# Seismic reflection imaging of the subducting Juan de Fuca plate

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**McKenzie and Parker's early suggestion[1] that the Juan de Fuca plate is underthrusting North America has since been confirmed by numerous studies. Evidence for plate convergence along this junction includes: a sediment-filled trench[2–7], intense compressional deformation of the continental slope and shelf sediments[2–7], seafloor magnetic anomalies that extend beneath the continental slope[2,4], inland andesitic volcanoes[8], paired low/high heat flow and gravity anomalies[9,10], active onshore deformation[11,12], onshore crustal earthquakes with compressional axes parallel to the direction of plate convergence[13], sinistral strike-slip earthquakes along the Nootka Fault (Fig. 1)[14], and a well-defined Benioff–Wadati zone[6,15,16]. Here we report the results of a seismic reflection survey that has delineated two slabs of oceanic lithosphere underlying Vancouver Island, one that is currently being subducted and one that is underplated. These findings lead us to speculate that successive underplating of oceanic lithosphere may be an important process in the evolution and growth of continents.**

A total of 205 km of deep seismic reflection data have been collected along the four profiles shown in the simplified geological map of southeastern Vancouver Island (Fig. 1). The VISP1 line crosses the width of the island and is almost coincident with one of the gravity profiles studied by Riddihough[10] and with the combined onshore/offshore seismic refraction line of Spence *et al.*[17]. Some three-dimensional control on the interpretation of VISP1 is available from the VISP3 line located 15–20 km to the east and from a short test line described by Clowes *et al.*[18]. The two southeasterly lines, VISP2 and VISP4, were designed to determine the attitudes and significance of the San Juan, Survey Mountain and Leech River faults.

Line drawings of the reflections are shown in Fig. 2 and a typical example of the data, with an accompanying simplified interpretation, is shown in Fig. 3. Two very prominent reflection zones, C and E in Figs 2 and 3, are observed on all seismic sections. They underlie most of southeastern Vancouver Island including the youngest allochthonous terrains along the southeastern tip of the island. Both reflection zones dip to the north-east, parallel to the direction of convergence between the Juan de Fuca and North American plates (Fig. 1).

Reflection zone E probably originates from the boundary region between the descending Juan de Fuca plate and the overriding North American plate. It lies at a depth of only ~23 km beneath the southern end of VISP1, based on migrated travel-times and velocities from Spence *et al.*'s[17] seismic refraction model, and is deepest at ~34 km beneath the north-central region of the island. Its overall dip in the vicinity of VISP1 is to the north-east at an angle of 9–13°. From Fig. 2, the average

