Seismic Reflection Imaging of Two Megathrusts in the Northern Cascadia Subduction Zone (MS No. 2003-10-10707A)

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At convergent continental margins, the relative motion between the subducting oceanic plate and the overriding continent is usually accommodated by movement along a single, thin interface known as a megathrust[1]. Great thrust earthquakes occur on the shallow part of this interface where the two plates are locked together[2]. Earthquakes of lower magnitude occur within the oceanic plate, and have been linked to geochemical dehydration reactions caused by the plate's descent[3-7]. Here I present deep seismic reflection data from the northern Cascadia subduction zone which show that the inter-plate boundary is up to 16 km thick, and comprises two megathrusts that bound a >5 km-thick, ~110 km-wide region of imbricated crustal rocks. Earthquakes within the subducting plate occur predominantly in two geographic bands where the dip of the plate is inferred to increase as it is forced around the edges of the imbricated inter-plate boundary zone. This interpretation implies that seismicity in the subducting slab is controlled primarily by deformation in the upper part of the plate. Slip on the shallower megathrust, which may occur by aseismic slow slip, will transport crustal rocks into the upper mantle above the subducting oceanic plate, and may, in part, provide an explanation for P wave velocities as low as 6800 m s^{-1} that are observed there[8,9].

The Cascadia subduction zone, where the oceanic Juan de Fuca plate descends

beneath the overlying North American plate, extends 1100 km from northern California to northern Vancouver Island. Sedimentary rocks originally deposited on the oceanic plate are scraped off and accreted to the western edge of the continent; the initiation of this process is indicated by the deformation front in Fig. 1. The intersection of the deformation front with the SW-trending Nootka transform fault, which is characterized by high levels of seismicity, marks the approximate northern limit of the subduction zone. Beneath the western and eastern edges of Vancouver Island, earthquakes within the oceanic plate occur in two well-defined, ~45 km wide, geographic bands that merge further south. These earthquakes have been attributed to dehydration embrittlement of the oceanic mantle[7] and the gradual transformation of basalt to eclogite[6,7]; this latter process may begin at depths as shallow as 40 km[6].

West of Vancouver Island, seismic refraction and normal incidence reflection surveys show that the top of the subducting oceanic crust lies immediately beneath a seismic reflector that dips landward at between 12 and 25 km depth[10,11] (JdF in Fig. 2a and Fig. 3). Beneath southern Vancouver Island and its margins, seismic reflection surveys also identify two regionally extensive structures: a thick zone of reflectors, denoted by the letter E, and a deeper, likely individual, reflector, identified by the letter F[12-15]. On a composite reflection section across the northern Cascadia forearc (Fig. 2a), the E zone appears as a sequence of anastomosing reflections that extends over 1.0 to 3.2 s (corresponding to a thickness of 3-10 km), dips at 4-15°, and reaches a depth of at least 45 km east of Vancouver Island. The second reflection, F, is observed intermittently, between ~0.5 and 2.0 s (~2-6 km) later than the deepest reflector of the E sequence. The short duration of this reflection implies that it originates either from a thin, <2 km thick, region, or at a single interface.

In offshore surveys, the F reflection can be traced seaward and upward towards the

reflection from the top of the subducting plate west of Vancouver Island. As the F reflection shallows it approaches to within 0.5 s (<2 km) of the deepest of the E reflections, defining a wedge-like geometry (Fig. 2b). If the top of the subducting plate were located at the base of the E reflectors, then the most plausible interpretation of the F reflector would be as the oceanic Moho[16], implying that the descending oceanic crust is <2 km thick in places. However, this conclusion is inconsistent with observations in the deep ocean basin where the Moho of the incoming oceanic plate is observed 1.8-2.2 s after the top of the igneous crust[17]. In fact, the Moho of the subducting plate is located by wide-angle reflections[7] recorded in the SHIPS[18,19] survey and occurs ~6 km deeper than the F reflector (Fig. 2b) consistent with modelling of gravity data[20] and analysis of teleseismic P to S wave conversions recorded near central Vancouver Island[21]. I therefore interpret the F reflector to be the top of the subducting plate.

