

LITHOPROBE — A NATIONAL PROGRAM FOR STUDYING THE THIRD DIMENSION OF GEOLOGY

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ABSTRACT

Lithoprobe is a new Canadian geoscientific research program which involves the coordination of geophysical, geological and geochemical techniques in a collaborative effort among scientists from universities, government and industry to extend and relate surface geology to structures at depth. Phase 1 Lithoprobe, a one-year program, began in 1984. Two transect locations were selected: Vancouver Island — a site that provides the opportunity to resolve fundamental problems in global tectonic processes, including the deep structural manifestations of accreted terranes and the geometry and characteristics of a young subducting oceanic plate; and Kapuskasing Structural Zone — a unique part of the Archean Superior Province that is interpreted to be an upthrust section of the middle to lower continental crust, thereby allowing direct access to the deep crustal levels of greenstone and gneissic belts.

On Vancouver Island, 205 km of high-quality reflection data recorded to 16 s were acquired by using Vibroseis sources. A preliminary interpretation indicates that the top of a continuous band of reflections sloping easterly from 8 to 10 s across the profile represents the top of the subducting Juan de Fuca plate. Above this, another band of reflections may represent the top of underplated oceanic crust, associated with an earlier phase of subduction, which has since acted as a *décollement* zone to listric faults within the overlying Wrangellia terrane. In the Kapuskasing region, a large-scale crustal refraction survey and pilot reflection experiment have been carried out. Field monitors indicate that good-quality refraction data were recorded. A preliminary processed section of the reflection data suggests that part of the fault along which upthrusting may have occurred has been imaged. A wide range of supporting geoscience studies is being carried out in both transects. A proposal for Phase 2 Lithoprobe, in which a number of transect corridors across the country are described, has been prepared.

INTRODUCTION

LITHOPROBE is a new geoscientific research program in Canada that involves the coordination of geophysical, geological and geochemical techniques in a collaborative effort among scientists from universities, government and industry to extend and relate surface geology to structures at depth. Phase 1 Lithoprobe, a one-year program, began in 1984. At the time of writing, preparation of a draft Phase 2 proposal for a continuing five-year program has been completed and discussions concerning it are in progress. In order to meet the objective of relating surface geology to structures at depth, the Lithoprobe project will be spearheaded by multichannel seismic reflection methods. Additional geoscientific investigations will provide essential supporting data to complement the reflection results and enable integrated interpretations.

A large-scale research program for extending studies of geology into the third dimension has been widely discussed by Canadian earth scientists since 1981 (Fyfe and Rust, 1981; McLaren, 1981; and CANDEL, 1981). In May 1982, the Canadian Geoscience Council selected Lithoprobe as a major, coordinated multidisciplinary research effort of national scope and importance. It established a Lithoprobe Steering Committee (LSC) to oversee the development of the program. Subsequently, correspondence and discussions took place between the LSC, the Natural Sciences and Engineering Research Council (NSERC) and the Department of Energy, Mines and Resources (EMR). The outgrowth of these discus-

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Veritas Geophysical Limited and Veritas Seismic Limited acquired and processed the reflection data on Vancouver Island. Their competence and cheerful cooperation with the requirements of a nonstandard research project are greatly appreciated. Funds for Phase 1 Lithoprobe have been provided by the Natural Sciences and Engineering Research Council and by the Earth Sciences Sector, Department of Energy, Mines and Resources.

sions was a commitment of funds from the Earth Sciences Sector of EMR and a decision by the LSC to select two regions, Vancouver Island and the Kapuskasing Structural Zone, for study in a one-year program. Following this, a Collaborative Special Project grant application, "Phase I LITHOPROBE — a Coordinated National Geoscience Project", was submitted to NSERC and funded for 1984-85 (see Clowes, 1984).

This article will concentrate on the research program for Phase I Lithoprobe. In so doing, we will provide background information on the two transect corridors, and present some of the first results and interpretations. We will conclude with a brief discussion of the plans for Phase 2 Lithoprobe.

THE RESEARCH PROGRAM FOR PHASE I LITHOPROBE

Phase I Lithoprobe includes three research components: 1) Vibroseis seismic reflection profiles on southern Vancouver Island, where preliminary studies and a major seismic refraction program have been completed

(VISP — see below); 2) seismic refraction and preliminary reflection studies on the Kapuskasing Structural Zone (KSZ) in northern Ontario, an upthrust section of middle to lower continental crust that is of fundamental significance for understanding the nature and evolution of Archean crust; and 3) supporting geological, geochemical and other geophysical investigations in both these regions to enable integrated interpretations of all geoscientific information. The seismic field work referred to in (1) and (2) has been completed; analyses and interpretation are in progress. Work on the supporting geoscience studies represents both new and continuing research and is progressing well.

VANCOUVER ISLAND

BACKGROUND

An active zone of plate convergence exists off the west coast of Canada. The oceanic Juan de Fuca and Explorer plates are being subducted beneath the continental America plate (Fig. 1) at convergence rates of

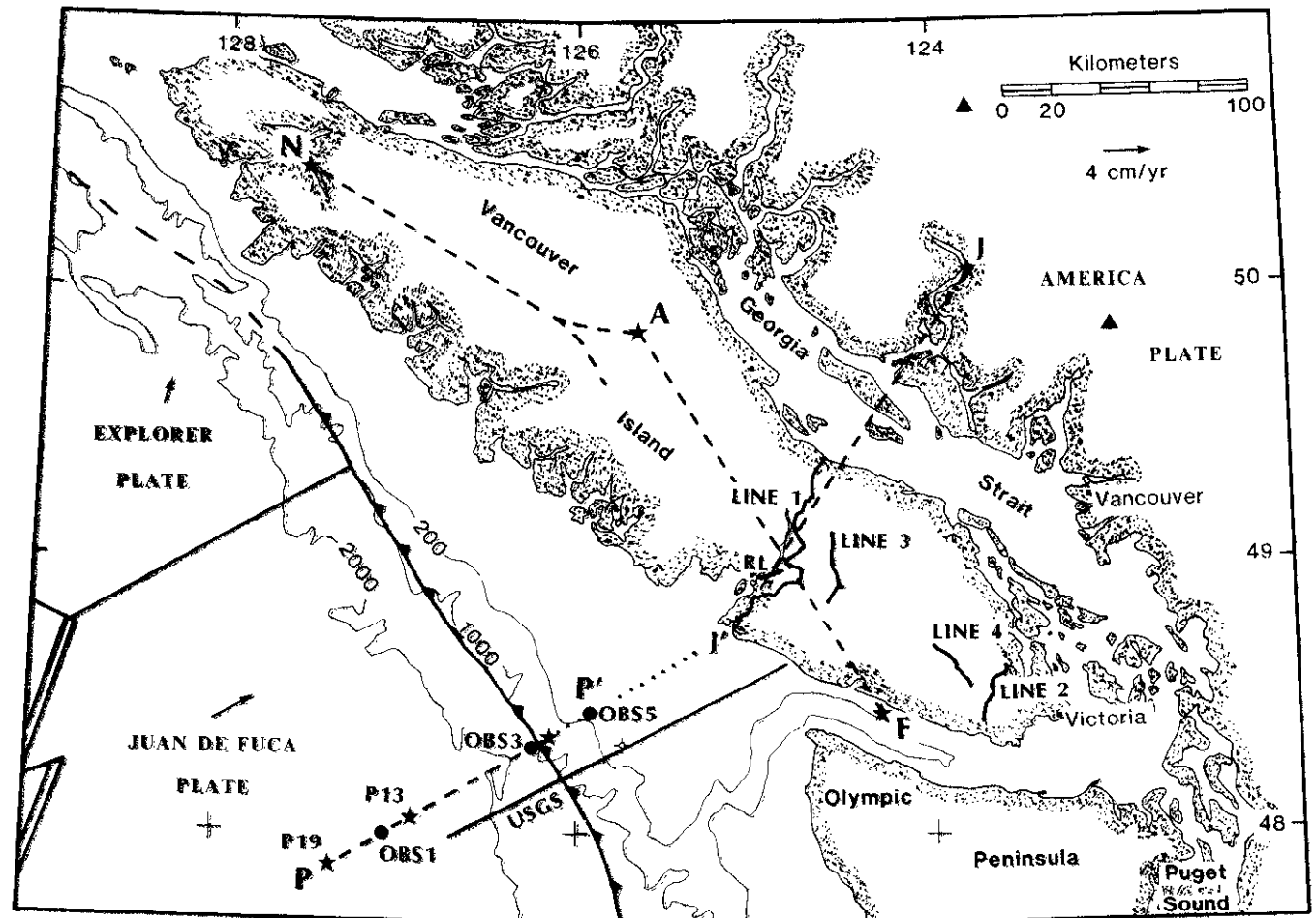


Fig. 1. Tectonic and profile location map. Arrows show directions and magnitudes of plate motions relative to North America. Solid triangles identify the locations of two inland volcanos. Heavy, short dashed lines show refraction profiles on Vancouver Island and the mainland along which individual portable seismographs were deployed at about 3- to 5-km spacings. For profile NAF, shot points were located at three lettered locations marked with stars. Instruments along J.J.' recorded 19 large explosive charges fired along the offshore line P.P'; stars near OBS3 and at P19 identify the ends of the explosion run. An additional 18 smaller charges were shot during the run for recording on the three ocean bottom seismographs (OBS, solid circles). USGS identifies the location of a 2400% offshore multichannel reflection profile (Snively and Wagner, 1981); the well symbol on the shelf is the location of the Shell-Anglo Cygnat drill hole. On Vancouver Island, RL is a 1200% explosion test reflection profile; Lines 1 to 4 are 3000% Vibroseis reflection profiles run in 1984 as part of Lithoprobe. Bathymetric contours are in metres.

about 4 cm/a and less than 2 cm/a respectively (Riddihough, 1977, 1984). Riddihough and Hyndman (1976) discuss the evidence for past and present subduction, while Keen and Hyndman (1979) provide a comprehensive geophysical review of the region. Seismicity studies in Washington state (Crosson, 1981) and in the southern Vancouver Island and Georgia Strait region (Rogers, 1983) show a Benioff zone dipping 12° to the northeast, consistent with the relative plate motions.