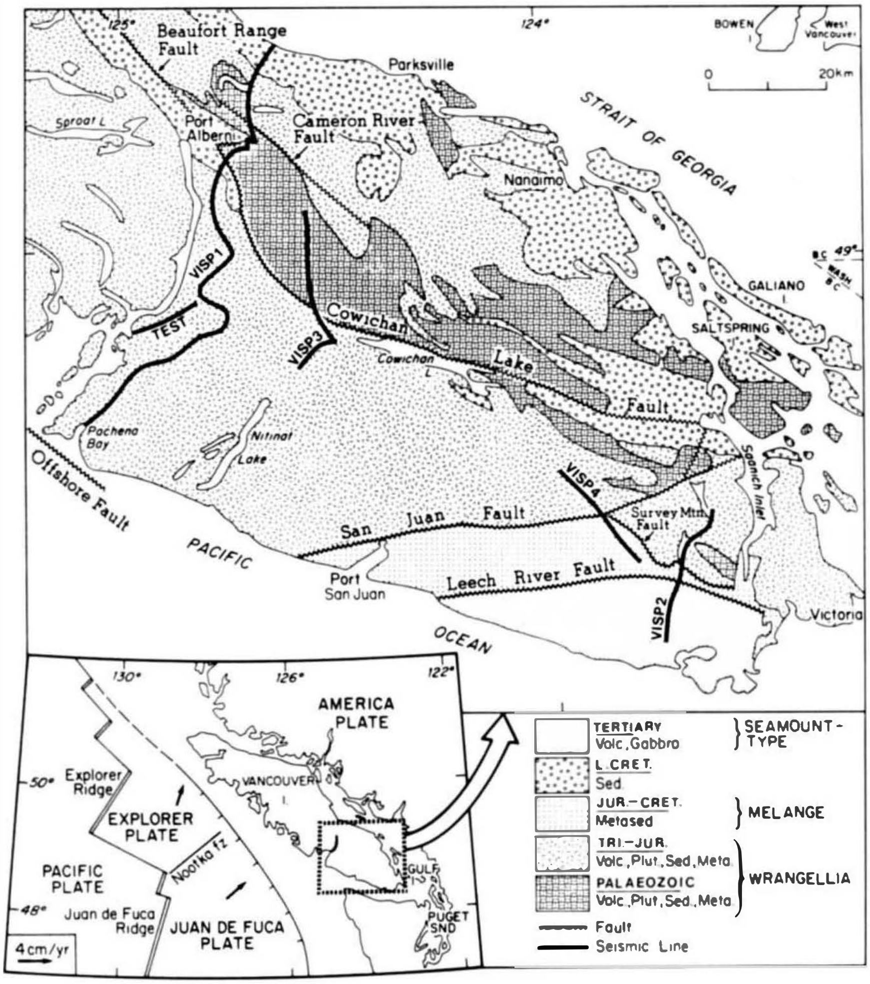


**Fig. 1** Simplified geological map of southeastern Vancouver Island showing the locations of the four seismic reflection profiles, VISP1 to VISP4, and the short seismic reflection profile, TEST, of Clowes *et al.*[18]. Geology is mostly from Muller[44], with minor modifications based on recent mapping programmes. The region to the north of the San Juan Fault is part of the exotic Wrangellia terrain of Palaeozoic and Mesozoic age. Between the San Juan and Leech River faults is an allochthonous mélange of Mesozoic metasediments and to the south of the Leech River Fault lies a volcanic terrain that may have been part of a Cenozoic seamount chain. The inset shows the location of the geological map with respect to the major plate boundaries.

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depth to zone E is shown to be somewhat less than the depth to the active subduction zone of the seismic refraction model. However, Spence *et al.*[17] have demonstrated that the depth and structure of the subducting plate beneath Vancouver Island are only weakly constrained by the onshore/offshore seismic data. The location and attitude of zone E match well Riddihough's[10] estimates for the top of the subduction zone based on a variety of seismic and gravity data, and the northeasterly dip of 9–13° is in excellent accord with the ~9° value obtained from an onshore/offshore seismic refraction study of the Washington continental margin[19] and the 11–15° dip of the Benioff–Wadati zone below southern Vancouver Island, Puget Sound and western Washington[6,15,16]. The shallow dip estimates are also consistent with the pattern of recent onshore deformation in this region[11] and with teleseismic waveforms recorded at seismographic stations on Vancouver Island and in western Oregon[20].

Towards the northern end of VISP1 there is some evidence for an increase in the dip of reflection zone E (Fig. 2). It is near to this location that the subducting plate in Riddihough's density models[10] begins to plunge more steeply into the mantle. Such a feature is common in other subduction zones[21] and is generally consistent with the steeply dipping slab of high-velocity material required to explain the pattern of travel-time anomalies to the north-east of Puget Sound[22]. The apparent absence of the deepest reflections beneath the northernmost region of VISP1 has at least two possible explanations. This part of the profile traverses the nose of a NW–SE-trending anticlinal ridge that exposes the oldest rocks on the island before crossing an escarpment onto a late Cretaceous sedimentary basin (Fig. 1), so the absence of deep reflections here may be related to geological and topographic complexities. Alternatively, if the dip of the subducting plate increases to a value in excess of ~45°, as shown in some of Riddihough's density models[10] and as required by McKenzie and Julian's travel-time analysis[22], the relatively conventional data processing that we have applied would have effectively filtered out any reflections from this zone.

