A REFRACTION SURVEY ACROSS THE CANADIAN CORDILLERA

BY

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ABSTRACT

Record sections from partially reversed refraction lines in northern British Columbia show that the amplitudes of upper mantle arrivals vary smoothly with distance. The pattern of crustal arrival amplitudes is not smooth. Normalization of the seismograms to remove the amplification caused by shot size and instrument response show the effects of recording sites on P_n amplitudes are minimal.

Models derived from ray theory indicate a crust which thins from about 40 km in the Omineca Crystalline Belt to about 25 km in the Insular Trough. The average P_n velocity is 8.06 km/s. The average crustal velocity is 6.4 km/s. The secondary energy would indicate the models are greatly simplified.

A time-term profile between the Omineca Crystalline Belt and the Coast Mountains suggests a Mohorovicic transition which is characterized by two significant topographic wavelengths. The shorter (200 km) wavelength correlates roughly with the Cordilleran structural elements of Wheeler et al. (1972). The larger (800 km) wavelength may have tectonic significance.

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Data for this project was collected by teams from the Earth Physics Branch and the University of British Columbia and analysed in Ottawa.

Basic computer programs for data handling and interpretation pre-existed at the Seismology Division and were modified by the author to cope with the present study.

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CHAPTER 1

INTRODUCTION

1-1. Background

With increasing interest in plate tectonics, the emphasis on large scale refraction studies has declined in favour of surface-wave and array analyses to study the lithosphere-asthenosphere relationship. However, refraction and reflection lines used to determine the velocity-depth structure and its lateral behaviour may yet provide a means of relating surface features to lithospheric plates in some detail. In particular, the study of this signature in the neighbourhood of plate boundaries may prove most interesting.

The geology of the Canadian Cordilleran region, both onshore and offshore, would strongly favour its candidacy as a region where plates are and have been active (Souther, 1972; Monger, 1972; Berry et al., 1971; Johnson and Couch, 1970; Stacey, 1972). When subdivided into geological provinces, the region includes the Rocky Mountain Trench, the zone containing the Cassiar, Omineca and Columbia Mountains, the Intermontane Belt, the Coast Mountains and the Insular Belt (Monger, 1972). The present refraction study covers the area from Greenbush Lake in the Columbia Mountains to Bird Lake on Graham Island in the Insular Belt (Fig. 1).

1-2. Previous work in the area

From a seismic viewpoint, the picture of the Canadian Cordillera has been incomplete as a result of limited surveys and rather incoherent data. The interpretation is rendered additionally difficult due to the complexity of at least the upper crust as evidenced by the surface geology.

Work adjacent to the area presently under study has been outlined by Shor (1962), by White et al. (1968) and by Jacoby (1970). In the area of the Insular Belt northwest of Prince Rupert, Shor suggested that the M occurred at a depth of 26 km. In southern British Columbia, studies were concentrated along profiles from Puntchesakut Lake and from near Barkerville to Osoyoos and from Greenbush Lake to Hope. Mine blasts at Merritt enabled partial reversal of the line from Puntchesakut Lake. The Hope line was unreversed.

White et al. proposed alternative interpretations for their data. Both models were characterized by minor topography on the M discontinuity at a depth of from 28 to 30 kilometers. Their first model indicated a lateral change in upper mantle velocity from 8.1 km/s beneath Williams Lake to 7.8 km/s in the south. The alternate model depicted a velocity of 8.0 km/s.

During 1967, shots detonated at the south end of Vancouver Island were recorded along the line used in 1966, re-occupying many old sites. This data, plagued with considerable noise, gave an apparent velocity of 8.43 km/s, pertinent to the upper mantle east of Merritt. A preliminary time-term analysis indicated a southwesterly dipping M discontinuity with an upper mantle velocity of 8.27 km/s (Jacoby, 1970).

1-3. Present study

During the summers of 1969 and 1970, refraction profiles were recorded by Earth Physics Branch and University of British Columbia (UBC) teams across the three interior geological provinces. In August 1969, shots detonated at Greenbush Lake were recorded by teams from the Earth

Physics Branch along roads running from southwest of Revelstoke to Vancouver Island, from Little Fort to McLeod Lake, from Nazko to Barkerville and from Williams Lake to Bella Coola (Fig. 1). A monitor station was located at Lumby to record all shots. Teams from UBC recorded along roads from Prince George to Prince Rupert.

During July of 1970 an attempt was made by the same teams to reverse the Prince Rupert-Prince George line from Bird Lake and the Bella Coola-Williams Lake line from Ripley Bay. The Nazko-Barkerville line was reversed from Ripley Bay and an upper crustal velocity was obtained along this same line from a shot in Puntchesakut Lake.

The present study includes data from Little Fort to Prince Rupert using the Greenbush shot point and from Prince Rupert to Prince George using the Bird Lake shot point. Fig. 1 shows the location of shots and stations.

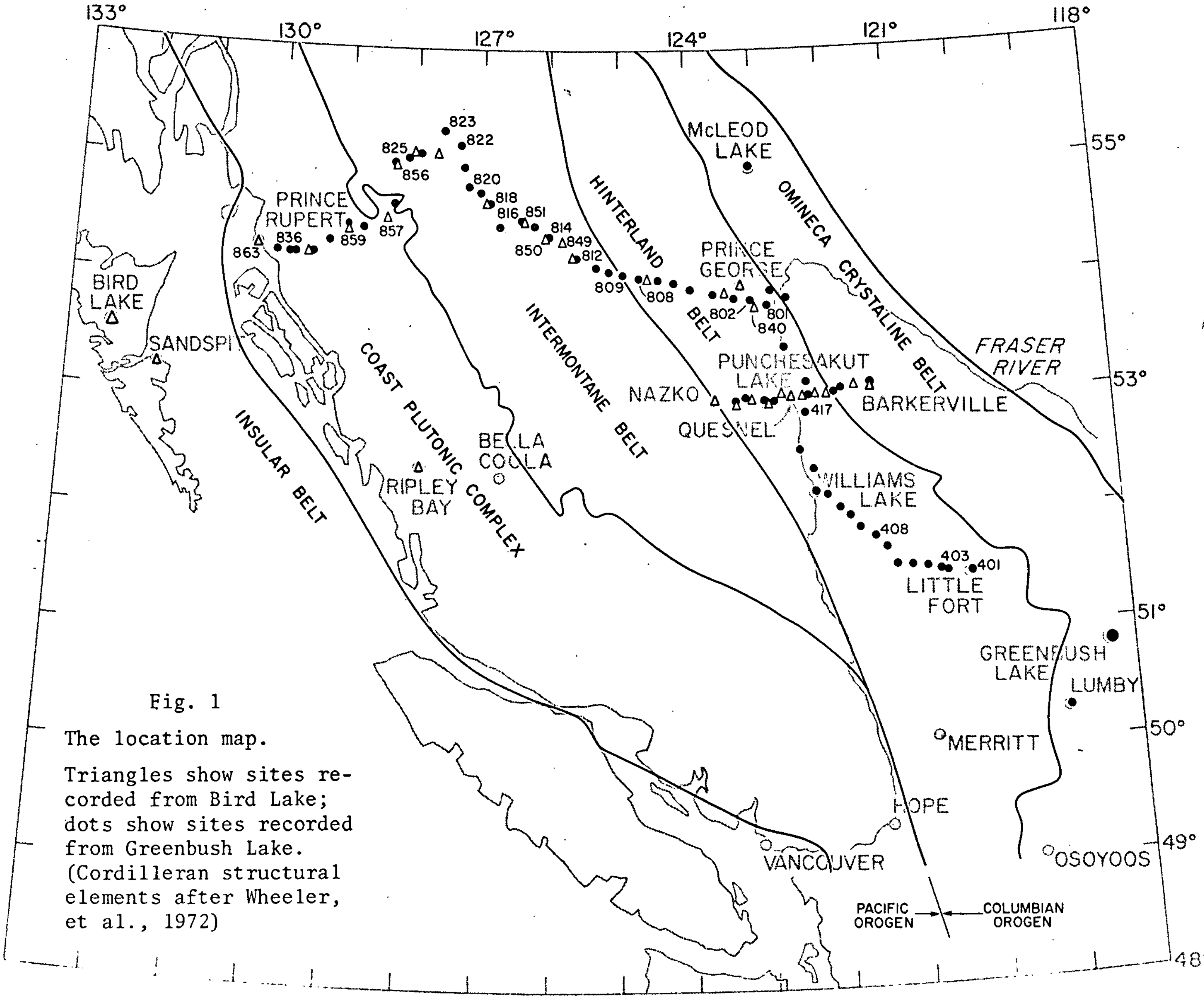

Fig. 1

The location map.

