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LITHOPROBE - PHASE 1: SOUTHERN VANCOUVER ISLAND: PRELIMINARY ANALYSES OF REFLECTION SEISMIC PROFILES AND SURFACE GEOLOGICAL STUDIES

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Abstract

Seismic reflection and geological studies conducted on southern Vancouver Island during 1984 show that the region has sustained considerable shortening above a widespread décollement zone. Beneath Wrangellia, a thick interval of possibly underplated pre-Upper Miocene oceanic crust overlies the modern subducting Juan de Fuca Plate. The latter is clearly seen on all record sections and comprises an undeformed layered sequence resting upon presumed oceanic crust. The Leech River Fault is identified as a surface dipping towards the north at 35°. Beneath the fault the Eocene Metchosin Volcanics and Sooke Gabbro are seen to overlie a succession that may have its correlatives in the core zone Olympic Mountains of northern Washington.

Résumé

Des levés de sismique-réflexion et géologiques effectués dans le sud de l'île de Vancouver en 1984 montrent que cette région a subi un rétrécissement considérable au-dessus d'une vaste zone de décollement. Au-dessous de Wrangellia, un épais intervalle de croûte océanique, peut-être sus-jacent à une plaque et formé avant le Miocène supérieur, recouvre l'actuelle plaque de subduction de Juan de Fuca. On voit clairement cette dernière dans tous les diagrammes basés sur les enregistrements; elle est constituée d'une séquence stratifiée non déformée, reposant sur la croûte océanique hypothétique. On a identifié la faille de Leech River comme étant une faille superficielle dont le pendage est de 35° vers le nord. Au-dessous de la faille, les roches volcaniques de Metchosin et le gabbro de Sooke d'âge Eocène recouvrent une succession dont les éléments corrélatifs se trouvent sans doute dans la zone centrale des monts Olympiques, dans le nord de l'Etat de Washington.

Introduction

LITHOPROBE is a collaborative geoscientific project involving the co-ordination of geophysical, geological and geochemical techniques to elucidate the geology of the lithosphere in Canada by extending and relating surface geology to structures at depth. The project is spearheaded by the use of the Vibroseis[1] technique which permits deep seismic sounding to depths of as much as 16 seconds (two way-time, ca 50 km). In conjunction with the reflection profiling other important avenues of research are being conducted so as to facilitate the interpretation of the record sections and to help answer important questions about the nature and processes affecting the deep crust. The project is funded jointly by NSERC and the Department of Energy, Mines and Resources and involves university, government and industrial geoscientists in all phases from initial planning to final interpretation. For further details on the history of development of the project the reader is referred to Fyfe and Rust (1981), CANDEL (1981) and Clowes (in press).

Phase 1 of LITHOPROBE comprised field components in two areas: southern Vancouver Island (this report) and the Kapuskasing structural zone of Ontario (Woods, 1985). Veritas Geophysical Ltd. of Calgary was the company chosen to conduct the reflection seismic program which was completed during late May and June. It is to the credit of this young and vigorous company that it did an outstanding job and with such cooperative personnel. Supporting geoscience studies were carried out by many scientists. This report presents preliminary interpretations of the seismic reflection data and new suurface geological studies. It also lists other studies which have been completed or are in progress.

Regional geological and tectonic setting

The regional geological setting of southern Vancouver Island is largely known through the work of Muller (1977, 1980a) and his co-workers. During the past three decades other authors, eg. Fyles (1955) and Yole (1969) have discussed various aspects of the geology of the region. Numerous university postgraduate research theses have been devoted to both topical and regional studies.

The Tofino Basin, underlying the continental shelf off western Vancouver Island, received considerable attention during and following the exploration program in that region by Shell Canada Resources Ltd. in the late 1960s (Shouldice, 1971; MacLeod et al., 1977; Tiffin et al., 1972 and Yorath, 1980). Recently several geophysical studies have focused on the plate tectonic regime of the convergent margin (Keen and Hyndman, 1979; Riddihough, 1977, 1979, 1982).

A wide range of data was previously available (although of variable density and quality) to constrain models of deep crustal structure (notably those of Riddihough, 1979 and Spence, 1984). These include magnetotellurics studies in the Victoria and Buttle Lake areas, gravity data at 5 to 15 km spacing, repeated geodetic levelling and positioning for vertical movements, seismicity data, aeromagnetic surveys over the southernmost part of Vancouver Island, geothermal cross-sections and crustal temperatures and paleomagnetic studies.

A series of seismic refraction, reflection and surface-wave experiments have progressively defined the structure beneath the Island (White and Savage, 1965; Tseng, 1968; Wickens, 1977; McMechan and Spence, 1983; Ellis et al., 1983; Spence, 1984). The most recent of these references described aspects of the VISP experiment which involved four reversed refraction profiles across and parallel to the island, and two short reflection lines near the southwestern end of LITHOPROBE line 1. It was the success of these lines in identifying deep crustal reflectors that gave strong support to Vancouver Island being chosen as the first LITHOPROBE study area. Previously acquired data, particularly refraction, gravity and seismicity, have been interpreted in terms of a shallowly dipping subducting slab from beneath the edge of the continental shelf to beneath central Vancouver Island; beyond there the dip is believed to increase. Several authors have pointed out the requirement for a discontinuity or bend in the subducted slab in the area of Juan de Fuca Strait and the south end of the Island.

The regional geology of southern Vancouver Island and the location of the four multichannel seismic reflection profiles is shown in Figure 67.1. The island is made up of Paleozoic, Mesozoic and Cenozoic volcanic, plutonic, sedimentary and metamorphic rocks, which are complexly partitioned by a dominant northwesterly aligned structural grain. The main stratigraphic and structural unit is the Karmutsen Formation, a thick, relatively uniform basaltic lava sequence of Late Triassic age that separates middle and upper Paleozoic from Jurassic and younger volcanic, sedimentary and plutonic units. Along its axis and eastern margin, northwesterly aligned structural culminations expose the island's oldest rocks, the Sicker Group, in the Cowichan, Buttle and Nanoose uplifts and in the Victoria Arch. On the west coast and beneath the continental margin an apron of Cenozoic clastic rocks (Carmanah Group) overlies complexly deformed Upper Triassic to Cretaceous slope and trench deposits (Pacific Rim Complex) and Eocene oceanic basalts. The latter unit represents the structurally highest slice within the modern subduction complex. On the east coast the Nanaimo Group of Late Cretaceous age comprises cyclical graded sequences of conglomerate, sandstone and shale that developed within a successor basin occupying a forearc setting adjacent to the Coast Plutonic Complex. Beneath the Strait of Georgia, Nanaimo strata are overlain by a thick succession of dominantly nonmarine Tertiary clastics and subordinate Pleistocene sediments. The stratigraphy of the region is partly illustrated by the legend of Figure 67.1.

Objectives

The primary crustal architecture of Vancouver Island is thought to comprise an underthrusting oceanic plate overlain by a complex of accreted terranes. During the past several years many workers have identified Vancouver Island as part of Wrangellia, a terrane known to be allochthonous by virtue of paleomagnetic studies on Triassic and Jurassic volcanics (Yole and Irving, 1980; Irving and Yole, 1983). The manner of assembly of this and other adjacent terranes and their accretion to the ancient continental margin is largely unknown. However, a reasonable model has recently been proposed by Monger et al. (in press) which shows the various terranes of the Cordillera as having underthrust one another during accretion such that they are presently vertically juxtaposed, one above the other. Part of this model is shown in Figure 67.2b, which portrays Wrangellia as having been underplated by later accretionary terranes such as the Pacific Rim Complex along with the Crescent volcanics and Hoh and Ozette mélanges. Beneath these ancient terranes, the modern Juan de Fuca Plate is thought to decend beneath the margin, first at a relatively shallow angle beneath the continental shelf and then more steeply beneath the Island. LITHOPROBE was designed to test this terrane accretion and subduction model.