Figure 4 shows a contour map of two-way travel-times to the top of reflection zone E. Particularly noteworthy is the structure that is required to explain the variations in depth and attitude of the reflection zone between the western pair of seismic profiles (1 and 3) and the eastern pair (2 and 4). Of course, the dashed parts of the contour diagram are speculative; a major fault anywhere between the two pairs of profiles would allow an equally valid interpretation of existing data. Warping and frac-

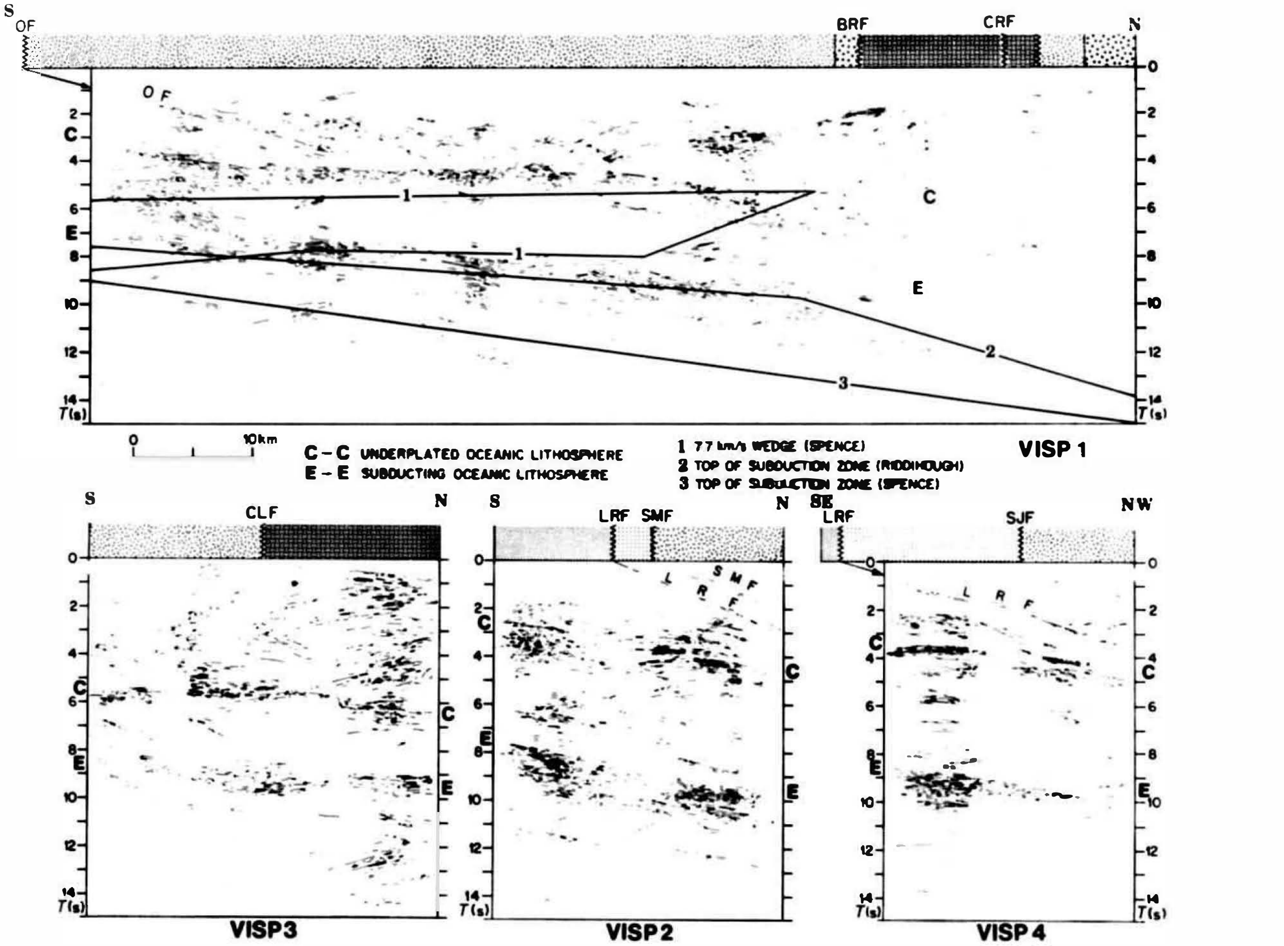


**Fig. 2** Line drawings showing the unmigrated reflections recorded on the four seismic reflection profiles. Vertical scale is two-way travel-time in seconds ($T$). All lines were recorded to 16 s with 30-fold coverage. Acquisition methods were similar to those used in the US by the COCORP group[45]. Final processing included single-fold trace editing, crooked line geometry and elevation corrections, automatic gain control, normal move-out corrections, trim statics using a correlation window of $T = 1$–12 s, common reflection point stacking, bandpass filtering of 8–40 Hz and trace-to-trace amplitude equalization using a $T = 4$–8 s window. Patterns at the top of each section show the surface geology crossed; an explanation of the various patterns is given in Fig. 1. On the VISP1 section the -1- border delineates the high-velocity (7.7 km s$^{-1}$), high-density (3.3 g ml$^{-1}$) block proposed by Spence *et al.*[17], and the -2- and -3- boundaries show, respectively, the Riddihough[10] and Spence *et al.