LITHOPROBE—southern Vancouver Island: Cenozoic subduction complex imaged by deep seismic reflections[1]

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The LITHOPROBE seismic reflection project on Vancouver Island was designed to study the large-scale structure of several accreted terranes exposed on the island and to determine the geometry and structural characteristics of the subducting Juan de Fuca plate. In this paper, we interpret two LITHOPROBE profiles from southernmost Vancouver Island that were shot across three important terrane-bounding faults—Leech River, San Juan, and Survey Mountain—to determine their subsurface geometry and relationship to deeper structures associated with modern subduction.

The structure beneath the island can be divided into an upper crustal region, consisting of several accreted terranes, and a deeper region that represents a landward extension of the modern offshore subduction complex. In the upper region, the Survey Mountain and Leech River faults are imaged as northeast-dipping thrusts that separate Wrangellia, a large Mesozoic–Paleozoic terrane, from two smaller accreted terranes: the Leech River schist, Mesozoic rocks that were metamorphosed in the Late Eocene; and the Metchosin Formation, a Lower Eocene basalt and gabbro unit. The Leech River fault, which was clearly imaged on both profiles, dips 35–45° northeast and extends to about 10 km depth. The Survey Mountain fault lies parallel to and above the Leech River fault and extends to similar depths. The San Juan fault, the western continuation of the Survey Mountain fault, was not imaged, although indirect evidence suggests that it also is a thrust fault. These faults accommodated the Late Eocene amalgamation of the Leech River and Metchosin terranes along the southern perimeter of Wrangellia. Thereafter, these terranes acted as a relatively coherent lid for a younger subduction complex that has formed during the modern (40 Ma to present) convergent regime.

Within this subduction complex, the LITHOPROBE profiles show three prominent bands of differing reflectivity that dip gently northeast. These bands represent regionally extensive layers lying beneath the lid of older accreted terranes. We interpret them as having formed by underplating of oceanic materials beneath the leading edge of an overriding continental place. The upper reflective layer can be projected updip to the south, where it is exposed in the Olympic Mountains as the Core rocks, an uplifted Cenozoic subduction complex composed dominantly of accreted marine sedimentary rocks. A middle zone of low reflectivity is not exposed at the surface, but results from an adjacent refraction survey indicate it is probably composed of relatively high velocity materials (~7.7 km/s). We consider two possibilities for the origin of this zone: (1) a detached slab of oceanic lithosphere accreted during an episodic tectonic event or (2) an imbricated package of mafic rocks derived by continuous accretion from the top of the subducting oceanic crust. The lower reflective layer is similar in reflection character to the upper layer and, therefore, is also interpreted as consisting dominantly of accreted marine sedimentary rocks. It represents the active zone of decoupling between the overriding and underthrusting plates and, thus, delimits present accretionary processes occurring directly above the descending Juan de Fuca plate. These results provide the first direct evidence for the process of subduction underplating or subcretion and illustrate a process that is probably important in the evolution and growth of continents.

Le projet de sismique réflexion LITHOPROBE sur l'île de Vancouver a été conçu pour étudier la structure à grande échelle de plusieurs terranes d'accrétion exposés sur l'île et pour déterminer la géométrie des traits structuraux de la plaque subductante Juan de Fuca. Dans le présent article, nous interprétons deux profils LITHOPROBE de l'extrémité sud de l'île Vancouver traversant trois importants terranes limités par des failles—Leech River, San Juan et Survey Mountain—afin de

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déterminer leur géométrie en subsurface et leurs relations avec les structures profondes dans la zone actuellement en voie de subduction.

La structure sous-jacente à l'île peut être divisée en une région crustale supérieure formée de plusieurs terranes d'accrétion et en une région plus profonde qui représente une extension vers le continent d'un complexe océanique de subduction contemporaine. Dans la région supérieure, les failles Survey Mountain et Leech River apparaissent sur image sismique comme des chevauchements de pendage nord-est qui séparent le vaste terrane mésozoïque–paléozoïque Wrangellia de deux terranes d'accrétion plus petits: le schiste de Leech River, formé de roches mésozoïques métamorphisées durant l'Éocène supérieur; et la formation de Metchosin, une unité de basalte et gabbro d'âge de l'Éocène inférieur. La faille Leech River clairement réfléchie dans le profil sismique présente un pendage nord-est de 35–45°, et elle se prolonge jusqu'à environ 10 km de profondeur. La faille Survey Mountain apparaît au-dessus de la faille Leech River et se prolonge parallèle à cette dernière jusqu'à la même profondeur. La faille San Juan, la continuité accidentale de la faille Survey Mountain, n'apparaît pas dans le profil, cependant d'autres indices révèlent qu'elle est aussi une faille de chevauchement. Ces failles ont largement facilité l'amalgamation à l'Éocène des terranes Leech River et Metchosin sur le périmètre sud de la Wrangellia. Par la suite, ces terranes se comportèrent comme un couvercle relativement solidaire en un complexe de suduction plus récent formé durant le régime convergent de subduction (40 Ma à présent) contemporaine.

Les profils sismiques LITHOPROBE dans le complexe de subduction révèlent trois bandes dominantes de réflectivité différente avec faible pendage nord-est. Ces bandes représentent des couches d'extension régionale sous-jacentes au couvercle formé des terranes accolés plus anciens. Nous croyons que les bandent sont dues à une pénétration sous-plaque de matériaux océaniques au-dessous du front de la plaque continentale chevauchante. La couche supérieure de réflexion peut être extrapolée vers le sud en montant le pendange en un lieu d'affleurement dans les monts Olympiques représenté par les roches de Core, un complexe cénozoïque de subduction soulevé et composé principalement de terrains marins sédimentaires accolés. La zone centrale de faible réflectivité n'est pas exposée en surface, mais les résultats obtenus par un levé adjacent de sismique réflexion indiquent qu'elle est formée principalement de matériaux de vitesse relativement rapide (~7,7 km/s). Cette zone peut être expliquée de deux façons: (1) une dalle détachée de la lithosphère océanique s'est accalée durant un incident tectonique, ou (2) un paquetage imbriqué de roches mafiques dérivées par un accrétion continue de la partie sommitale de la croûte océanique subductante. La couche inférieure de réflexion présente un profil sismique analogue à celui de la couche supérieure, et par conséquent nous la croyons formée aussi principalement de terrains marins sédimentaires accolés. Elle représente une séparation entre les plaques de chevauchement et de sous-charriage, et elle délimite ainsi le processus d'accrétion actuel apparaissant directement au-dessus de la plaque plongeante de Juan de Fuca. Ces résultats apportent pour la première fois une preuve directe d'un processus de subduction sous la plaque ou de subaccrétion et illustre un mécanisme probablement très significatif de l'évolution de la croissance des continents.

[Traduit par le journal]

Introduction

LITHOPROBE is a Canadian geoscience research program involving a collaborative effort among university, government, and industry geoscientists to study in an integrated fashion the deep structure, composition, and tectonic evolution of the Canadian continental lithosphere and adjacent offshore margins (CANDEL 1981; Clowes 1984; Clowes *et al.* 1984). The principal tool of the LITHOPROBE program is the multichannel seismic reflection method, the only available geophysical method with adequate resolution to help unravel complex geological structures at depth. Additional geological, geophysical, and geochemical studies provide essential supporting data to complement the reflection results and to enable integrated interpretations.

Southern Vancouver Island was selected as the principal locale for the 1984 LITHOPROBE program because (1) it provided an important site where terrane accretion and plate subduction could be investigated, (2) a preliminary reflection experiment had been successfully accomplished (Clowes *et al.* 1983), and (3) a seismic refraction experiment (Ellis *et al.* 1983) provided a seismic structure model from the deep ocean to the inland volcanic arc (Spence *et al.* 1985). The major component of this phase of the LITHOPROBE program was the acquisition and processing of 206 km of Vibroseis reflection profiles along four lines (Fig. 1): line 1 crossed Vancouver Island coincident with the refraction profile; line 3 was located subparallel to line 1, to assist in resolving three-dimensional structural variations; and lines 2 and 4 crossed important terrane boundaries on the southernmost end of the island.

These profiles contain abundant reflection arrivals. They image many of the upper crustal faults on the island and also show numerous coherent reflections from an underlying subduction complex. The deep reflections are especially interesting because they probably represent the first direct evidence of subduction underplating (Scholl *et al.* 1980; von Huene and Uyeda 1981; Moore *et al.* 1982; Karig 1983), a process by which oceanic materials are accreted at depth beneath a subduction complex. Yorath *et al.* (1985*a*) presented preliminary interpretations for all of the seismic lines. A more refined interpretation of line 1 was given in Yorath *et al.* (1985*b*). Green *et al.* (1986) used reflection data from all four lines to interpret the deep structure associated with the modern subducting plate.

In this paper, we present data from lines 2 and 4 and use surface geological relations from southern Vancouver Island and the Olympic Mountains (northwestern Washington) to develop an integrated geologic and tectonic interpretation. These two lines cross three important faults—San Juan, Survey Mountain, and Leech River—that separate distinctly different geologic terranes. The main topics addressed are (1) the subsurface distribution of the terranes and the geometry of bounding faults, (2) the structure and origin of the accretionary complex or underplated zone imaged beneath southern Vancouver Island, and (3) the tectonic implications of the geologic interpretations.

Regional geology and tectonics

The geology of southern Vancouver Island and surrounding areas can be divided into four major tectonic units that emphasize the tectonic framework established during the Late Eocene

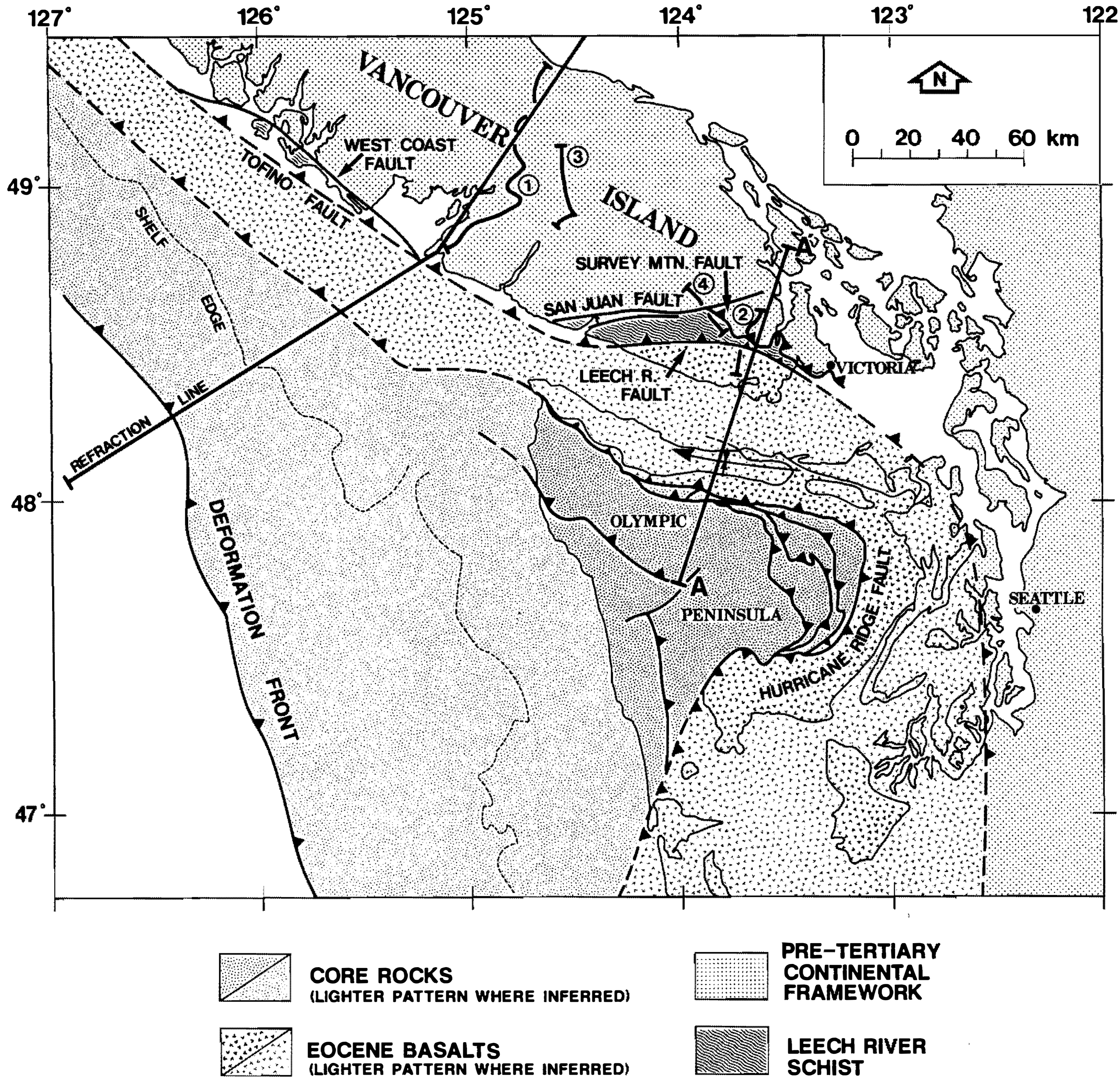

FIG. 1. Geologic location map of southern Vancouver Island and the Olympic Peninsula of northwestern Washington (modified from Johnson *et al.* (1984) and Brandon (1985)). The circled numbers identify LITHOPROBE reflection lines 1–4. Cross section A–A′ is shown in Fig. 8. Cross section B–B′ in Fig. 7 follows the refraction line of Spence *et al.* (1985). The map pattern for a geologic unit is screened where that unit is not exposed but is known to occur in the subsurface.

initiation of the present-day convergent margin (Fig. 1). (Time-scale correlations used below are based on Prothero and Armentrout (1985) and the Decade of North American Geology (DNAG) scale of Berggren *et al.* (1985).) The tectonic units are as follows:

(1) A pre-Tertiary continental framework consisting of an amalgam of Paleozoic and Mesozoic terranes that were sutured to continental North America sometime during or prior to the Late Cretaceous (Monger *et al.* 1982; Brandon and Cowan 1985; Howell *et al.* 1985). This framework represents the relatively rigid part of the overriding continental plate during Cenozoic subduction. On Vancouver Island, this continental framework is represented by the Wrangellia terrane (Jones *et al.* 1977), a thick Paleozoic and Mesozoic sequence dominated by volcanic and plutonic rocks (Muller 1977*a*).