Triangles show sites recorded from Bird Lake; dots show sites recorded from Greenbush Lake. (Cordilleran structural elements after Wheeler, et al., 1972)

CHAPTER 2

SYSTEMS

2-1. Components and configurations

The field recording systems are outlined in Fig. 2. The Earth Physics Branch systems had two variations within the arrangement shown. On one of the systems, Electro-Tech SPA-10 amplifiers were used instead of the AS-330 models. The Electro-Tech amplifiers were modified to produce the same overall gain as the AS-330 models and the difference between responses is negligible for the frequencies encountered in the present data. The other system employed Electro-Tech EV-17 seismometers with a natural period of one second, Texas Instrument amplifiers and an Ampex tape recorder. The shape of the velocity sensitivity curve for this system is not significantly different from the curve for the UBC systems (0.8 Hz-12.5 Hz) shown in Fig. 3.

All data presented herein from the 1969 field trip were recorded using a three-component seismometer configuration. In 1970, the UBC teams continued with the three-component arrangement, while the Earth Physics Branch teams used six vertical seismometers set at a spacing of 500 meters. The array nominally provided the option of stacking records or determining a phase velocity to more confidently identify arrivals. It was found, however, that the lack of freedom in choosing locations for the spreads compared to picking isolated or bedrock seismometer sites for the three components resulted in significantly noisier seismograms and little, if any, advantage was gained in discerning P_n first arrivals.

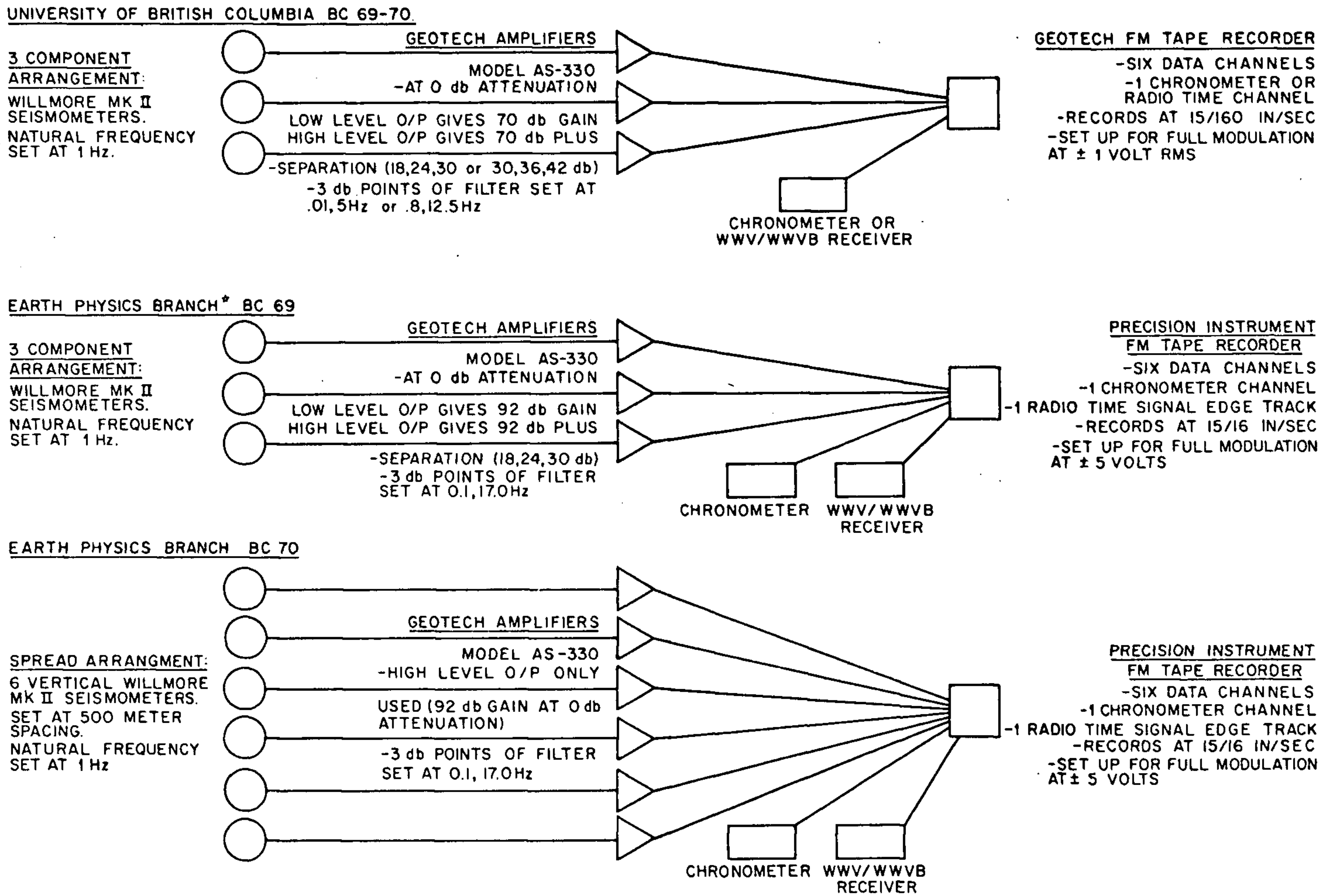

Fig. 2 The chart of the recording systems used in the field.
*Variations on this system are described in the text.

2-2. Calibration

The University of British Columbia systems were calibrated before each field season using a Maxwell bridge in the manner described by Kollar and Russell (1966). In the field, the systems were checked before each shot by monitoring the response to an acceleration step given to the seismometer mass. K tests (Bancroft and Basham, 1967) were also performed before each shot.

Earth Physics Branch systems were checked in Ottawa before each field season, while amplifier response, K test and system response checks were made before each shot in the field. Typical band-pass response curves for the various systems are shown in Fig. 3.

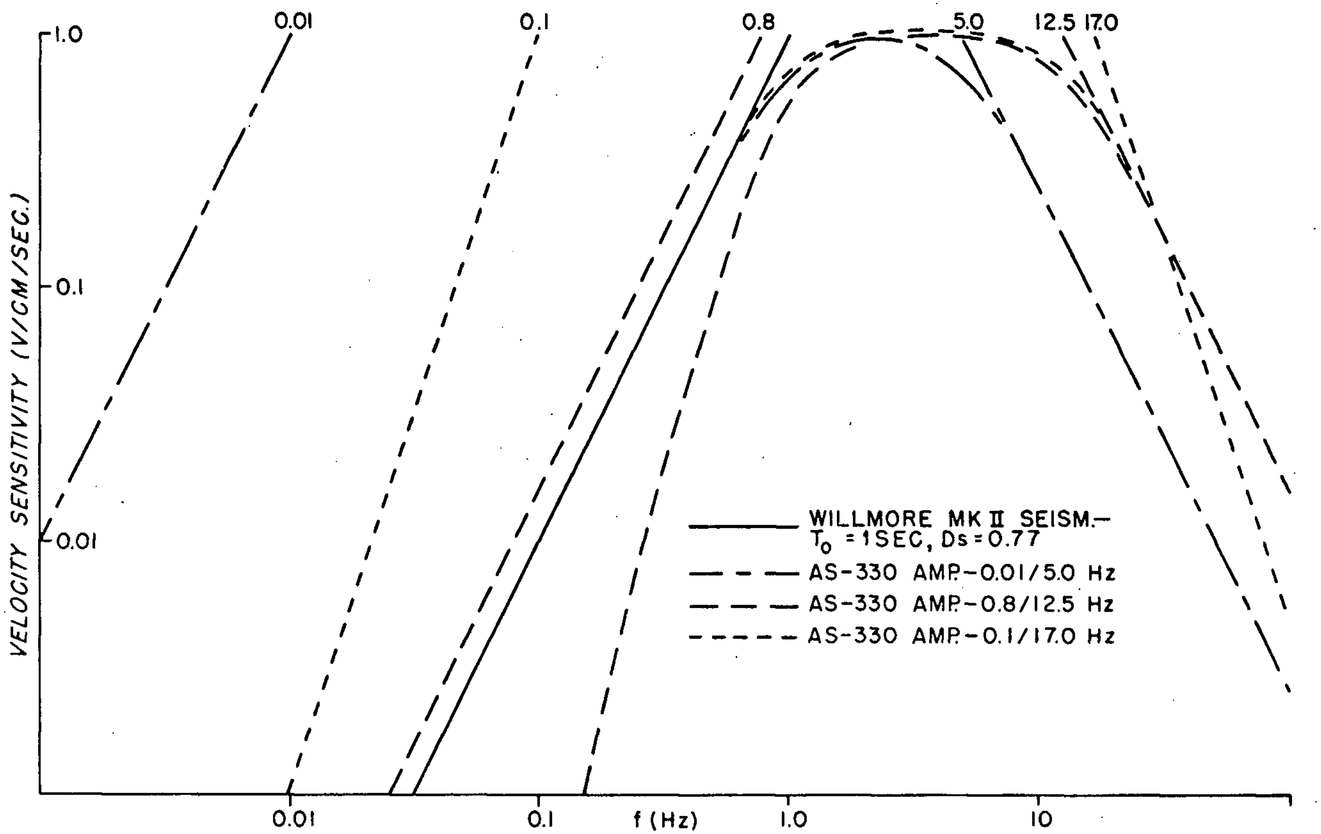

Fig. 3 The response curves of the systems shown in Fig. 2.

