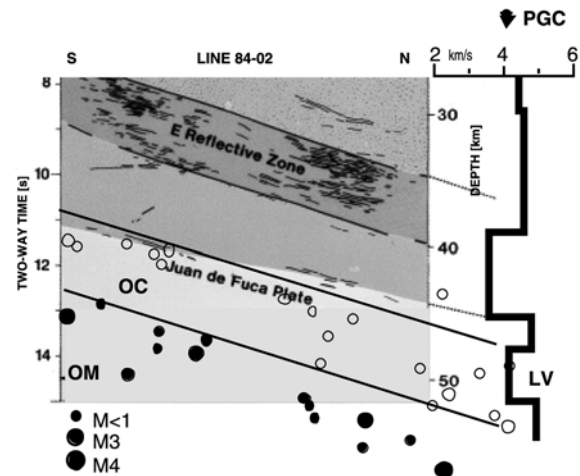


Figure 3. Superposition of active and passive seismic data. Earthquakes in the upper (open circles) and lower (solid circles) seismic layers are projected onto the seismic structure from reflection profile 84-02 (see Figure 4) of *Clowes et al.* [1987] and the S-velocity structure from receiver functions at PGC [*Cassidy, 1985*]. The oceanic crust (OC) and the oceanic mantle (OM) are indicated. LV marks the low velocity zone representing the oceanic crust.

from active and passive-source seismic data. Relocated earthquakes along cross section C-C' (see Figure 4) are projected onto the 24-km-long NNW-oriented seismic reflection profile Line 84-02 [*Clowes et al., 1987*]. The S-velocity structure from receiver function analysis [*Cassidy, 1985*] at the broadband station PGC (see Figure 4) is also shown in Figure 3. Most of the projected earthquakes fall beneath a thin reflective band seen on the reflection profile at depths of 40 to 45 km. This reflective band is interpreted as the top of the JdF plate [*Hyndman et al., 1990*], and correlates with the top of a 4–5-km thick low velocity zone (LV in Figure 3) that has been imaged using receiver function data at PGC [*Cassidy, 1985*]. Many relocated hypocentres (open circles) clearly fall within this low velocity zone which has been interpreted as the subducting oceanic crust (OC). Note however, that many of the hypocentres (filled circles) are deeper, clearly placing them within the uppermost mantle (OM) of the subducting plate. This is the first unambiguous evidence that deep earthquakes in this region occur within both the crust and mantle of the subducting oceanic plate. Note that the largest events in this limited dataset (Figure 4) occur in the uppermost mantle of the oceanic plate. We have used the same recording stations to locate all of the earthquakes, therefore we can rule out the possibility of the locations of the larger earthquakes being biased by the station distribution.

[8] To further examine the detailed seismicity structure of the subducting JdF plate, we examine two slightly overlapping N30°E-trending profiles (Figure 4). This direction is approximately perpendicular to the strike of the subducting slab, and by using two narrow profiles we can avoid complications that might arise from any curvature in the JdF plate in the study area. The northern profile (A-A') extends across the Strait of Georgia between southeastern Vancouver Island and the Lower Mainland. Seismicity along this profile shows a 19° northeast dipping structure