The 1980 Vancouver Island Seismic Project (VISP) was undertaken to provide a seismic structural model from the deep ocean of the Juan de Fuca plate to the inland volcanic arc of the America plate, and in particular to provide better delineation of the subduction zone and other structures in the region of Vancouver Island. A series of onshore-offshore refraction and reflection experiments was carried out; details of the program are included in Ellis *et al.* (1983). The success of VISP in terms of the feasibility reflection experiments (Clowes *et al.*, 1983) and the derivation of a plausible seismic structural model (Spence, 1984; Spence *et al.*, 1985) contributed significantly to the selection of Vancouver Island for the Phase 1 Lithoprobe study. Here we will review briefly some of the relevant results.

Figure 1 shows the location of refraction profiles for which interpretations have been completed. An offshore crustal structure model was developed for a 100-km segment along PP' from OBS1 to OBS5. The principal refraction data set consisted of seismograms recorded on the three ocean bottom seismographs (OBS1, OBS3 and OBS5) from 37 explosive charges detonated along PP' at spacings of ~ 2.5 km. This effectively produces a reversed data set between OBS1 and OBS5. To provide better control on the interpretation of upper crustal structure near each OBS, shots from a 32-L airgun were fired into the individual OBSs, typically with 250-m spacings. For OBS1, good refraction arrivals were recorded from shots up to 20 km distance. For OBS3, only the data from shots southwest of the instrument along PP' to a distance of about 12 km were useful for interpretation; for OBS5 only the data southwest to a distance of about 15 km were usable. Interpretation of the OBS refraction data included both traveltime and amplitude modelling through the use of a 2-d synthetic seismogram computer algorithm.

A continuous seismic profile (CSP, single-channel streamer) using a 5-L airgun was shot along PP' from P to a position 9 km southwest of OBS3. This section thus provided constraints on sediment structure for refraction modelling from OBS1 to the base of the slope (approximately the 2000-m contour). The interpreted seismic models were also constrained by two nearby multichannel reflection sections. One section was recorded approximately parallel to PP' and a few kilometres northwest of it; the line extended for about 45 km from near P13 to near OBS3 (Chevron Canada Resources file data). The second multichannel section was recorded along the line marked USGS (Snaveley

and Wagner, 1981). Log data from the well (Shouldice, 1971, 1973) indicated on the outer shelf near the USGS line also provided useful constraints. Finally, the interpreted two-dimensional velocity structural section was converted to a density section and the gravitational response calculated to ensure that the seismic model was consistent with the observed gravity data. Waldron (1982) provides details of the complete interpretation procedure and results.

The upper part of the interpreted seismic structural section is shown in Figure 2c. Note that the number following the semicolon (when included) is the velocity gradient in km/s/km. Thus the gradient in the dark stippled block from 0 to 40 km distance is high, resulting in a velocity of about 6.6 km/s at a depth of 6 km. In contrast, the gradient in the light stippled block from 40 to 80 km distance is low, resulting in a velocity of 5.0 km/s at the same depth. This suggests a major structural change beneath the outer edge of the continental shelf — from the relatively high velocities of the upper oceanic crust to a block of material with an over-all lower velocity. The complete crustal model indicates the block extends to about 9 km depth. The position of this relatively low velocity block agrees well with that of a middle Miocene melange unit as interpreted from a multichannel reflection profile by Snaveley and Wagner (1981). By using the velocities from our seismic refraction model we have converted the Snaveley and Wagner (1981) interpretation of the seismic time section (Fig. 2a) to a depth section (Fig. 2b), which corresponds well with the refraction model (Fig. 2c). This comparison demonstrates the importance of combining seismic refraction data with seismic reflection data to provide a more complete interpretation of both.

The 350-km offshore-onshore line PJ consisted of 32 land-based seismographs deployed across Vancouver Island and on the mainland (Fig. 1). These instruments recorded two shots at the eastern end (J) of the line and 17 shots (P series) along the westernmost 100 km of the profile. Important constraints on the interpretation were provided by the offshore crustal model and the two-dimensional interpretation of profile NAF along Vancouver Island (McMechan and Spence, 1983). Interpretation procedures included an iterative inversion technique for travel-time modelling and the calculation of synthetic seismograms for 2-d models. Spence (1984) and Spence *et al.* (1985) provide details and results.

Figure 3a shows a generalized presentation of the interpreted structural section for profile PJ across the subduction zone. A few features are worth noting. The bend in the subducting slab occurs more than 35 km landward of the base of the continental slope; at this location the dip of the oceanic plate increases from 3° to 15° . The upper mantle reflector (velocity contrast of 8.3 to 7.7 km/s) in the velocity model may correspond to the base of the subducting oceanic lithosphere. An anomalous but necessary feature of the model is a segment of high-velocity material (7.7 km/s) above the downgoing

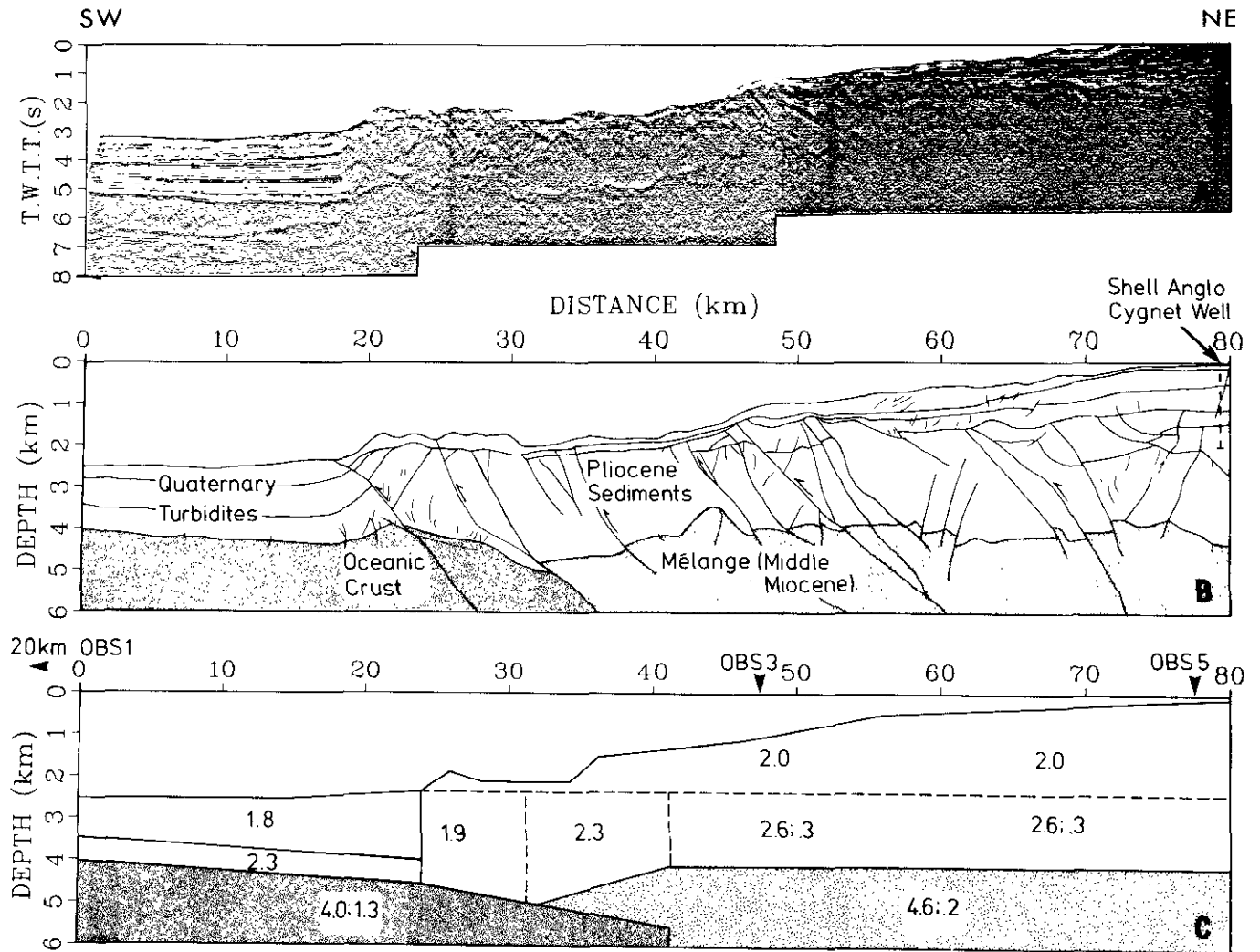


Fig. 2. (a) Unmigrated 2400% seismic reflection profile along line USGS of Figure 1 (from Snively and Wagner, 1981). (b) Geological interpretation of (a). The interpretation of the distance-time section by Snively and Wagner (1981) was converted to a distance-depth section using the refraction velocities of (c). (c) Upper crustal velocity structure for the continental margin along PP', interpreted from data on OBS 1, 3 and 5; to be compared with (b). Velocities (km/s) are given for the top of each region, followed after the semicolon by the velocity gradient (km/s/km) if one was used. The latter is important to note. For example, at 0 km distance the velocity at a depth of 4 km is 4.0 km/s, while at 6 km depth it is 6.6 km/s. In contrast, at 80 km distance the velocity at a depth of 4 km is 4.6 km/s, whereas at 6 km depth it is 5.0 km/s. Note the good correspondence between the two interpretations