(2) The Leech River schist (Leech River Formation of Muller (1977*a*); Leech River complex of Fairchild and Cowan (1982)) composed of Mesozoic marine sedimentary and basaltic rocks that were regionally metamorphosed and penetratively deformed during the Late Eocene (42 Ma, based on K/Ar mineral dates from the schist; recalculated from Wanless *et al.* (1978) using new decay constants). The Leech River schist is restricted to the southern part of Vancouver Island, where it occurs as a fault-bounded unit, separated from adja-

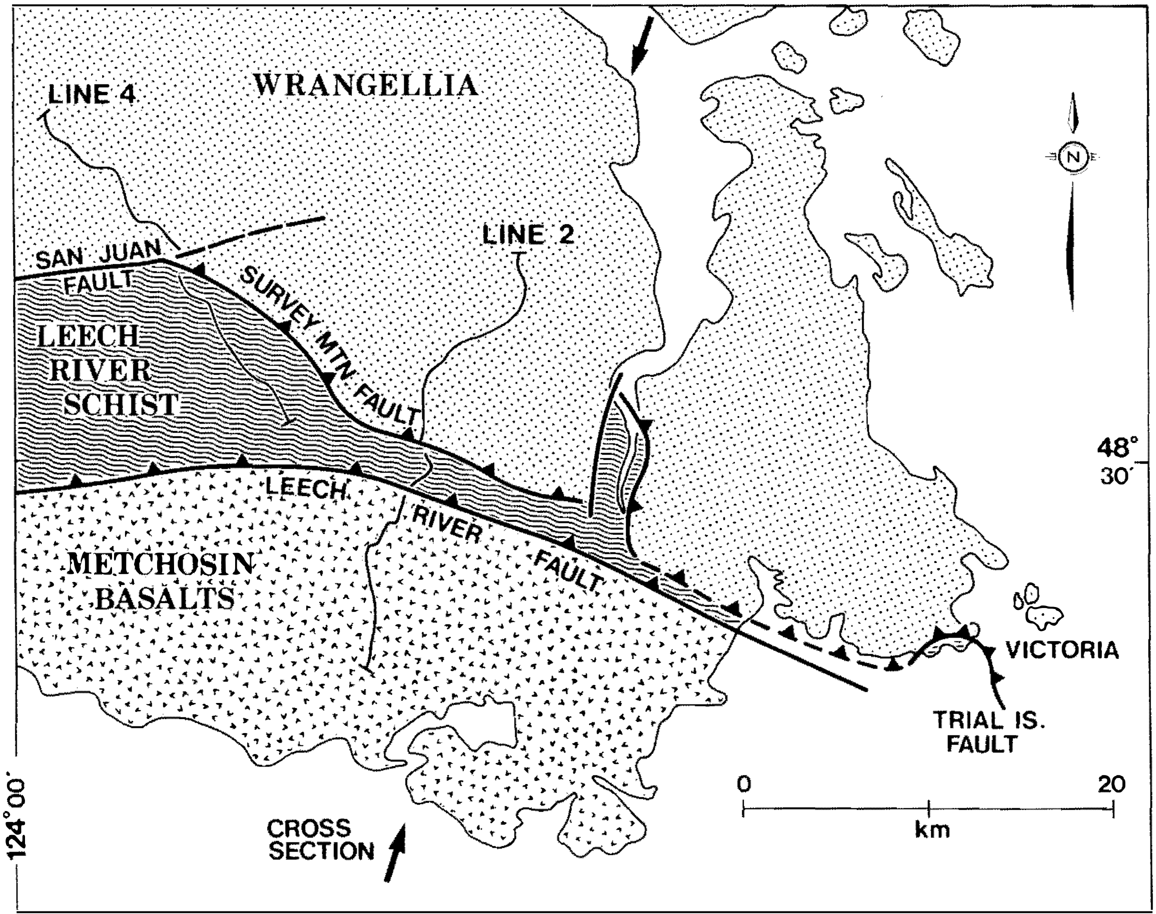

FIG. 2. Summary map of the major faults in the vicinity of lines 2 and 4. Legend given in Fig. 1.

cent terranes by the Survey Mountain, San Juan, and Leech River faults. Metamorphism was under low-pressure conditions and culminated in amphibolite facies in the southern part of the unit (Fairchild and Cowan 1982). For simplicity, the Leech River schist as used here also includes some similar Mesozoic rocks that were not involved in Leech River metamorphism but were juxtaposed with Wrangellia at about the same time. These are the Pandora Peak unit (Rusmore and Cowan 1985) on southern Vancouver Island and the Pacific Rim Complex (Brandon 1985) on western Vancouver Island.

(3) Lower Eocene basalts, which are called the Crescent Formation in northwestern Washington (Tabor and Cady 1978*b*) and the Metchosin Formation on Vancouver Island (Muller 1977*a*; Massey 1986). These basalts also extend into the offshore area west of Vancouver Island, where they were penetrated in exploratory wells and lie beneath Tertiary sediments of the Tofino basin (Shouldice 1971; MacLeod *et al.* 1977). Based on close similarities in age and stratigraphy (Muller 1977*a*; Tabor and Cady 1978*a*; Duncan 1982) and in geochemistry (Muller 1980; unpublished data of Brandon for the offshore basalts), all of these units are directly correlative. Magnetic anomaly maps (Shouldice 1971; MacLeod *et al.* 1977; Tiffin and Riddihough 1977) and surface geologic maps (Muller 1977*b*; Tabor and Cady 1978*b*) show that these units are regionally continuous, extending from southwestern Washington to the continental shelf off central Vancouver Island (Fig. 1). In the following text, these units are collectively called the Eocene basalts. Their regional continuity is an important relationship in our interpretation of the LITHOPROBE profiles.

(4) The Core rocks (Tabor and Cady 1978*a*), a Cenozoic accretionary complex that is exposed in the Olympic Peninsula beneath the Eocene basalts and underlies the continental margin west of Vancouver Island and Washington (Fig. 1).

The Leech River schist and the Eocene basalts are interpreted as representing allochthonous terranes that were accreted to the pre-Tertiary continental framework during the Late Eocene (Fairchild and Cowan 1982). The faults separating these terranes are exposed on southern Vancouver Island and can be grouped into two sets (Figs. 1, 2) as follows:

(1) The San Juan, Survey Mountain, and Trial Island faults collectively mark the boundary between Wrangellia and the Leech River schist (Muller 1983; Rusmore and Cowan 1985). These faults were formed during the Late Eocene (42–38 Ma), after Leech River metamorphism and prior to latest Eocene deposition of the overlapping Carmanah Group (Fairchild and Cowan 1982; Rusmore and Cowan 1985). Brandon (1984) and Rusmore and Cowan (1985) argued that the Survey Mountain and Trial Island faults are northeast-dipping thrusts. The San Juan fault is not exposed, but it merges eastward with the Survey Mountain fault, suggesting that it also is a thrust, coextensive with the Survey Mountain fault. In contrast to this interpretation, Muller (1983) showed the San Juan fault continuing along strike to the northeast of the Survey Mountain fault (dashed segment of the fault in Fig. 2). However, Upper Cretaceous strata of the Nanaimo Group overlap this proposed

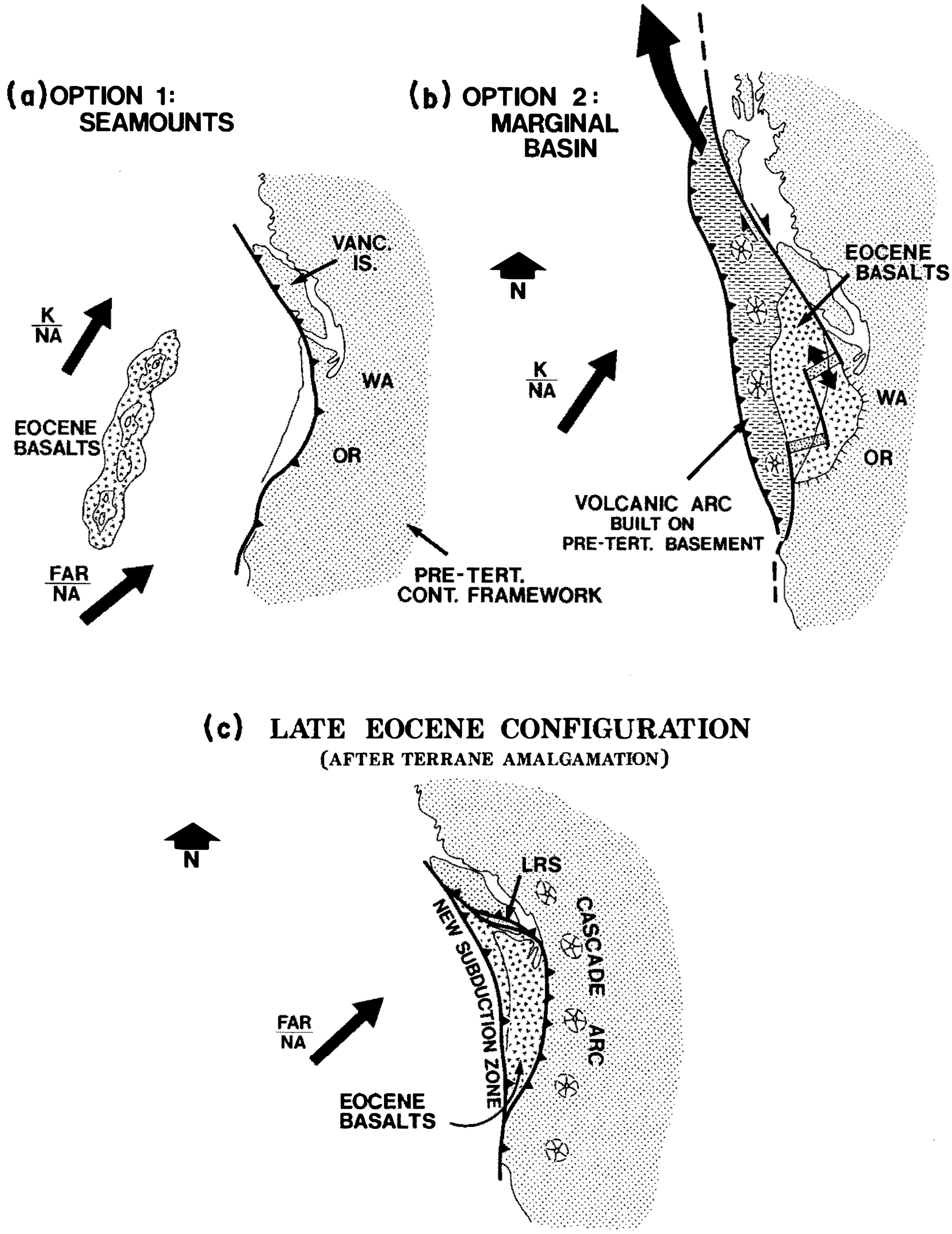

FIG. 3. Two alternative interpretations for early Eocene terrane accretion. Arrows indicate the relative plate motion of Kula (K) and Farallon (FAR) with respect to North America (NA) (after Wells *et al.* 1984). (*a*) Option 1 shows the Eocene basalts as a seamount chain, which subsequently collided with the margin. (*b*) In option 2, the Eocene basalts are formed within an obliquely spreading marginal basin, similar to rifting in the modern Andaman Sea (Curray *et al.* 1979). Oblique rifting causes the forearc to be translated northward, leaving just the Eocene basalts behind. (*c*) Terrane amalgamation, whether by option 1 or 2, was completed by Late Eocene. At that time, a new subduction zone was developed west of the Eocene basalts, thereby marking the beginning of the modern subduction regime. LRS, Leech River schist.

continuation and indicate that it is an older feature, unrelated to the main part of the San Juan fault, which was active during the Late Eocene (Fairchild and Cowan 1982).