*[17] estimates for the top of the actively subducting Juan de Fuca plate. C–C and E–E are prominent reflection zones that delineate the upper boundary of the high-velocity, high-density block (the underplated oceanic lithosphere) and the top of the actively subducting Juan de Fuca plate respectively. OF, Offshore (or Tofino[46]) Fault; BRF, Beaufort Range Fault; CRF, Cameron River Fault; CLF, Cowichan Lake Fault; LRF, Leech River Fault; SMF, Survey Mountain Fault; SJF, San Juan Fault (locations of faults are shown in Fig. 1). A typical example of the seismic reflection data is shown in Fig. 3.

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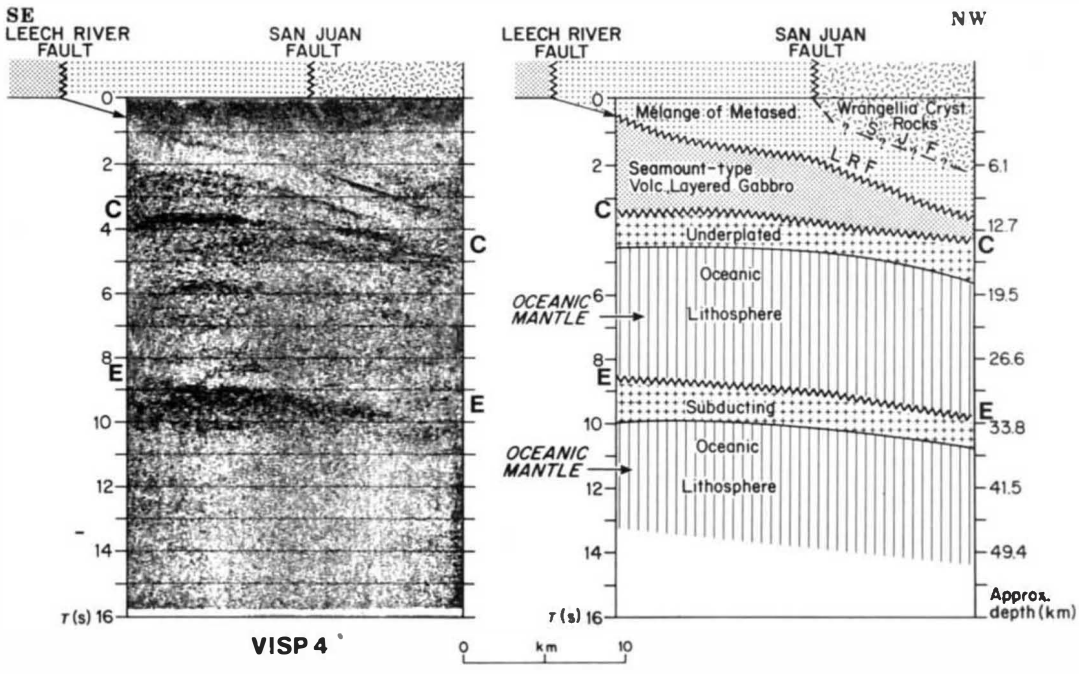


**Fig. 3** A typical unmigrated seismic reflection section and simplified interpretation obtained from data recorded on Vancouver Island. Figure 1 shows the location of the profile and Fig. 2 (bottom right) shows a line diagram of the individual reflections recorded on the section. Patterns at the top of both the section and the interpretation diagram show the surface geology; an explanation of the various patterns is given in Fig. 1. The regions of + signs correspond to the reflection zones C and E. Approximate depths shown are based on the seismic refraction model of Spence *et al.*[17]. The seismic reflection data were recorded by Veritas Geophysical Ltd and processed by Veritas Seismic Ltd.

turing of the subducting plate in this general region have been predicted by Rogers[15] and by Keen and Hyndman[9] on the basis of seismicity patterns, fault plane solutions and the geometry of the Juan de Fuca-North American plate interactions. Some relatively deep strike-slip earthquakes in western Washington suggest that intra-plate faulting or segmentation may be a common feature of the downgoing Juan de Fuca plate[16].