CHAPTER 3

RECORD SECTIONS

3-1. System response and shot correction factors

As the field units were continually checked and corrected, it was deemed worthwhile to consider all the system factors from seismometer to computer and use these, along with shot factors, in constructing record sections. The records from any one shot point might then be expected to show some coherent energy pattern - notwithstanding the effects of seismometer site - although record sections would differ by relative shot point response. The system factors are show in Fig. 4. A single number was used to account for the seismometer-amplifier response, since the recorded P coda frequencies are naturally restricted to the passband from 3 to 6 Hz. The response of the systems is essentially flat in this range. No records from the system with a 0.01-5 Hz filter are included in the present study.

The Greenbush Lake shots were relatively rated using amplitudes from helicorder records obtained at a station near Lumby. The largest amplitude was given the rating 1.0 and weaker shots were then normalized by a number which would make all shots effectively the same size. This same form of rating was used for the 1970 Bird Lake shots using helicorder records from a station at Sandspit. This mode of shot rating was preferred to that of using nominal charge weight, as it gives a better estimate of true seismic energy yield. The shot factors are shown in Table 1 and Table 1a.

3-2. Formation of Record Sections

The analog field data were digitized and arranged on permanent data tapes in a manner which facilitated the formation of record sections.

All programs, except the digitizing program, were first written to work on a CDC 3100 computer. The program used to digitize the data operates on a DDP 124 computer at the Earth Physics Branch. The programs used to form permanent data tapes were originally written by K.G. Barr and M.J. Berry and were modified by the writer to cope with the present data and operate on a CDC 6400 computer. The program used to filter the seismograms was written by M.J. Berry. The program which constructs the record sections has evolved at the Earth Physics Branch through the efforts of M.J. Berry and the writer. The limitations of the playback and digitizing systems enabled a digitizing rate of 50 samples per second for tapes recorded at 15/160 inches per second. The tapes recorded at 1-7/8 or 15/16 inches per second were digitized at either 100 or 200 samples per second. Records digitized at 200 samples per second were then filtered to remove 60 Hz energy (from power lines) and the resultant time series were decimated to 100 samples per second. Data digitized at 50 samples per second were expanded to the 100 sample per second standard upon formation of permanent data tapes. The lowest Nyquist frequency is thus 25 Hz, significantly greater than the passband of recorded energy.

Record sections were then constructed in a reduced travel-time form with the system and shot factors applied to the individual time series. For 3-component systems, a vertical trace was used. Where six vertical seismometers were deployed, a "best trace" was chosen.

3-3. Normalization

To distinguish individual seismograms, it was necessary to

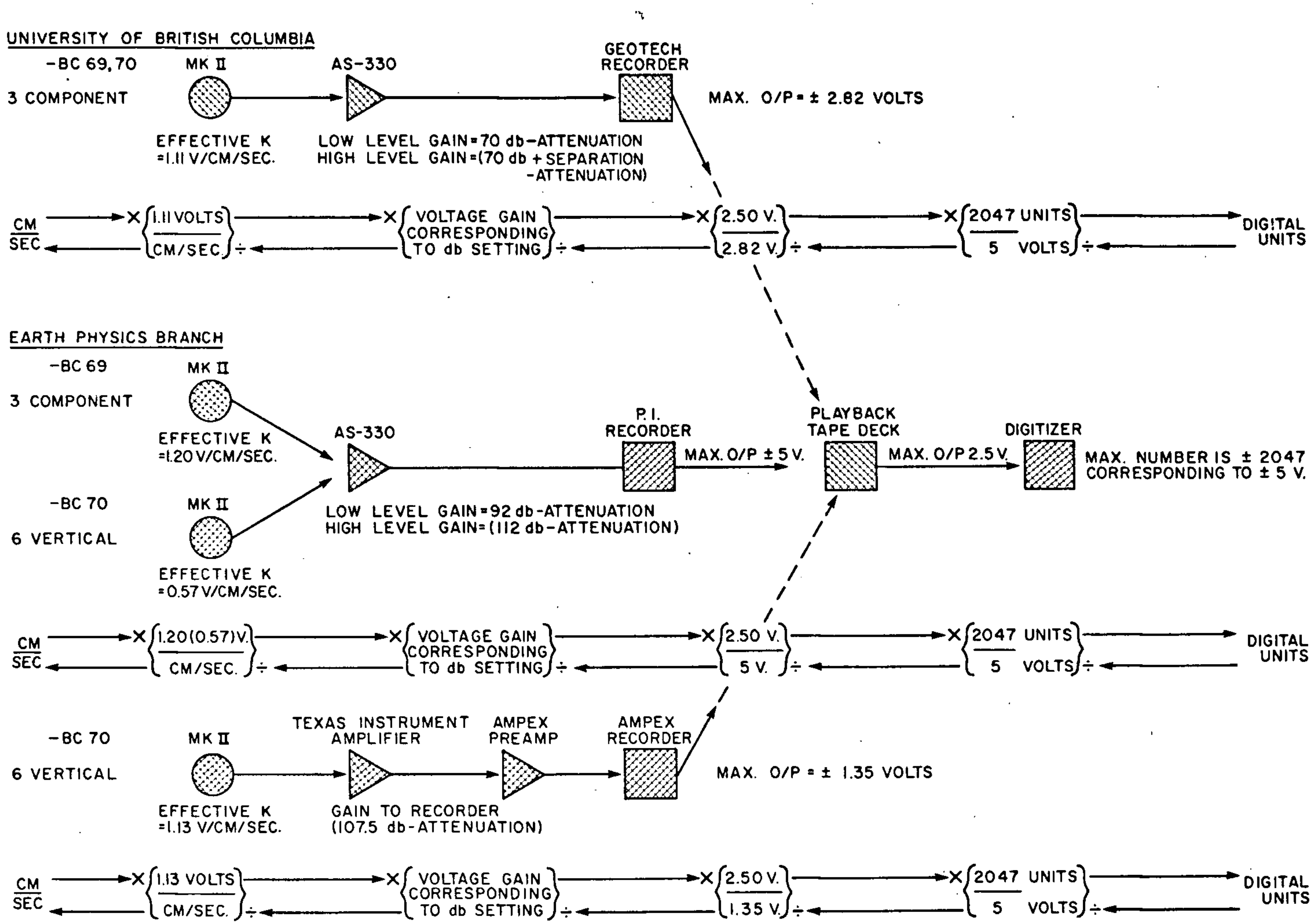

Fig. 4 The system factors for conversion of ground velocity to digital units and back to ground velocity. Note effective K applies to passband centre only.

TABLE 1

BC 69 SHOT DATA

Greenbush Lake - Shot Point

Coordinates 50° 46.90' N 118° 20.66' W   Water Depth 60 m

Number	Date	Time GMT	Charge	Type	Amplitude at Lumby	Shot Factor
1	Aug.5, '69					
2	6	07:05:00.15	17,100 lbs TNT	Pattern	2	4.75
3	7	07:05:00.14	17,100 lbs TNT	Point	1	9.5
4	8	07:05:00.18	12,027 lbs MINOL	Pattern	6	1.55
5	9	07:05:00.23	13,293 lbs MINOL	Pattern	1 1/2	6.3
6	10	07:05:00.23	13,293 lbs MINOL	Pattern	6	1.55
7	11	07:05:00.18	12,660 lbs MINOL	Pattern	2	4.75
8	12	07:05:00.20	13,293 lbs MINOL	Pattern	2	4.75
9	13					
10	14	07:05:00.19	12,660 lbs MINOL	Pattern	2 1/2	3.8
11	15	07:05:00.17	13,293 lbs MINOL	Pattern	2	4.75
12	16	07:05:00.17	13,293 lbs MINOL	Pattern	8	1.19
13	17	07:05:00.17	13,293 lbs MINOL	Pattern	9 1/2	1.0
14	18	07:05:00.16	13,293 lbs MINOL	Pattern	8 1/2	1.12
15	19	07:05:00.17	13,293 lbs MINOL	Pattern	8 1/2	1.12
16	20	07:05:00.15	13,293 lbs MINOL	Pattern	9	1.05
17	21	07:05:00.19	13,293 lbs MINOL	Pattern	9 1/2	1.0
18	22	07:05:00.17	12,660 lbs MINOL	Pattern	8 1/2	1.12
19	23	07:05:00.17	13,293 lbs MINOL	Pattern	7 1/2	1.27
20	24	07:05:00.16	17,100 lbs TNT	Pattern	9 1/2	1.0