(2) The Leech River fault, which marks the southern limit of the Leech River schist, is a north-dipping thrust that places the Metchosin basalts beneath the schist (Yorath *et al.* 1985*a*; this paper). This result is in contrast to some previous interpretations that argue that the Leech River fault is a left-lateral transcurrent fault (Yorath 1980; Fairchild and Cowan 1982; Rusmore and Cowan 1985). Based on similar age and structural position, the Leech River fault appears to be similar to the Tofino fault (Brandon 1985), which lies off the west coast of Vancouver Island and separates the offshore basalts from older Mesozoic and Paleozoic rocks to the east (Fig. 1). Results from line 1 indicate that, like the Leech River fault, the Tofino fault is also a major thrust dipping to the northeast (Yorath

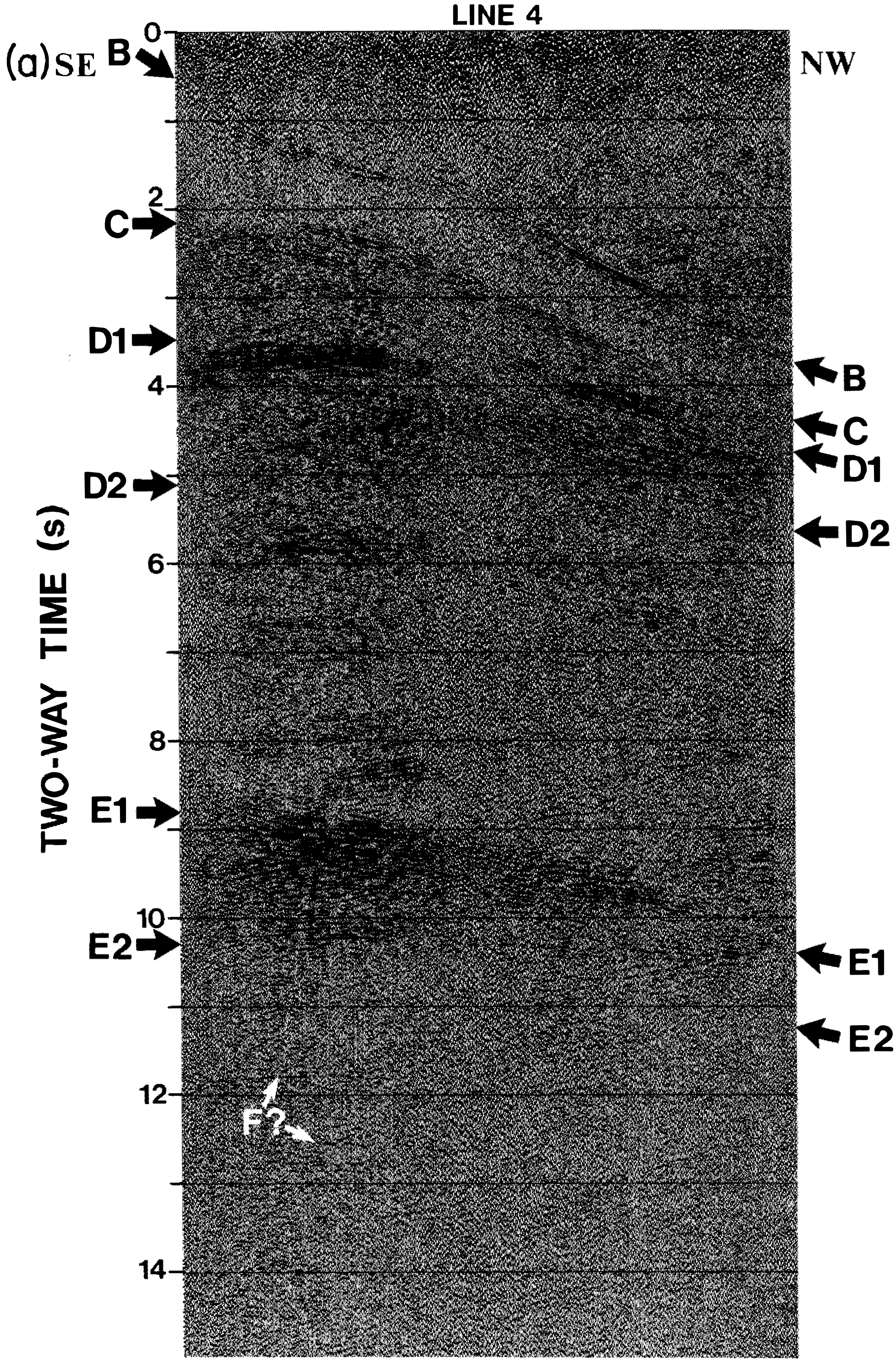

FIG. 4. Seismic reflection results for line 4. Letters identify reflection features discussed in text: upper-case letters refer to discrete reflective events or highly reflective intervals, and lower-case letters refer to local features. Vertical exaggeration (VE) is approximately ×0.9, based on an average velocity of 6.6 km/s. (*a*) Processed, but unmigrated, seismic reflection section.

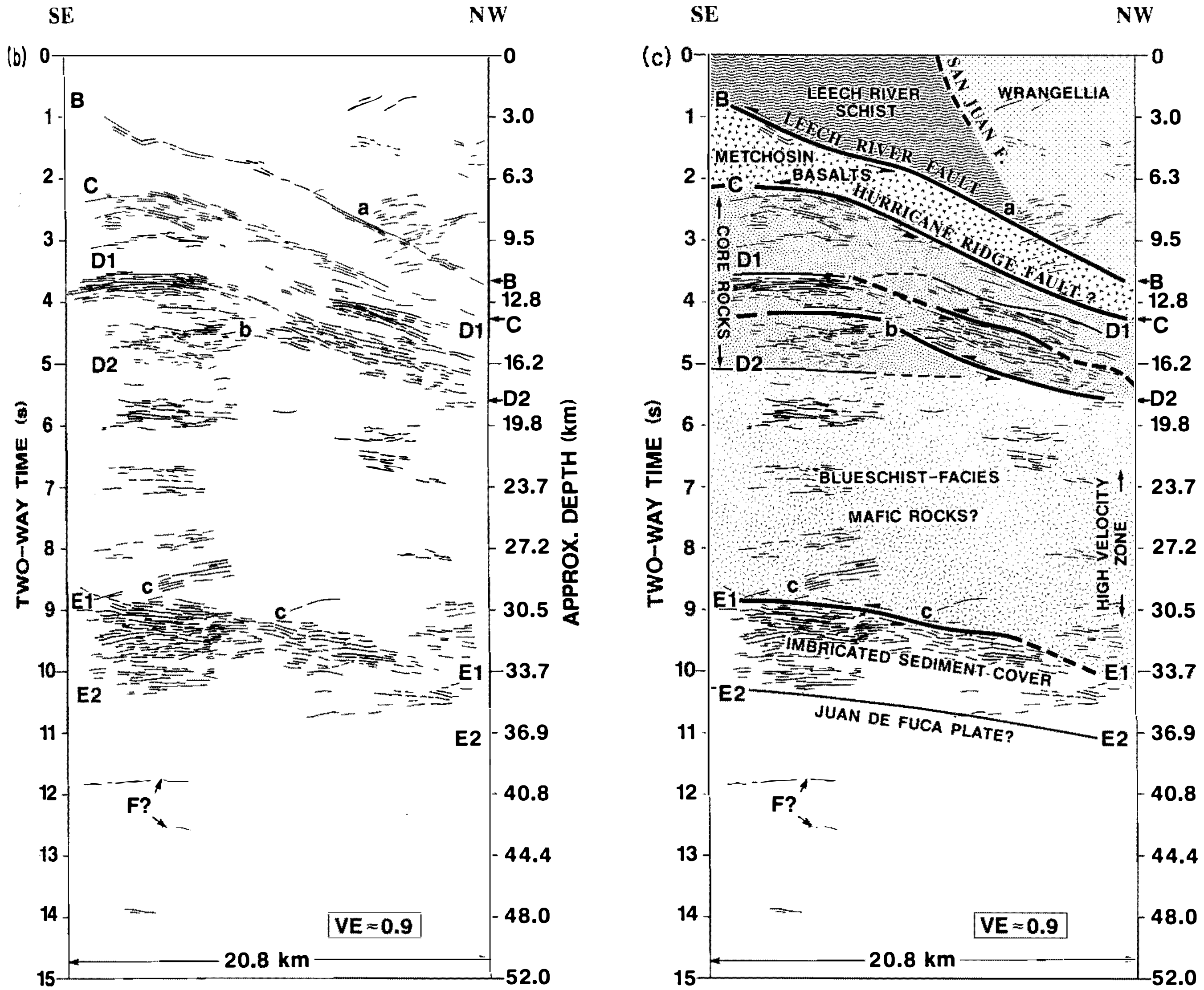

FIG. 4. (*Concluded.*) (*b*) Line drawing summary of record section using the same letters as in (*a*). (*c*) Geologic interpretation superimposed on the line drawing of (*b*). The approximate depth scale is based on the refraction results of Spence *et al.* (1985). These depths are probably accurate to ±1 km, judging from horizontal variations in the velocity structure of the two refraction models of Spence *et al.* (1985).

et al. 1985*b*). Movement on both faults was probably restricted to the Eocene (Brandon 1985; Rusmore and Cowan 1985); however, overlap relationships across the Leech River fault were not established until the Late Oligocene (Rusmore and Cowan 1985).

As mentioned previously, these faults record the Late Eocene accretion of the Leech River schist and Eocene basalt terranes against a continental framework that at that time was the western edge of North America. There has been considerable debate about the tectonic setting of these accretionary events, with most of the debate centred around the origin of the Eocene basalt terrane (Duncan 1982; Wells *et al.* 1984). One interpretation (Fig. 3*a*) argues that the Eocene basalts represent a seamount chain formed on one of the Pacific plates (e.g., Duncan 1982). Terrane accretion occurred when this chain collided with the margin and caused a westward jump in the Eocene subduction zone. In another interpretation (Fig. 3*b*), the Eocene basalts were erupted close to or within the continental margin, either in a marginal basin setting (Wells *et al.* 1984) or a volcanic arc setting (Lyttle and Clarke 1974). The latter interpretation accounts for continent-derived sediments in the basaltic sequences (Cady 1975; Wells *et al.* 1984), geochemical data that appear to preclude an open-ocean eruptive setting for the basalts (Brandon and Massey 1985), and the absence of a precollision convergent margin (Brandon 1985). Wells *et al.* (1984) and Brandon and Massey (1985) suggested a transform-dominated margin basin setting, such as the Andaman Sea or Gulf of California, for the Eocene basalts. This type of setting would be compatible with other evidence for transcurrent faulting and continental truncation during the early Tertiary (Johnson 1984; Brandon 1985). In this interpretation, eastward underthrusting of the Eocene basalts along Leech River and related faults (Fig. 3*c*) is considered to be indirectly caused by Late Eocene formation of a subduction zone west of the Eocene basalts.

The modern configuration of the Pacific Northwest convergent margin was established during this Late Eocene (~40 Ma) accretionary event (Fig. 3*c*) as marked by (1) the initiation of a modern Cascade volcanic arc (Armstrong 1978; Robinson *et al.* 1984); (2) the formation of a regionally exten-

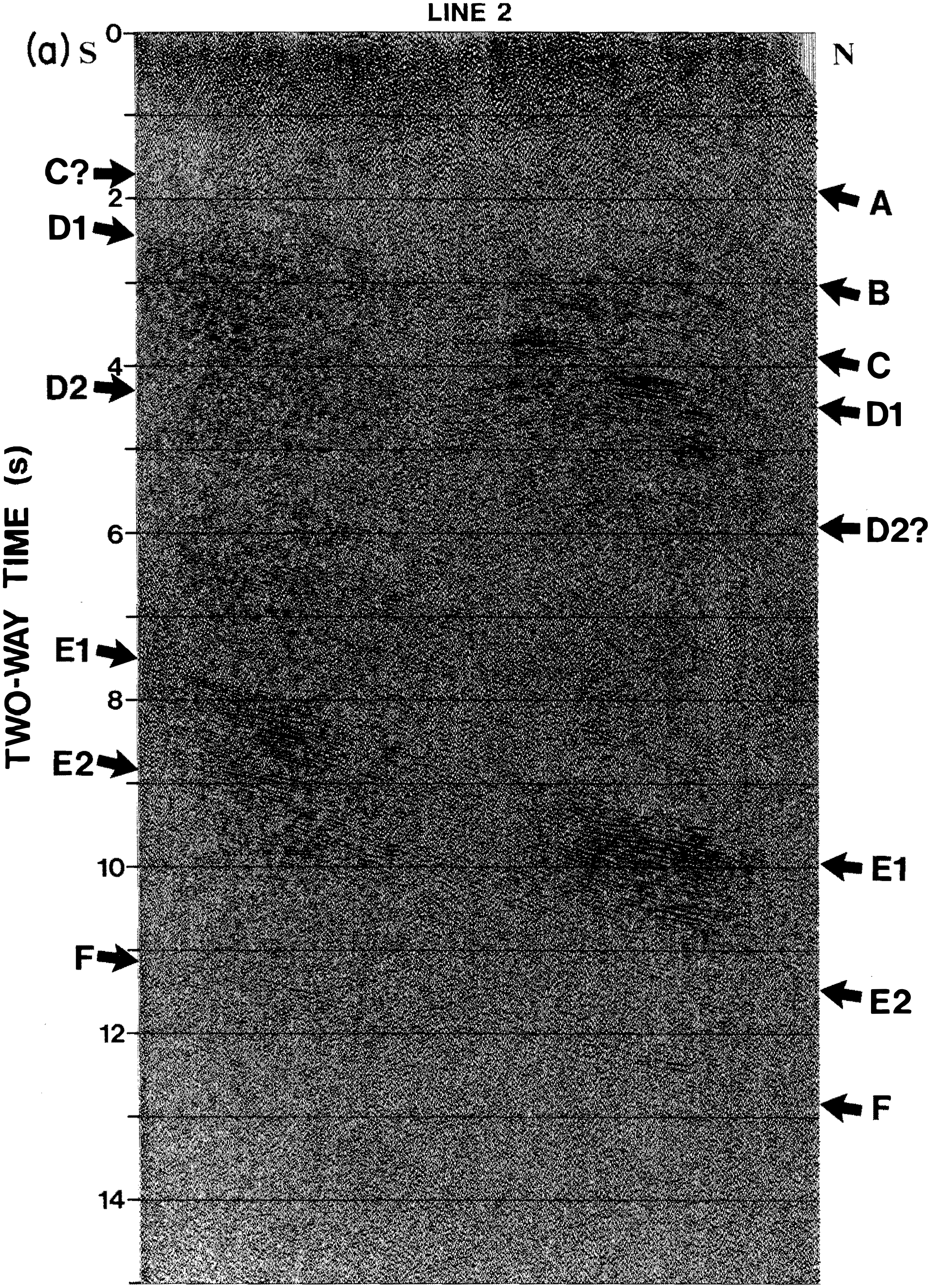

FIG. 5. Seismic reflection results for line 2. See Fig. 4 for explanation.