In order to accomplish the above objective a number of specific studies are being carried out by EMR. Geological projects include:

a. The construction of detailed corridor maps at 1:50 000, each of which is to contain one or more of the seismic profiles.

[1] Registered trademark of Continental Oil Company.

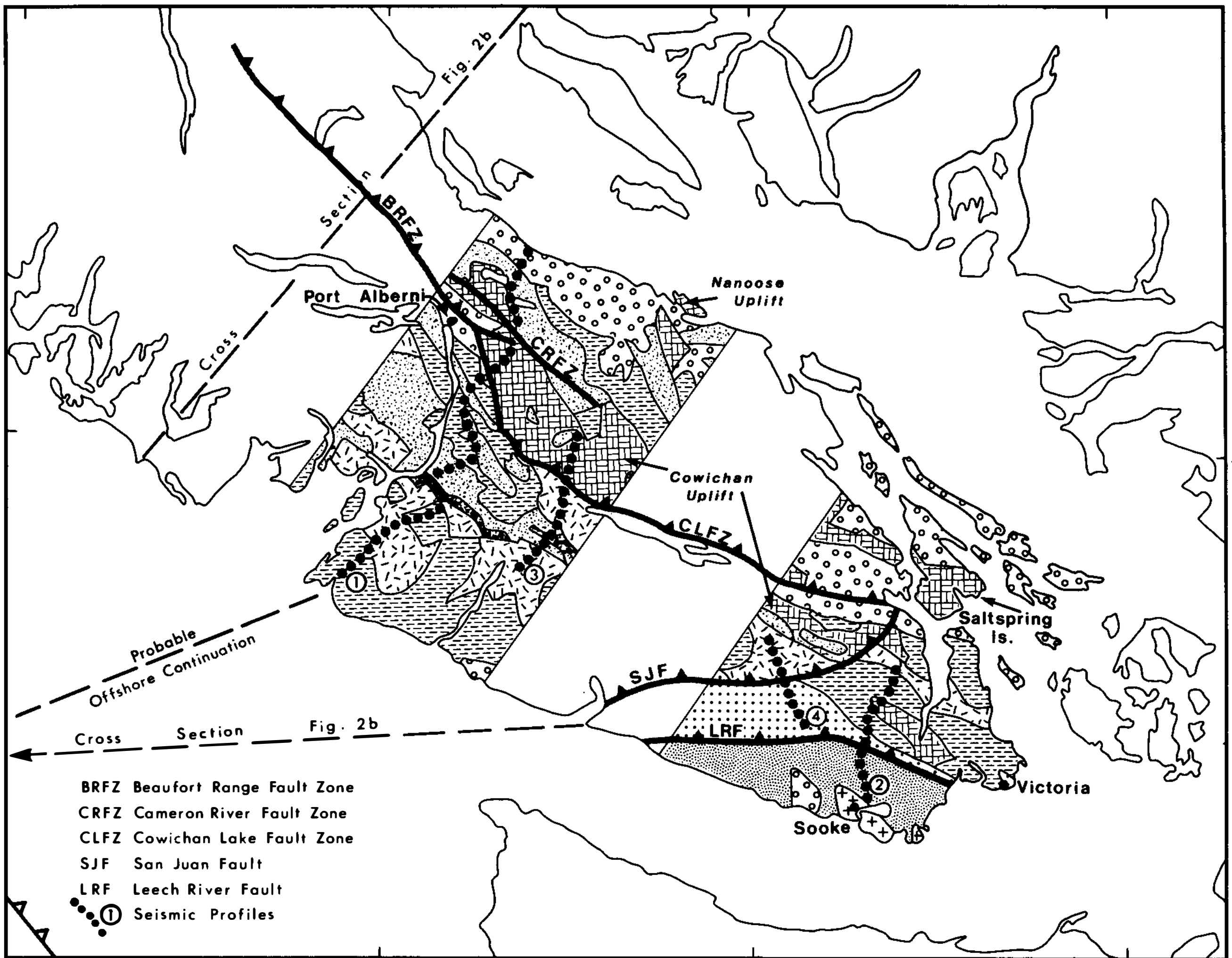
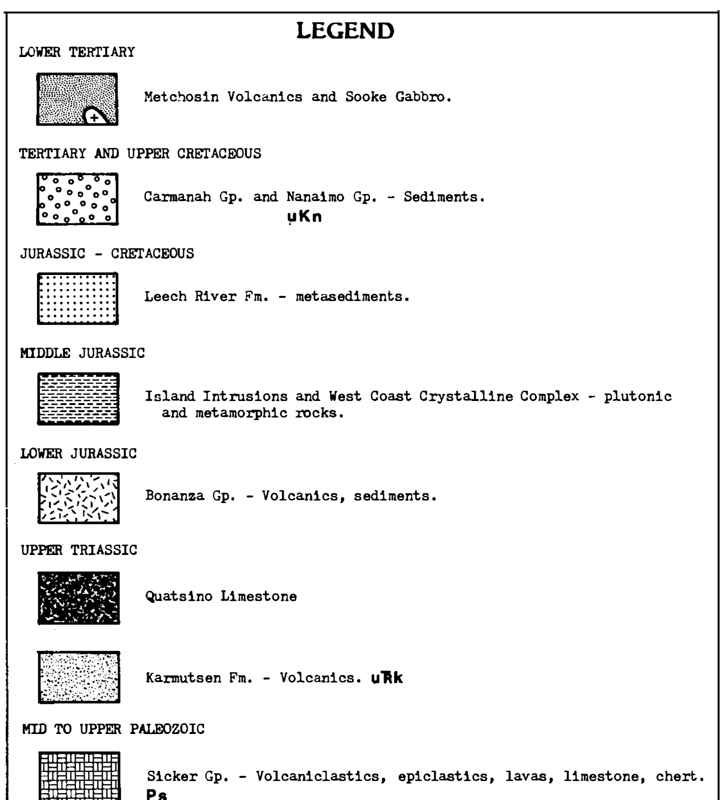


Figure 67.1. *Partial geological map of southern Vancouver Island showing the locations of the four seismic profiles.*



b. The identification of major structures and stratigraphic relationships which could be recognized on the record sections and traced to depth.

c. The examination of the differences in structural style of various units so as to be able to identify their seismic signatures on the reflection profiles.

d. Conducting stratigraphic and biostratigraphic studies of the middle to upper Paleozoic Sicker Group in the Cowichan and Nanoose uplifts and adjacent areas in order to identify stratigraphic units that may be identifiable on the seismic sections.

e. The determination of the uplift history of eastern Vancouver Island through studies of the Upper Cretaceous Nanaimo Group and Tertiary Chuckanut Formation, thus permitting the construction of mechanical and thermal models.