TABLE 1a

BC 70 SHOT DATA

Bird Lake - Shot Point

Coordinates 53° 35.83' N Water depth 24 m
132° 23.92' W

Number	Date	Time GMT	Charge	Type	Amplitude at Sandspit	Shot Factor
1	July 25, 1970	07:05:00.00	2,000 lbs NITRONE SM	Pattern	4.7	3.0
2	26	07:05:00.01	6,000 lbs NITRONE SM	Pattern	11.0	1.3
3	27	07:04:59.90	7,000 lbs NITRONE SM	Pattern	10.3	1.4
4	28	07:05:00.00	8,000 lbs NITRONE SM	Pattern	14.2	1.0

normalize trace amplitudes in the following manner. Firstly, in order to discern first arrivals, it was necessary to eliminate the larger shear energy. Hence, the sections are terminated at a reduced travel time of 20 or 25 seconds. Next, the trace containing the largest amplitude wavelet - normally a record in the vicinity of crossover - was chosen, its largest peak-to-peak amplitude set to 1 inch and the rest of the traces in the section were normalized relative to this trace. Finally, to possibly distinguish the first arrival beyond crossover as either a headwave or a bodywave and to make distant records more legible, an additional multiplicative factor of distance or distance squared was applied.

The results as shown in Figs. 5 and 6 indicate that by removing most of the shot and system amplitude effects, a rather smoothly varying energy pattern may be obtained. Closely spaced, adjacent records rarely differ by a factor of two in amplitude. In the case of traces 40702 and 81802 (Fig. 5) which have been arbitrarily reduced, the possibility exists of an incorrectly logged amplifier setting. Traces 81102 and 81202 are considered to be located on sites suitably "tuned" to 3-4 Hz energy. It is notable that only 2 out of 51 sites respond in this manner.

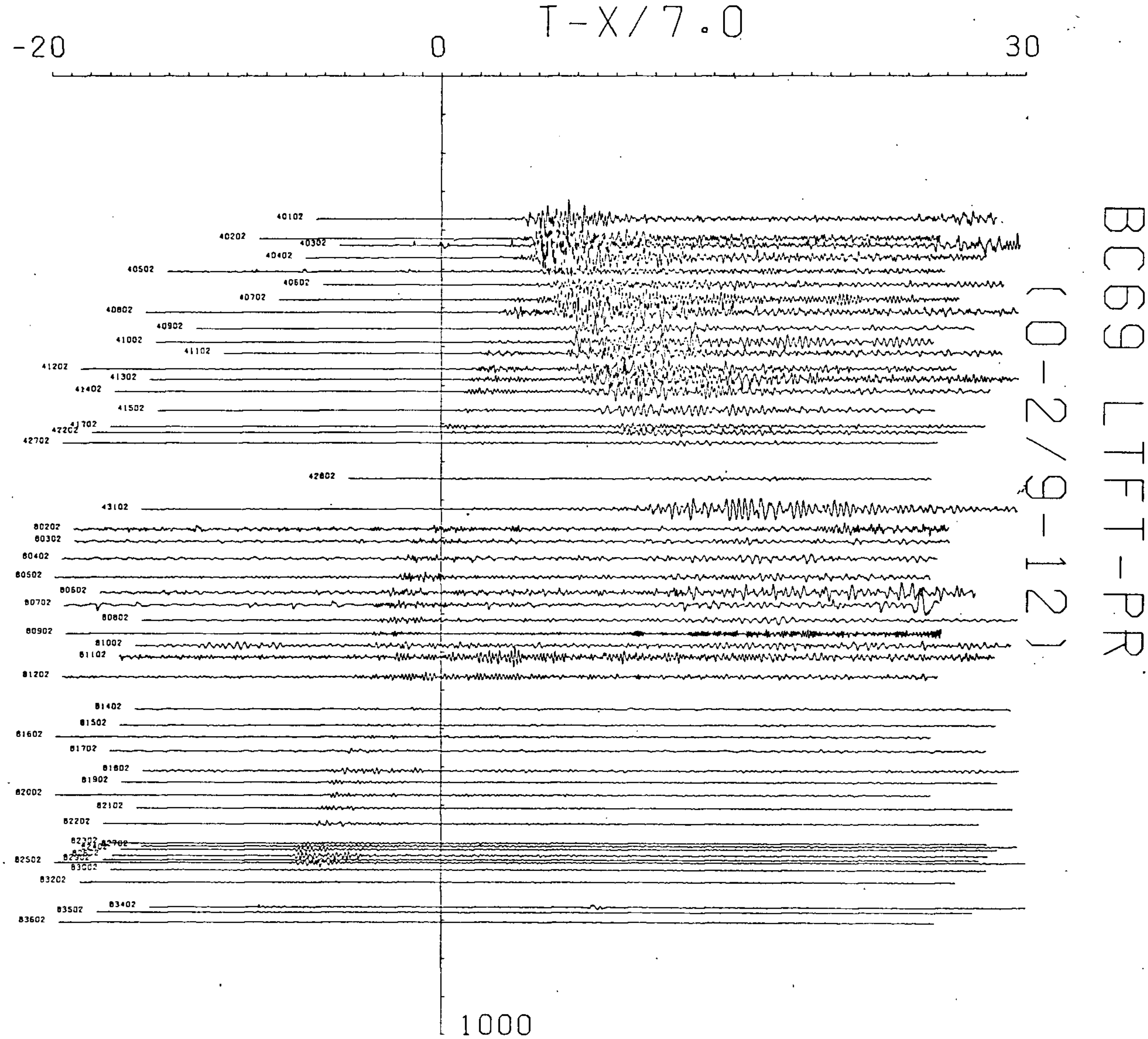

Fig. 5 The record section recorded at sites from Little Fort to Prince Rupert from shots in Greenbush Lake. The seismograms have been multiplied by distance and the following operations performed:
--normalized with respect to trace 40402
--trace 40702 reduced by 4
--traces 81102, 81202, 81802 reduced by 2
--bandpass filtered from 2 to 9 Hz.
--tics on x-axis are at 40 km. intervals