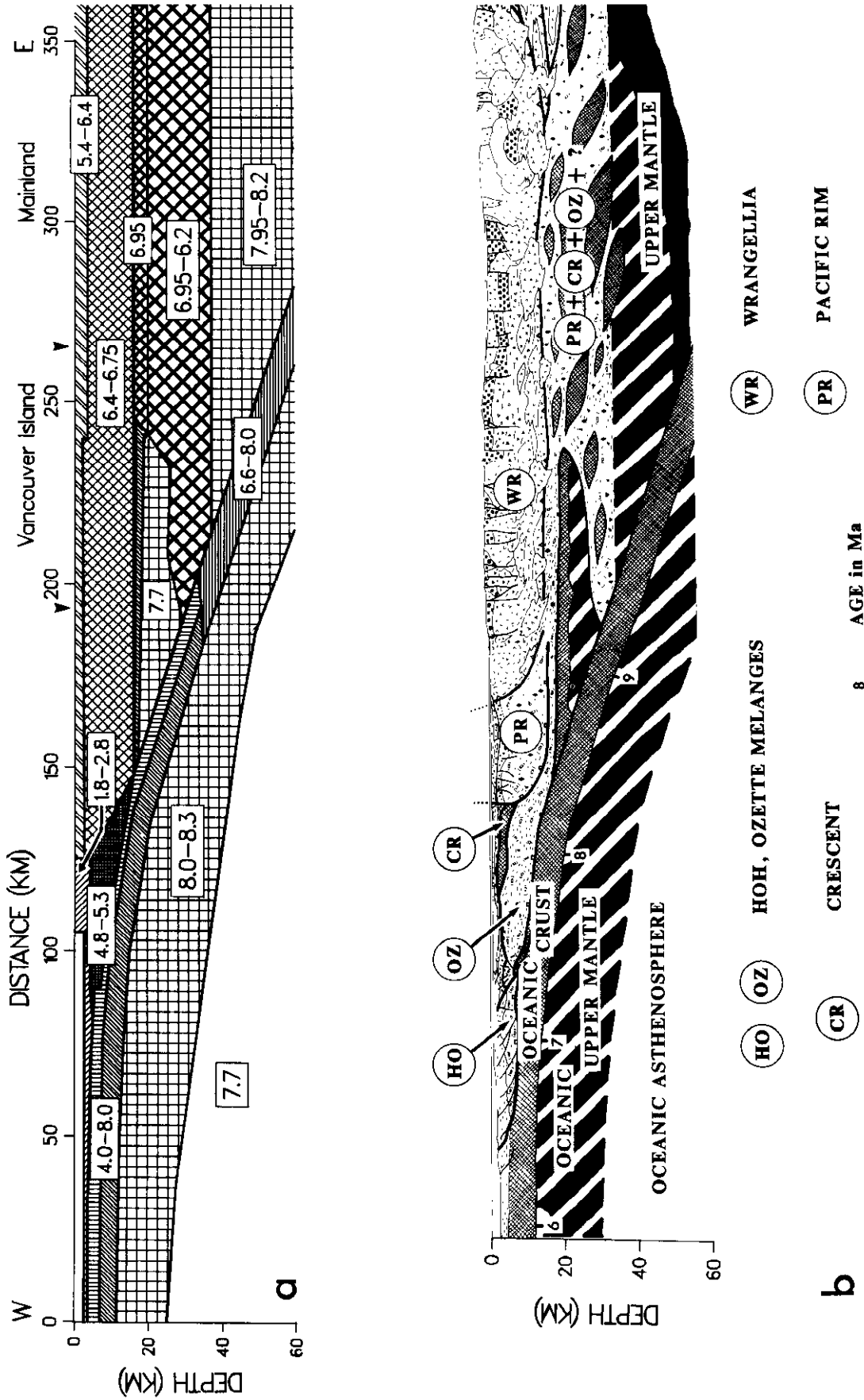


Fig. 3. (a) Generalized seismic structural model for line PJ of Figure 1; details of all blocks included in the modelling are not shown. P' (or OBS5) of Figures 1 and 2c is located at a distance of about 125 km. Numbers are velocities (km/s) at the top and bottom of a block distinguished by its shading. Vancouver Island lies between the arrowheads. Line NAF (Fig. 1) crosses PJ at about 225 km distance. (b) Stylized tectonic cross section modified from the Continent-Ocean Transect B2 of Monger et al. (1985). The cross section predates acquisition of the Lithoprobe reflection data and its interpretation (Fig. 8). No vertical exaggeration in either section.

crust in the depth range 20 to 25 km. Along profile NAF (Fig. 1), McMechan and Spence (1983) concluded that a similar region of high-velocity material was required at 20 km depth along their profile. Spence *et al.* (1985) speculate that such features may represent remnants of a subducted slab, perhaps detached when the subduction zone jumped westward to its present position (Keen and Hyndman, 1979).

Figure 3b is a stylized tectonic model (Monger *et al.*, 1985) based on surface geology, the geometry represented in Figure 3a, and other geophysical information. Included in the model is the speculative concept that underthrusting has resulted in vertical stacking of the older terranes, which are underlain by the currently descending Juan de Fuca plate. Offshore, these terranes include the Hoh melange (Fig. 2b) of upper Oligocene to middle Miocene age and the Eocene Ozette melange. Rocks believed to be equivalent to the Metchosin volcanics and Crescent terrane have been drilled (Shouldice, 1971, 1973). Where the Crescent terrane is

exposed in the Olympic Mountains of northern Washington, it includes tholeiitic pillow basalts, flows, tuff and breccia with intercalated volcanic sandstones of Eocene age. The Pacific Rim terrane comprises slope and trench deposits of Late Triassic to Early Cretaceous age (Brandon, 1984). Together with possible remnants from a phase of subduction older than the present one, most of these terranes are considered to have been underthrust below Wrangellia in some over-all melange-type mixture.

Wrangellia (Jones *et al.*, 1977) is the core of the Insular Belt, the westernmost province of the Cordillera. It is composed principally of a thick sequence of late Paleozoic metavolcanics and metasediments, the Sicker Group, and another thick overlying sequence of Triassic volcanics, the Karmutsen Formation. Paleomagnetic measurements on Karmutsen volcanics by Yole and Irving (1980), among others, have established the allochthonous nature of Wrangellia. Tectonic models (Yorath and Chase, 1981) indicate that it accreted to

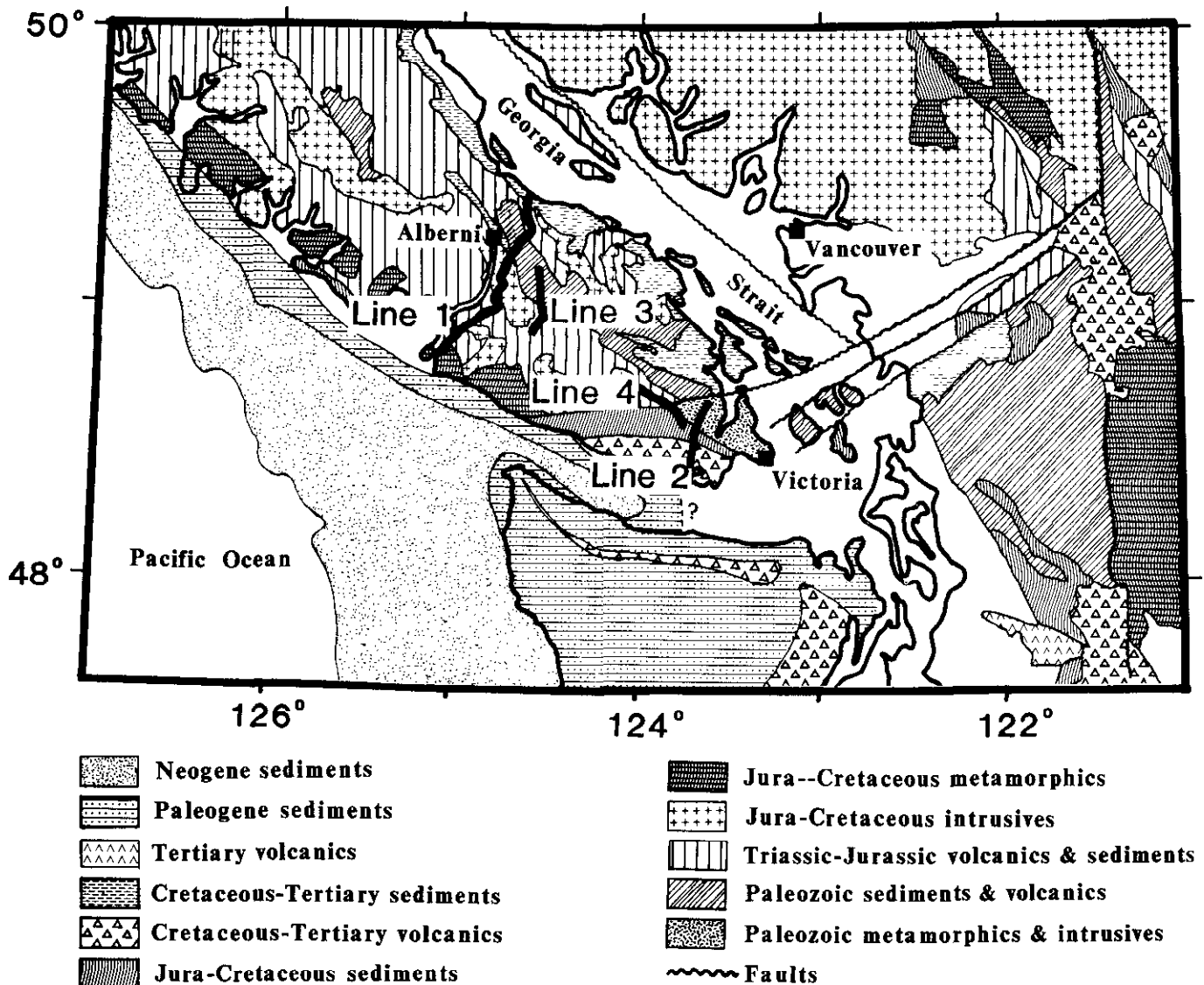


Fig. 4. Geological sketch map for southern Vancouver Island and adjacent regions (adapted from Muller, 1977 and Yorath, 1980). The thick black lines show the location of Vibroseis reflection profiles run on the island in June 1984 as part of Phase 1 Lithoprobe.

western North America during the Mid- to Late Cretaceous. That part of the terrane model of Figure 3b that underlies Vancouver Island was a principal target of the Phase 1 Lithoprobe seismic reflection survey.