Geophysical studies include:

a. Magnetotelluric studies – a Phoenix Geophysics Ltd. system was used at several stations along line 1 and at several other sites to obtain information on the electrical conductivity structure of the crust and of the upper mantle, particularly of conductive layers associated with the underthrusting Juan de Fuca Plate. (J.M. DeLaurier, R.D. Kurtz)

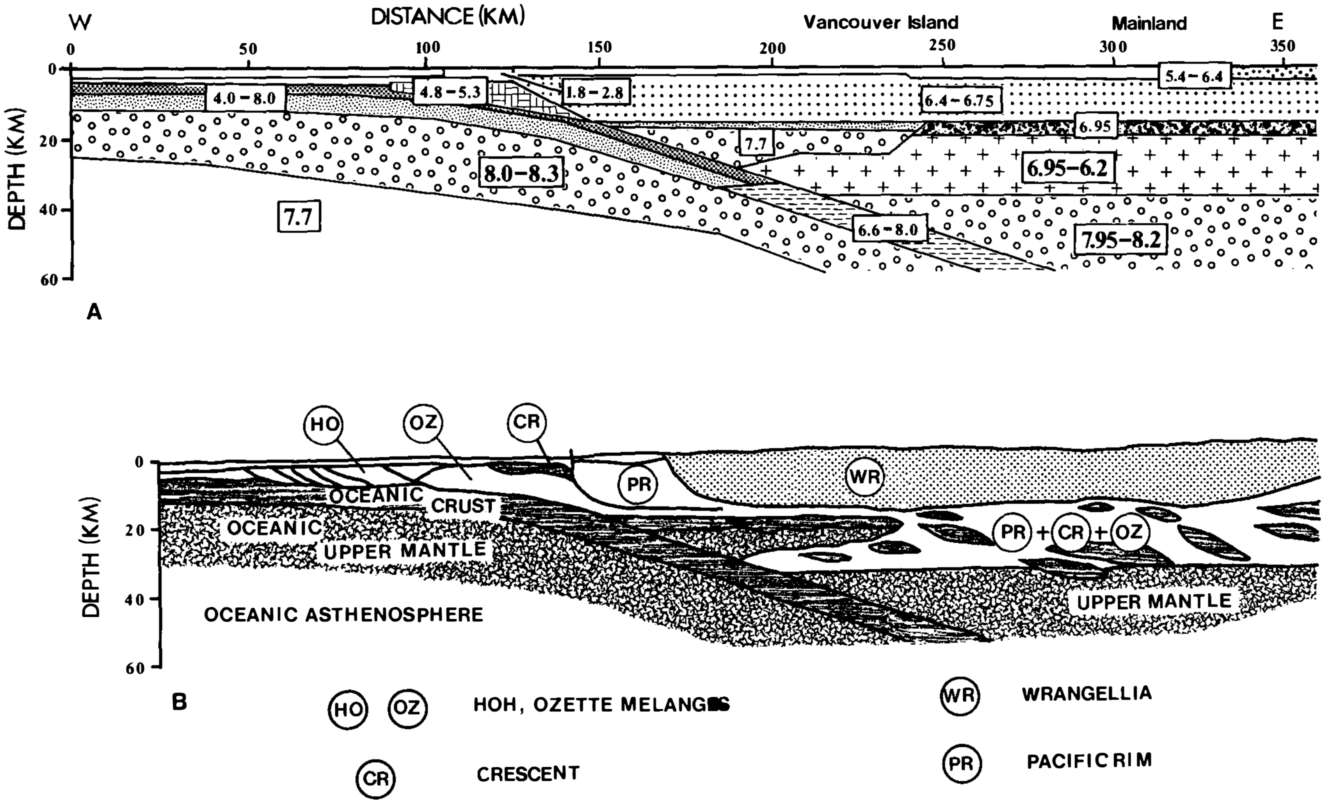


Figure 67.2. *(a) Velocity model across the continental margin (from Spence, 1984); (b) Tectonic cross-section across the continental margin (location shown in Fig. 67.1) (modified from Monger et al., in press).*

b. Gravity profiles were conducted along line 1 and along the east coast of the Island to improve the previous data density. These will further constrain the interpretation of the deep structure of the crust and upper mantle. (J. Sweeney, D. Seemann, J.B. Boyd, H. Dragert)

c. Geodetic levelling and positioning – a levelling profile was carried out by the Surveys and Mapping Branch that will be combined with previous and future Vancouver Island data to determine contemporary uplift and subsidence rates in the region.

d. Seismicity cross-section – this section is being constructed along a corridor which includes line 1 and is to be integrated with the reflection profiles so as to enhance deep crustal and tectonic models. (G.C. Rogers)

e. Aeromagnetic surveys – existing aeromagnetic coverage of southern Vancouver Island was expanded so as to include all of the area traversed by the seismic profiles. (P.J. Hood)

f. Geothermal measurements – a profile of heat flow and crustal radioactive heat production measurements and implied crustal temperatures is being constructed. (T. Lewis)

g. Paleomagnetic studies of Tertiary and Paleozoic rocks are being undertaken in cooperation with R.W. Yole of Carleton University. (E. Irving)

A number of supporting geoscientific studies are being conducted by university professors and their students. R.L. Armstrong and C.E. Isachsen of the University of British Columbia are further refining the geochronological relationships between the Early and Middle Jurassic Island Intrusions and the West Coast Crystalline Complex. Results to date suggest that the two are closely related in time but originated at different crustal levels (R.L. Armstrong, personal communication). R.M. Bustin and G.E. Rouse, also of U.B.C., are carrying out stratigraphic, biostratigraphic, thermal maturation and clay mineralogical studies on parts of the Upper Cretaceous Nanaimo Group. C.M. Scarfe along with K. Muehlenbachs at the University of Alberta are undertaking detailed geochemical studies on volcanic and plutonic rocks so as to help determine depths of emplacement, source materials and alteration history. H. Dosso of the University of Victoria is studying electromagnetic induction models of Vancouver Island and the adjacent sea to facilitate the interpretation of the magnetotelluric data. It is reported that W.S. Fyfe of the University of Western Ontario has found evidence of dewatering of the subducting Juan de Fuca Plate.

A few results

Surface geology

A. The dominant structural style of southern Vancouver Island is one of horizontal shortening across the northwesterly trending axis of the Island. All rock units have sustained at least moderate folding subparallel to the axis although penetrative deformation is relatively rare except in the Mt. Sicker – Saltspring Island area. Fold axes and the trends of major faults are subparallel and the latter appear to combine significant thrust as well as dextral separation. Two structural culminations, the Cowichan and Nanoose uplifts (Fig. 67.1), expose Paleozoic Sicker Group rocks and each are thought to have been elevated during the Late Cretaceous by uplift along easterly dipping faults. The Cowichan Uplift and its colinear expression in the Beaufort Range are bounded on the southwest by two fault zones that are believed to be dynamically linked. These are the Cowichan Lake Fault Zone (Fig. 67.3) and the Beaufort Range Fault Zone (Fig. 67.4), the latter is thought to have been the locus of the 1946 earthquake that caused significant damage to several communities in central Vancouver Island (Rogers and Hasegawa, 1978).