The E reflections dip shallowly to the ENE at approximately 4° across southern Vancouver Island. As the reflections reach the eastern edge of the island, their dip increases sharply to ~15° and they continue into the uppermost mantle with this dip. In contrast, the F reflection from the top of the subducting plate dips to the ENE at ~15° near the western edge of Vancouver Island, and then flattens out further to the east. It is not possible to identify unequivocally the shorter F reflection segments near the east coast of Vancouver Island due to elevated levels of coherent noise; however, it seems unlikely that the F reflection would crosscut the E reflections. Therefore the F reflector must also increase in dip as it presumably merges into the deepest of the E reflectors near the eastern edge of Vancouver Island. Thus identified, the E and F reflectors define a ~110 km-wide duplex structure: the F reflection, which marks the top of the subducting plate, is the floor thrust with a ramp-flat-ramp geometry, and the E reflectors form the roof thrust (Fig. 4). In the region bounded by the E and F reflectors, P wave velocities derived by 3-D tomographic

inversion of first arrivals from local earthquakes and first arrivals of the SHIPS survey[9], vary laterally between 6800 and 7200 m s^{-1} (Fig. 2b). These velocity values are consistent with crustal rocks of both the oceanic plate and of the lower continental plate.

Earthquake hypocentres relocated as part of the 3-D tomographic inversion[9], can be correlated accurately with the seismic reflection data and a corresponding vertical section extracted from the 3-D velocity model. Earthquakes that occurred within 15 km of the seismic profiles have been projected laterally onto the profile and are shown in Fig. 2b, in which the reflection section has been converted to depth. The depth conversion utilised the extracted velocity model extended seaward with a combination of refraction velocities[10] and stacking velocities from the reflection profile[22], and removed the effects on deep reflectors of lateral velocity variations in the near-surface. Earthquakes can be divided into two main groups, upper and lower, depending on whether they are above or below the E reflectors, which appear to be notably aseismic[16].

Earthquakes occur above the E reflectors to depths as great as 35 km, but the seismicity terminates abruptly at the shallowest of the E reflectors. This distribution of earthquakes suggests that the region of the lower continental crust in which the E reflectors are located either cannot sustain stress accumulation or is completely locked; the latter is unlikely given an estimated temperature at the E reflectors of ~400 ^{o}C[23]. Landward of the locked part of the inter-plate boundary, which extends landward 60 km from the deformation front[2], accumulating stress is released through episodic, aseismic slow-slip events[24]. Simultaneous non-volcanic tremors[25], have been approximately located at multiple depths over at least 15 km above the subducting plate[26]. The existence of tremors at depths corresponding to the E reflectors, and the absence of conventional seismicity within the E reflectors implies that slow-slip is occurring here. Tremors occur at depths

corresponding to the F reflector, suggesting that slip is also occurring at the top of the subducting plate. With the roof thrust of the duplex active, the enclosed imbricated rocks will be transported downward (Fig. 4), perhaps into the forearc upper mantle, and this process may provide an explanation for P wave velocities as low as 6800 m s^{-1} that have been observed there[8,9].

Near the west coast of Vancouver Island, numerous earthquakes, with a variety of focal mechanisms[27], occur beneath the top of the subducting oceanic crust where it dips most steeply; only one earthquake occurs above the top of the plate, being located in the imbrication enclosed within the duplex structure (Fig. 2b, Fig. 3). As the top of the plate flattens, the number of earthquakes within the slab decreases markedly even though dehydration of the crust should be occurring here[6]. As indicated in Fig. 1, there is another belt of inslab earthquakes near the east coast of Vancouver Island, and Fig. 2b shows that this belt corresponds to the location where the inferred dip of the subducting plate increases once more. I propose that the two belts of inslab seismicity (Fig.1) are due either to flexure or fragmentation of the oceanic plate as it subducts obliquely around the edges of the imbricated inter-plate boundary zone (Fig. 4). Dehydration reactions may reduce the effective normal stresses across faults[7] and facilitate rupture when the subducting plate flexes, for example near the west coast of Vancouver Island. At the eastern edge of Vancouver Island, the oceanic crust reaches 40 km depth where the transformation of basalt to eclogite begins[6], and focal mechanisms are dominated by downdip tension[27]. The consequent increase in density of the crust may facilitate the sudden increase in dip of the subducting slab here, and perhaps result in delamination of the crust as suggested by an alignment of earthquake hypocentres just above the oceanic Moho (Fig. 2b).