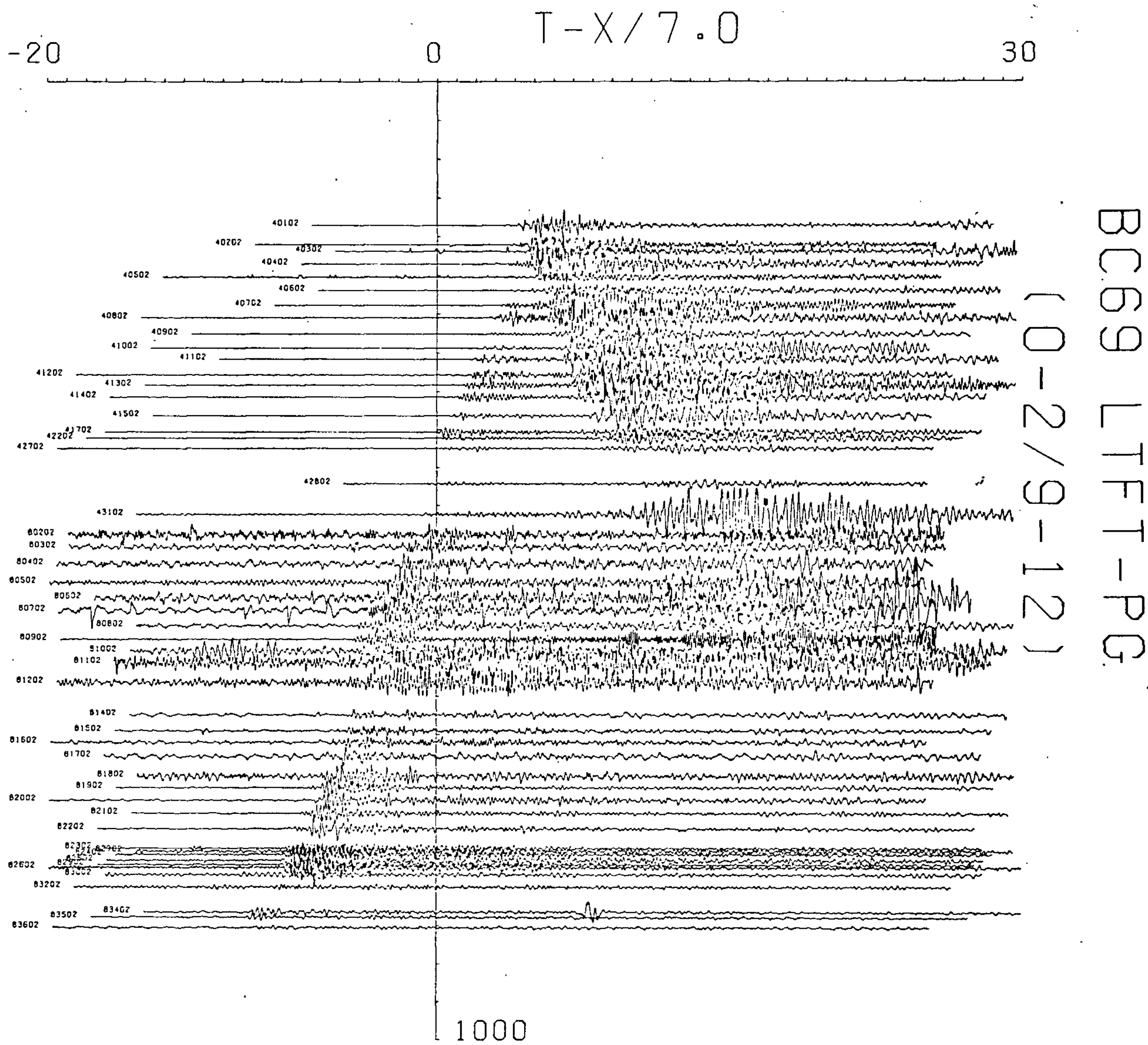

Fig. 5a The record section from Greenbush as shown in Fig. 5 except that a factor of distance squared has been applied. Note the rather uniform level of the amplitude of the first arrival out to at least trace 82302. Tics on x-axis are at 40 km. intervals.

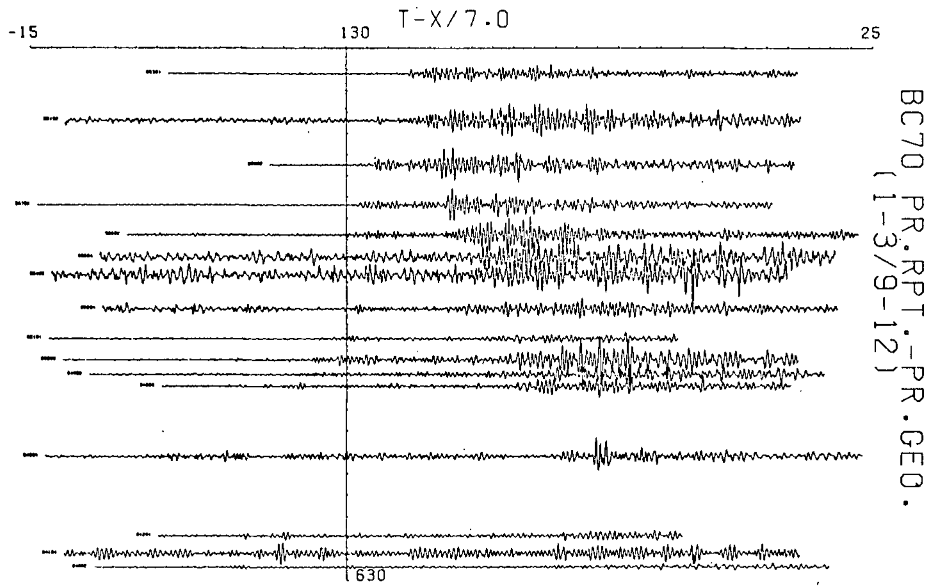

Fig. 6 The record section recorded from Prince Rupert to Prince George from shots in Bird Lake. A factor of distance squared has been applied along with the following operations:
--normalized with respect to trace 86102 (2nd trace)
--bandpass filtered from 3 to 9 Hz
--tics on x-axis are at 20 km. intervals

CHAPTER 4

INTERPRETATION

4-1. General principles and method

In this thesis first arrivals beyond about 150 km, travelling with a velocity greater than 7.5 km/s will be designated as P_n. This event is characterized by a frequency of about 4 Hz, a somewhat emergent arrival and an amplitude which is generally less than any other well-correlated event on the record sections. It is interpreted as the arrival that behaves kinematically like an event which is critically refracted at the Mohorovicic (M) transition and which travels with the velocity of the immediately underlying medium.

The larger amplitude secondary arrival is interpreted as the reflection from the M. It is assumed that this reflection is preceded by a smaller amplitude, directly refracted arrival. The former behaves as a wave continuously refracted within the crust above the M and appears as a first arrival from Greenbush only out to about 175 km.

Within 340 km of Greenbush and beyond 800 km from Greenbush, first arrivals travelling with P_n velocities may indicate energy from shallower and deeper horizons respectively. This will be elaborated upon in the next section.

First arrivals were picked from analogue records with the aid of record sections. Least square velocities were determined using a weighted analysis and preliminary models were computed using plane layer travel-time equations (Jakosky, 1961).

In order to refine the preliminary models, travel-time curves based on ray theory for the case of horizontal layers with a velocity gradient (Bullen, 1965; Officer, 1958) were calculated. Gradients were perturbed until first and secondary arrival branches were obtained which subjectively best fit the observed amplitude distribution.

The program which uses a weighted least-square analysis to derive velocities from travel-times was originally written by K.G. Barr, modified by M.J. Berry and adapted for the CDC 6400 by the writer. Dr. Gerhard Mueller wrote the original version of the travel-time program outlined in Appendix A. This program has been altered by M.J. Berry and the writer to calculate and plot the p-Δ graph and operate on the CDC 6400.

Using the results of the travel-time analysis as basic models for the easterly and westerly ends of the area, a time-term approach was then used to study structure in the interval between the shot points. The program which computes the time-term profile was written by M.J. Berry and adapted for the 6400 by the writer.

4-2. Least square analysis

First arrival data observed westward from Greenbush Lake to Prince Rupert - exclusive of data from sites 401 and 402 where the first arrival is considered a crustal phase - indicate a P_n velocity of 8.09 ±0.01 km/s. First arrivals picked on records observed eastward from Bird Lake indicate a velocity of 8.03 ±0.03 km/s.

Local consistent variations from "normal" P_n velocity were noted. From sites 403 to 408 inclusive, for example, the data indicate a velocity of 7.61 ±0.06 km/s. First arrivals at sites 408 to 417 inclusive indicate a velocity of 8.41 ±0.07 km/s. Farther to the north, over the relatively short (50 km) line from Barkerville to Quesnel (Fig. 1), first arrivals from Greenbush indicate a P_n velocity of

10.04 ±.3 km/s, whereas from Quesnel to Nazko the observed P_n velocity is 8.16 ±.4 km/s. This line as reversed from Ripley Bay indicates velocities of 6.94 ±.3 km/s and 8.12 ±.1 km/s over the same respective sections.

Since the area from site 401 to site 417 is unreversed, the problem of separating the effects of vertical (or lateral) velocity variation from M topography cannot be resolved at present. Assigning the local velocity change from 401 to 417 to dip would require an M "surface" which dips down at about 4 degrees to the area immediately east of site 408 and rises with the same slope to the region immediately east of the Fraser River (Fig. 1). The apparent velocities immediately east of Quesnel also require an M surface which rises at about 10 degrees towards the Fraser River.

From Fig. 1 it is noted that, rather than a profile, these data are actually "fan shot" over rather small angles. The fan angles subtended at Greenbush and Bird Lake are about 20 and 24 degrees respectively. The resultant model therefore must represent an average for the area covered. The areal distribution of recording sites, the distance range and the reversed velocities would indicate that 8.06 km/s is close to a true upper mantle velocity for the region under study.

4-3. Travel-time curves

A program, based on ray theory which uses as input simply the velocity-depth structure, was used to construct travel-time curves for comparison with the record sections (Appendix A). As an approximation to the wave solution, the use of ray theory is valid provided the change in velocity gradient over a wavelength is small compared with c/λ_o , where c is the velocity and λ_o is the surface wavelength (Officer, 1958). For a surface wavelength of 1 km, any change in velocity gradient at M surface depths must then be small compared with a gradient of about 8 s^{-1}. In fact, the derived models shown in Fig. 7 and Fig. 8 violate this restriction in the neighbourhood of each boundary. These areas are precisely those which determine the nature of the cusps in the travel-time curves.

From published wave solutions, it is instructive to note some of the limitations of ray theory which should be considered when interpreting real data. For the case of spherical, longitudinal waves in a plane-layered structure, Cerveny (1961) has shown that the amplitude maximum is displaced beyond the ray theory critical point by a distance dependent mainly upon the index of refraction and the frequency of the incident wave. This distance interval increases and the shape of the amplitude maximum broadens as the refractive index approaches unity and the incident wave frequency decreases. Therefore, the amplitude maximum would be expected to appear on a record section as a region of large amplitudes displaced from the ray-theoretical critical point. Comparison of the present models with curves given by Cerveny (1966) and Fuchs (1970, p 536) suggests that the true amplitude maximum may be displaced some 40 to 50 km beyond the ray-theoretical critical point.