Figure 67.3. *View looking southeast along Cowichan Lake. The trace of the Cowichan Lake Fault Zone occurs along the lower slopes of the ridge on the north side of the lake.*

Figure 67.5. *Upper strand of the Beaufort Range Fault Zone on Highway 4 near Port Alberni. The man (K. Dom) has his hand on the breccia zone immediately adjacent to the fault which dips easterly at 45°. Ps = Paleozoic Sicker Group. uKn = Upper Cretaceous Nanaimo Group.*

Figure 67.4. *View looking northwesterly along the west flank of the Beaufort Range and the Alberni Valley. The trace of the Beaufort Range Fault Zone occurs near the base of the steeper slope of the range.*

Figure 67.6. *Assymetric fold in interbedded limestone and siliceous mudstone. View looking northwesterly down plunge. Copper Canyon, Chemanus River. ls = limestone;* S_1 *= trace of axial plane cleavage.*

The Beaufort Range Fault Zone juxtaposes upper Paleozoic Sicker Group and Upper Triassic Karmutsen Formation rocks in the hanging wall above the lowermost units of the Upper Cretaceous Naniamo Group (Comox and Haslam formations) which underlies the floor of the Alberni Valley. The fault zone comprises at least two strands, each about 40 km long; one dips eastward at about 45° (Fig. 67.5) and the other is nearly vertical. The zone is thought to connect with either the Cameron River Fault Zone (35 km) or the Cowichan Lake Fault Zone (85 km +) although the latter is considered more likely because of the close similarity in relative stratigraphic separation and structural style as well as physiographic expression. The Cowichan Lake Fault zone comprises two to three strands, each of which dip steeply easterly and which separate Sicker and Karmutsen rocks in the hangingwall from Nanaimo Group strata in the footwall.

The Cowichan Uplift is a gently northwesterly plunging structure within which Sicker Group sedimentary and pyroclastic rocks are typically folded into tight to isoclinal folds. More massive volcanic and intrusive rocks are penetratively deformed, and are flattened to varying degrees; the resulting foliation is coplanar with the vertical axial planes of the folded rocks. Locally these rocks are converted to quartz-mica and chlorite-epidote schists. Bedded limestones, perhaps correlative with the Buttle Lake Formation, also are involved in this deformation (Fig. 67.6) and hopefully will provide some useful age control for the folding.

The timing and tectonic significance of deformational events that affected Sicker rocks are poorly understood, in part due to the paucity of reliable age control and the lack of distinctive and widely recognizable stratigraphic units. It may be that in the southeastern Cowichan Uplift more highly deformed rocks represent an older part of the group that sustained deformation prior to the deposition of younger Sicker units. Previously reported radiometric dates (Muller, 1980a, b; Eastwood, 1983) lend some support to this view. The Tyee quartz porphyry and hornblende porphyry intrusions in the Mt Sicker – Saltspring Island area yielded Devonian ages thus suggesting a pre-Devonian age for the host rocks. Conclusive intrusive contacts are rare; however, one occurs in the Duncan area (Fig. 67.7). It is noted, however, that if the folded limestones in this region belong to the Buttle Lake Formation, a post Permian age of deformation would be indicated.

In the Nanoose Uplift most Sicker rocks are isoclinally folded about vertical axial planes; penetrative strain occurs in argillites. Some support for the presence of thrust faults is suggested by the apparent position of the Campanian Extension-Protection Formation above the Santonian Comox Formation, however, the principal Paleozoic packages within the uplift are separated by faults of unknown type.

B. The stratigraphy of the Sicker Group has been the subject of much study. Muller (1980a) divided the sequence beneath the Buttle Lake Limestone into an informal "Sediment-Sill Unit" and two formal units, the Myra and Nitinat formations, all in descending stratigraphic order. Our preliminary work indicates that these units are not useful since their relative position and continuity are poorly understood. We have resorted to the establishment of local, informal units, and hope to resolve their stratigraphic relationships after more extensive detailed studies and dating.

In the Cowichan Uplift only the uppermost stratigraphic succession is known with confidence. The top of the group is represented by an unnamed unit, some 50 to 100 m thick, of turbiditic sandstones, shales and intercalated basaltic intrusions or flows (Fyles, 1955; Yole, 1969). This unit rests conformably upon the Buttle Lake Limestone which comprises about 500 m of bioclastic, locally tuffaceous and cherty calcarenite and minor interbedded argillite and volcanic sandstone (Fig. 67.8). The formation has yielded fossils ranging in age from Middle Pennsylvanian to Early Permian (Yole, 1969; Muller, 1980a). Both the uppermost unnamed unit and much of the Buttle Lake Limestone are widely truncated by the unconformity at the base of the Upper Triassic Karmutsen Formation.

Beneath the Buttle Lake Formation is a homogeneous succession, about 1000 m thick, of dominantly epiclastic strata consisting of massive, well bedded volcanic sandstones, lithic tuffs with lesser amounts of pyroxene-bearing agglomerate and volcanic conglomerate. This succession is underlain by a much thicker sequence of mainly pyroclastic rocks dominated by pyroxene-bearing agglomerate (Fig. 67.9), tuff, volcanic sandstone and minor green chert. This sequence includes some pillow lavas, commonly in relatively thin flow units but at least 200 m are exposed at one locality. These pillow lavas are of different character than those of the Upper Triassic Karmutsen Formation; individual pillows tend to be much larger, richly pyroxene-bearing and with jasper as interpillow material.

In the Nanoose Uplift, which includes the Nanoose Peninsula and adjacent offshore islands, the Sicker Group is dominated by epiclastic strata with lesser amounts of volcanic and pyroclastic rocks. Calcarenite and quartz arenite grain flows, chert and argillite breccia, volcanic sandstones, turbidites, tuffs and pillow basalts characterize the uppermost part of the succession. On the offshore islands this unit is underlain by rocks thought to be equivalents of the Buttle Lake Formation comprising bioclastic limestone, chert, volcanic sandstone and conglomerate. On the peninsula, rocks in a structurally equivalent position include olistostromes (Fig. 67.10) and tectonic mélange made up of bioclastic limestone, argillite, basalt breccia and quartzite. The lowermost unit in both areas comprises rhythmite, turbidite, orthoquartzite and argillite, the latter enclosing pods of limestone; on the peninsula these rocks are underlain by green and white banded tuffaceous chert and minor interbedded argillite. The Paleozoic rocks are overlain with spectacular unconformity by massive, resedimented conglomerate of the Upper Cretaceous Nanaimo Group (Fig. 67.11).

C. The Nanaimo Group of the Alberni, Cowichan and Comox valleys received much attention. Extensive sampling of coals and shales for vitrinite reflectance, as well as biostratigraphic data and sandstones for porosity and thermal conductivity values, was carried out to obtain input data for the calculation of mechanical and thermal models of basin formation. The coarse sandstones and conglomerates of the Extension-Protection Formation contain significant quantities of white quartz, unlike other conglomerate members of the Nanaimo Group. This quartz was sampled as was the interpillow quartz ("dallasite") of the Karmutsen Formation to determine through fluid inclusion and oxygen ratio studies if the latter was the source for the former. The significance of this lies in its relationship to the timing of uplift of the Beaufort Range, much of which is underlain by Karmutsen pillow basalts.