The two seismic belts may indicate the lateral extent of the imbricated zone between

the E and F reflectors, implying that most of southern Vancouver Island is underlain by a ~110-km wide duplex structure, an order of magnitude greater than lenses of sediment that can be eroded from the base of accretionary wedges beneath the continental slope[28]. Within the imbricate zone, a few earthquakes occur where P wave velocities change laterally, suggesting that these earthquakes might be attributable to imbricate thrusting that has juxtaposed different lithologies. If these imbricated rocks are derived mostly from the forearc, then the duplex may result from erosion of the lower crust, perhaps below shelf basins where high inter-plate coupling has been proposed[29]. Alternatively, if the imbricated rocks originated in the oceanic plate, they would be underplated to the North American plate should aseismic slip along the E reflectors cease, and reorganisation of faults within the duplex occur. If slip along the F reflector were to cease, the duplex would become welded to the downgoing slab, and thickened crust would be subducted, as proposed for the Yakutat terrane in Alaska[30].

Subduction is usually viewed as occurring along a single, thin interface beneath which an oceanic plate descends into the mantle, and inslab seismicity is considered to be driven by dehydration metamorphism[3-7]. In the northernmost Cascadia subduction zone, however, the inter-plate boundary is a complex zone up to 16 km in vertical extent, and inslab seismicity is controlled by deformation in the upper part of the subducting plate.

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Figure 1 Map of the northern Cascadia subduction zone showing the distribution of inslab earthquakes (filled black circles) along the margin. The approximate northern limit of the Cascadia subduction zone is marked by the intersection of the deformation front with the Nootka fault, which is characterized by high levels of seismicity caused by relative motion between the Juan de Fuca plate and a small oceanic plate to the north. Earthquakes within the subducting slab occur predominantly along the western and eastern edges of Vancouver Island. The seismic lines combined to form the cross-section across the forearc region in Figure 2 are shown in red, the azimuth of the simulated cross-section in green (dashed). The lines combined to form the section in Figure 3 are shown in yellow. LRF – Leech River fault.

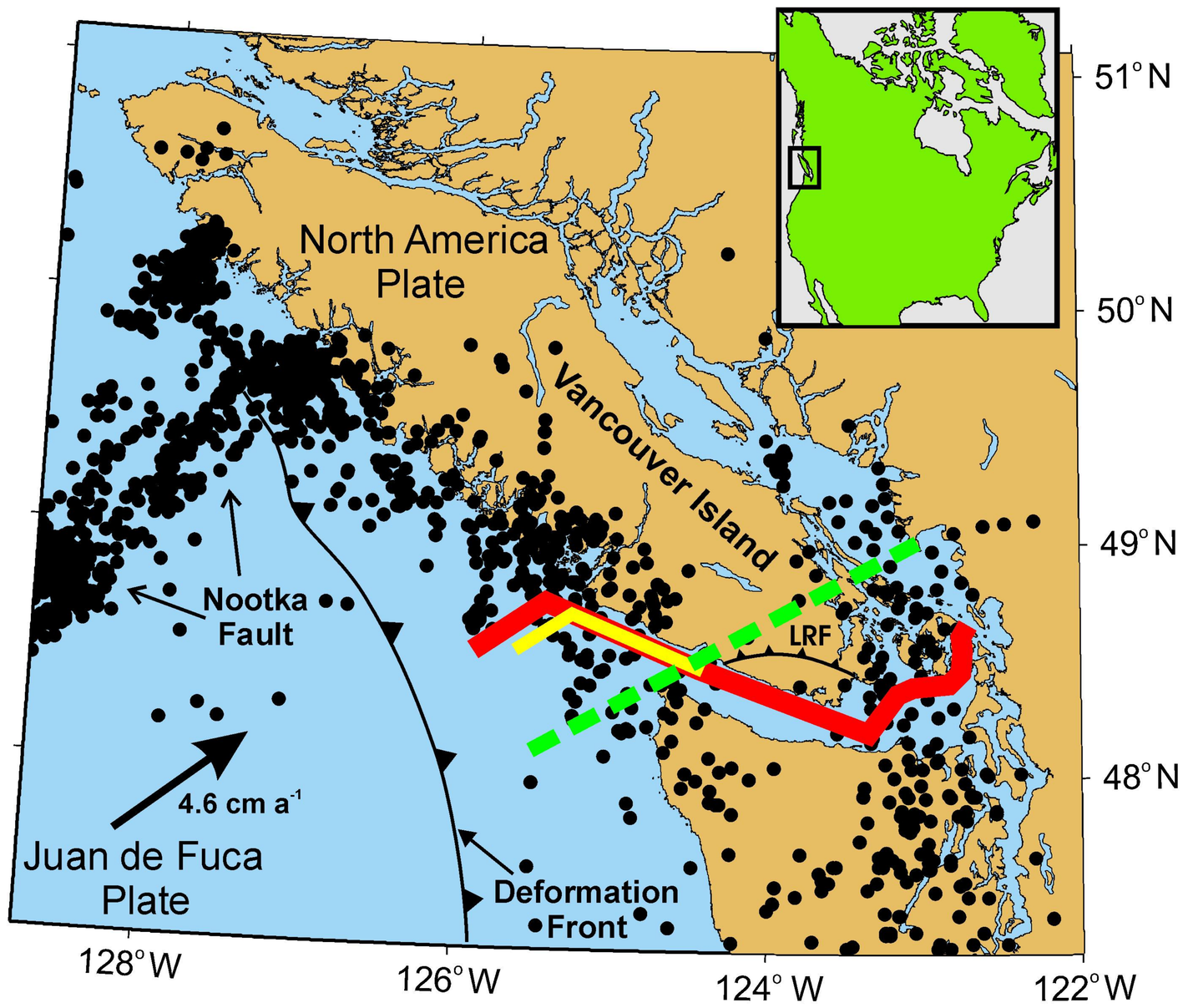
Figure 2 Composite seismic cross-section across the Cascadia forearc region in the vicinity of southern Vancouver Island. **a**, Unmigrated section showing the reflection, JdF, from the top of the subducting Juan de Fuca plate west of Vancouver Island, the E reflection zone, and the F reflection which marks the top of the subducting Juan de Fuca plate further east. Reflections from the Leech River