SEISMIC REFLECTIONS STUDIES

Approximately 205 km of deep seismic reflection profiling were carried out along the four lines shown on Figure 1 and on the simplified geological map of Figure 4. Line 1 crosses Vancouver Island coincident with that part of the offshore-onshore refraction profile PJ. Some three-dimensional control on the interpretation is provided by the short test line (RL on Fig. 1), recorded during the VISP project (Clowes *et al.*, 1983), and Line 3, located approximately parallel to Line 1 and about 20 km east of it. Lines 2 and 4, recorded at the southeastern end of the island, are intended to resolve particular

tectonic features in the region — the Leech River, San Juan and Survey Mountain faults.

Instrumentation used for data acquisition included a 120-channel Texas Instruments DFS V recording system with four Mertz Model 18 Vibroseis sources. Group intervals of 90 m and source intervals of 180 m provided 30-fold coverage. Eighteen 8-Hz geophones per group were laid out and sixteen 8- to 40-Hz upsweeps of 16 s duration were input over an array of one source interval length. Data were recorded at a sampling rate of 4 ms and with a 32-s listen time, the record length was 16-s. Basic processing included demultiplexing, crooked-line geometry and elevation corrections, automatic gain control, trim statics using a correlation procedure with a $T = 1-12$ s window, stacking, digital bandpass filtering from 8 to 40 Hz, and amplitude equalization using the mean over a $T = 4-8$ s.

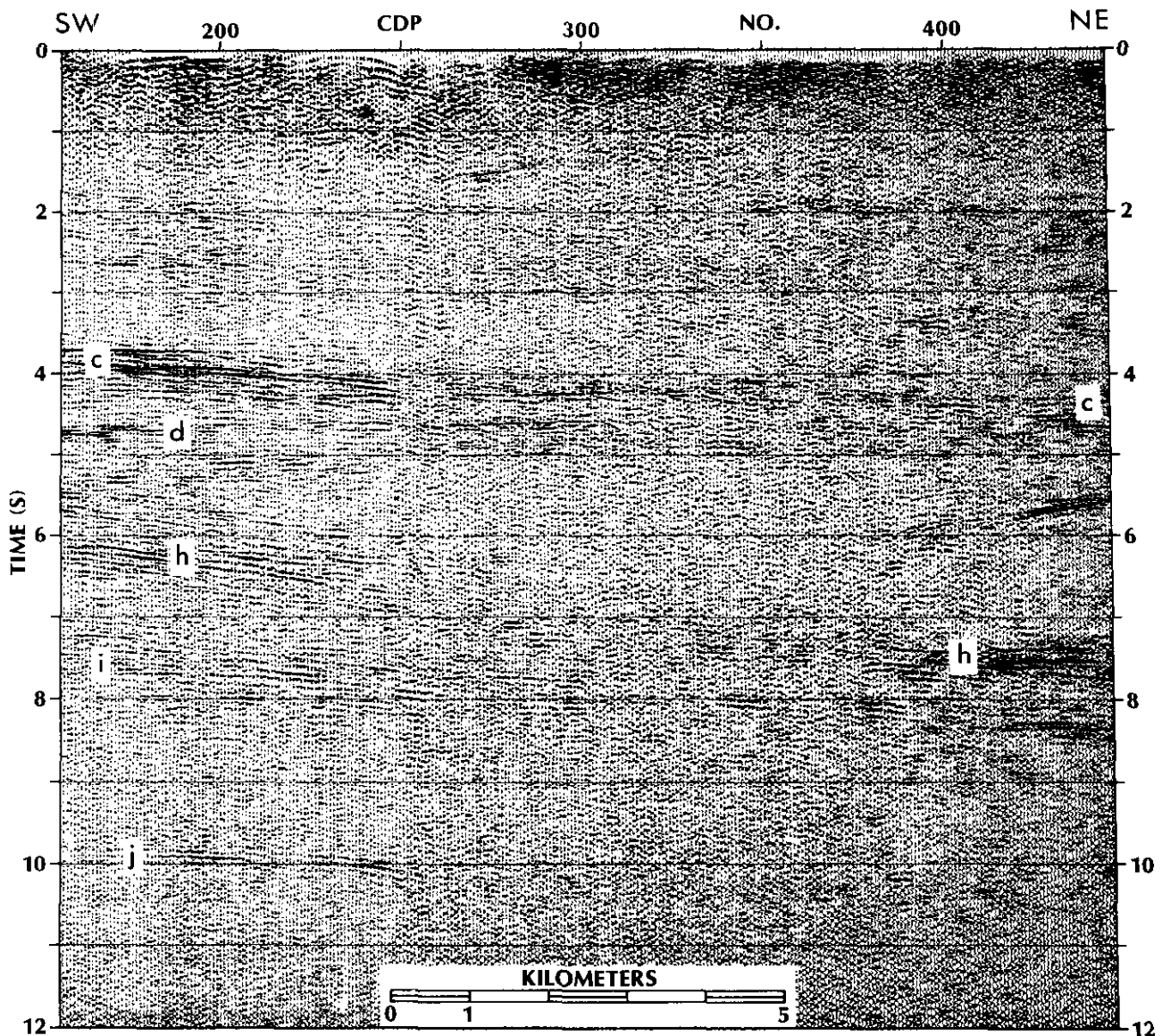


Fig. 5. Segment of the 3000% Vibroseis Line 1 (Fig. 4) located near the southwestern end of the line. Lower-case letters identify some of the more prominent reflectors. Horizontal exaggeration is $\sim 2.5\times$.

Two data examples from Line 1 are shown in Figures 5 and 6. The former illustrates a 13-km section near the southwestern end of the line, the latter shows a 13-km section a little more than half-way across the island. On both sections a number of clearly prominent reflectors are identified. Horizons c and h are continuous across nearly the entire profile. Figure 7 displays the processed record section for Line 4 and includes a description of the local geology along the line. Note that the Leech River fault is particularly well imaged. Horizons c and h are correlative with the same horizons on Figures 5 and 6, and indeed are observed clearly on all four lines.

A line drawing of all reflections observed along Line 1 is shown in Figure 8; a very preliminary and coarse interpretation is superimposed. The lowermost zone of

reflectors (h on Figs. 5 and 6) is considered to represent the top of the actively descending oceanic plate and probably comprises a 3-km thick interval of interdigitated sediments and volcanics resting upon oceanic crust. The northeastward dip of this reflector zone is about 10-12°. Above this subducting plate is a layer, in some places more than 10 km thick, with few coherent reflectors. We interpret this as an underplated zone that may be an older oceanic slab, now accreted to the overlying continental crust. A seaward jump in the locus of subduction prior to the late Miocene that might have left the underplated slab was proposed by Keen and Hyndman (1979). Another layered zone of reflections (c on Figs. 5 and 6), within which some reflectors show dip divergence, is present above the underplated slab. This interval, like the similar one below, may represent mainly sediments with some intercalated vol-