D. In at least two areas west of the Beaufort Range Fault zone, well indurated and lithified marine sandstones of the Comox Formation, the lowermost formation of the Nanaimo Group, rest upon deeply weathered quartz diorite of the Lower to Middle Jurassic Island Intrusions. The weathering has resulted in a soft quartz diorite grus which can be mined by hand from beneath the sandstones, the lowermost levels of which contain clasts of the weathered granitic rocks (Fig. 67.12). Moreover, the weathered granitic rocks provide

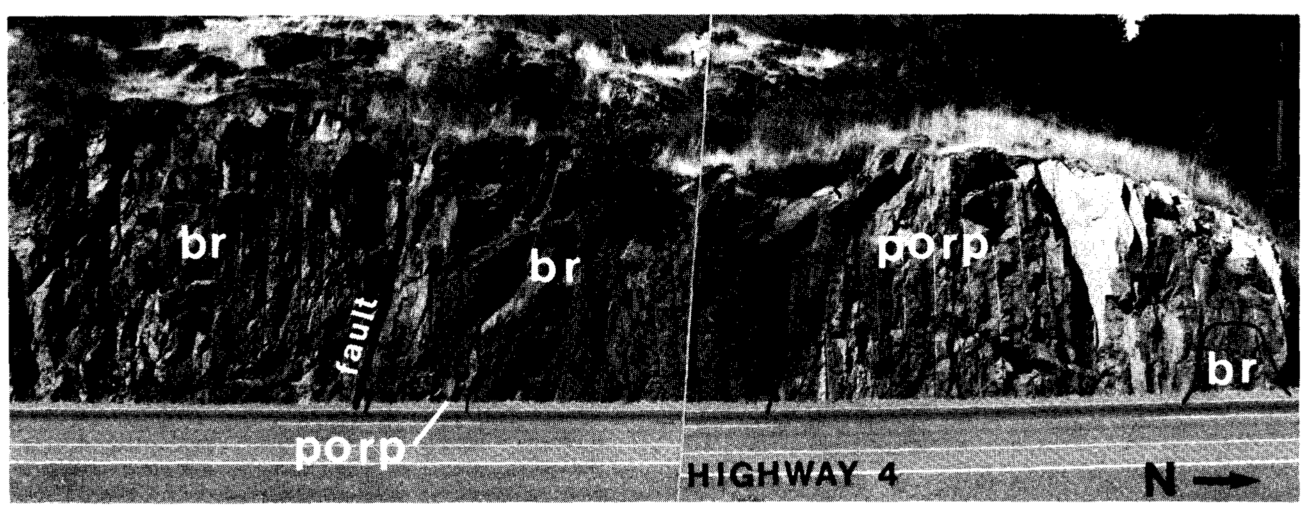


Figure 67.7. *Intrusive contacts between quartz porphyry (porp) and older fragmental rocks (br) consisting of rounded volcanic clasts within a tuffaceous matrix. The volcanic rocks typically contain abundant mafic phenocrysts and have been strongly epidotized. Highway 1, north of Duncan, British Columbia.*

Figure 67.8. *View looking northwesterly across Horne Lake at Mount Mark. Pbl = Paleozoic Buttle Lake Limestone; uTRk = Upper Triassic Karmutsen Formation.*

Figure 67.10. *Olistostrome in upper Paleozoic Sicker Group, Nanoose Peninsula. Outlined blocks are mainly limestone, turbidites and quartzite in an argillite matrix.*

Figure 67.9. *Pyroxene-bearing agglomerate in the upper part of the pyroclastic unit, upper Sicker Group; Upper Cameron River.*

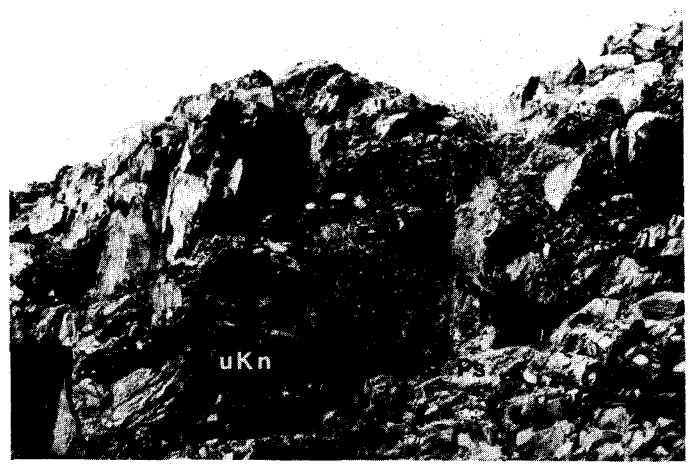


Figure 67.11. *Resedimented conglomerate of the upper Cretaceous Nanaimo Group (uKn) resting on sheared argillites of the upper Paleozoic Sicker Group (Ps); Nanoose Peninsula.*

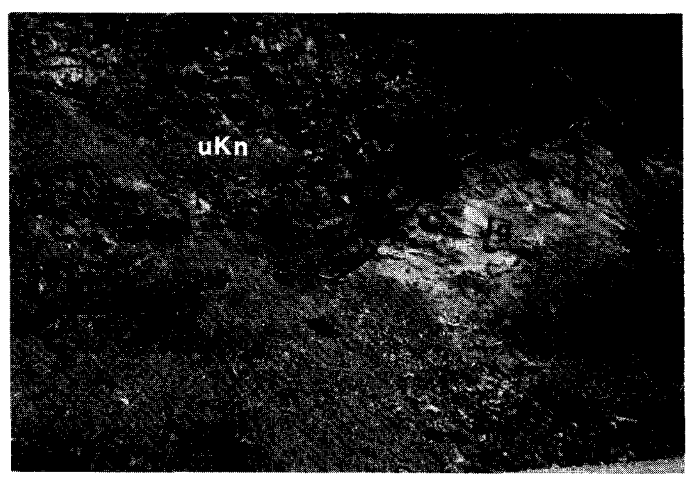


Figure 67.12. *Upper Cretaceous Nanaimo Group (uKn – Comox Formation) resting upon deeply weathered quartz diorite (Jg); Bainbridge Lake.*

an ^{18}O value of 14.1‰ which suggests low temperature weathering with relatively high ^{18}O water, perhaps in a different climate and location than at present (K. Muehlenbachs, personal communication, 1984). In other areas to the east of the fault zone basal nonmarine Nanaimo sandstones and conglomerates likewise rest upon plutonic rocks but no evidence of deep chemical weathering is evident. This and other criteria, such as the difference in relative size and distribution of plutonic rocks on either side of the "Beaufort Range – Cowichan Valley Fault System" suggests that the plutonic rocks in the two regions are different in some way and, moreover, that those on the west side sustained different chemical weathering conditions than those on the east side. Detailed chemical analyses and geochronology may resolve this question.

E. The early Eocene Metchosin Volcanics and Sooke Gabbro, south of the Leech River Fault (Fig. 67.1) show a pseudo-ophiolitic stratigraphy. Massive and layered gabbros (Fig. 67.13) pass upward into and are intruded by a well developed sheeted dyke complex. This in turn is succeeded by subaqueous pillow and sheet flow basalts with minor pyroclastics which in turn are overlain by subaerial(?) amygdaloidal flows. The general stratigraphy suggests that the succession developed as seamounts, probably in a marginal basin setting, close to a continental edge. Muller (1980b) came to a similar conclusion on the basis of chemical studies.