The nature of the E reflection zone requires some discussion. On the migrated sections it is 3-5 km thick (1-1.5 s two-way travel-time) and has a strongly laminated character that could result from layered sediments, intercalated volcanics and sediments, layered igneous rocks or tectonic structures induced by underthrusting. Undeformed sediments are known to have been subducted to considerable depths beneath the forearc basins of several island arcs, including those of Japan[23,24], the Aleutians[25,26] and the Caribbean[27,28]. However, in the general region of Vancouver Island there are numerous single- and multi-fold seismic reflection profiles which show that the majority of sediments have been scraped off the descending oceanic plate to form the accretionary wedge that now constitutes the continental margin[2-7]. Reflection zone E is therefore unlikely to have originated from a simple stack of sedimentary layers riding on top of the descending oceanic plate. Nevertheless, it is feasible that the lowermost layers of lithified sediments have been taken down into the subduction zone and that these sediments and possibly the upper crystalline layers have been transferred or underplated to the base of the overriding plate. Successive underplating of this type would result in the formation of a thick layered sequence between the descending Juan de Fuca slab and the overriding North American plate. This particular process of accretion, termed subcretion by Karig and Kay[29], has been invoked by Von Heune[25] to explain some multi-fold seismic reflection data collected across the Aleutian trench and forearc basin.

Episodic and rapid sedimentation from the North American continent[2-7], combined with episodic volcanism involving extensive lava flows from the nearby oceanic spreading centres[30], have probably resulted in the widespread interlayering of oceanic basalts and sediments on the Juan de Fuca plate. Comprehensive studies across the northern parts of the Explorer plate (Fig. 1) and adjacent ridge segments have revealed ubiquitous interfingering of basaltic lavas and turbidites[3,30-33], and similar features are shown on the generalized geological cross-section of the central Oregon continental margin[34].

Based on the results of multi-fold seismic reflection surveys, high-quality seismic refraction surveys and deep-sea drilling, Talwani *et al.*[27] have proposed that interlayered extrusive and intrusive (mostly sills) rocks are the source of some laterally extensive reflections from within the acoustic basement of the small Caribbean plate. As similar lava flows and sills are expected to occur in the upper regions of the Juan de Fuca plate, some of the reflections in the E zone, particularly those near to the base of the zone, could have originated from structures within the descending oceanic crust.

Finally, at some subduction zones, notably those off the coasts of Java and Ecuador[24], there is a hint that layered reflections along the boundary of the descending plate only become pronounced landward of the trench. Layering of this nature could either be produced by the selective slicing away of sedimentary rocks from the underside of the accretionary wedge or it could result from brittle and/or ductile deformation induced by the relative motion between the two plates.

We interpret the region between reflection zones C and E as a tectonically underplated slab of older oceanic lithosphere, which was accreted to the base of Vancouver Island after the westward jump in the locus of subduction in Eocene times[35,36]. As shown in Fig. 2, our interpretation is supported by the gravity and seismic refraction models which require high-density ($3.3\ g\ ml^{-1}$) and high-velocity ($7.7\ km\ s^{-1}$) mantle-type material and velocity discontinuities at the appropriate shallow depths. The upper boundary of the high-velocity material at ~18 km depth is well-delineated from interpretations of the combined onshore/offshore seismic refraction line[17] and an intersecting refraction line that was recorded along the length of the island[37], so its coincidence with the base of reflection zone C is significant. On the seismic reflection lines the thickness of the interval between zones C and E varies from 9 to 18 km, which is comparable to the 17-20 km range that Spence *et al.*[17] derived for the thickness of the high-velocity mantle material in the descending Juan de Fuca plate.

Reflection zone C is strikingly similar to reflection zone E. It has a similar laminated character, an average thickness of 3-5 km and an overall dip to the north-east of 5-8°. It seems to have acted as a decollement zone to a number of major northeasterly-dipping structures, most of which can be projected to the surface where they coincide with mapped faults or plutonic contacts.