crustal fault, LRF, are truncated by the E reflections. The lack of continuity of the F reflector beneath the western half of Vancouver Island is largely due to the gain used for this display; on higher gain displays, the F reflector is continuous over ~80% of the profile with breaks attributable to localised variations in near-surface basement topography. The cross-section was constructed by projecting individual seismic profiles onto an azimuth of 063°, which is a representative dip direction for the subducting plate near the seismic profiles. The apparent dips of reflections such as JdF, E, and F, which dip shallowly in directions close to the projection azimuth, are close to true dip on the simulated section. The orientation of the original line segments used to construct the composite section are shown at the top. **b**, Migrated section superimposed on a display of P wave velocities derived by 3-D tomographic inversion of first arrivals from local earthquakes and wide-angle airgun shots around Vancouver Island[9]. The velocities were extracted from the 3-D velocity model along the composite seismic profile shown by the red line in Figure 1 and projected in the same way as the seismic reflection data. Earthquakes, which were relocated in the tomographic inversion, are shown by filled black circles. The near-linear alignment of east-dipping inslab earthquakes just above the oceanic Moho at 45-55 km depth may indicate delamination of the oceanic crust. Steeply dipping seismic reflectors oblique to the line of projection may be mispositioned; however, for the shallowly ~ENE-dipping reflectors interpreted here, any lateral positioning errors will likely be of the order of the accuracy of the hypocentre locations and the cell size used in the tomographic inversion, namely 3 km, or less. Oceanic Moho constrained by wide-angle reflections - blue; oceanic Moho assuming subducting crust is 6 km thick – dashed blue; top of subducting plate - yellow; deepest E reflection - green; shallowest E reflection – brown; Leech