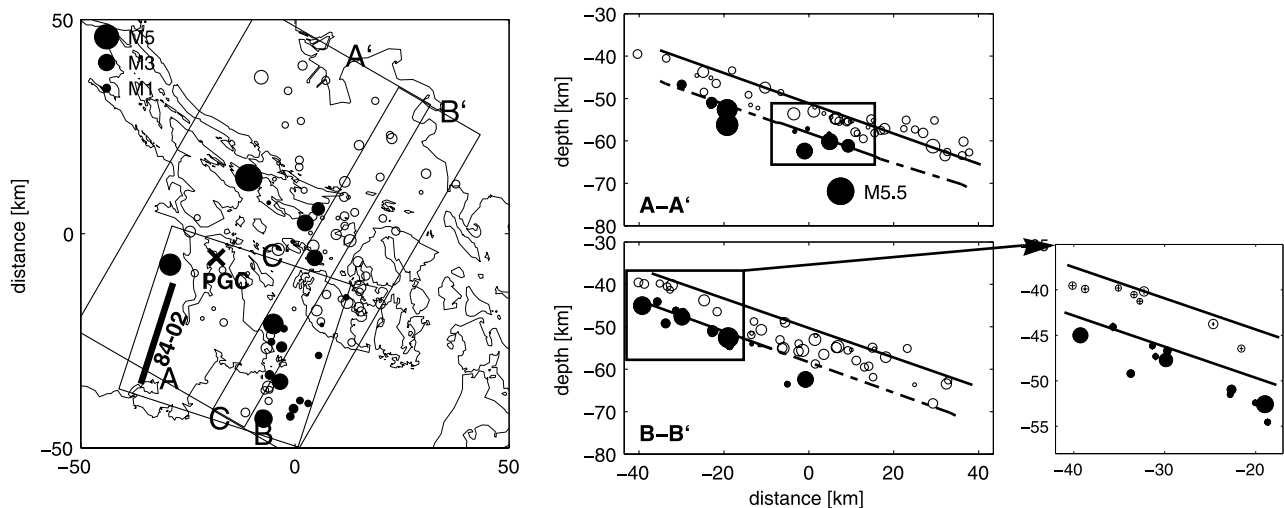


Figure 4. Relocation of earthquakes shown in larger box in Figure 1. Map view (left) and cross sections (right). Circle size is proportional to magnitude. Filled circles indicate events that form the deeper layer of the double seismic zones. In map view, boxes include events shown in the cross sections (except for C-C' shown in Figure 3), 'x' and thick line indicate the location of station PGC and reflection profile 84-02, respectively. Thin solid lines in cross sections indicate top surfaces of seismic layers assuming a 19° dipping plate. Dashed lines indicate segments not constrained by earthquakes. The box in cross section A-A' indicates location of events shown in Figure 2.

that extends from about 43 km depth to about 65 km depth. Most of the seismicity occurs at depths between 50 and 62 km (Figure 4) where there appears to be two subparallel planes of seismicity separated by an aseismic zone of about 2–3 km thickness (see also Figure 2). Between 0 and 15 km distance (A-A' in Figure 4) events in the upper layer (open circles) are confined to a narrow zone about 4 km thick. Events in the lower zone (filled circles) are sparse, and larger events seem to locate deeper in the slab (e.g., the 1976 M = 5.5 earthquake). Towards the northeastern end of the profile, event locations become more diffuse.

[9] The second cross section (B-B') also shows a band of seismicity dipping to the northeast between 40 and 70 km. Between about 40 and 52 km depth (–40 to –15 km distance, inset in B-B' in Figure 4) a double seismic zone appears to exist, and is most clear at depths of about 40–50 km. At greater depths the two layers seem to merge into a single WBZ with most events locating in the oceanic crust (see Discussion). Superimposed on the cross sections in Figure 2 and Figure 4 are thin 19° dipping lines that indicate what we interpret as the top surfaces of the two seismic layers. The separation is 6–7 km.

4. Discussion and Conclusion

[10] High-resolution hypocentres obtained using a DD technique allow us to resolve the detailed seismicity pattern within the subducting JdF plate in southwestern British Columbia. This study shows that earthquakes are occurring both within crust and the uppermost mantle of the subducting plate. The largest events (including the 1976 M = 5.5 earthquake) locate in the uppermost oceanic mantle. This may be an artifact of this limited data set, or there may be a physical explanation; more extensive studies will be required to determine this.

[11] The DD locations determined in this study have relative uncertainties that are generally less than 1 km

(Figure 2), revealing a shallow double-seismic zone with the seismic layers separated by only 2–3 km. This is the first time that a double-seismic zone has been observed in the JdF plate. Double-seismic zones have been found elsewhere [see *Abers*, 1992 for a review], including the Gorda plate at the southern end of the Cascadia subduction zone [*Smith et al.*, 1993]. Most of these exhibit layers that are separated by more than 30 km [e.g., *Hasegawa et al.*, 1978; *Abers*, 1992; *Comte and Suarez*, 1994], and only in a few cases were separation distances 15 km or less [*Smith et al.*, 1993; *McGuire and Wiens*, 1995; *Kao and Rau*, 1999].