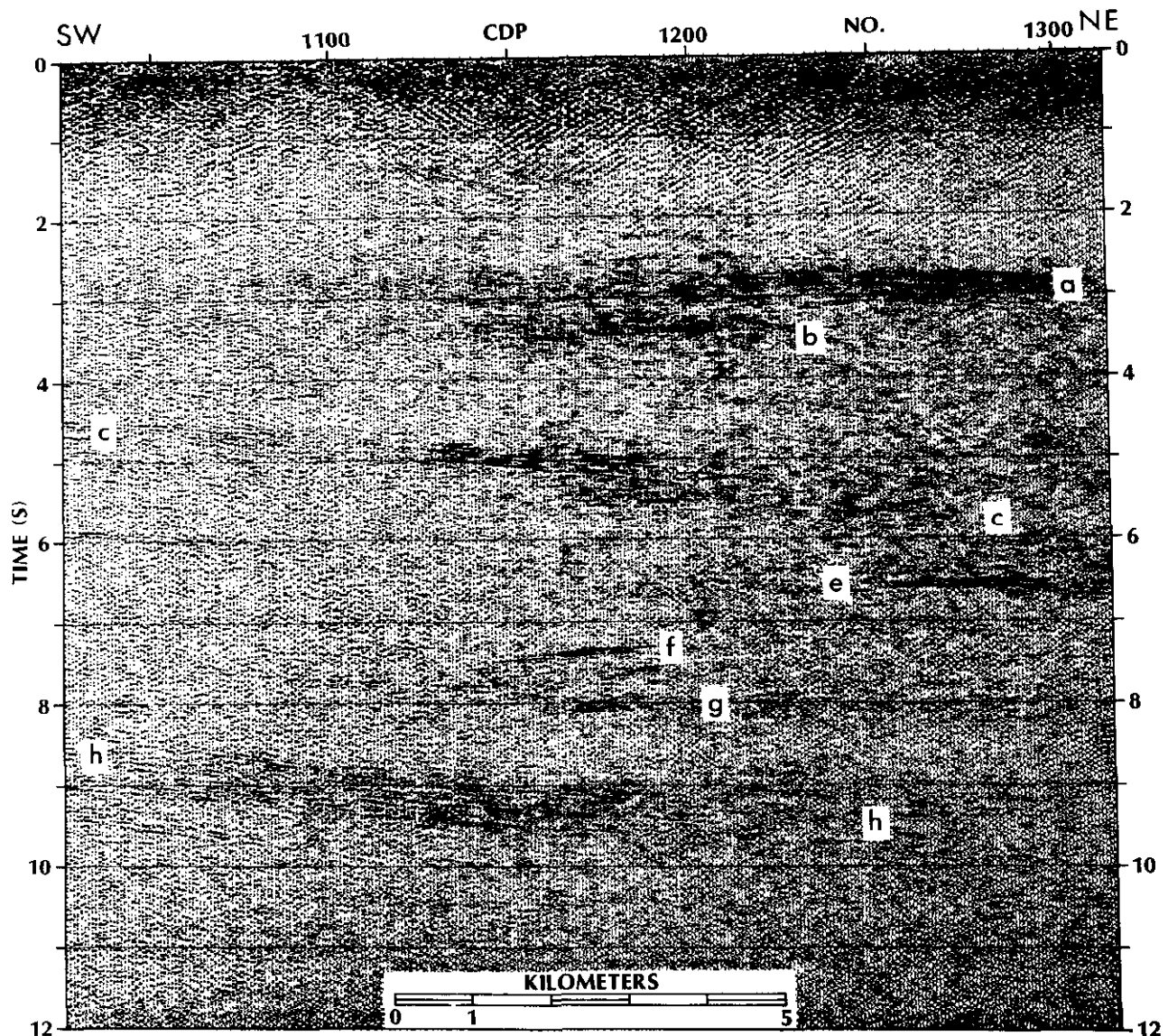


Fig. 6. Segment of the 3000% Vibroseis Line 1 (Fig. 4) starting 45 km from the southwest end of the line. Lower-case letters identify some of the more prominent reflectors; events c and h are continuous across the section. Horizontal exaggeration is $\sim 2.5\times$.

canics that were underplated beneath Wrangellia when the older oceanic slab was being underthrust. This zone may since have acted as a *décollement* zone for listric faults that extend upward into the Paleozoic Sicker Group (Ps), the lower part of Wrangellia. The region above the Sicker Group, where few reflections could be identified, corresponds to the Mesozoic section of Wrangellia, mainly the Triassic-Jurassic volcanics and

Jura-Cretaceous plutons which are observed at the surface (Fig. 4). At the time of final writing, our first attempts at incorporating results from some new detailed geological mapping in the region, carried out in the summer of 1984 (Yorath *et al.*, 1985), into the seismic interpretation are taking place. We find that the interpreted listric faults at depth (continuous oblique lines above and in the *décollement* zone) generally can be projected

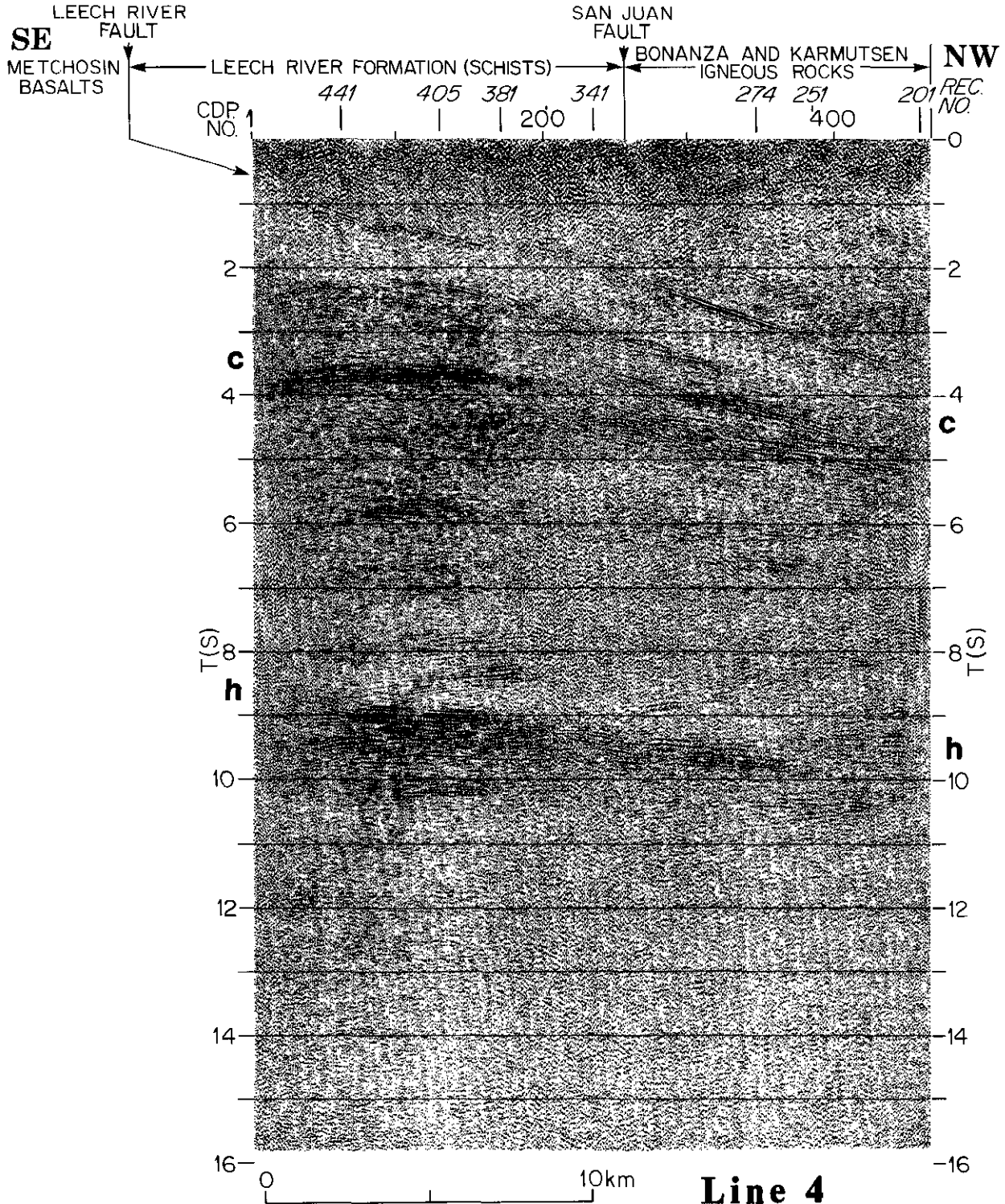


Fig. 7. Processed seismic section for Line 4. Detailed geology (Fig. 4) indicated at the top of the figure. Note the clear imaging of the Leech River fault. Events c and h are correlative with those on Figures 5 and 6. Horizontal exaggeration is $\sim 1.6x$.

to the surface where either faults or plutonic contacts are mapped. The uppermost prominent band of reflectors (a and b on Fig. 6; to the left of B.R.F.Z. on Fig. 8) is considered to represent the Buttle Lake limestone which, on the basis of geological mapping, is unconformably overlain by the upper Triassic Karmutsen Formation and younger Mesozoic rocks. It should be noted that the thick dashed lines roughly define the limits of similarity of reflection type and geometry; they do not necessarily have stratigraphic significance.

The shallow fault (V.F.) at the southwest end of Line 1 is considered to be a surface below which Eocene volcanic rocks have been emplaced beneath the western edge of Wrangellia. These volcanics have been recognized in offshore seismic profiles and were penetrated by three offshore wells drilled in the late 1960s (Shouldice, 1971, 1973; MacLeod *et al.*, 1977; Yorath, 1980; Snively and Wagner, 1981). If we assume that the underplated and *décollement* zones are younger than the early Tertiary volcanics, there are implications that considerable material has been removed from the base of Wrangellia prior to, or concurrently with, the emplacement of the underplated zone, or that the Wrangellia terrane was only about 15 km thick when it docked with North America. The two eastern faults are identified with the Beaufort Range and Cameron River fault zones, known from surface geology (Muller, 1977; Yorath *et al.*, 1985). The former tends to truncate the uppermost band of reflectors to the southwest, while the latter terminates the few reflectors to the northeast. Between these faults is a large, broad and internally disrupted anticlinorium, a feature that may explain the poor reflection quality in the region.

The top of the *décollement* zone (reflections c on Fig. 5, 6 and 7) corresponds well with the refraction model

interface at 16 km depth, as interpreted from profile NAF along the island (McMechan and Spence, 1983) and line PJ across it (Fig. 3a). However, the more detailed reflection data show that some structure occurs on this boundary. Events i on the left and h on the right of Fig. 5 correspond well with the base of the 7.7 km/s sliver of Figure 3a, but its continuation eastward (h on Figure 6) dips to significantly greater depths than shown by the structural model. Reflection j of Figure 5 is from a depth corresponding to the top of the subducting oceanic plate in Figure 3a, but its short lateral extent does not allow a convincing correlation. The other identified reflections on Figures 5 and 6 do not show correlations with boundaries in the refraction model, for which of course the resolution of structural features is much less than for the reflection data.