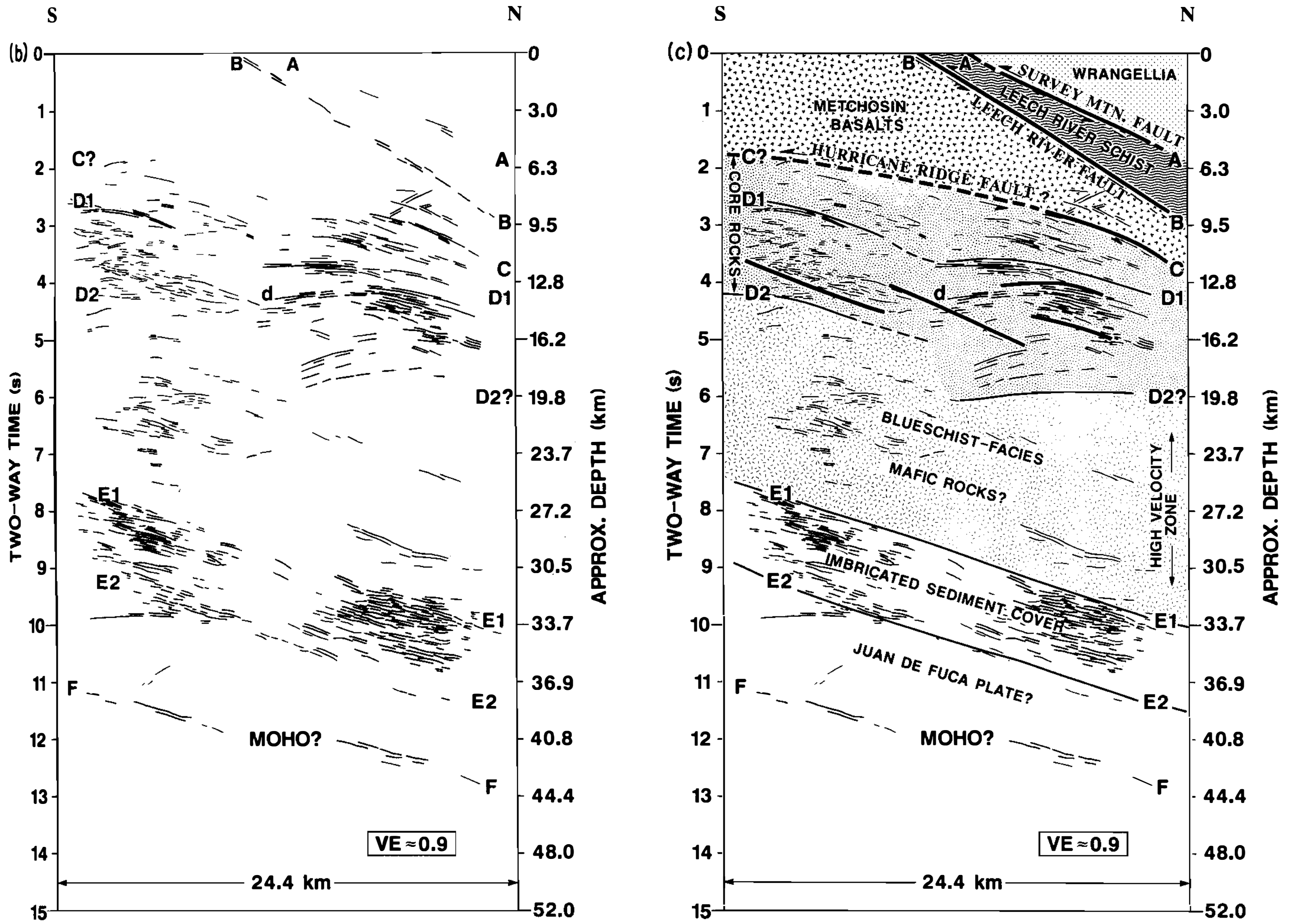

FIG. 5. (*Concluded*.)

sive forearc basin (Tofino–Fuca basin: Tiffin *et al.* (1972); Snavely *et al.* (1980)); and (3) the development of an accretionary complex west of the Eocene basalts (Core rocks: Tabor and Cady (1978*a*)). The subsequent evolution of this margin, from latest Eocene (40 Ma) to present, has been relatively simple and continuous. Plate motion studies indicate a relatively constant convergence vector between the Farallon and North American plates for this area (Wells *et al.* 1984, Figs. 7, 8). The Core rocks show a continuous record of subduction accretion (Tabor and Cady 1978*a*), with no evidence for the arrival of allochthonous terranes.

Data acquisition and processing

Along the four seismic lines (Fig. 1), 206 km of deep reflection data was recorded. Procedures were similar to, but not identical with, those used by COCORP (Schilt *et al.* 1979). Instrumentation included a 120-channel Texas Instruments DFS V recording system with four Mertz model 18 Vibroseis sources (each 20 000 kg maximum mass). An important feature of the vibrators was a feedback system that maximized the energy input to the vibrator pads while maintaining good coupling with the ground. Receiver intervals of 90 m and source intervals of 180 m provided a nominal 30-fold coverage. The receiver array consisted of 120 groups of geophones with 18 8-Hz geophones per group. This array was set up in an asymmetric split spread configuration ("pushing" 3 km and "dragging" 8 km) to provide a long offset and also to enable subsequent reprocessing of near traces from a shorter spread for enhancement of upper crustal features. Over each source interval, 16 upsweep signals were generated, with each sweep ranging from 8 to 40 Hz during a 16 s time interval. On the 120 channels, digital data (4 ms sampling rate) from the 16 vibrator sweeps were correlated and summed to produce a seismogram of 16 s length.

For the record sections presented here, data processing parameters were chosen mainly to enhance relatively low amplitude, deep reflections. Individual traces were edited at an early stage in the processing sequence. The refraction model of Spence *et al.* (1985) was used to determine initial stacking velocities; these were refined, particularly for the upper 3 s, by optimizing the reflection quality of segments of the data through a series of stacks using different velocity functions. Final processing included elevation corrections, automatic gain control, normal moveout corrections, residual static corrections using a correlation procedure with a $T = 1-12$ s window, stacking in bins based on crooked-line geometry, bandpass filtering from 8 to 40 Hz, and trace-to-trace amplitude equalization using the mean over a $T = 4-8$ s window.

Available funds limited the extent to which the data could be migrated. Consequently, sections were migrated only in a pre-

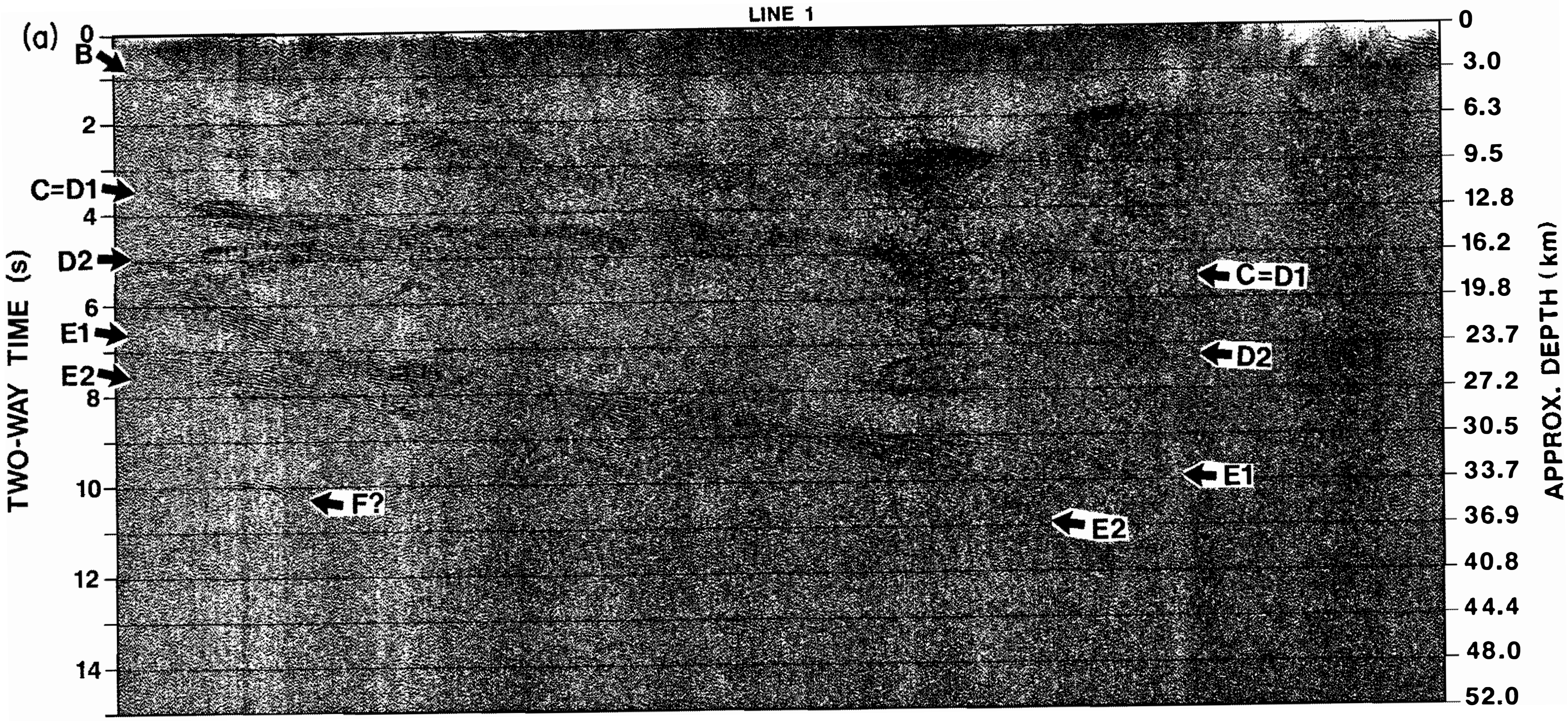

FIG. 6. Seismic reflection results for line 1. (*a*) Processed but unmigrated seismic reflection section. Labelled reflections correlate with those shown in lines 4 and 2 (Figs. 4 and 5). Total length of processed line is 100 km.

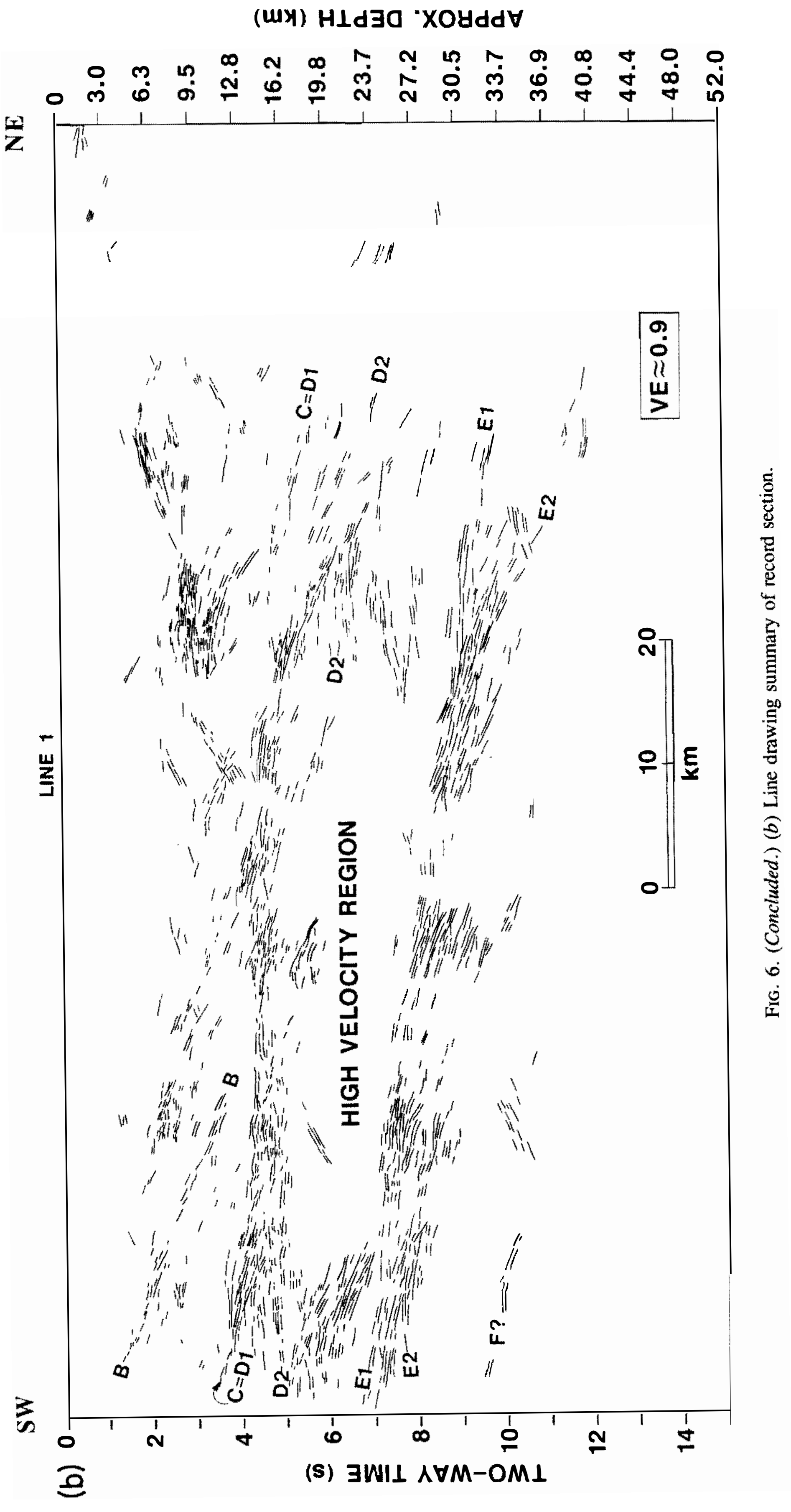

FIG. 6. (*Concluded.*) (*b*) Line drawing summary of record section.