Ray theory predicts that the reflected and head wave travel-time branches meet at the critical point. The wave solutions indicate that the travel-time branches, in fact, intersect beyond the ray-theoretical critical point in the zone of interference of the reflected and head waves. However, the difference in time between travel times predicted by ray theory and those computed using wave solutions - for a model characterized by velocities and frequencies not grossly different from those in the present study - appears too small to be detectable in the real data (Cerveny, 1966).

It would therefore appear that travel-time curves might be good estimates of arrival times along both the reflected and refracted branches to within about 40 km of critical. Used as such, they would give only a general indication of where the largest amplitudes might be expected.

4-4. Fitting travel-time curves

It was to be expected, in addition to the theoretical limitations, that in such a geologically complex area a simple, continuous travel-time curve could not explain all the apparent energy correlations. It was therefore necessary to decide which energy correlations must be explained and to produce a model which would have acknowledged limitations.

Primary consideration was given to the first arrivals and the well-developed reflected branches. Since ray theory predicts a critical point displaced from the amplitude maximum, the attempt was not directed at placing the cusps coincident with the largest energy on the section. Rather, because the reflected branch is relatively well defined, the models were adjusted so as to give a good fit to the curvature of this branch. The curvature, of course, is rather sensitive to the velocity gradients in the region of the transition.

Using the models suggested by the least square velocities - with discontinuous velocity increases - the curvature of the reflected branches was a poor fit to the observed data. In order to produce a better fit, the gradients shown in Fig. 7a, Fig. 8a and Fig. 9a were required. The gradients also bring the cusp B within about 50 km of

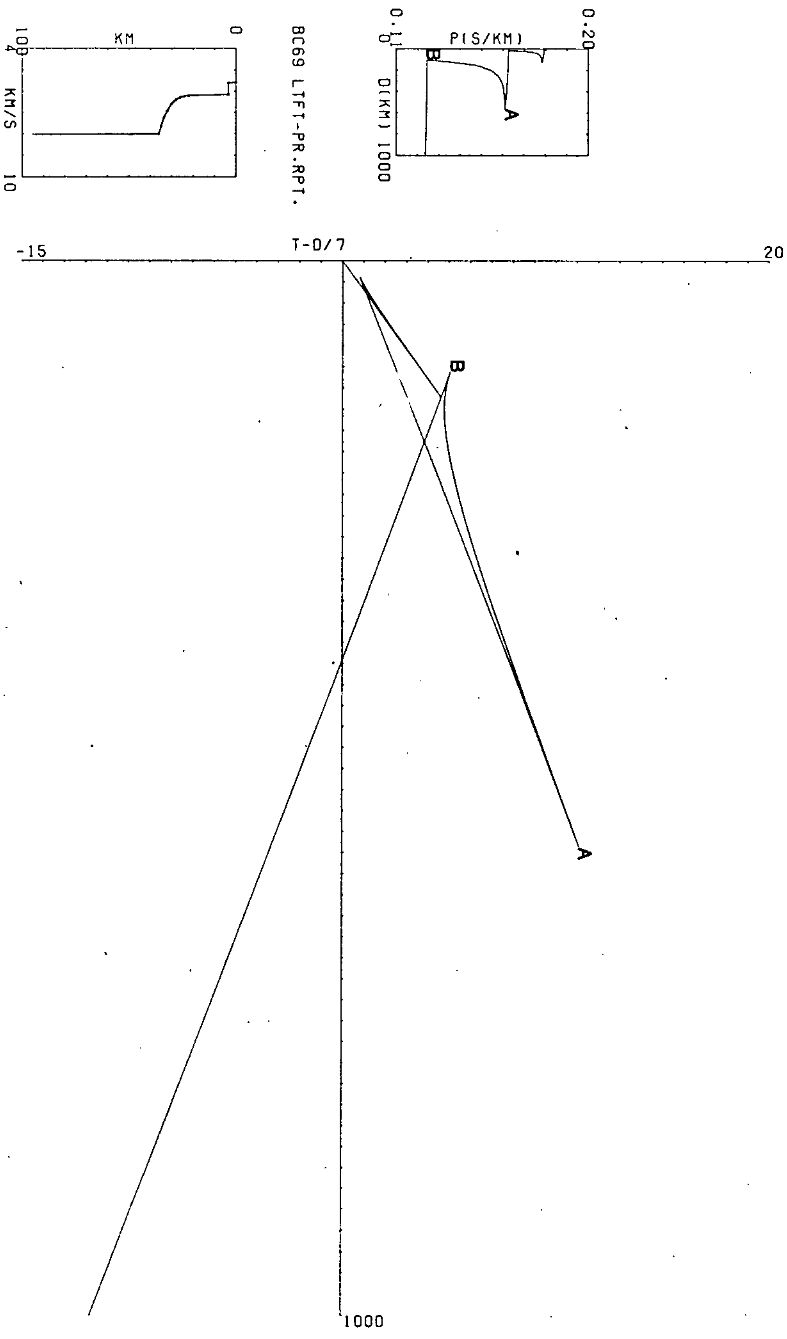

Fig. 7 The travel-time (model 1) for the Greenbush record section. Note the gradient necessary to produce the curvature of the reflected A-B branch. Tics on x-axis are at 20 km. intervals.

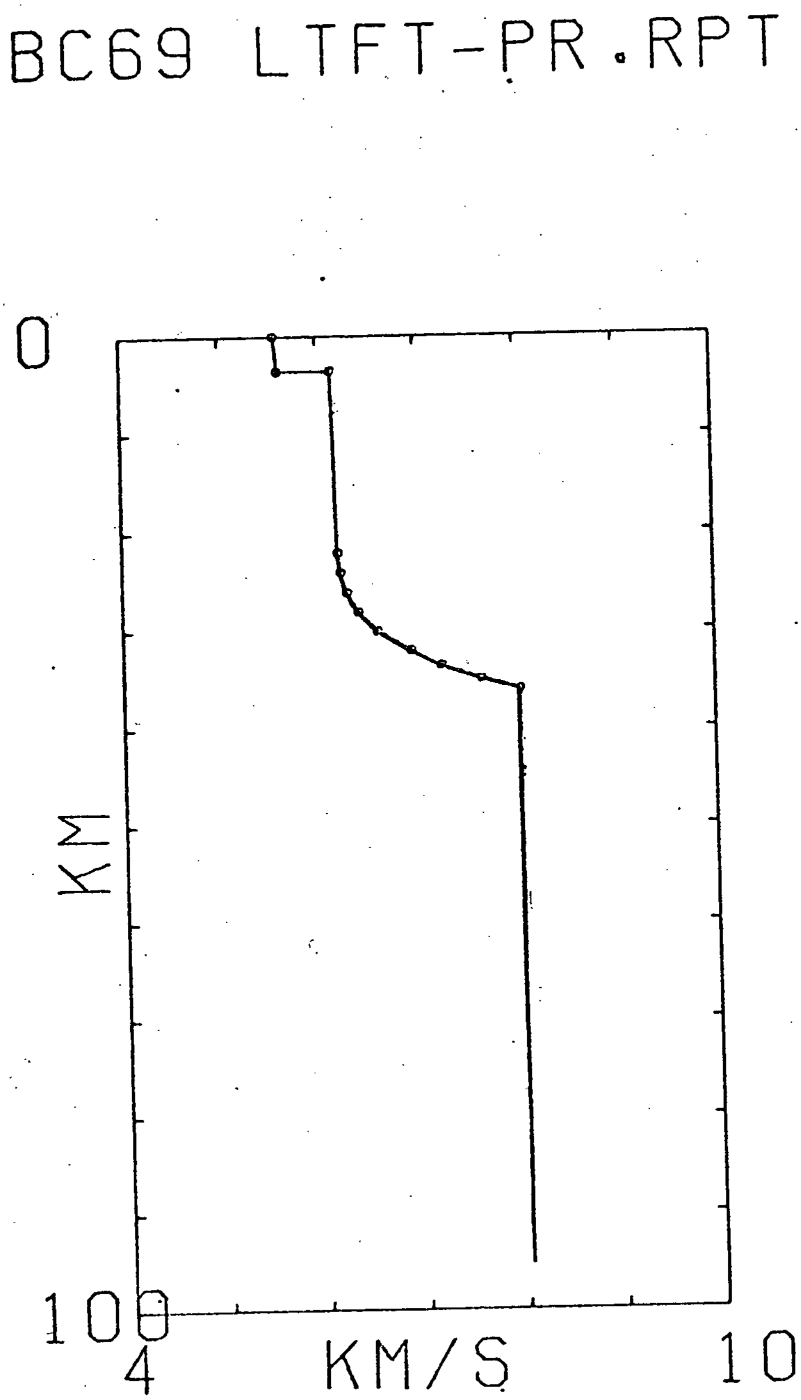

Fig. 7a The velocity-depth structure for Model 1.