[12] The origin of double-seismic zones is still enigmatic. The local concentration of seismicity near the top surface of the subducting JdF plate (Figure 1) may indicate that the plate internal stress is build up by asperities - irregularities on, or close to, the interface between the subducting and the overriding plate that prevent the two plates from sliding smoothly past each other. Such an interpretation, however, does not provide a direct explanation for the existence of the lower seismic zone. A popular hypothesis is that the two zones represent the upper and lower bending (or unbending) fibers of a flexing plate [e.g., *Engdahl and Scholz*, 1977]. A study by *Igarashi et al.* [2001] provides evidence (changes in focal mechanisms) for a triple seismic zone beneath Northeast Japan. *Wang* [2002] demonstrates that this triple seismic zone can be explained as a combination of slab unbending and dehydration embrittlement (see below). Unfortunately, in our study area, there are insufficient first motion data available to clearly identify focal mechanisms. For the largest events located in the oceanic mantle (e.g., M5.5, Figure 4) computed focal mechanisms show normal faulting with down-dip tension [*Rogers*, 1979], consistent with the bending hypothesis. Shallower events observed elsewhere within the crust of the JdF plate, however, show a mixture of focal mechanisms (Bolton, personal communication), indicating a fractured zone of deformation.

[13] The strong correlation of the relocated seismicity with the seismic structure and location of the subducting oceanic plate (Figure 3) indicates that seismic failure is related to changes in mechanical strength within the subducting plate. *Wang and Rogers* [1994] argue that the origin of a double-seismic zone observed within the Gorda plate [*Smith et al.*, 1993] may be a direct consequence of the thermally controlled rheology. They conclude, consistent with our observation, that the upper and lower seismic layer represent the brittle upper oceanic crust and the brittle uppermost mantle, respectively, with the two seismic layers being separated by a ductile lower oceanic crust.

[14] *Kirby et al.* [1996] showed that large volume changes related to the transformation from basalt to eclogite at the top surfaces of subducting plates may produce locally high deviatoric stresses, and dehydration reactions may produce embrittlement and large transients in pore fluid pressures. This model predicts downdip tension in the crust and downdip compression in the mantle. With the exception of the $M = 5.5$ 1976 earthquake (downdip tension) that we relocate in the oceanic mantle, we cannot address these predictions due to a lack of detailed focal mechanisms in the region.

[15] In a recent study, *Hacker et al.* [2002a, 2002b] tested the hypothesis that the intermediate-depth earthquakes in the upper and lower seismic zones are related to dehydration reactions. Based on thermal-petrological models, they predict eclogite transformation and associated seismicity in the upper oceanic crust, while serpentine or chlorite dehydration cause seismic failure in the upper mantle, with an aseismic layer between them. Further, they predict that the seismicity in the oceanic crust begins at the top of the slab, and then descends slowly towards the slab Moho with increasing subduction depth [*Hacker et al.*, 2002b]. This is consistent with our observation of the seismicity pattern in the oceanic crust at 40–50 km depth where there are two clear layers (inset of cross-section B-B' in Figure 4), and our observation that the top layer of the seismicity appears to migrate into the lower crust at greater depths (Figure 4).

[16] Most recently, *Wang* [2002] indicates that a combination of the above factors controls slab seismicity and the presence of double, and triple seismic zones. *Wang* [2002] demonstrates that plate unbending, combined with metamorphic densification and dehydration controls the local stress regime and triggers slab seismicity in both the crust and mantle of subducting slabs.

[17] Results from our study suggest that the double-seismic zone in the JdF plate represents the localization of conditions where brittle failure is met within the upper crust and uppermost mantle of the subducting plate. The small distances over which the transition from seismic to aseismic behaviour occurs indicate that composition and associated metamorphism are controlling the distribution of seismic activity within the double-seismic zone. High-resolution seismicity studies in other areas of the Cascadia subduction zone, and other subduction zones around the world (especially warm slab environments), are necessary to investigate whether shallow double seismic zones are a more common feature than previously thought.

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