The general interpretational concept of subhorizontal layers and underthrusting represented in Figure 3 seems to be justified by the new reflection results. However, the lower part of the Vancouver Island segment of Figure 3a is not particularly consistent with the preliminary reflection interpretation. Spence (1984) and Spence *et al.* (1985) presented an alternative model (as well as the preferred one of Fig. 3a), which also satisfied the refraction data. In this model the subducting plate beneath the continental shelf and western Vancouver Island remained at a shallower depth and dipped less steeply than the plate in Figure 3a, in effect replacing the 7.7 km/s high-velocity segment included in Figure 3a, but at a slightly greater depth. However, to satisfy the refraction data, the plate had to bend and dip much more steeply below eastern Vancouver Island. While the alternate model is more consistent with the reflection interpretation, improvement is still required. That is, the new reflection results provide additional constraints

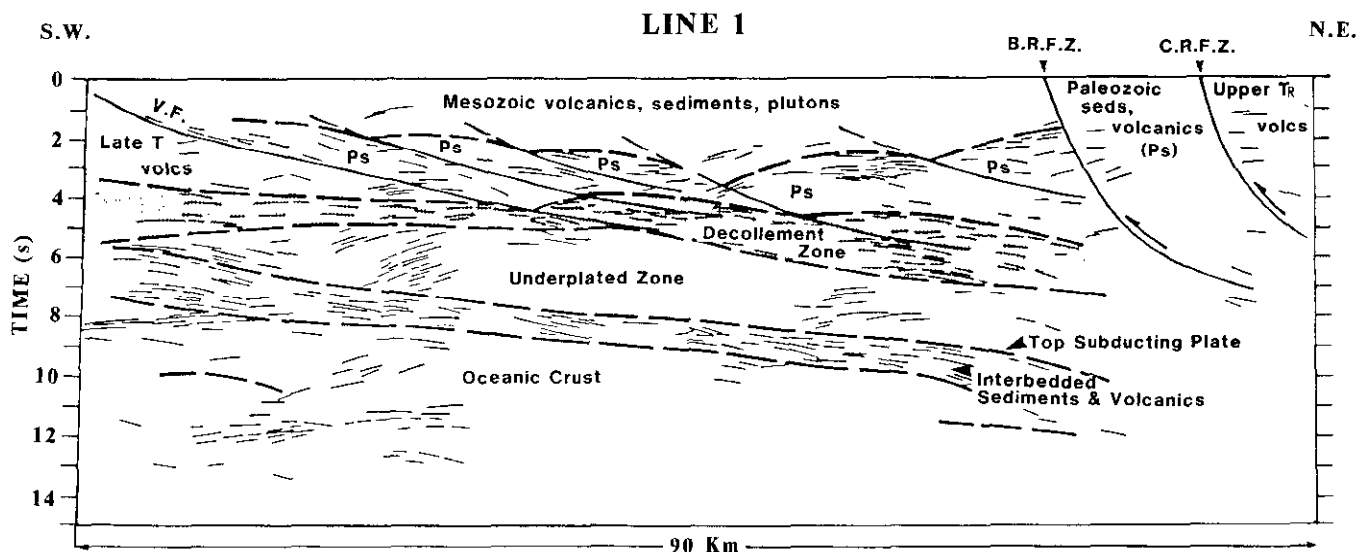


Fig. 8. Preliminary interpretation of Line 1 (Fig. 4). See text for discussion. P.S. - mainly Paleozoic Sicker group; V.F. - Vancouver Fault (Brandon, 1984); B.R.F.Z. - Beaufort Range Fault Zone; C.R.F.Z. - Cameron River Fault Zone. The heavy dashed lines roughly define the limits of similarity of reflection type and geometry; they do not necessarily have stratigraphic significance.

for the interpretation of the refraction data set, and indicate that additional modelling of the refraction profiles PJ and NAF (Fig. 1) is required to incorporate these constraints. On the other hand, the initial refraction models provide the necessary velocity information for stacking and converting the reflection sections to depth as well as yielding the large-scale architecture of the region. The two data sets applied in conjunction will enable a more thorough interpretation of both.

SUPPORTING GEOSCIENCE STUDIES

The integration of supporting geoscientific investigations with the seismic reflection and refraction studies is fundamental to the Lithoprobe program (*see Yorath et al.*, 1985). These are being carried out both in the government sector and by university research groups. On Vancouver Island, they include refinement of the existing reconnaissance studies of the geological structure and stratigraphy through the construction of detailed corridor maps at a scale of 1:50 000, identification of major structures, their structural style and stratigraphic relationships, and related studies. Geochronological relationships between the Jura-Cretaceous intrusives and metamorphics (Fig. 4) are being refined. Results to date suggest that the two are closely related in time but originated at different crustal levels (R.L. Armstrong, *pers. comm.*, 1984). Detailed geochemical studies on volcanic and plutonic rocks are being undertaken to help determine depths of emplacement, source materials and alteration history. Stratigraphic, biostratigraphic, thermal maturation and clay mineralogical studies are being carried out on parts of the Upper Cretaceous Nanaimo Group on the northeast coast of the island (Fig. 4). Preliminary examinations have been made of fluids near major faults for evidence of dewatering of the subducting Juan de Fuca plate. On the geophysical side, a magnetotelluric investigation using a new Phoenix Geophysics system was carried out along Lines 1 and 3 to obtain information on the electrical conductivity of the crust and upper mantle. Preliminary analyses of the data indicate a conductive layer at depths around 15 km, coincident with the upper oceanic crustal layer / *décollement* zone interpreted from the refraction and reflection data (R.D. Kurtz, *pers. comm.*, 1984). Electromagnetic induction modelling of Vancouver Island and adjacent regions, especially the sea, is being undertaken to assist the interpretation of the magnetotelluric data. Gravity profiles have been collected along Line 1 and along the east coast of the island to improve the data density and provide additional constraints on structural interpretations. Existing aeromagnetic coverage of southern Vancouver Island has been expanded to include all of the area encompassing the four seismic profiles. A first-order geodetic levelling profile was carried out, which will be combined with previous and future measurements to determine contemporary uplift and subsidence rates of the region. A profile of heat

flow and crustal radioactive heat production measurements and interpreted crustal temperatures is being constructed. Additional paleomagnetic studies of Tertiary and Paleozoic rocks are being undertaken. Finally, a seismicity cross section is being compiled along a corridor about Line 1. It will be combined with the interpreted reflection profiles to enable better tectonic modelling of the region.

Integration of these extensive and complementary data sets will enable a thorough interpretation of the three-dimensional geotectonic architecture in this complex region of accreted terranes and active subduction.

KAPUSKASING STRUCTURAL ZONE

BACKGROUND

According to some estimates, 70% of the present continental crust existed by the end of the Archean. However, the nature and extent of the large-scale processes involved in the formation of that crust are not known for lack of critical information about the lower crust. All models of the geological, thermal and mechanical behaviour of the lower crust depend on knowledge of its composition and structure. Yet there is continuing debate as to whether lower continental crust was constructed vertically by processes of differentiation early in the Earth's history, by progressive lateral accretion of magmatic arcs throughout geologic time, by some other process unique to the Archean, or possibly by different processes in different regions. To investigate these processes, it is necessary to identify any relics of deep crust that are exposed at the surface.

In Canada, we have an excellent opportunity to contribute significantly to this debate. The nucleus of the North American continental craton is the Archean Superior Province, part of the Canadian Shield. It is a vast complex of metamorphic and igneous rocks, mainly granitoid gneisses and plutons, within which are preserved numerous metamorphosed and deformed volcanic and sedimentary rocks. The Superior Province can be divided into several subprovinces or superbelt in which the nongranitoid component is either largely metavolcanic or largely metasedimentary. Within the metavolcanic subprovinces are found the characteristic metavolcanic assemblages (greenstone belts) and their associated mineral deposits for which the Superior Province is famous.

A unique feature of this province is the Kapuskasing structural zone (KSZ), a linear region of high-grade metamorphic rocks that transects the east-west structural grain in the central part of the province (Fig. 9). Geological, gravity and aeromagnetic maps demonstrate the continuity of geological features and geophysical anomalies across the uplift. The Wawa and Abitibi greenstone belts to the west and east respectively have similar lithological characteristics and nearly identical ages of deposition and intrusion, suggesting that they are parts of a formerly continuous belt, now interrupted by the Kapuskasing uplift.