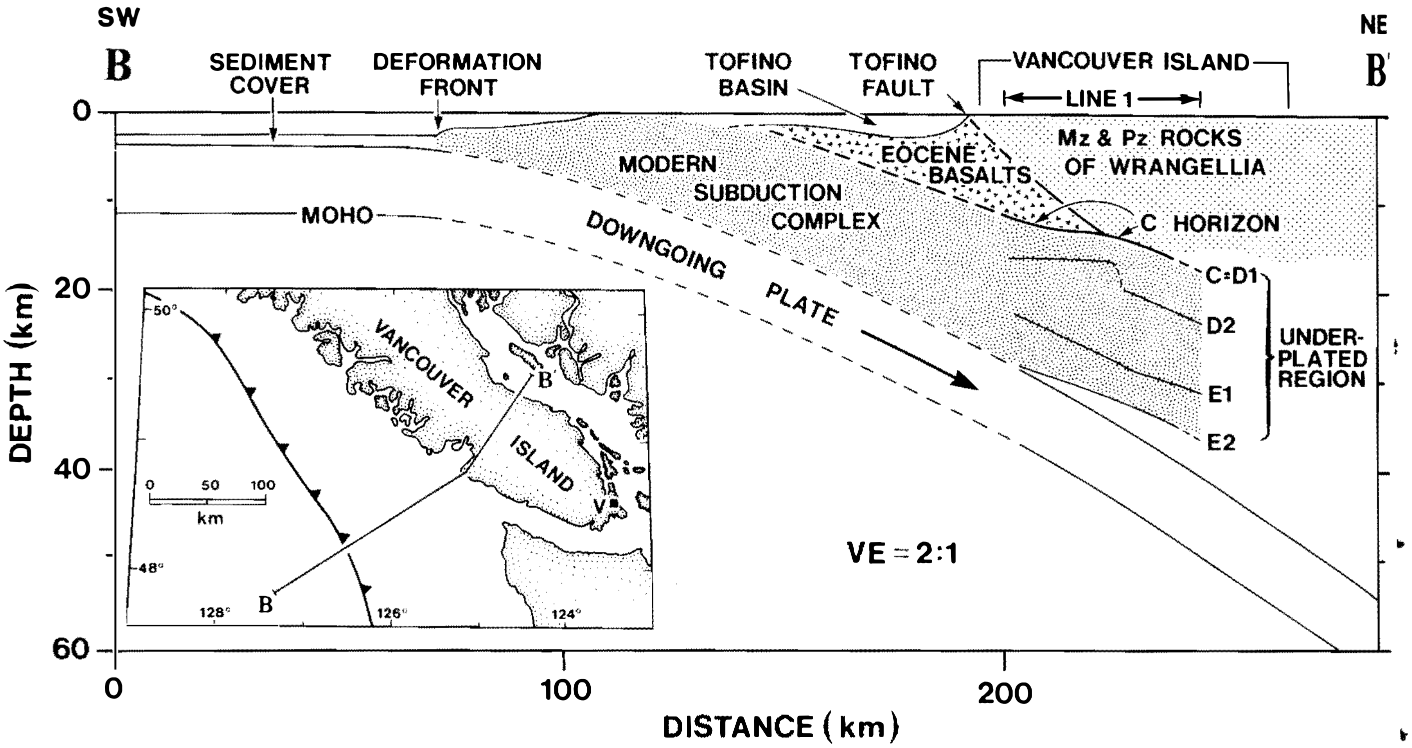

FIG. 7. Interpreted geologic depth section summarizing the main results of line 1 across central Vancouver Island (follows refraction line in Fig. 1). Major reflection features are shown and follow the features labelled in Fig. 6. In this area, the C = D1 horizon (top of décollement zone of Yorath *et al.* 1985*a*, 1985*b*) is a major thrust that underlies Mesozoic and Paleozoic rocks of the Wrangellia terrane as well as an accreted slice of Eocene basalt (correlative with the Metchosin basalts in lines 2 and 4). The underplated region lies beneath this horizon and represents a landward continuation of the modern accretionary wedge that underlies the Vancouver Island margin. Conversion to depth is based on velocity data from Spence *et al.* (1985) and is probably accurate to ±1 km. Position of the downgoing slab is based on compilation of Benioff zone seismicity by G. Rogers (personal communication, 1985). Offshore geology beneath the shelf region is from Shouldice (1971).

liminary fashion using a frequency–wave-number algorithm and a single velocity function for each profile. This procedure caused some degradation of reflection coherence. Therefore, the following interpretations are based primarily on the unmigrated sections; however, the migrated sections were used to check the dips of principal reflectors. Only for the more steeply dipping events in the upper part of the seismic sections was this migration significant. Further details of the acquisition and processing of the seismic data, and information concerning the availability of these data were provided by Green *et al.* (1985).

Interpretations of lines 2 and 4

Figures 4 and 5 show unmigrated record sections, line drawings, and interpretations for lines 4 and 2, respectively. For purposes of comparison, an unmigrated record section and line drawing of line 1 are shown in Fig. 6. Data quality is excellent, especially for line 4, with coherent reflections recorded between 0.5 and 14.0 s. The upper-case labels in these figures refer to prominent and continuous reflection features, such as discrete events (A, B, C, and F) or broad zones of high-amplitude, discontinuous reflections (D1 – D2 and E1 – E2). All of these reflection features, except for A (Fig. 5), are correlatable between lines 2 and 4 and also northward to line 1 (Fig. 6), thereby indicating that they extend regionally beneath southern Vancouver Island. Figures 7 and 8 show two larger scale interpretative depth sections that were constructed in the vicinity of line 1 and lines 2 and 4, respectively, and that integrate the reflection data with other available geological and geophysical data for the margin.

In the following discussion, we divide lines 2 and 4 into two structural regions separated by a boundary that lies at the C or D1 horizon. Seismic features in the upper region can be directly correlated with surface exposures of faults, whereas those in the lower region are not directly related to the surface geology of the island. We argue that these deeper features represent a relatively young structural complex associated with Cenozoic subduction accretion beneath Vancouver Island.

Upper structural region

The structurally uppermost feature imaged is reflection A in line 2 (Fig. 5), which intersects the surface at the Survey Mountain fault (Fig. 2). The low-angle dip of this fault is consistent with surface geologic relationships indicating that it is a northeast-dipping thrust fault (Brandon *et al.* 1984; Rusmore and Cowan 1985). Its western continuation, the San Juan fault (Fig. 2), is not apparent in line 4 (Fig. 4). This fault has been interpreted as a high-angle structure (Fairchild and Cowan 1982; Rusmore and Cowan 1985), although to our knowledge it is nowhere exposed. However, a high-angle orientation would be consistent with its lack of seismic expression.

Both the San Juan and Survey Mountain faults are underlain by a prominent, high-amplitude reflection (labelled B in Figs. 4 and 5), which intersects the surface at the Leech River fault. This reflection is present in both lines but is less distinct in line 2, probably because the apparent dip of the fault is greater there. Structure contours on the B reflection (using migrated

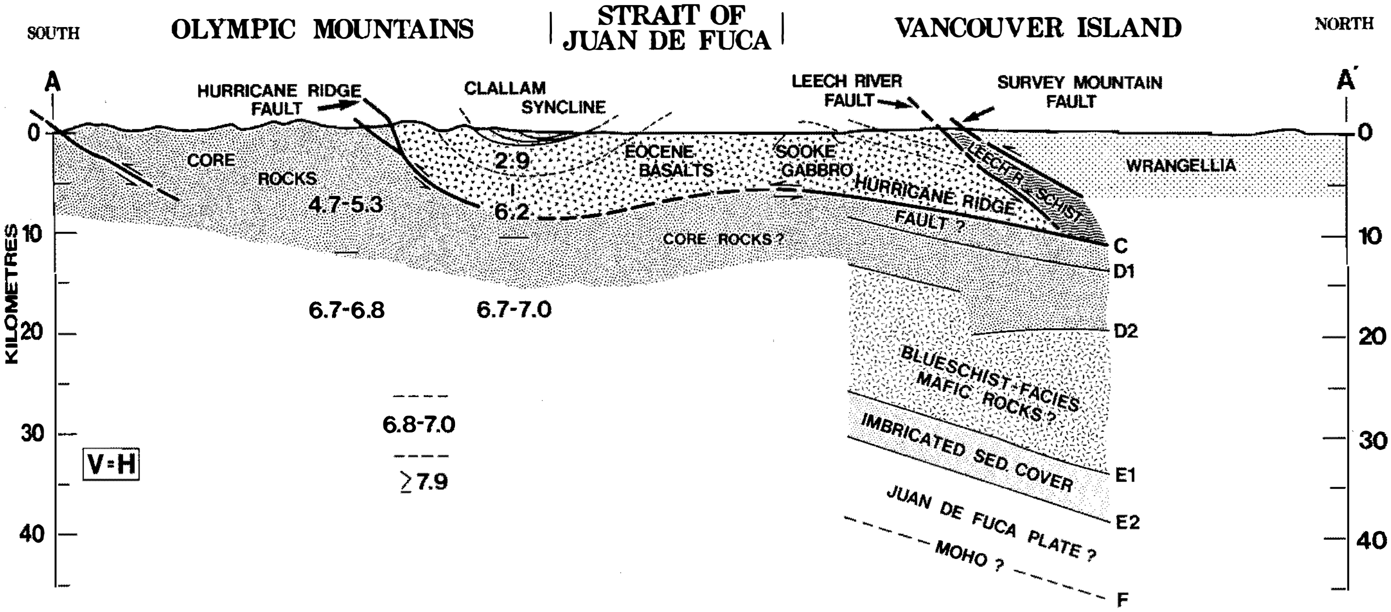

FIG. 8. Interpreted geologic depth section along A–A′ (Fig. 1), modified from Brandon *et al.* (1984) to include the results of our study (Figs. 4 and 5). In constructing this section, the reflection features in lines 2 and 4 were first converted to depth using the migrated records and then were projected into the cross section by extrapolating structure contours eastward from the two seismic lines. On the south side of the section, the numbers with bars indicate the velocity structure (km/s) beneath the Olympic Peninsula as determined by the refraction study of Taber (1983).

data) indicate that the fault dips to the northeast at between 35 and 45°, which is about the same attitude as the Survey Mountain fault has.

If the Leech River fault is a thrust, then the region beneath the B reflection should consist of the Eocene Metchosin basalts. Where this unit crops out at the surface in line 2, it corresponds to an acoustically transparent zone that, in both lines, can be followed beneath the B reflection, indicating the Metchosin basalts lie beneath the Leech River schist. Further evidence that B is a fault is seen in line 4 (a in Fig. 4*b* and 4*c*) where southeast-dipping reflections above the fault are clearly truncated (when migrated, these southeast-dipping reflections lie entirely above the fault).

The continuity of the reflection from the Leech River fault indicates that the San Juan fault does not extend with a high-angle attitude to depths greater than about 6 km. One possibility is that the San Juan fault is a high-angle structure, as interpreted by Fairchild and Cowan (1982) and Rusmore and Cowan (1985), which was truncated at depth by a younger Leech River fault. An alternative and preferred interpretation is that the San Juan fault is a listric thrust that becomes parallel to, or joins with, the Leech River fault at depth. This interpretation is more consistent with the observation that the San Juan fault merges to the east with the Survey Mountain fault, which is clearly a northeast-dipping thrust.

Lower structural region

The lower structural region, extending from C or D1 down to E2, consists of two highly reflective layers (D1–D2 and E1–E2) and an intervening zone of low reflectivity (D2–E1). These reflective layers are present in all four LITHOPROBE profiles and underlie both the Eocene basalts and the Wrangellia terrane without any apparent break in their continuity (Figs. 4, 5, and 6). As shown by the data and line drawing of Fig. 6 and the simplified cross-sectional interpretation in Fig. 7, the C–D2 layer truncates the Eocene basalts penetrated in the offshore wells, so that the unit is now a wedge-shaped slice. Its upper boundary is the Tofino fault (B in Fig. 6), a feature that plays the same role as the Leech River fault. Lines 2 and 4 (Figs. 4*c* and 5*c*) show that the Metchosin basalts also occur as a wedge-shaped slice, bound by the Leech River fault and an underlying thrust that probably lies at C. As shown in Figs. 4*c* and 5*c* and in the cross section of Fig. 8, we suggest that the thrust fault at C is a northern continuation at depth of the Hurricane Ridge fault exposed in the Olympic Mountains, 45 km to the south. Like the thrust fault at C, the Hurricane Ridge fault truncates the base of the Crescent Formation, a unit correlative and contiguous with the Metchosin basalts on southern Vancouver Island (Fig. 1). A consequence of this interpretation is that the region immediately below C consists of rocks equivalent to the Core rocks of the Olympic Peninsula (Tabor and Cady 1978*a*), a Cenozoic subduction complex that underlies the Hurricane Ridge fault. The deformed but well-layered turbidites that constitute most of the Core rocks are consistent with the highly reflective and discontinuous character of the region below C.

In Figs. 4, 5, and 8, we have interpreted the C horizon as marking the top of this subduction complex because it separates a nonreflective region (B–C), correlated with the Metchosin basalts, from a region of variable reflectivity (C–D2). Another possibility is that this boundary lies at the top of the highly reflective D1–D2 zone, because D1 is a more prominent event on the seismic sections. In line 1, this ambiguity is not a problem because C and D1 are apparently equivalent there. In that profile, the nonreflective Eocene basalts (below B in Fig. 6) are directly underlain by a highly reflective layer (C = D1–D2 in Fig. 6), without an intervening interval of moderate reflectivity, like that between C and D1 on lines 4 and 2 (Figs. 4 and 5). In our subsequent discussion, we adopt the interpretation that the C horizon on lines 4 and 2 represents the top of the subduction complex. We note that regardless of the ambiguity concerning the exact location of the top of this complex—whether at C or D1—the substance of our interpretation does not change.

Therefore, to summarize, we view the region below C as having formed by underplating, i.e., subduction-related accretion of oceanic materials *beneath* an overriding plate. Consequently, this underplated region would represent a deeper and more rearward extension of the Cenozoic subduction complex exposed in the Olympic Mountains and underlying the offshore continental margin of Vancouver Island and Washington. Furthermore, the regionally extensive thrust fault at C appears to be responsible for the removal of the crustal and mantle underpinnings of the Wrangellia terrane and the Eocene basalts, so that these terranes presently occur only within the upper structural region. Like the Leech River, San Juan, and Survey Mountain faults, the thrust at C is relatively young; a post-Early Eocene age is indicated because it cuts Lower Eocene basalts.

The reflection profiles give only limited information on the internal structure of this underplated region. Although some features of the data for this region may be due to diffractions, the general characteristics of planar, subhorizontally layered structures indicate that primary reflections are the dominant features. In particular, the reflective layers D1 – D2 and E1 – E2 show an overall structural grain dipping gently to the northeast (structural attitude, 110°, 18°N; based on structure contours using migrated data). In fact, only one clear set of reflections (c in Fig. 4*b*) dips in the opposite direction. Locally in the section, there is evidence for thrust faults, which are expected features in an accretionary complex. Several interpreted thrust faults are shown in Fig. 4*c* and 5*c*. Their presence is indicated by truncation of specific reflectors and abrupt changes in dip across the faults (e.g., b and c in Fig. 4 *b* and *c* and d in Fig. 5 *b* and *c*). A further indication of the presence of thrust faults is variation in the thickness of the reflective layers, which is attributed to structural repetition (e.g., D1 – D2 in Fig. 4*c*).