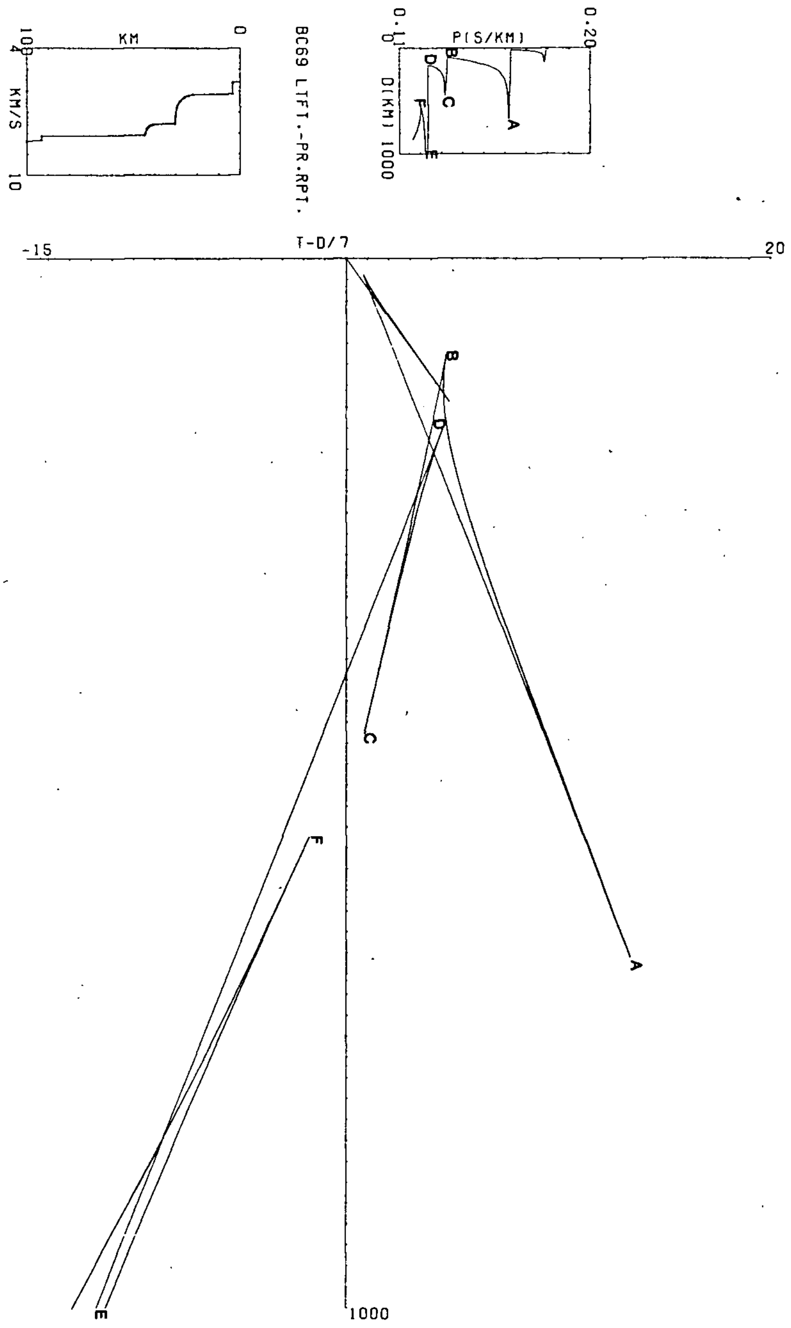

Fig. 8 The travel-time model 2 for the Greenbush Lake section. Minor triplications, C-D and E-F, have been added to explain significant secondary energy. Tics on x-axis are at 20 km. intervals.

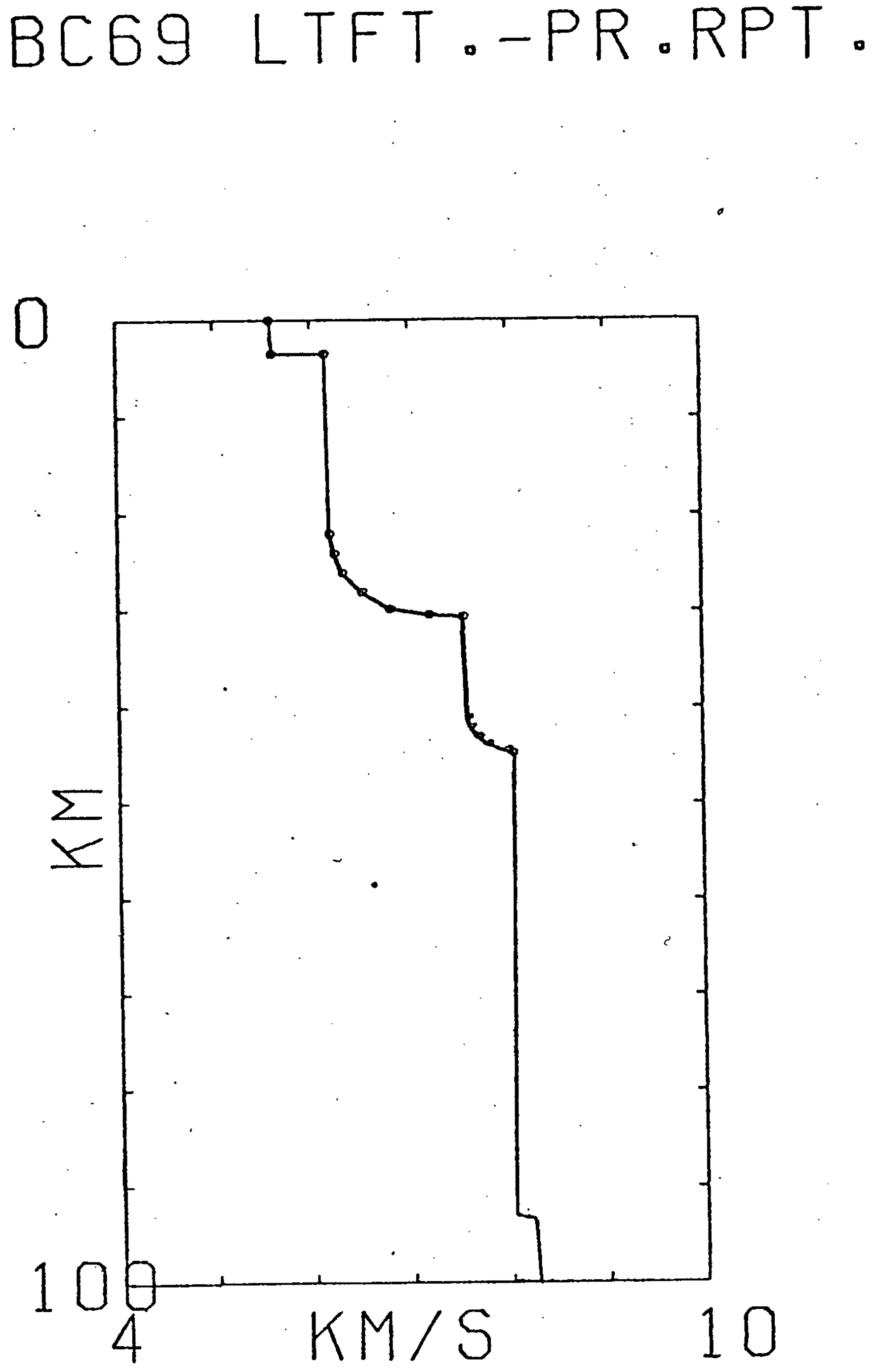

Fig. 8a The velocity-depth structure for Model 2.