Reflection seismic profiles

Approximately 205 km of reflection seismic profiling was conducted along the four lines illustrated in Figure 67.1. The instrumentation employed was a 120 channel DFS 5 system employing up to four synchronized vibrator sources (Fig. 67.14) along a geophone layout with a 90 m group spacing. The data were digitally recorded to 16 s using a 4 ms sampling rate and stacked to 3000%. Processing included crooked line correction, demultiplexing, AGC, filtering, automatic static correction and stacking. Figures 67.15, 67.16 and 67.17, selected from lines 1 and 4, provide good examples of the excellent data quality achieved (horizontal exaggeration approximately 1.5 to 1.7; original display = 24 traces/inch). The illustrated line drawings (Fig. 67.18, 67.19) represent preliminary coarse interpretations of lines 1 and 4. Some structural boundaries pass through groups of dipping reflectors; these will ultimately shift in position and increase in dip when the sections are migrated.

Figure 67.18 summarizes the initial interpretation of line 1. The lowermost reflector zone is considered to represent the top of the present descending oceanic plate, and comprises an interval (approximately 3 km thick) of interdigitated sediments and volcanics resting upon oceanic crust. Within this lower group some reflectors suggest that the upper part of the interval may have been accreted to the overriding upper plate. Widely scattered reflectors, possibly within the mantle, occur below this zone. The depth to the deepest zone of strong reflectors is remarkably close to that postulated in previous models for the top of the underthrusting oceanic crust; about 20 km beneath the west coast of the island and 30 km beneath the east coast (Riddihough, 1979; Spence, 1984). These models were constrained by the depth to the top of the oceanic crust beyond the continental slope where it can be seen in single channel seismic reflection profiles, and, by seismic refraction data obtained on Vancouver Island. The reflectors show some indication of an increase in dip towards the eastern end of the line, beyond which continuity is lost. At about this location, previous models have shown a change in dip from about 10° to at least 30°. A change to steeper dips is a common feature of many models of subducting plates (e.g. Karig et al., 1976); Rogers (in press) has suggested that this is due to the initiation of high density phase changes at those depths. It is possible that at these depths, the underthrust slabs become decoupled from the base of the overlying lithosphere and penetrate the aesthenosphere (Riddihough, 1984).

Above the lower zone is a thick layer with few coherent reflectors which may be an older oceanic slab now accreted to the overlying continental crust (the underplated zone). A seaward jump in the locus of subduction prior to the Late Miocene that might leave such an underplated slab was proposed by Keen and Hyndman (1979). Above this is another layered zone within which groups of reflectors show dip divergence at several localities. This interval, like the one below, may represent oceanic sediments that were underplated beneath Wrangellia when the older oceanic slab (the underplated zone) was being underthrust. This sediment zone may since have acted as a zone of décollement for listric faults that extend upwards into the Sicker Group. The uppermost prominent band of reflectors is considered to represent the Buttle Lake Limestone which is unconformably overlain by the Upper Triassic Karmutsen Formation and younger Mesozoic rocks. It should be noted that the thick dashed lines roughly defined the limits of similarity of reflector type and geometry; they do not necessarily have

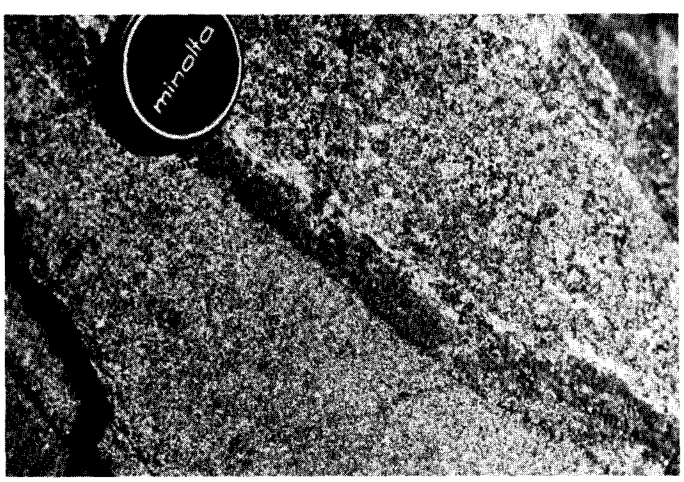


Figure 67.13. *Size-graded layering in the Rocky Point Gabbro.*

Figure 67.14. *Vibrator trucks at the beginning of line 1 near Bamfield.*

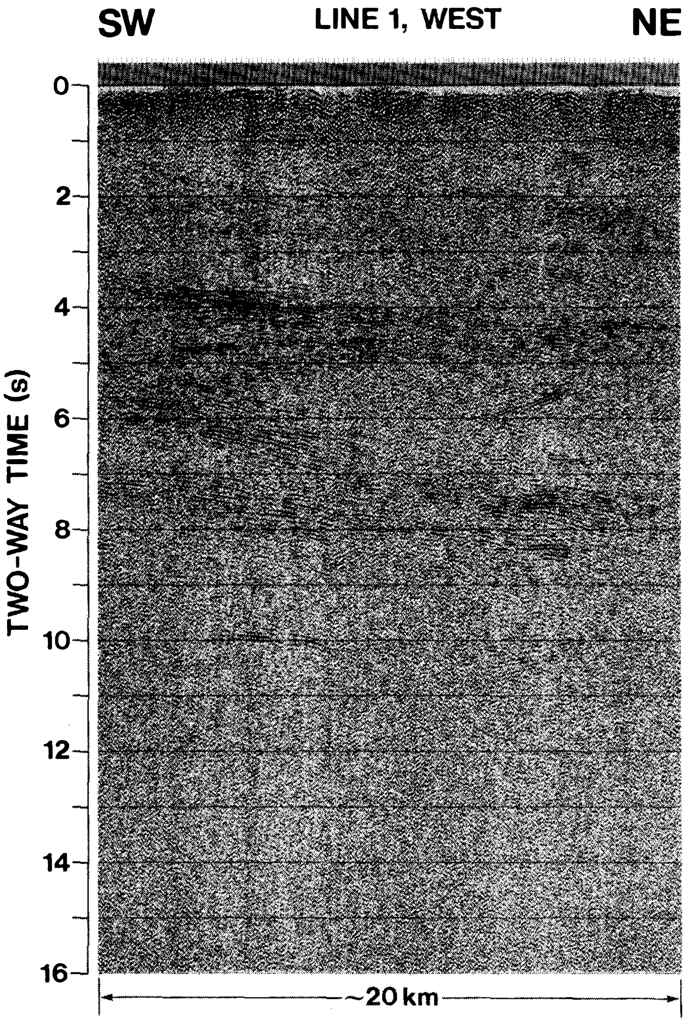


Figure 67.15. Example of record section selected from the southwestern end of line 1. Horizontal exaggeration approximately 1.7 x.