The presence of discrete layers of high and low reflectivity (D1 – D2 and E1 – E2 versus D2 – E1) indicates that there are large-scale variations in rock type or structural style within this region. As mentioned above, the discontinuous, reflective interval below C probably represents accreted turbidites. The less reflective D2 – E1 interval may consist of a similar but more highly deformed assemblage of turbidites; alternatively, it may mark a change in rock type. As discussed below, the latter is probably the case.

E1 marks the top of a layer, approximately 5 km thick, of quasi-continuous, closely spaced, high-amplitude reflections. Yorath *et al.* (1985*a*) and Clowes *et al.* (1984) interpreted E1 as the modern subduction thrust and the reflective zone below it as interbedded sediments and volcanics of the presently subducting Juan de Fuca plate. Another alternative is that the E1 – E2 layer represents another imbricated sequence within the underplated zone, similar to D1 – D2. These alternatives are considered below.

Discussion and summary

The interpretations of lines 2 and 4, combined with the additional interpretation of line 1 (Yorath *et al.* 1985*b*) and of the deep structure for all lines (Green *et al.* 1986), provide new insights into the process of subduction accretion and the tectonic evolution of southern Vancouver Island and northwestern Washington. In the following discussion, we will begin with those aspects of the interpretation for which good support exists and follow with those of a more speculative nature.

Contrary to previous interpretations (Yorath 1980; Fairchild and Cowan 1982; Rusmore and Cowan 1985), the Leech River fault is a north- and northeast-dipping thrust fault along which the Eocene Metchosin basalts were thrust beneath the Leech River schist during the Late Eocene. Such underthrusting provides an attractive explanation for the rapid uplift of the regionally metamorphosed Leech River schist (Fairchild and Cowan 1982). The Survey Mountain fault is also a thrust, which is subparallel to and structurally above the Leech River fault. The San Juan fault is not resolved on the record sections, but continuity of reflection B from the Leech River fault indicates that it cannot extend vertically to depths greater than about 6 km (Fig. 4*c*) and, therefore, may merge at depth with the Leech River fault. Thus, the Survey Mountain fault, and perhaps the San Juan fault, represent boundaries along which the Leech River schist was thrust beneath Wrangellia during the Late Eocene.

The Metchosin basalts are underlain by a highly reflective assemblage of rocks, beginning at the C horizon (or possibly D1, as discussed previously). This marker horizon is regionally extensive in all four LITHOPROBE lines and appears to truncate the base of the Wrangellia terrane, as well as the base of the Eocene basaltic units in those lines (Figs. 4, 5, and 6). In a similar fashion, the Hurricane Ridge thrust fault in northwestern Washington truncates the base of the overlying Eocene Crescent basalts (Fig. 8). Therefore, we suggest that this fault extends northward at depth and is continuous with the C horizon beneath Vancouver Island. Continuing the analogy, the underlying reflective layer, up to 10 km thick (C – D2), is correlative with the Core rocks of the Olympic Peninsula. We view this layer as having formed by subduction underplating of oceanic materials, predominantly turbidites, beneath the Eocene basalts and, farther north, beneath Mesozoic and Paleozoic rocks of the Wrangellia terrane.

The section between D2 and E2 is considered a deeper and younger part of the underplated region discussed above; details about the structure and dominant rock types in this region are poorly constrained compared with those for the shallower part of the sections. More specifically, we have had difficulty coming to a consensus concerning interpretation of the two major features in this region: (1) the poorly reflective interval between D2 and E1 and (2) the highly reflective layer E1 – E2. In the remaining discussion, we present various alternatives, perhaps showing a bias toward those preferred by the first two authors.

Origin of the D2 – E1 interval

The 10 – 15 km thick interval between D2 and E1 is characterized by variable but generally low reflectivity. Furthermore, this zone, which is present in all the LITHOPROBE sections, is probably coincident with a 10 km thick block of high-velocity (~7.7 km/s) material that Spence *et al.* (1985) found to be a necessary part of their refraction model (Green *et al.* 1986, Fig. 2).

We consider four alternative interpretations for the D2 – E1 region, of which only the last two are considered acceptable. We reject (1) the premise (Fig. 9*a*) that the region from D2 to E1 was derived from or represents part of the base of the Metchosin Formation and other related Eocene basaltic units, because we clearly see the acoustically layered region from C to D2, intervening between the Eocene basalts and the deeper structure; and (2) the premise (Fig. 9*b*) that the region is equivalent to the Core rocks (such as proposed for C – D2),

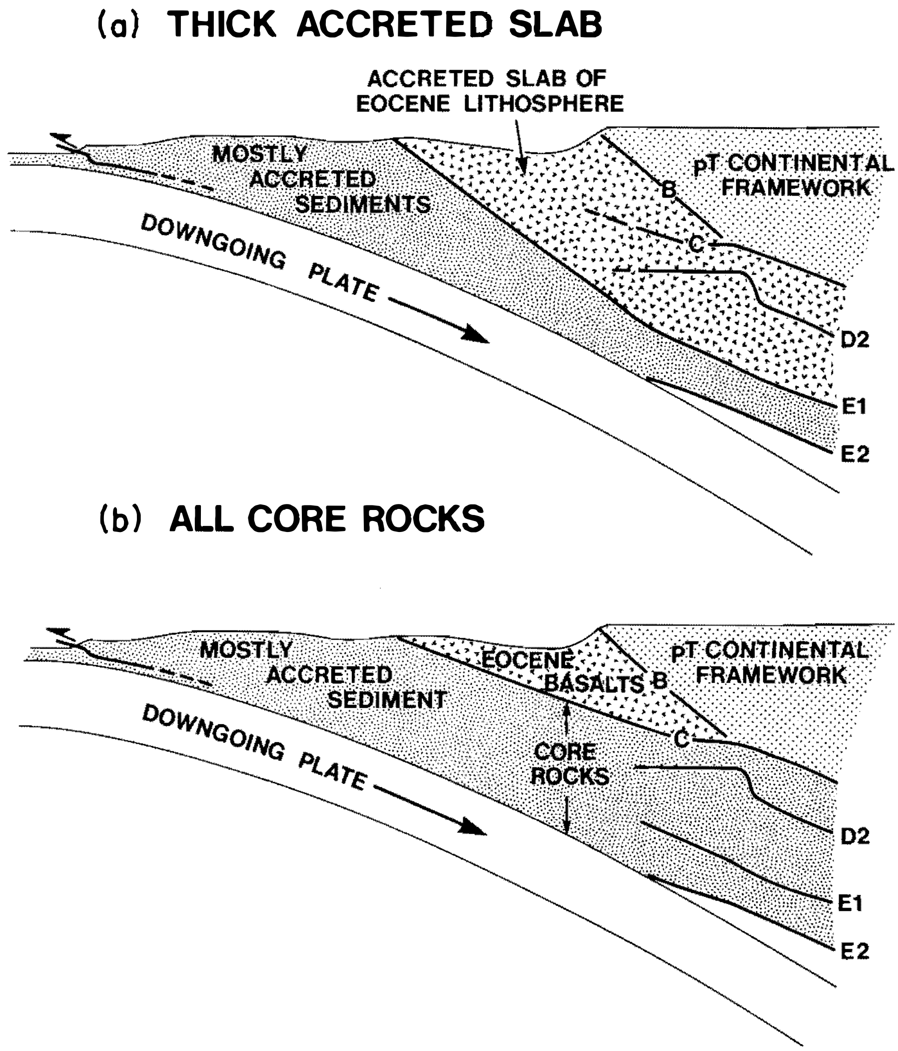

FIG. 9. Two rejected hypotheses for the D2 – E1 interval. (*a*) The first hypothesis would extend the Eocene basalts down to the El horizon. Significant reflectivity, especially in the C – D2 interval, precludes this possibility. (*b*) The second hypothesis would have the entire C – E2 interval composed of accreted sedimentary rocks, like the Core rocks. This possibility is ruled out by the high velocity of the D2 – E1 region as determined from seismic refraction (Spence *et al.* 1985).

because such rocks could not provide the high velocities required by the refraction results. Velocity measurements for accreted sandstones and shales from the Core rocks of the Olympic Mountains and from the Franciscan Complex of California, including unmetamorphosed to highly metamorphosed varieties, have velocities ranging from 5.6 to 6.5 km/s at pressures of 6 kbar (600 MPa) (Hubert 1979; Stewart and Peselnick 1977), much less than the 7.7 km/s velocity required by the refraction data.

The two remaining alternatives have one common conclusion: the high-velocity region is composed of mafic, and perhaps ultramafic, rocks that were probably added to the underplated zone from the downgoing oceanic plate. The difference between the two lies in the possible process by which the accretion took place. Figure 10 illustrates schematically how the underplated region may have formed. In these schematic cross sections, the accretionary wedge or subduction complex grows by addition of newly imbricated materials that are offscraped at the toe of the wedge or underplated beneath the wedge. We show accretion as occurring primarily by thrust imbrication, as proposed by Karig (1983), Brandon (1984), and Silver *et al.* (1985). The resulting imbricate structures are the same as those responsible for offscraping and underplating in on-land thrust belts (imbricate fans and duplexes (Boyer and Elliott 1982)).

Stage 1 (Fig. 10*a*) shows the formation of the C – D2 interval; offscraped material in front of the accretionary wedge and underplated material accreted at deeper levels were largely derived from the sediment cover on the downgoing plate. Stage 2 (Fig. 10*b*) illustrates the two alternatives for the D2 – E1 interval. The first alternative (option A in Fig. 9*b*) involves episodic accretion of a single slice of crust and mantle from the downgoing plate (Spence *et al.* 1985; Green *et al.* 1986), perhaps similar to the slice of Eocene basalt present above the C horizon. A possible difficulty with this scenario is that, based on the limited reflection data available for the oceanic crust (e.g., NAT Study Group 1985), we might expect somewhat less reflected energy than is present on the observed record sections within the D2 – E1 interval. An additional difficulty is that the episodic accretion of a thick oceanic slab might be expected to show other effects, such as a relatively rapid uplift of the overlying subduction complex. The Tofino

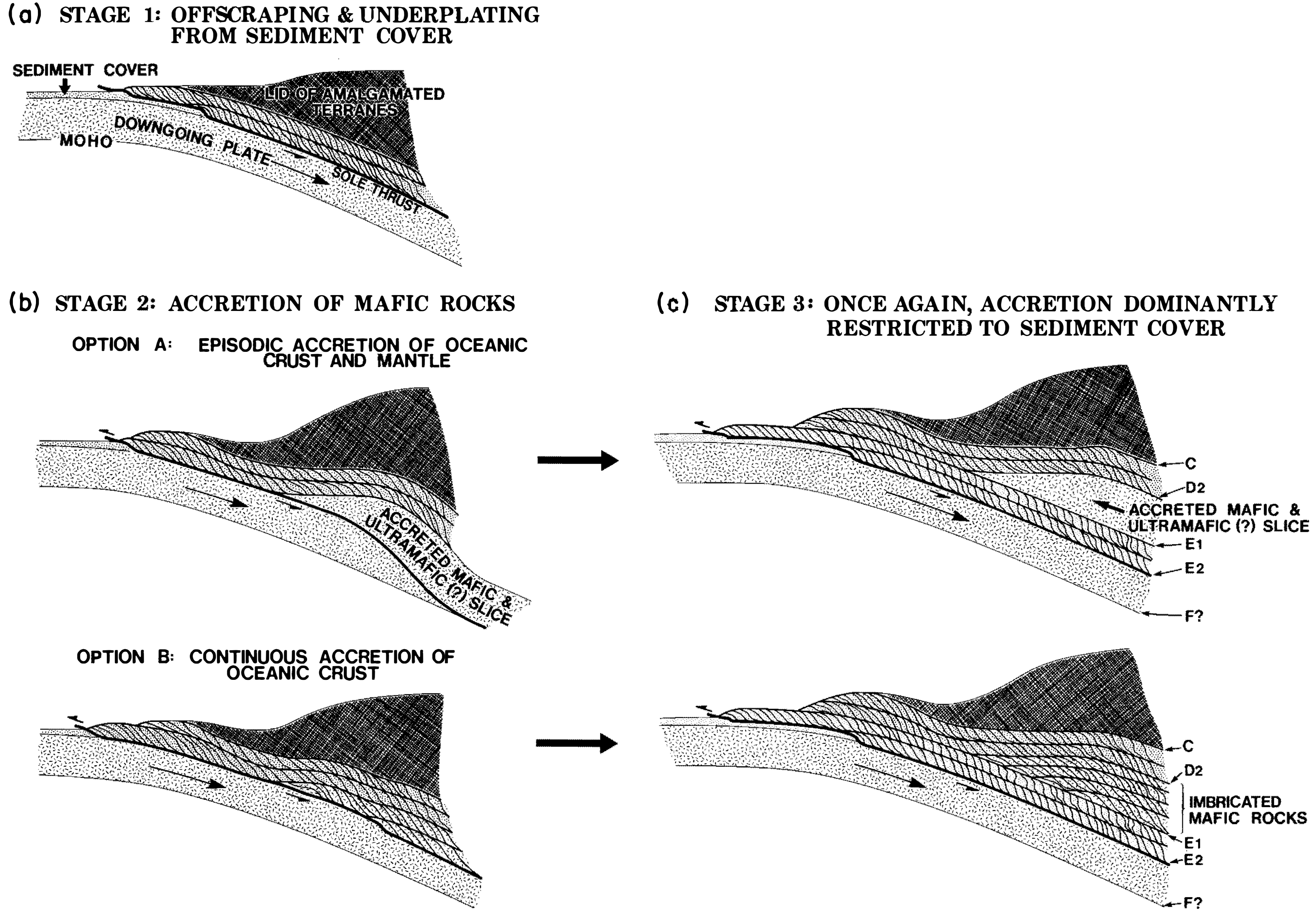

FIG. 10. Schematic illustrations of the formation of the underplated region. (*a*) Stage 1: The C–D2 interval (equivalent to the Core rocks) is formed by accretion of material dominantly from the sediment cover on the downgoing plate. (*b*) Stage 2: Options A and B show two alternative possibilities for the formation of the D2–E1 interval. Option A shows episodic accretion of a single, thick slice of oceanic lithosphere. Option B shows continuous accretion of imbricated slices of mafic rock derived from the top of the downgoing plate. (*c*) Stage 3: In the formation of the E1–E2 interval, accreted materials are derived once again from the sediment cover, similar to stage 1.