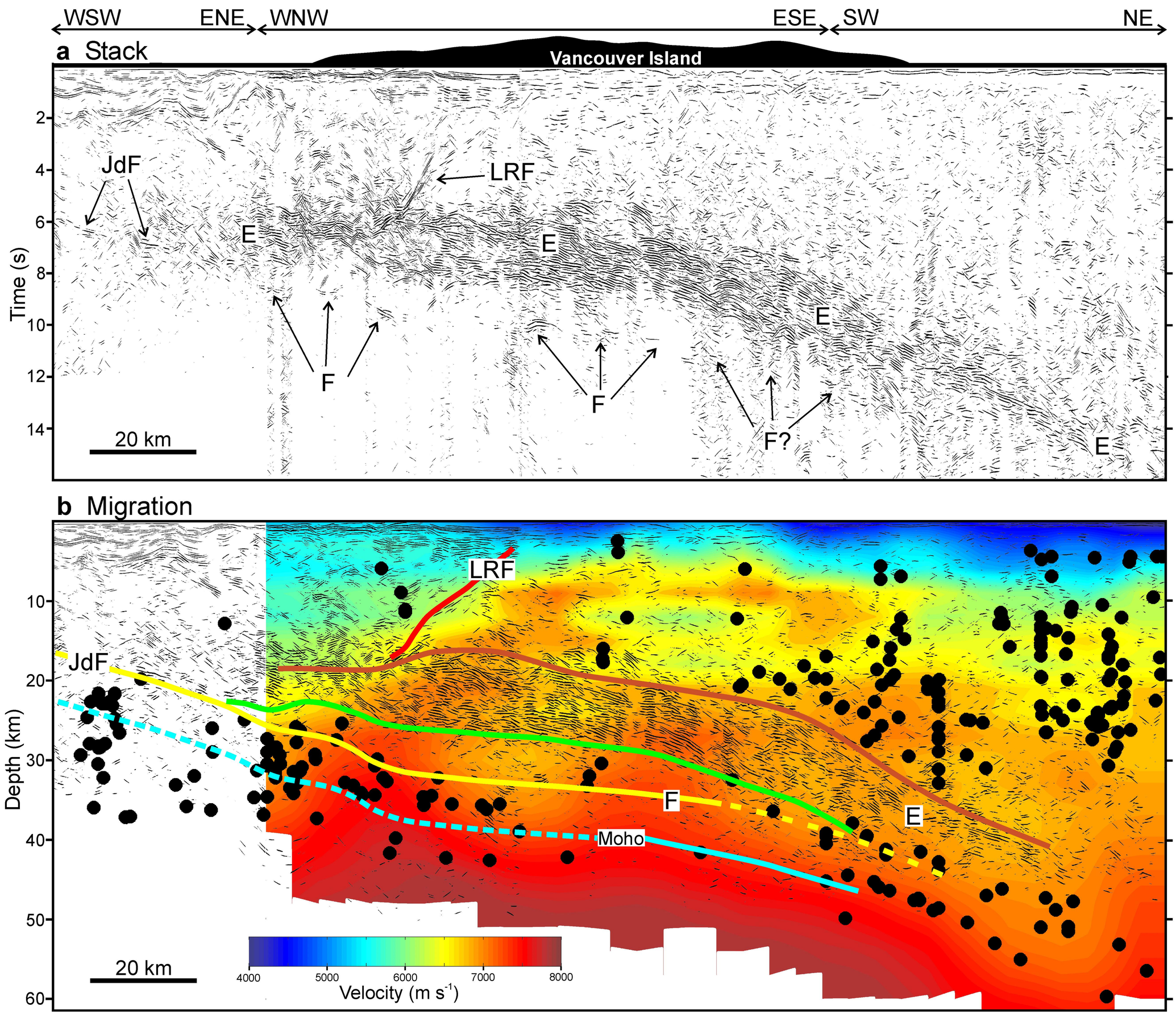
River fault – red. Vertical exaggeration is 1.5:1.

Figure 3 Composite seismic section near the west coast of Vancouver Island showing that the shallowest of the inslab earthquakes follow the geometry of the top of the subducting Juan de Fuca plate (yellow line). Inslab earthquakes occur predominantly where the dip of the subducting plate increases to 15°, and infrequently elsewhere. Earthquake hypocentres within 15 km of the seismic profiles are shown by black filled circles. The seismic data are unmigrated, but the position of the top of the plate is derived from a migrated section, indicating that the position of the interface does not move a great distance after migration due to its relatively low dip. The orientation of the original line segments used to construct the composite section are shown at the top. Oceanic Moho assuming subducting crust is 6 km thick – dashed blue line. Vertical exaggeration is 1.5:1.

Figure 4 Schematic cross-section of the northern Cascadia convergent margin at southern Vancouver Island. The plate boundary forms a thick duplex structure, within which crustal rocks are imbricated. Inslab earthquakes occur where the dip of the top of the subducting slab, which defines the floor thrust, increases suddenly, suggesting that the earthquakes are caused by deformation in the upper part of the subducting slab as it responds to the geometry of the inter-plate boundary zone. The E reflectors form the roof thrust, and are probably one location of the aseismic, slow-slip events. Slip along the roof thrust will transport the imbricated crustal rocks into the upper mantle above the subducting oceanic slab. Slow slip is also likely occurring along the floor thrust, which is inferred to be the top of the subducting plate. Vertical exaggeration is 1.5:1.