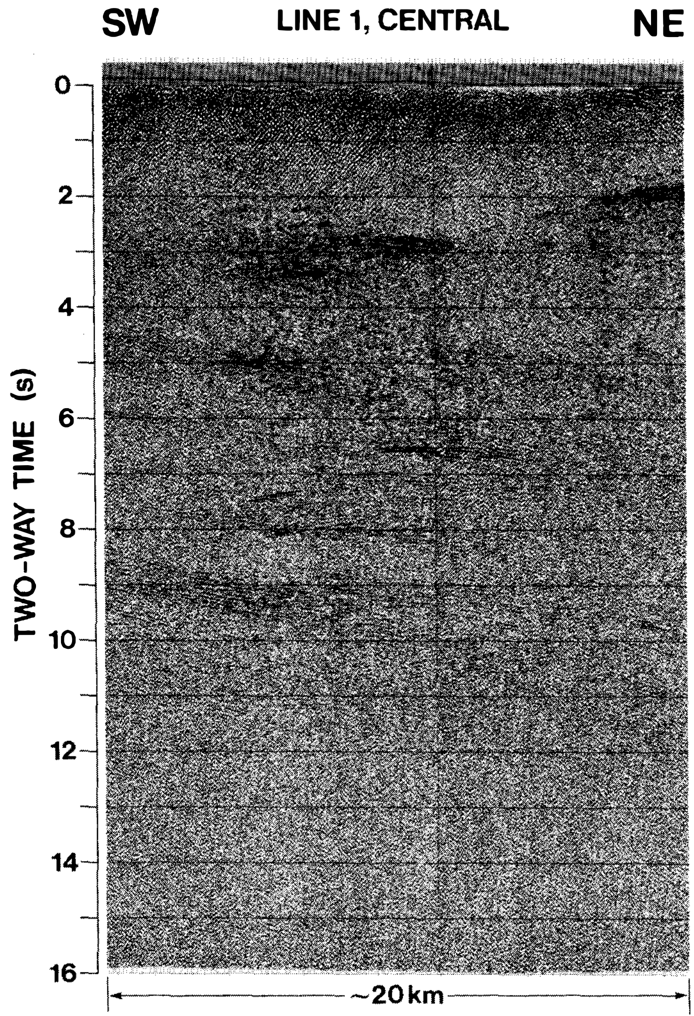


Figure 67.16. Example of record section selected from the central portion of line 1. Horizontal exaggeration approximately 1.7 x.

precise stratigraphic significance. The lack of good reflectors in the uppermost part of the record is a function of velocity and processing parameters chosen; future processing of the higher frequencies within the first 4 s should enhance the data in this interval. It is hoped that migrated sections with enhanced data quality in the upper section will permit some degree of palinspastic restoration along the arcuate faults. Note the apparent near doubling in thickness of the décollement zone where each of these becomes listric. This suggests that these faults are thrusts, however, there is an apparent normal displacement to the Sicker/Karmutsen contact.

The westernmost fault is thought to be a surface along which Eocene volcanic rocks have been emplaced beneath the western edge of Wrangellia (Brandon, 1984). These volcanics have been recognized in offshore seismic profiles to the south where they were penetrated by three offshore wells drilled in the late 1960s (Snavely and Wagner, 1981, Shouldice, 1971; MacLeod et al., 1977; Yorath, 1980). Assuming that the underplated and décollement zones are younger than the early Tertiary volcanics, then considerable material may have been removed from the base of Wrangellia prior to or concurrently with the emplacement of the underplated zone. Also, the necessary uplift as a consequence of underthrusting and underplating would have resulted in considerable erosion of westernmost Vancouver Island; this may be reflected in the geochronological and geochemical studies of the Island Intrusions and Westcoast Crystalline Complex described above. The easternmost faults are the high angle reverse faults identified as the Beaufort Range and Cameron River fault zones. At the northernmost end of the Cowichan Uplift these faults bound a large and broad, internally disrupted anticlinorium, thus reflection quality in this region is poor.

Figure 67.19 shows our initial interpretation of line 4 which crossed the San Juan Fault and terminated close to the Leech River Fault on southern Vancouver Island (Fig. 67.1). The San Juan Fault has been interpreted as a high angle reverse fault and/or sinistral fault (Muller, 1977) separating the Lower and Middle Jurassic Bonanza volcanics to the north from Jura-Cretaceous Leech River schist and Wark and Colquitz gneiss to the south. The Leech River Fault, with both high angle reverse and sinistral separation, bounds the Leech River Formation to the north and the Eocene Metchosin volcanics and Sooke gabbro to the south (Muller, 1977, 1983; Fairchild and Cowan, 1982).

The San Juan Fault (outcrop location shown) is not evident on line 4, (Fig. 67.19) probably due to its very steep dip and/or to processing parameters and velocity choices employed. Reprocessing of the uppermost part of the record section might reveal the geometry of the fault. The Leech River Fault is clearly shown with an apparent dip of 28° (true dip about 35°) towards the north. Beneath the fault the Metchosin Volcanics and underlying layered Sooke Gabbros

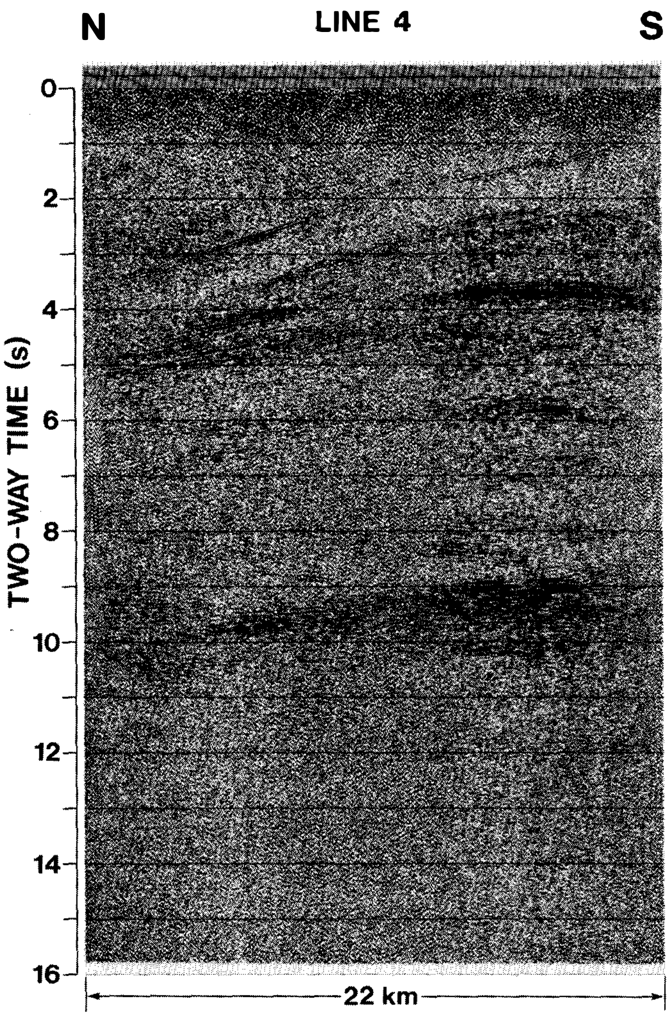


Figure 67.17. *Complete record section of line 4. Horizontal exaggeration approximately 1.7 x.*