TABLE 1. Aggregate compressional velocities of minerals common in blueschist-facies mafic rocks

Mineral	V (km/s)
Glaucophane	~8.7*
Crossite	~7.1*
Lawsonite	~7.8*
Epidote	~7.43†
Omphacite (50% jadeite)	~8.5*
Garnet (almandine)	~8.52†
Chlorite (clinochlore)	~8.4*

*Estimated velocity at room temperature and 10 kbar (1 GPa), using empirical relationship of Birch (1961).

†Measured velocity at room temperature and atmospheric pressure, calculated for isotropic aggregate (Christensen 1982).

basin, a forearc basin that developed above the underplated region (Fig. 7), shows no evidence of the rapid, kilometre-scale uplift that might be expected with the accretion of a single 10−15 km thick slice of oceanic lithosphere. Instead, it records relatively slow changes in water depths, ranging from 1000−3000 m (midbathyal) during the Late Eocene through Early Pliocene to about 100 m (neritic) during the Late Pliocene and Pleistocene (Shouldice 1971; Tiffin *et al.* 1972), indicating that the underplated region grew in a relatively slow and continuous fashion.

A second and preferred alternative (option B in Fig. 10*b*) is that the D2−E1 interval consists of imbricated slices of mafic rocks derived from the top of the subducting plate during a period when offshore sedimentation was low or most of the sediments were offscraped at the front of the accretionary wedge. In this case, slices of mafic rocks would have been continuously added to the base of the underplated region, whereas in the first alternative, accretion would have occurred rapidly during a single event. High-pressure metamorphism of the imbricated mafic rocks could account for the relatively high refraction velocities. Temperatures and pressures for this region are about 300−500°C (based on heat-flow studies by T. Lewis, personal communication, 1985) and 5.5−8.5 kbar (550−850 MPa), which correspond to blueschist-facies conditions (Turner 1981). Table 1 lists seismic velocities for the dominant metamorphic minerals stable under these conditions. A typical mafic rock would be converted into a glaucophane or crossite schist with subordinate epidote or lawsonite and minor amounts of the other minerals shown in Table 1 (Ernst 1965; Ernst *et al.* 1970; Turner 1981, pp. 329, 330, 428). Velocity measurements for blueschist-facies mafic rocks are rare; Ernst (1965) reported a value of 7.3 km/s for a crossite schist. According to Table 1, a glaucophane schist should yield an even higher value. Weak reflections in the D2−E1 interval could be due to lithological layering (metamorphic foliation?) or to fault zones.

Origin of the E1−E2 layer

As discussed above, the E1−E2 layer, which is present in all four LITHOPROBE lines (Green *et al.* 1986), is a relatively thick (up to 5 km) layer with numerous high-amplitude reflections. The problem in interpreting this interval is that we have no definitive evidence in any of the LITHOPROBE lines on the position of the downgoing plate. Furthermore, other studies of the subducting Juan de Fuca plate (refraction: Taber (1983), Spence *et al.* (1985); gravity: Riddihough (1979); Benioff-zone seismicity: Rogers (1983), Taber and Smith (1985); magnetotellurics: Kurtz *et al.* (1986)) have given only poorly constrained results, especially at the scale with which we are concerned; a 1−2 km change in depth corresponds to a 0.3−0.6 s (two-way time) change in the reflection profiles. Two interpretations are considered. The first is that the E1−E2 interval represents a sequence of interbedded sediments and basalts presently being subducted with the Juan de Fuca plate (Yorath *et al.* 1985*a*; Clowes *et al.* 1984). A problem with this interpretation is that the reflective sequence is more than twice as thick as the sedimentary section presently overlying the Juan de Fuca plate, seaward of the subduction zone (Connard *et al.* 1984). Furthermore, the preferred refraction model of Spence *et al.* (1985) places the top of the subducting slab about 10 km (2−2.5 s two-way time) beneath E1, although this position is not well constrained.

A second and preferred interpretation, schematically illustrated in Fig. 10*c*, is that the reflective sequence represents the upper part of a zone of active accretion in which oceanic materials of the downgoing plate are presently being underplated to the base of the overriding subduction complex. We suggest that the anomalously thick reflective layer has been structurally thickened by imbrication of sediments, and perhaps volcanics, sliced from the top of the subducting Juan de Fuca plate. Therefore, the reflective layer, E1−E2, delimits a region of active decoupling between the overriding continental plate and the subducting oceanic plate. This interpretation has the additional advantage that an upward shift by about 1 s (3.5 km) of the oceanic plate in the Spence *et al.* (1985) model would effectively align the top of the crustal section with E2, the base of the reflective interval. Such a shift would also conveniently align the base of the oceanic crust (oceanic Moho) with the weak but clear reflection labelled F in lines 2 and 4 (Figs. 4, 5, and 8).

A recently interpreted magnetotelluric profile recorded along lines 1 and 3 as part of phase 1 LITHOPROBE (Kurtz *et al.* 1986) gives further evidence that the E1−E2 layer consists of recently subducted oceanic materials. The two-dimensional conductivity model required to fit the data has a highly conductive, northeasterly dipping layer, with its top boundary at about the same depth as E1. Saline fluids filling the pore spaces of interbedded sediments and basalts are presumed to account for the high conductivity. The presence of trapped fluids at these depths suggests a relatively short residence time for the subducted materials in which the fluids are present.

Mass-balance calculation

Our interpretation of the LITHOPROBE reflection profiles indicates that the modern Vancouver Island subduction complex contains a relatively large volume of accreted material. A crude test of this result is provided by comparing the volume of sediment carried into the subduction zone on the downgoing plate with the volume of accreted sediment in the subduction complex. As discussed previously, the subduction complex beneath Vancouver Island has formed over the last 40 Ma. Plate reconstructions (Wells *et al.* 1984; Engebretson *et al.* 1985) indicate that the Farallon plate was offshore during that time. Table 2 summarizes the relative motion between the Farallon and North America plates and shows that about 1800 km of plate has been subducted during the last 40 Ma.

TABLE 2. Estimated length of Farrallon plate subducted beneath Vancouver Island during the last 40 Ma

Time (Ma) To	Time (Ma) From	Approximate strike of subduction zone* (° from N)	Convergence angle (° from N)	V_C (km/Ma)	V_T (km/Ma)	$V_C\,\Delta t$ (km)
0	5	155	85	43	4	215
5	9	155	71	41	14	164
9	17	154	58	39	24	312
17	28	157	52	40	31	440
28	37	158	58	50	31	450
37	40	160	61	71	39	213
						1794†

NOTES: Calculated from velocity vectors in Engebretson *et al.* (1985) (location, 48°N, 236°E); V_C, velocity perpendicular to strike of subduction zone; V_T, velocity parallel to strike.

*Paleostrike of subduction zone. Based on orientation of the margin after correction for rotation of the North American plate with respect to the spin axis.

†Total length of subducted plate.

TABLE 3. Volume of sediment cover subducted during the last 40 Ma compared with volume of accreted sediment in subduction complex

Average thickness of sediment cover (km): Initial*	Final† ($\bar{n}$=4%)	Final volume of subducted sediment cover (km³/km)‡	Volume of accreted sediments (km³/km)‡,§
2 ($\bar{n}\cong$35%)	1.38	2475	
1.5 ($\bar{n}\cong$38%)	1.04	1865	1725
1 ($\bar{n}\cong$45%)	0.69	1240	

NOTES: $\bar{n}$, average porosity. All volumes are in cubic kilometres per kilometre length parallel to trench axis.

*$\bar{n}$ is estimated from basinal reference sections of Bray and Karig (1985, Fig. 1).

†The equivalent thickness of the sediment cover after accretion. $\bar{n}$ is estimated from accreted sediments at 3–24 km depth in Bray and Karig (1985, Fig. 1).

‡Volumes are corrected for the oblique angle between the section line B–B′ and the strike of the subduction complex (~155°).

§Volume of subduction complex in Fig. 7 (stippled region, 2040 km³/km) minus volume of accreted mafic rocks (D2–E1, 315 km³/km).

The mass-balance calculation is summarized in Table 3. Porosity curves from Bray and Karig (1985) were used to estimate the average porosity of the sediment cover on the downgoing plate and the average porosity for those sediments after accretion, thereby giving a rough estimate of the volume loss due to tectonic compaction and deep burial during subduction. The largest uncertainty in this calculation is the time-averaged thickness of the sediment cover on the downgoing plate. Table 3 shows results for varying initial thicknesses of the sediment cover, ranging from 1 to 2 km, which over 40 Ma yields an equivalent final volume (average porosity, 4%) between 1240 and 2475 km³/km (volume is in cubic kilometres per kilometre length parallel to the trench axis). These figures are probably conservative estimates when compared with the modern Cascadia basin, which is about 2 km thick at the subduction zone (Connard *et al.* 1984). The cross section in Fig. 7 was used to estimate the volume of accreted sediments in the subduction complex, which is about 1725 km³/km, after correction for the oblique angle of the section and after subtraction of the approximate volume of the accreted mafic rocks in the D2–E1 interval. Therefore, this mass balance calculation shows that there is reasonable agreement between the estimated volumes of subducted sediment cover and accreted sediment in the subduction complex. Perhaps more important, however, this calculation also serves to illustrate that in cases where sediment cover is relatively thick, such as on the Juan de Fuca plate west of Vancouver Island, it does not take much time to form a relatively large subduction complex.

Summary

In summary, our preferred interpretation is that the region from C to E2 has formed by steady-state accretion and underplating of materials from the downgoing plate. Vertical variations in reflection character and velocity probably indicate changes in the type of accreted materials. As interpreted, the underplated region consists of three major lithologic components: (1) the highest (C–D2), consisting of accreted turbidites, similar to the Core rocks of the Olympic Peninsula; (2) a middle package, consisting of imbricated mafic rocks; and (3) a lower package of turbidites and perhaps basalts. This sequence suggests that the position of the subduction-zone thrust in the downgoing plate has changed with time, some-times riding high, so that only the sedimentary cover of the plate is accreted, and other times incising deeply into the plate and accreting mafic crustal rocks (e.g., Fig. 10*b*). This migration of the thrust may occur in a random fashion; alternatively, it may be controlled by the thickness of the sediment cover on the downgoing plate.

The data of phase 1 LITHOPROBE and their interpretation probably provide the first direct evidence for the process of subduction underplating or subcretion (Scholl *et al.* 1980; von Huene and Uyeda 1981, Moore *et al.* 1982; Karig 1983). The E1−E2 interval is a region where oceanic sediments and (or) basalts are being accreted at depth beneath an overriding subduction complex. It coincides with a highly conductive layer attributed to saline fluids carried down with the subducting plate (Kurtz *et al.* 1986). The lower part of the subduction complex (D2−E1) could have formed by a similar process involving imbrication of mafic rocks from the subducting slab (our preferred interpretation) or by an episodic event that resulted in a remnant oceanic slab being emplaced above the currently descending plate.

We suspect that subduction underplating may be a more widespread phenomenon than heretofore considered, and therefore it may be an important process by which continents can grow (see also Green *et al.* 1986). Evolutionary models for continental growth generally do not consider this possibility; we suggest it requires serious consideration.

Another important general result of phase 1 LITHOPROBE is the discovery of a series of terrane-bounding thrust faults and the fact that the intervening terranes have thicknesses significantly less than their original lithospheric dimensions. This is illustrated in Fig. 7, where, for example, Wrangellia is shown to be only 14−18 km thick (Yorath *et al.* 1985*b*). This discovery underscores the importance of the process of thin-skinned thrusting during the accretion of allochthonous terranes (cf. Cook *et al.* 1979). Furthermore, it may have significant implications for the manner in which the other terranes of the Canadian Cordillera (Monger *et al.* 1982) have accreted. Have subduction, removal of the original lower lithosphere, and its replacement by a younger oceanic plate (as may have occurred beneath Vancouver Island) also been features of the older terranes east of Wrangellia? This is a problem that will be addressed during LITHOPROBE phase 2.

Acknowledgments

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ARMSTRONG, R. L. 1978. Cenozoic igneous history of the U.S. Cordillera from latitude 42 to 49° north. *In* Cenozoic tectonics and regional geophysics of the western Cordillera. Geological Society of America, Memoir 152, pp. 265−282.

BERGGREN, W. A., KENT, D. V., FLYNN, J. J., and VAN COUVERING, J. A. 1985. Cenozoic geochronology. Geological Society of America Bulletin, **96**, pp. 1407−1418.

BIRCH, F. 1961. The velocity of compressional waves in rocks to 10 kilobars. Part 2. Journal of Geophysical Research, **66**, pp. 2199−2224.

BOYER, S. E., and ELLIOTT, D. 1982. Thrust systems. American Association of Petroleum Geologists Bulletin, **66**, pp. 1196−1230.

BRANDON, M. T. 1984. Deformational processes affecting unlithified sediments at active margins: a field study and a structural model. Ph.D. thesis, University of Washington, Seattle, WA, 160 p.

——— 1985. Mesozoic melange of the Pacific Rim Complex, western Vancouver Island. *In* Field guides to geology and mineral deposits of the southern Canadian Cordillera. *Edited by* D. Templeman-Kluit. Geological Society of America, Cordilleran Section Meeting, Vancouver, B.C., pp. 7-1−7-28.

BRANDON, M. T., and COWAN, D. S. 1985. The Late Cretaceous San Juan Islands − north-western Cascades thrust system [abstract]. Geological Society of America, Abstracts with Programs, **17**, p. 343.

BRANDON, M. T., and MASSEY, N. W. D. 1985. Early Tertiary tectonics of the Pacific Northwest: truncation and rifting within a transform plate boundary [abstract]. Geological Association of Canada, Victoria Section, April 19 Symposium, Programme and Abstracts, pp. 8−9.