Nature MS No. 2003-10-10707: Fig. 1 Calvert



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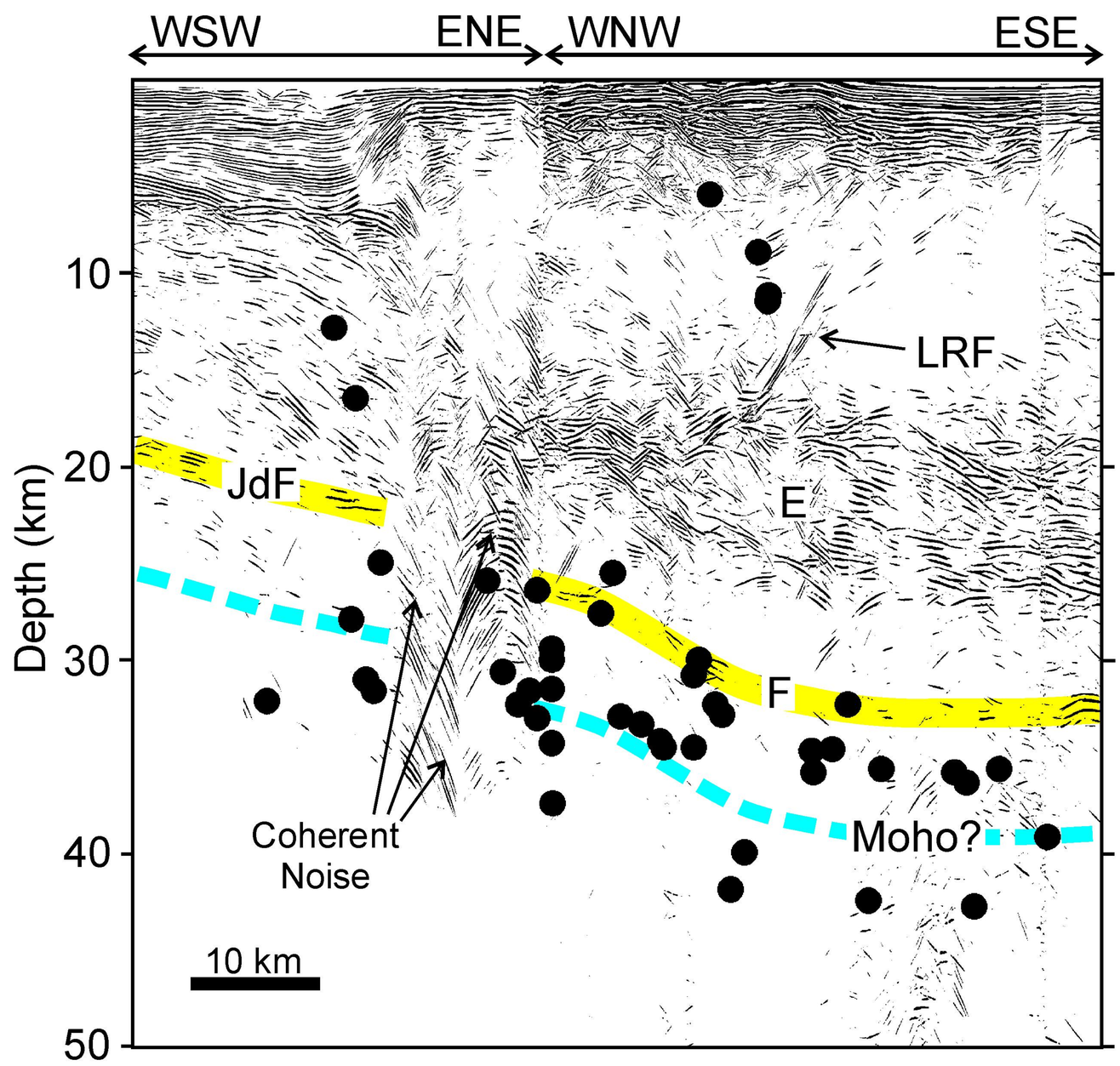