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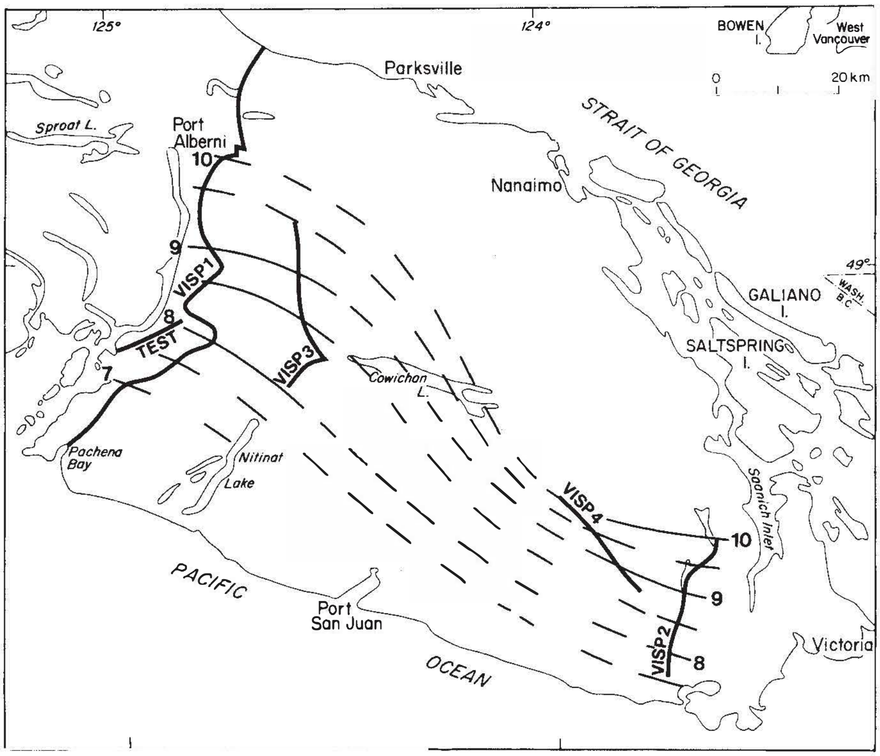


**Fig. 4** Contours are two-way travel-times (unmigrated) (in s) to the top of reflection zone E. The curvature of the dashed contours between the western pair of seismic profiles (VISP1 and VISP3) and the eastern pair (VISP2 and VISP4) is speculative; a major fault anywhere between the two pairs of profiles would be an equally valid interpretation of the travel-time information.

Relative motion during the waning stages of this earlier phase of plate convergence would have occurred along these moderately dipping structures and along the decollement zone. A necessary consequence of our tectonic model is the removal of the lower lithosphere of the overriding plate during Eocene and earlier times.

It seems to us that under favourable but frequently occurring conditions, tectonic underplating of oceanic lithosphere at the base of convergent margins is a rapid means of adding large volumes of material to terrains that eventually become continental. This process is capable of creating root zones beneath the mountain ranges of active continental margins and of substantially increasing the crustal thicknesses of island arc–trench systems. In addition to our Vancouver Island example, thin slabs of underplated oceanic lithosphere have been proposed to underlie parts of Java[38], the Aleutians[25] and southern Alaska[39]. The underplated oceanic lithosphere would generally be of higher density, higher velocity and more basic than the overlying material. Across such terrains now interior to the continents, seismic refraction methods would resolve a broad-scale subhorizontal layering of the crust (including zones of high and low velocity), whereas seismic reflection techniques would see the pronounced reflection zones. Although many regions do not reveal such a simple image of the continental crust, a two- to four-layered crustal section with laminated reflections in the mid- to lower regions is a common feature on most continents[40]. Of course, we do not claim that underplating is the only or the dominant means of crustal thickening, but it is an important process that requires further investigation. In particular, the new mechanism could help to explain the anomalously high continental growth rates obtained for Precambrian shields[41,42]. Tectonic processes in Archaean times were probably dominated by the rapid movements of small, short-lived oceanic plates[41,43] and, like the present situation along the west coast of North America, subduction of the young and buoyant oceanic lithosphere would have occurred at relatively shallow angles.

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