BRANDON, M. T., JOHNSON, S. Y., and STEWART, R. J. 1984. Cross-section A−A′, western Washington. *In* Western North American continental margin and adjacent ocean floor off Oregon and Washington. *Edited by* L. D. Kulm *et al.* Ocean Margin Drilling Program, Regional Atlas Series, Marine Science International, Woods Hole, MA, Atlas 1, sheet 19.

BRAY, C. J., and KARIG, D. E. 1985. Porosity of sediments in accretionary prisms and some implications for dewatering processes. Journal of Geophysical Research, **90**, pp. 768−778.

CADY, W. M. 1975. Tectonic setting of the Tertiary volcanic rocks of the Olympic Peninsula, Washington. Journal of Research of the U.S. Geological Survey, **3**, pp. 573−582.

CANDEL. 1981. Lithoprobe: geoscience studies of the third dimension—a coordinated national geoscience project for the 1980's. Geoscience Canada, **8**, pp. 117−125.

CHRISTENSEN, N. I. 1982. Seismic velocities. *In* Handbook of physical properties. Vol. 2. *Edited by* R. S. Carmichael. CRC Press Inc., Boca Raton, FL, pp. 1−228.

CLOWES, R. M. 1984. Phase 1 Lithoprobe—a coordinated national geoscience project. Geoscience Canada, **11**, pp. 122−126.

CLOWES, R. M., ELLIS, R. M., HAJNAL, Z., and JONES, I. F. 1983. Seismic reflections from subducting lithosphere? Nature (London), **303**, pp. 668−670.

CLOWES, R. M., GREEN, A. G., YORATH, C. J., KANASEWICH, E. R., WEST, G. F., and GARLAND, G. D. 1984. Lithoprobe—a national program for studying the third dimension of geology. Journal of the Canadian Society of Exploration Geophysicists, **20**, pp. 23−39.

CONNARD, G. G., COUCH, R., KEELING, K., ROY, J., and TROSETH, S. 1984. Abyssal plain and continental net-objective sedimentary thickness. *In* Western North American continental margin and adjacent ocean floor off Oregon and Washington. *Edited by* L. D. Kulm, *et al.* Ocean Margin Drilling Program, Regional Atlas Series, Marine Science International, Woods Hole, MA, Atlas 1, sheet 7.

COOK, F. A., ALBAUGH, D. S., BROWN, L. D., KAUFMAN, S., and OLIVER, J. E. 1979. Thin-skinned tectonics in the crystalline southern Appalachians; COCORP seismic-reflection profiling of the Blue Ridge and Piedmont. Geology, **7**, pp. 563−567.

CURRAY, J. R., MOORE, D. G., LAWVER, L. A., EMMEL, F. J., RAITT, R. W., HENRY, M., and KIECKHEFER, R. 1979. Tectonics of the Andaman Sea and Burman. American Association of Petroleum Geologists, Memoir 29, pp. 189−198.

DUNCAN, R. A. 1982. A captured island chain in the Coast Range of Oregon and Washington. Journal of Geophysical Research, **87**, pp.

10 827 – 10 837.

Ellis, R. M., Spence, G. D., Clowes, R. M., Waldron, D. A., Jones, I. F., Green, A. G., Forsyth, D. A., Mair, J. A., Berry, M. J., Mereu, R. F., Kanasewich, E. R., Cumming, G. L., Hajnal, Z., Hyndman, R. D., McMechan, G. A., and Loncarevic, B. D. 1983. The Vancouver Island seismic project: a CO-CRUST onshore–offshore study of a convergent margin. Canadian Journal of Earth Sciences, **20**, pp. 719–741.

Engebretson, D. C., Gordon, R. G., and Cox, A. 1985. Relative motions between oceanic and continental plates in the Pacific basin. Geological Society of America, Special Paper 206, 59 p.

Ernst, W. G. 1965. Mineral parageneses in Franciscan metamorphic rocks, Panoche Pass, California. Geological Society of America Bulletin, **76**, pp. 879–914.

Ernst, W. G., Seki, Y., Onuki, H., and Gilbert, M. C. 1970. Comparative study of low-grade metamorphism in the California Coast Ranges and the Outer Metamorphic Belt of Japan. Geological Society of America, Memoir 124, 276 p.

Fairchild, L. H., and Cowan, D. S. 1982. Structure, petrology, and tectonic history of the Leech River complex northwest of Victoria, Vancouver Island. Canadian Journal of Earth Sciences, **19**, pp. 1817–1835.

Green, A. G., Clowes, R. M., and Yorath, C. J. 1985. LITHOPROBE seismic reflection profiles from southeastern Vancouver Island. Geological Survey of Canada, Open File 1180, 24 p.

Green, A. G., Clowes, R. M., Yorath, C. J., Spencer, C., Kanasewich, E. R., Brandon, M. T., and Sutherland Brown, A. 1986. Seismic reflection imaging of the subducting Juan de Fuca plate. Nature (London), **319**, pp. 210–213.

Howell, D. G., Jones, D. L., and Schermer, E. R. 1985. Tectonostratigraphic terranes of the circum-Pacific region. *In* Preliminary tectonostratigraphic terrane map of the circum-Pacific region. American Association of Petroleum Geologists, Tulsa, OK, scale 1 : 17 000 000.

Hubert, K. A. 1979. Physical properties of selected basalt and greywacke and the inferred seismic structure of the Olympic Peninsula, Washington, M.Sc. thesis, University of Washington, Seattle, WA, 96 p.

Johnson, S. Y. 1984. Evidence for a margin truncating transcurrent fault (pre-late Eocene) in western Washington. Geology, **12**, pp. 538–541.

Johnson, S. Y., Niem, W. A., Niem, A. R., Brandon, M. T., and Stewart, R. J. 1984. Geology, western Oregon and Washington. *In* Western North American continental margin and adjacent ocean floor off Oregon and Washington. *Edited by* L. D. Kulm, *et al.* Ocean Margin Drilling Program, Regional Atlas Series, Marine Science International, Woods Hole, MA, Atlas 1, sheet 14, scale 1 : 900 000.

Jones, D. L., Silberling, N. J., and Hillhouse, J. 1977. Wrangellia—a displaced terrane in northwestern North America. Canadian Journal of Earth Sciences, **14**, pp. 2565–2577.

Karig, D. E. 1983. Deformation in the forearc: implications for mountain belts. *In* Mountain building processes. *Edited by* K. J. Hsu. Academic Press, New York, NY, pp. 59–71.

Kurtz, R. D., DeLaurier, J. M., and Gupta, J. C. 1986. Magnetotelluric survey across Vancouver Island: a search for subducting oceanic lithosphere. Nature (London), **321**, pp. 596–599.

Lyttle, N. A., and Clarke, D. B. 1974. New analyses of Eocene basalts from the Olympic Peninsula, Washington. Geological Society of America Bulletin, **86**, pp. 421–427.

MacLeod, N. S., Tiffin, D. L., Snavely, P. D., Jr., and Currie, R. G. 1977. Geologic interpretation of magnetic and gravity anomalies in the Strait of Juan de Fuca, U.S.–Canada. Canadian Journal of Earth Sciences, **14**, pp. 223–238.

Massey, N. W. D. 1986. The Metchosin Igneous Complex, southern Vancouver Island; ophiolite stratigraphy developed in an emergent island setting. Geology, **14**, pp. 602–605.

Monger, J. W. H., Price, R. A., and Tempelman-Kluit, D. J. 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera. Geology, **10**, pp. 70–75.

Moore, J. C., Watkins, J. S., Shipley, T. H., McMillen, K. J., Bachman, S. B., and Lundburg, N. 1982. Geology and tectonic evolution of a juvenile accretionary terrane along a truncated convergent margin: synthesis of results from leg 66 of the Deep Sea Drilling Project, southern Mexico. Geological Society of America Bulletin, **93**, pp. 847–861.

Muller, J. E. 1977*a*. Evolution of the Pacific margin, Vancouver Island, and adjacent regions. Canadian Journal of Earth Sciences, **14**, pp. 2062–2085.

——— 1977*b*. Geology of Vancouver Island. Geological Survey of Canada, Open File 463, scale 1 : 250 000.

——— 1980. Chemistry and origin of the Eocene Metchosin volcanics, Vancouver Island, British Columbia. Canadian Journal of Earth Sciences, **17**, pp. 199–209.

——— 1983. Geology, Victoria. Geological Survey of Canada, Map 1553A, scale 1 : 100 000.

NAT Study Group. 1985. North Atlantic transect: a wide-aperture, two-ship multichannel seismic investigation of the oceanic crust. Journal of Geophysical Research, **90**, pp. 10 321 – 10 341.

Prothero, D. R., and Armentrout, J. M. 1985. Magnetostratigraphic correlation of the Lincoln Creek Formation, Washington: implication for the age of the Eocene/Oligocene boundary. Geology, **13**, pp. 208–211.

Riddihough, R. P. 1979. Gravity and structure of an active margin—British Columbia and Washington. Canadian Journal of Earth Sciences, **16**, pp. 350–363.

Robinson, P. T., Brem, G. F., and McKee, E. H. 1984. John Day Formation of Oregon: a distal record of early Cascade volcanism. Geology, **12**, pp. 229–232.

Rogers, G. C. 1983. Seismotectonics of British Columbia. Ph.D. thesis, The University of British Columbia, Vancouver, B.C., 247 p.

Rusmore, M. E., and Cowan, D. S. 1985. Jurassic–Cretaceous rock units along the southern edge of the Wrangellia terrane on Vancouver Island. Canadian Journal of Earth Sciences, **22**, pp. 1223–1232.

Schilt, S., Oliver, J., Brown, L., Kaufman, S., Albaugh, D., Brewer, J., Cook, F., Jensen, L., Krumhansl, P., Long, G., and Steiner, D. 1979. The heterogeneity of the continental crust: results from deep crustal seismic reflection profiling using the Vibroseis technique. Reviews of Geophysics and Space Physics, **17**, pp. 354–368.

Scholl, D. W., von Huene, R., Vallier, T. L., and Howell, D. G. 1980. Sedimentary masses and concepts about tectonic processes of underthrust ocean margins. Geology, **8**, pp. 564–568.

Shouldice, D. H. 1971. Geology of the western Canadian continental shelf. Canadian Society of Petroleum Geologists Bulletin, **19**, pp. 405–424.

Silver, D. A., Ellis, M. J., Breen, N. A., and Shipley, T. H. 1985. Comments on the growth of accretionary wedges. Geology, **13**, pp. 6–9.

Snavely, P. D., Jr., Niem, A. R., MacLeod, N. S., Pearl, J. E., and Rau, W. W. 1980. Makah Formation—a deep marginal basin sequence of Late Eocene and Oligocene age in the northwestern Olympic Peninsula, Washington. United States Geological Survey, Professional Paper 1162-B, 28 p.

Spence, G. D., Clowes, R. M., and Ellis, R. M. 1985. Seismic structure across the active subduction zone of western Canada. Journal of Geophysical Research, **90**, pp. 6754–6772.

Stewart, R., and Peselnick, L. 1977. Velocity of compressional waves in dry Franciscan rocks to 8 kbar and 300°C. Journal of Geophysical Research, **82**, pp. 2027–2039.

Taber, J. J., Jr. 1983. Crustal structure and seismicity of the Washington continental margin. Ph.D. thesis, University of Washington, Seattle, WA, 159 p.

Taber, J. J., Jr., and Smith, S. W. 1985. Seismicity and focal mechanisms associated with the subduction of the Juan de Fuca plate beneath the Olympic Peninsula, Washington. Bulletin of the Seismological Society of America, **75**, pp. 237–249.

TABOR, R. W., and CADY, W. M. 1978*a*. The structure of the Olympic Mountains, Washington—analysis of a subduction zone. United States Geological Survey, Professional Paper 1033, 38 p.

—— 1978*b*. Geologic map of the Olympic Peninsula. United States Geological Survey, Map I-994, scale 1 : 125 000.

TIFFIN, D. L., and RIDDIHOUGH, R. P. 1977. Gravity and magnetic survey off Vancouver Island, 1975. *In* Report of activities, part A. Geological Survey of Canada, Paper 77-1A, pp. 311–314.

TIFFIN, D. L., CAMERON, B. E. B., and MURRAY, J. W. 1972. Tectonics and depositional history of the continental margin off Vancouver Island, British Columbia. Canadian Journal of Earth Sciences, **9**, pp. 280–296.

TURNER, F. J. 1981. Metamorphic petrology: mineralogical, field and tectonic aspects. 2nd ed. McGraw-Hill, New York, NY, 524 p.

VON HUENE, R., and UYEDA, S. 1981. A summary of results from the IPOD transects across the Japan, Mariana and Middle America convergent margins. Proceedings of the 26th International Geological Congress, Geology of Continental Margins Symposium, Paris, France, July 1980, Oceologica Acta, **4** (Supplement), pp. 233–239.

WANLESS, R. K., STEVENS, R. D., LACHANCE, G. R., and DELABIO, R. N. 1978. Age determinations and geological studies, K–Ar isotopic ages. Report 13. Geological Survey of Canada, Paper 77-2, 60 p.

WELLS, R. E., ENGEBRETSON, D. C., SNAVELY, P. D., JR., and COE, R. S. 1984. Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington. Tectonics, **3**, pp. 275–294.

YORATH, C. J. 1980. The Apollo structure in Tofino Basin, Canadian Pacific continental shelf. Canadian Journal of Earth Sciences, **17**, pp. 758–775.

YORATH, C. J., CLOWES, R. M., GREEN, A. G., SUTHERLAND BROWN, A., BRANDON, M. T., MASSEY, N. W. D., SPENCER, C., KANASEWICH, E. R., and HYNDMAN, R. D. 1985*a*. Lithoprobe, phase 1: southern Vancouver Island: preliminary analyses of reflection seismic profiles and surface geological studies. *In* Current research, part A. Geological Survey of Canada, Paper 85-1A, pp. 543–554.

YORATH, C. J., GREEN, A. G., CLOWES, R. M., SUTHERLAND BROWN, A., BRANDON, M. T., KANASEWICH, E. R., HYNDMAN, R. D., and SPENCER, C. 1985*b*. LITHOPROBE, southern Vancouver Island: seismic reflection sees through Wrangellia to the Juan de Fuca plate. Geology, **13**, pp. 759–762.