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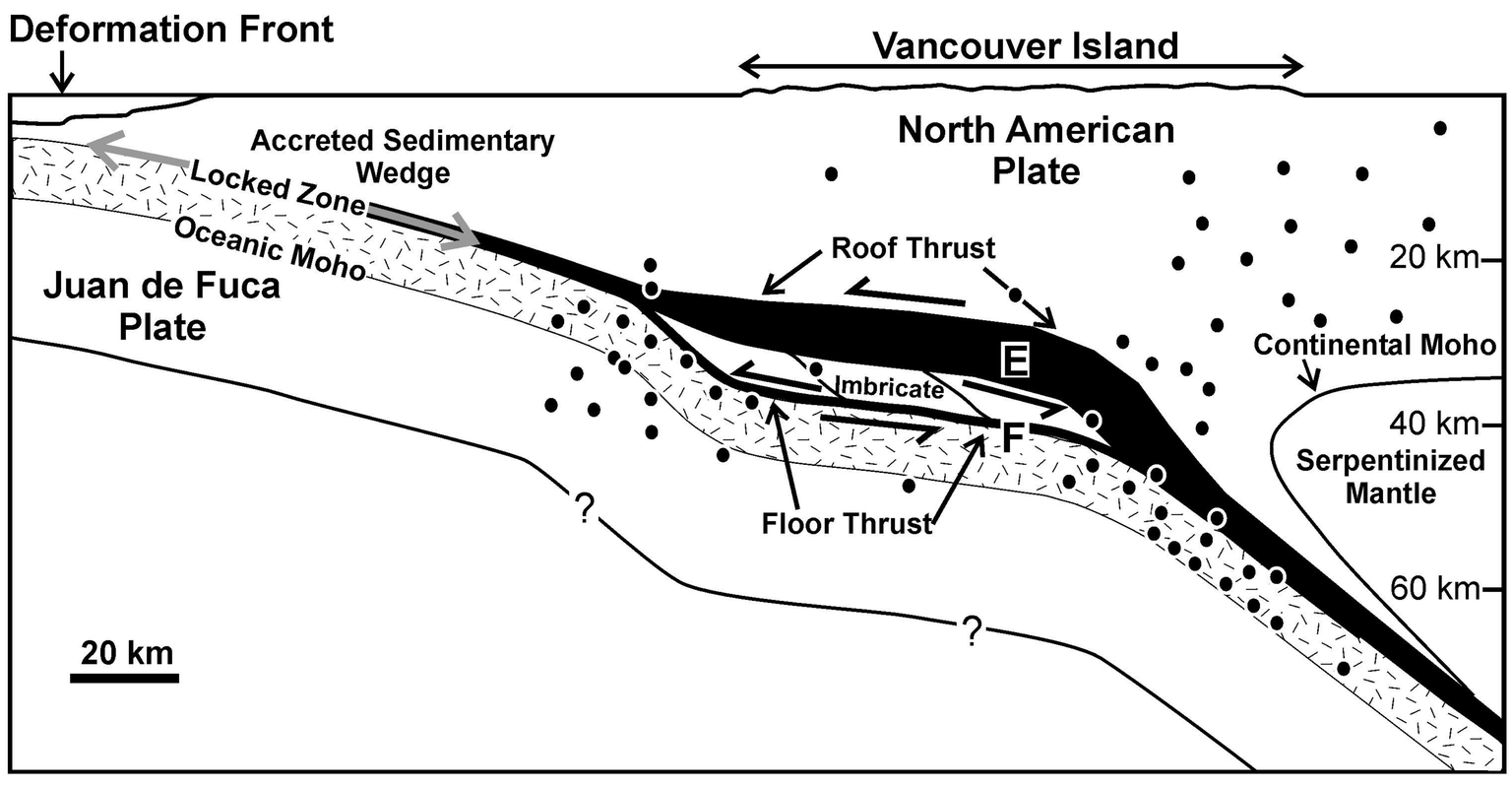
Deformation Front
Vancouver Island
Accreted Sedimentary Wedge
North American Plate
Locked Zone
Oceanic Moho
Juan de Fuca Plate
Roof Thrust
20 km
Continental Moho
E
Imbricate
F
40 km
Serpentinized Mantle
Floor Thrust
?
60 km
?
20 km