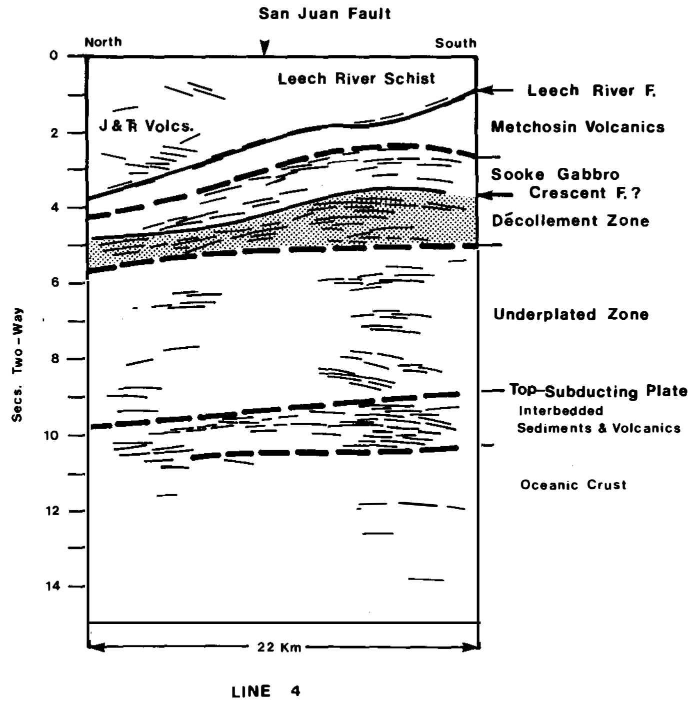


Figure 67.19. *Preliminary interpretation of line 4. See text.*

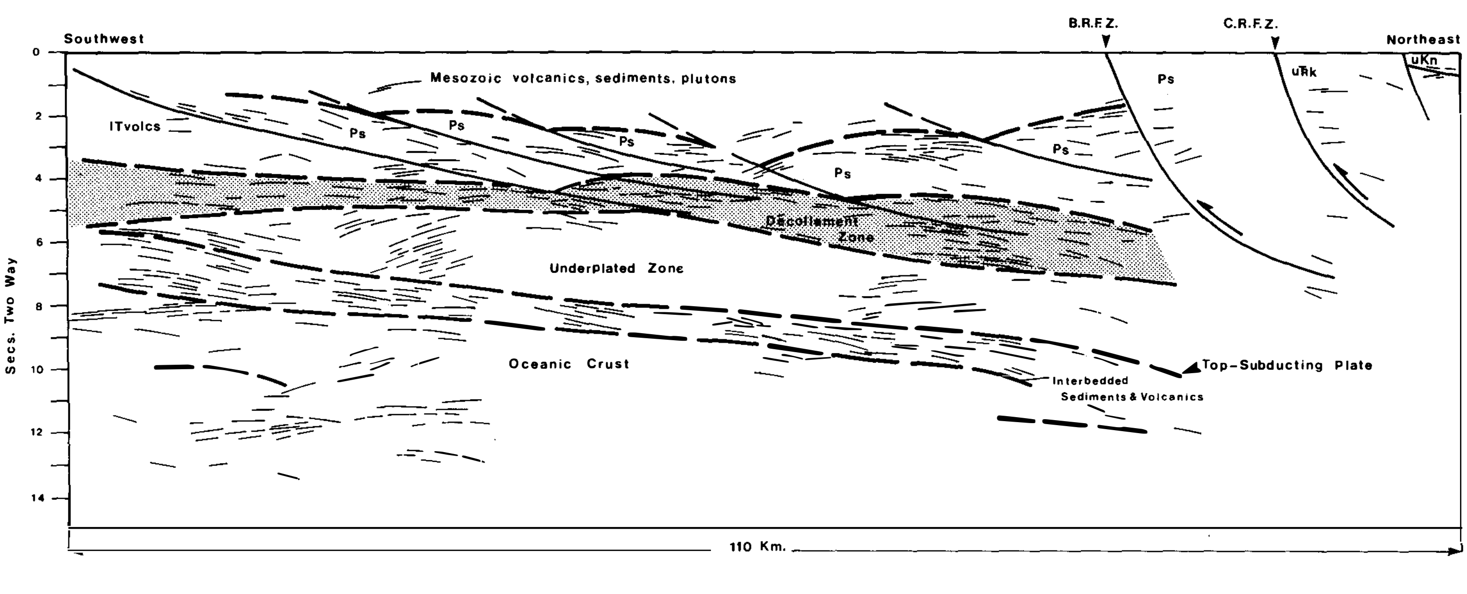


Figure 67.18. *Preliminary interpretation of line 1. See text.*

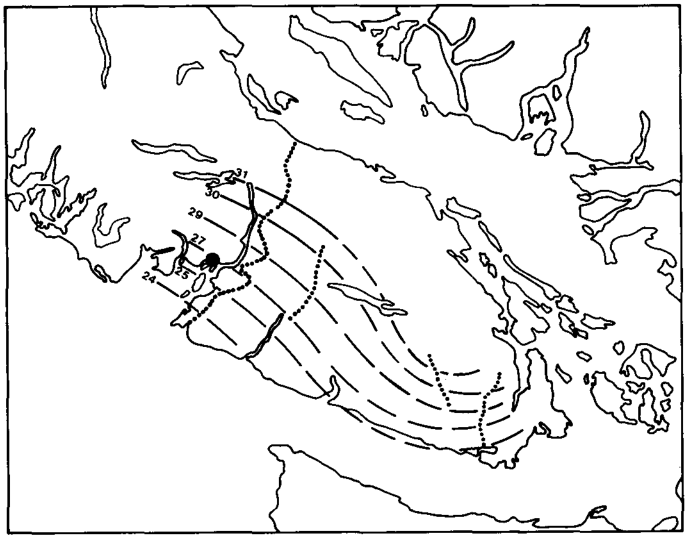


Figure 67.20. *Isochron surface, converted to depth in kilometres, drawn on the top of the subducting plate. Black dot is the epicentre of an earthquake with an estimated focal depth of 37 km.*

are displayed in a broad anticline, floored by the Crescent thrust, above layered sequences (Décollement Zone and Underplated Zone) which possibly have their surface expressions in the sedimentary rocks of the core zone of the Olympic Mountains in northwestern Washington. The modern descending Juan de Fuca Plate again comprises layered interbedded sediments and volcanics resting upon oceanic crust.

One of the principal features of all four seismic profiles is the uniformity and consistency of major reflecting horizons and zones. Both the décollement zone and the descending Juan de Fuca Plate are seen on all lines and show remarkably similar character throughout the southern half of Vancouver Island. Figure 67.20 is an approximation of the isochron surface, converted to depth in kilometres drawn on the surface of the subducting plate. The slope of the plate descends from about 24 km near the coast at line 1 to about 30 km beneath the centre of the island (Slope = 9°). Towards the south there is a bend or discontinuity in the plate, as predicted by Keen and Hyndman (1979) based on geometrical arguments and by Rogers (1983) on the basis of seismicity studies. Because of differences in input velocities for processing purposes between the northern two and southern two lines, the degree of plate curvature in the south may be either more or less than shown, but not significantly. The large black dot at the head of Barkley Sound is the epicentre of an earthquake that occurred on 18 October 1984. Its focal depth was estimated at 37 km which suggests that it occurred at or near the base of the descending plate.

Conclusions

The Vancouver Island component of Phase 1 of LITHOPROBE, to date has been extraordinarily successful. The quality of the seismic record sections far exceeded expectations. The modern underthrusting oceanic plate is clearly seen on all profiles as is an apparently older slab, now accreted to the overlying crust. Although the seismic data have not yet been processed to enhance reflections in the uppermost portions of the record sections, the profiles clearly show the major structural and stratigraphic features recognized in the surface geology. Geological field studies will continue through 1985 with the object of producing corridor maps for each profile as well as additional stratigraphic and structural control information for more detailed interpretations of the record sections. Furthermore, as indicated in Figure 67.1, an offshore extension of the seismic profile of line 1 is planned for the summer of 1985. This report describes the preliminary results only of the reflection seismic and part of the geological work. A wide variety of other studies are in progress. Most important will be the synthesis resulting from the integration of all aspects of the LITHOPROBE project on southern Vancouver Island.

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