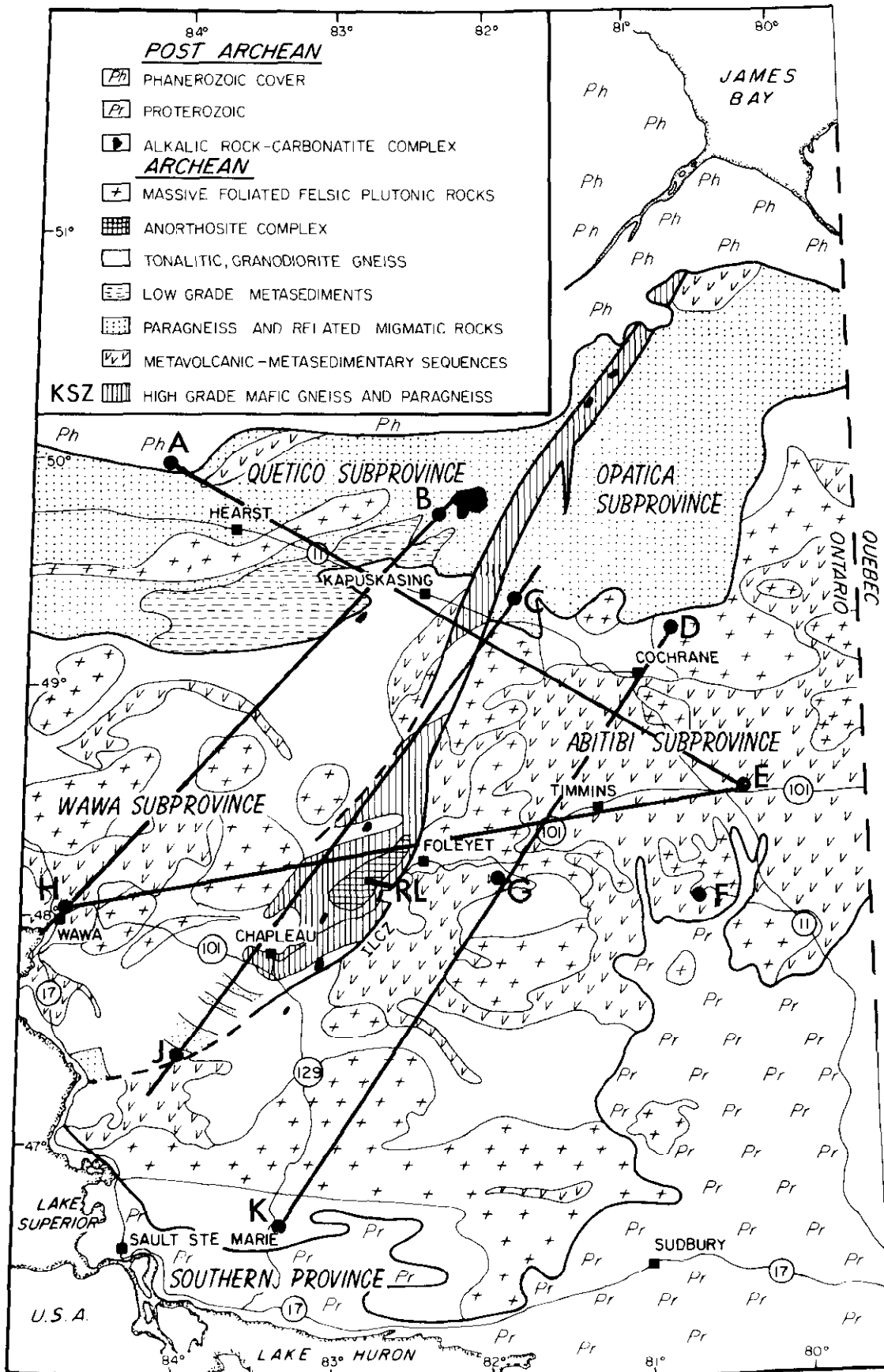


Fig. 9. Generalized geological map of the region surrounding the Kapuskasing structural zone, outlined by the heavy solid and dashed lines. ILCZ-Ivanhoe Lake Cataclastic Zone. Approximate locations of the 1984 refraction lines and shotpoints (closed circles identified with letters) and the location of the test reflection line (RL) are superimposed.

Recent studies by Percival (1981, 1983), and Percival and Card (1983) have shown that high-grade rocks in the Kapuskasing zone near Chapleau formed at lower crustal depths (25-30 km). As well, they have shown that there is a continuous transition in metamorphic level from low-grade greenschist facies rocks in the Wawa greenstone belt west of the KSZ, to upper amphibolite and granulite facies in the KSZ proper. Percival and Card (1983) have demonstrated that the Ivanhoe Lake cataclastic zone on the eastern margin is a major fault across which the metamorphic level drops abruptly to greenschist facies. They interpreted the Ivanhoe Lake cataclastic zone as a reverse or listric thrust fault that cuts through the entire continental crust. Thus, the Kapuskasing uplift provides an oblique cross section through the upper two-thirds of the Superior Province continental crust (Fig. 10).

The interpreted model of Figure 10 needs to be tested. If it is substantially correct, the relatively continuous oblique section provides a unique opportunity to study directly middle and lower crustal levels of greenstone and gneiss belts. Hopefully, seismic studies in the KSZ will map reflections within the middle to lower continental crust from depth to surface. Combined with other geoscientific studies, the results could provide a standard reference for the interpretation of deep reflection profiles of continental crust.

SEISMIC STUDIES

In July 1984, a large-scale seismic refraction program centred on the KSZ was carried out; Figure 9 shows the lines and shotpoints on the geological map. Some spe-

cific objectives of this study include the regional-scale crustal structure and upper mantle velocities, tracking the west-dipping mid-crust velocity discontinuities predicted by Percival and Card (1983), and providing independent estimates of crustal velocity structure to aid in the analysis and interpretation of reflection surveys. Twenty shots ranging in size from 800 kg to 2000 kg were recorded on approximately 58 seismographs, each including a 1- or 2-Hz vertical component seismometer, with some units also using horizontal component transducers. At the time of writing (November), the data are being transcribed from field tapes to 9-track computer tapes. Monitors played back in the field indicate that high-quality seismograms generally were obtained.

Another component of Phase 1 Lithoprobe in the KSZ was a pilot deep-crustal reflection experiment in the Chapleau area (see Fig. 9). Approximately 10 km of 2400% data were recorded on a 96-channel DFS V system using a Bolt Technology Corporation large (LSS-IT) truck-mounted land airgun. Preliminary processing has been completed. A steeply dipping reflection, approximately consistent with that predicted in the model of Percival and Card (1983) for the Ivanhoe Lake cataclastic zone, and another crustal reflection within the underlying Abitibi greenstone belt are evident on the stacked section (F.A. Cook, 1985). Experience gained from the pilot survey will assist planning for major deep reflection surveys across the KSZ, as proposed in Phase 2 Lithoprobe.

SUPPORTING GEOSCIENCE STUDIES

The Kapuskasing structural zone and surrounding region is an excellent area for integrated geosience

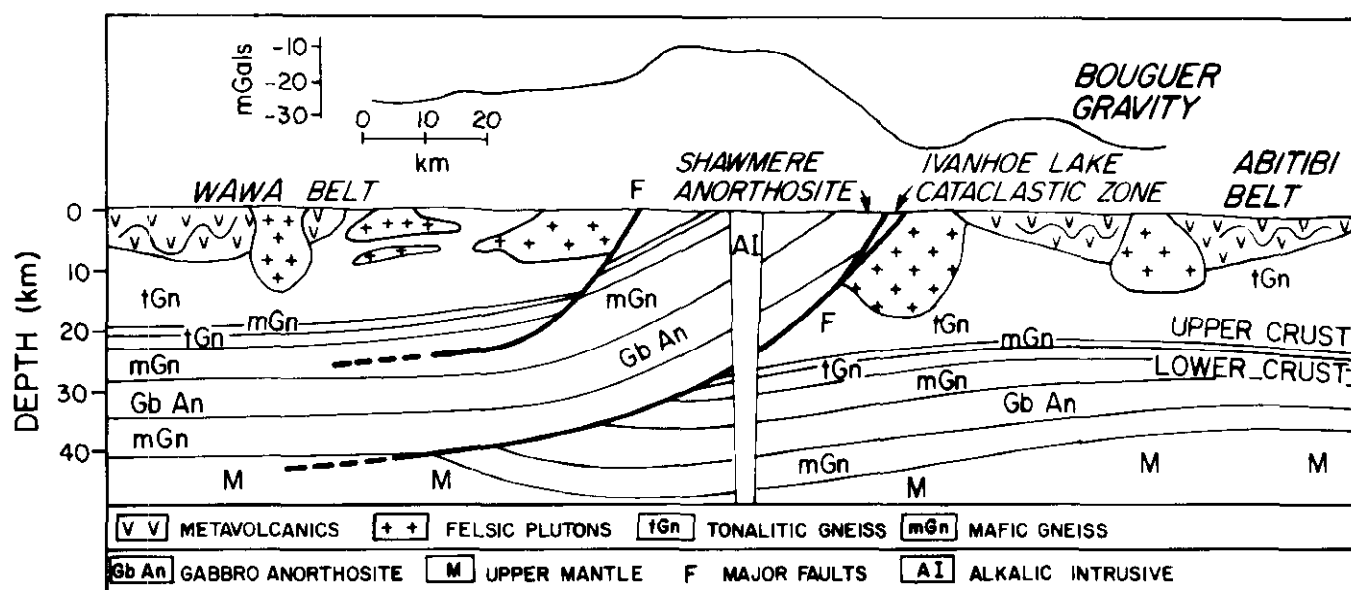


Fig. 10. Interpreted crustal section through the Kapuskasing structural zone showing high-grade rocks of the zone thrust over low-grade rocks of the Abitibi belt; Bouguer gravity anomaly above (section from J.A. Percival, *pers. comm.*, 1984; updated from Percival and Card, 1983).

studies. Indeed, much work has already been carried out in a broad range of earth science disciplines as part of continuing university and government research programs.

For 1984-85, nine of the fourteen supporting geoscience grants from the NSERC funds for Phase 1 were awarded to university researchers to expedite and expand the scope of the investigations of the KSZ. A geomagnetic depth sounding experiment using a magnetometer array was completed during the summer. Preliminary analyses of the data indicate that no significant conductivity anomaly exists across the zone (D.V. Woods, *pers. comm.*, 1984). Wide-band magnetotelluric soundings were recorded at sites on the KSZ and its flanking regions. A special seismic experiment using the land airgun was carried out in conjunction with the near-vertical incidence reflection survey. Standard refraction recorders using up to 12 geophones per location were deployed at distances of 1, 5, 20 and 50 km from the source to test the applicability of these systems, particularly for recording wide-angle reflections. A range of paleomagnetic studies are in progress to further our understanding of tectonic motions and deformations associated with the KSZ, and to establish remanent magnetizations, since these may be products of the cooling history of the rocks. Such studies are complemented by the Ar^{40}/Ar^{39} stepheating method of thermochronometry, which is well suited to determine the cooling and erosional histories of the KSZ and its neighbouring regions, and thereby its uplift history. Geochemical isotope studies are being undertaken to characterize the effects of high-grade metamorphism on elemental abundances, stable isotope ratios and radiogenic isotopes, particularly in relation to fluid movement and melting.

In addition, both federal and provincial government scientists will be continuing existing research projects and initiating new ones. Some of these projects have taken place as part of Phase 1; others are planned for the continuation of KSZ investigations as part of Phase 2. The scope of the experiments on the Kapuskasing structural zone and their integration with the seismic data will enable a comprehensive interpretation of this unique feature of the Archean crust.

PHASE 2 LITHOPROBE — THE CONTINUING PROGRAM

Phase 1, the first component of the continuing Lithoprobe program, has proved immensely successful. A draft Phase 2 proposal for submission to NSERC and EMR has been prepared and discussions are progressing. The basic tenet of the draft proposal follows the concepts developed by CANDEL (1981). It involves the effective integration of modern geophysical, geological and geochemical concepts and technology to extend knowledge of the surface geology, in various key areas in Canada, into the third dimension — depth. It includes the participation of scientists from universities, government and industry.

PROPOSED TRANSECTS

The research plans for Phase 2 Lithoprobe will be developed in national multidisciplinary planning workshops, the first of which was held in March 1984 as part of Phase 1. Plans that emerged from the workshop resulted in the selection of the following transects for study during Phase 2 (Figure 11):

Kapuskasing Structural Zone, to elucidate the nature, evolution and uplift of Archean continental crust exposed to a depth of at least 20 km across a crustal panel tilted above a northwest-dipping thrust fault; and to establish the geometry at depth of the underlying thrust fault, whereby this crustal section may provide the calibration for subsequent geophysical surveys of the nature and thickness of the Archean crust in the Superior Province.

Lithoprobe East, to establish the structure, geometry and relationships at depth of the crustal blocks (terranes) that comprise the Appalachian Orogen in and around Newfoundland as a means of understanding the Paleozoic assembly of its continental crust; to determine the nature of the crust beneath Carboniferous pull-apart basins associated with transcurrent faulting; and to compare the rifting processes that initiated the Appalachian Orogen with those that led to the development of the Mesozoic rifted and passive margin of the modern Atlantic Ocean basin.

Southern Canadian Cordillera, to establish the structure, geometry and relationships at depth of the crustal blocks (terranes) that make up the southern Canadian Cordillera as a means of comprehending the largely Mesozoic assembly of its continental crust. Particular emphasis will be placed on 1) the collage of displaced terranes that compose the Intermontane and Insular belts and that probably amalgamated offshore to form two huge mosaic blocks (Terranes I and II), which accreted to ancestral North America in mid-Jurassic and mid-Cretaceous times, respectively; 2) the Omineca Crystalline Belt straddling the boundary between the ancient miogeocline of North America and Terrane I; 3) the nature of the crust beneath the Coast Plutonic Complex, which spans the boundary between Terrane I and Terrane II, and 4) determining the crustal level and extent of Tertiary listric normal faults in the south-central Cordillera.

Abitibi-Grenville, to establish the three-dimensional geometry of the Abitibi Greenstone Belt, its internal structure including the major faults associated with numerous mineral deposits, and the depth and geometry of the base of the underlying continental crust; to determine the geometry and structure of the Grenville Front convergent boundary, and to establish if the base of the continental crust there is imbricated or stepped in a fashion similar to that related to the convergent boundary beneath Tibet.

Williston Basin, to provide a review and synthesis of the subsidence and depositional history, and a discussion of basin geometry relative to that of the base of the

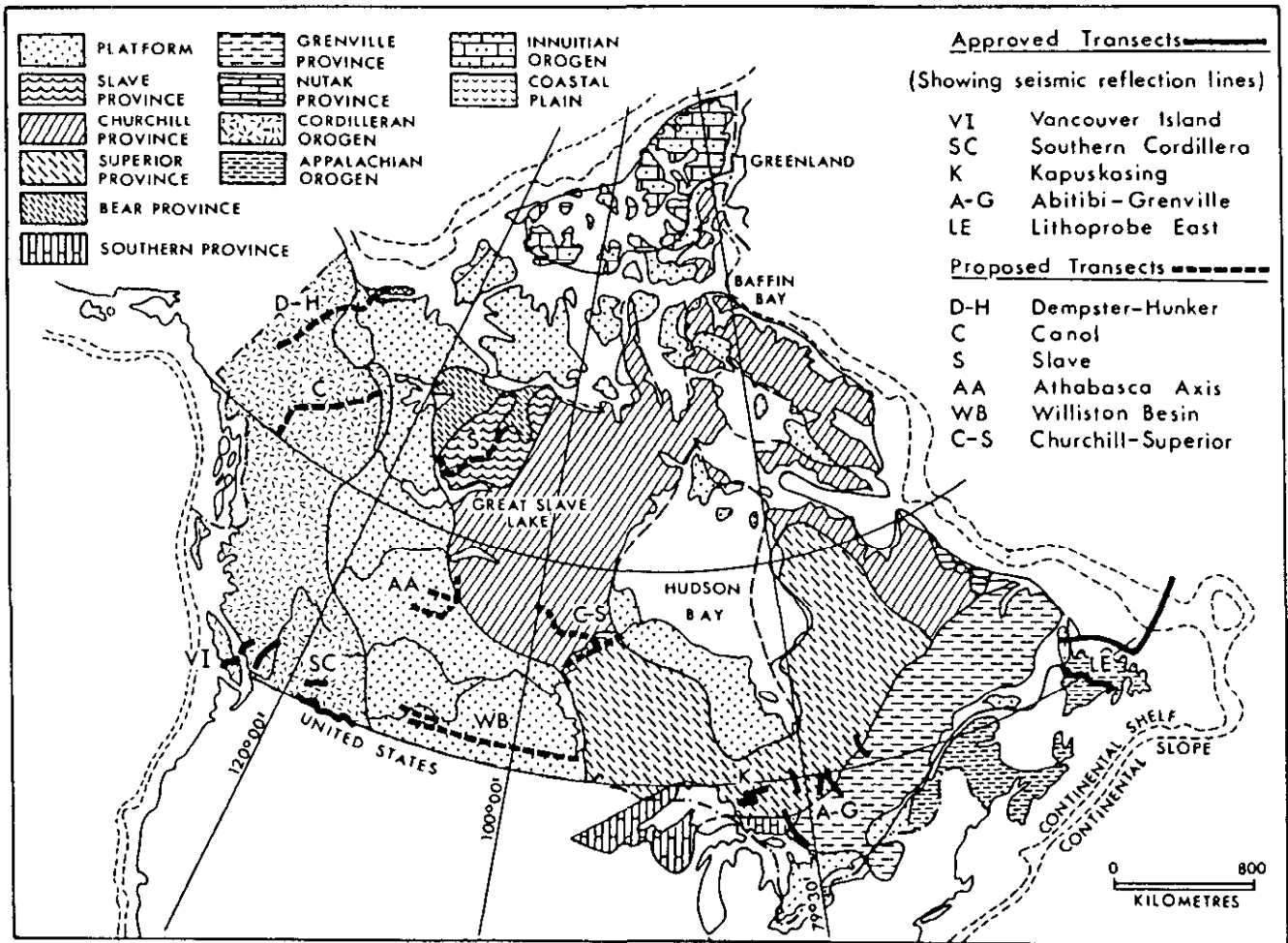


Fig. 11. Lithoprobe transects as described in the Phase 2 proposal.

crust, and of basin siting relative to the Central Plains electrical conductivity anomaly, preparatory to designing a geophysical program to elucidate the origin of this intracratonic basin.

PLANNING PROCESS

Lithoprobe Phase 2 will build upon the results and experience gained from the Phase 1 projects. Each five-year work plan will be reviewed annually. Plans for the first two years will remain reasonably firm, to facilitate logistical planning and the arrangement of contracts. The remaining three years will be flexible, to take advantage of special opportunities or particularly innovative ideas. Accordingly, proposals will be solicited annually for new transects and for new geoscience studies along approved transects.

ORGANIZATION

Lithoprobe is envisaged as a highly decentralized, regionally oriented multidisciplinary research program that will be carried out along a series of transects or corridors across various parts of Canada. Each transect will consist of several legs, each of which is devoted to a

particular domain with its own special character and problems. The scientific leadership will be delegated to transect leaders, but it will also need a central management structure. The latter will comprise a steering or management committee, a project manager who has a largely coordinating role, and a variety of standing subcommittees.

LITHOPROBE AND INDUSTRY

From its onset, the Lithoprobe program has strived to include all three "estates"—universities, government, and the petroleum and mining industries. A representative from each of the last is a member of the Lithoprobe Steering Committee. The Canadian Society of Exploration Geophysicists, the Canadian Society of Petroleum Geologists, and the Scientific Research Committee of the British Columbia - Yukon Chamber of Mines have all endorsed the Lithoprobe project. In addition, the CSEG set up a special committee to provide advice to Lithoprobe. During Phase 1 members of this committee or alternate persons recommended by it provided valuable counsel in the selection of the contractor for the

Vancouver Island reflection program. Industry representatives also contributed to the March 1984 planning workshop that led to the development of the Phase 2 Lithoprobe proposal.

One specific and important example of industry cooperation spawned by the Lithoprobe program is worth noting. PanCanadian Petroleum Limited, through the efforts of Peter J. Savage, W. Lorne Kelsch and Steven Campbell, and in cooperation with Ernest R. Kanasewich of the University of Alberta, have extended the recording length during some of their normal exploration programs to 20 s in order to observe deep reflections. The particular objectives are verification and further study of the Precambrian rift zone underlying the sedimentary sequence of southern Alberta (Kanasewich *et al.*, 1969). To this end about 32 km of 3200% Vibroseis coverage have been recorded along a north-south line parallel to the original line of Kanasewich *et al.* (1969) and approximately 40 km west of it. Such data represent valuable additions to the Lithoprobe program.

SUMMARY

Lithoprobe is an exciting and enterprising concept, building on recognized Canadian expertise, and aimed at addressing the next intellectual frontier in the Earth Sciences. The investigation of the third dimension of continental geology requires "big science" to take advantage of the technological developments, particularly in seismology, that now permit probing of the lithosphere as never before. By so doing, Canada, with its large share of the Earth's continental crust, will fulfil its responsibility to carry out Lithoprobe-type crustal studies in concert with other developed nations.

Lithoprobe is designed to involve a large cross section of the Canadian earth science community. By bringing together a mix of expertise, with its resulting synergism, there is more promise of achieving a deeper understanding of the continental crust than otherwise. Moreover, early grass roots support and current commitments in response to the geographically widespread nature of the studies appear to ensure the interest and participation of a large segment of the earth science community — including, in time, even greater participation from the provincial and industrial sectors. Lithoprobe, therefore, has the prospect of being a catalyst to revitalize the earth sciences in Canada.

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