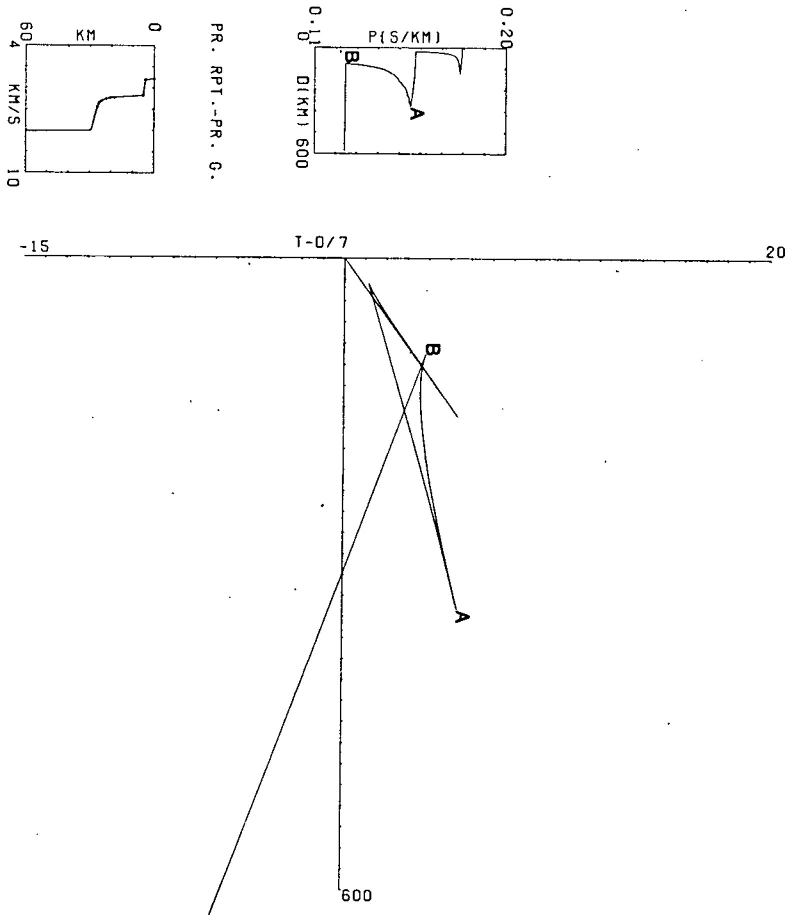

Fig. 9 The travel-time model for the Bird Lake record section. Tics on x-axis are at 20 km. intervals.

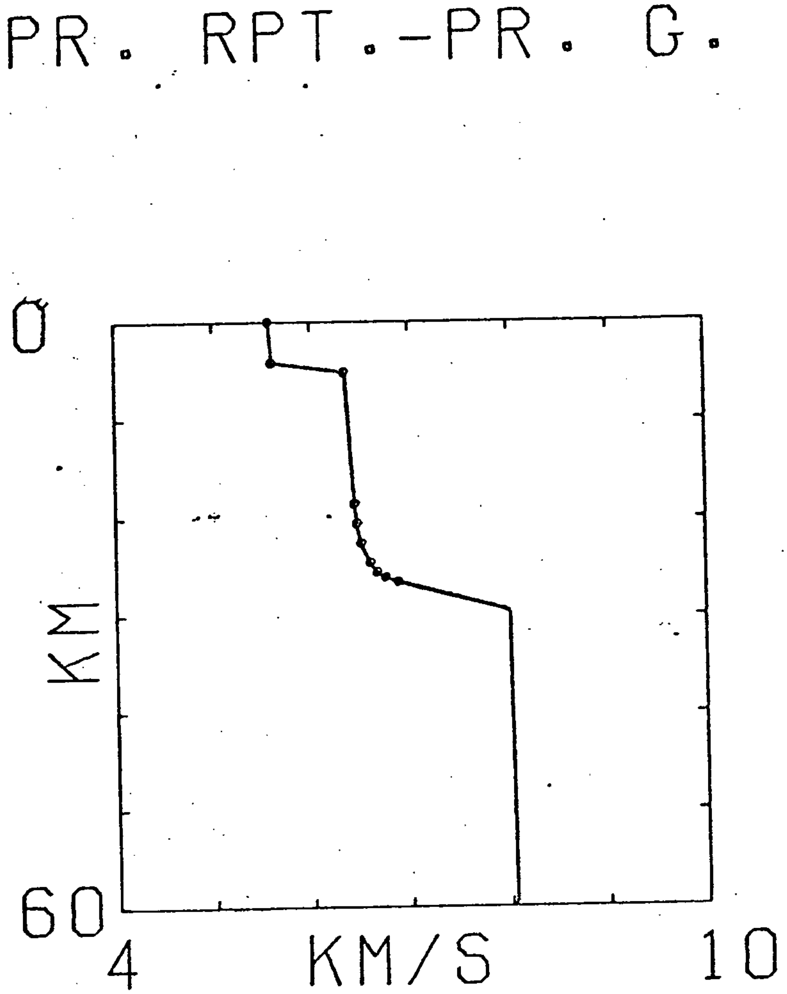

Fig. 9a The velocity-depth structure for the Bird Lake Model.

what may be the largest energy on the section (Fig. 10).

4-5. Record section from Greenbush

Fitting travel-time curves to data within 360 km of Greenbush was difficult due to the possibility of an intermediate layer. This layer is suggested by the first arrivals on traces 403 to 407, inclusive, with a velocity of 7.6 km/s. However, the quasi-correlatable nature of the secondary energy which must be used to define or suggest its travel-time triplication leaves some doubt as to the reality of this layer. Assuming the first arrival on traces 403 to 407 defines a refracted travel-time branch, then the larger secondary energy immediately following P_n on traces 411 to 417, inclusive, would make the branches to the cusp at C (Fig. 8 and Fig. 10) appear plausible. The energy in this region is confused by its proximity to P_n arrivals. Critical energy along the reflected branch, CD, is suggested by the larger secondary energy on traces 407 and 408, but again the reflected branch is not clear. The first part of the refracted branch from the cusp at D (Fig. 9) is perhaps indicated by secondary events (on records 402 and 404) which occur between the more widely separated travel-time branches producing the cusp at B. The alternative interpretation, in terms of an interface with a reasonable dip and the fact that this part of the section is unreversed, leaves the question open. Synthetic seismograms constructed for the different models might provide some other insight.

It is pertinent to note here a study, done on data applicable to the area beginning 100 km east of Greenbush Lake along latitude 50°30', by Chandra and Cumming (1972). Part of the data was recorded from the Greenbush shot point. The results show a 7.2 km/s layer at a depth of about 30 km which pinches out towards the Trench. Inclusion of an intermediate layer in the present model would thus be compatible with data to the east. However, since the two areas are some 300 km distant from one another, separated both by a zone of major geological complexity and one of the largest Bouguer anomalies in the Cordillera, it is probably not valid to relate the areas in any detail.

From Fig. 10, data on the record section from Greenbush are relatively sparse in the region about 400 km. However, the data from 360 to 480 km suggest that, while the amplitude of the P_n arrivals behaves normally, the amplitude of energy along the A-B travel-time branch increases abruptly. It is to be noted that at 450 km there exists another seismogram (in addition to trace 431 shown) recorded at site 801 which shows precisely the same amplitude character. Geologically, the phenomenon coincides with the fault trending southeast from McLeod Lake to the area immediately east of Prince George (Fig. 1). The fault separates Upper Paleozoic rocks immediately to the east from Triassic-Jurassic volcanics to the west. Assuming the behaviour of the crustal phase is related to the surface geology, it suggests that this surface division continues to the depths of the M transition.

Picking P_n becomes more uncertain with the occurrence of sinificantly more noise in the signal passband from sites 802 to 812. The rather abrupt appearance and disappearance of the noise would suggest a regional effect. Superposition of the site map on the geological map of British Columbia reveals that, excepting sites 808 and 809, all sites from 802 to 812 lie on Tertiary volcanic flows and pyroclastics. Sites immediately prior to 802 lie on Triassic and Jurassic volcanics and pyroclastics, sites 808 and 809 occur on Jurassic granites and sites immediately following 812 fall on Jurassic volcanics and pyroclastics. It appears that over this central region sites located on the tertiary sediments are characterized by a higher level of noise in the signal passband. The amplitude character of the first one or two seconds of energy in this range may be undergoing some interesting changes; however, the noise effectively precludes an interpretation.

Beginning at about 660 km (site 814), the character of the first second of energy has changed notably. The fairly consistent 4 to 5 Hz P_n phase which characterized records to at least site 809 is now more emergent in character and is followed at about 0.8 seconds by a larger amplitude energy band with a similar velocity and frequency. This phase is well developed from sites 818 to 823. Here again, the nature of the first energy begins to change and by sites 825 a very emergent cycle of 3 Hz energy is immediately followed by significantly larger amplitude 4 to 5 Hz energy. An enlarged picture of this part of the section is shown in Fig. 12. At subsequent sites, the first amplitudes decay and the first arrival may have a velocity of about 8.4 km/s at the end of the section.

A problem of phase identification arises here. Is the amplitude variation in the range about 820 km produced by a triplication of the P_n travel-time curve or is the larger secondary arrival the upper mantle P phase, seen in earthquakes studies? The P phase would then become the first arrival at about 820 km. For the present study, it is assumed that the effect is not due to a local surface effect. Alternative explanations to be considered are:

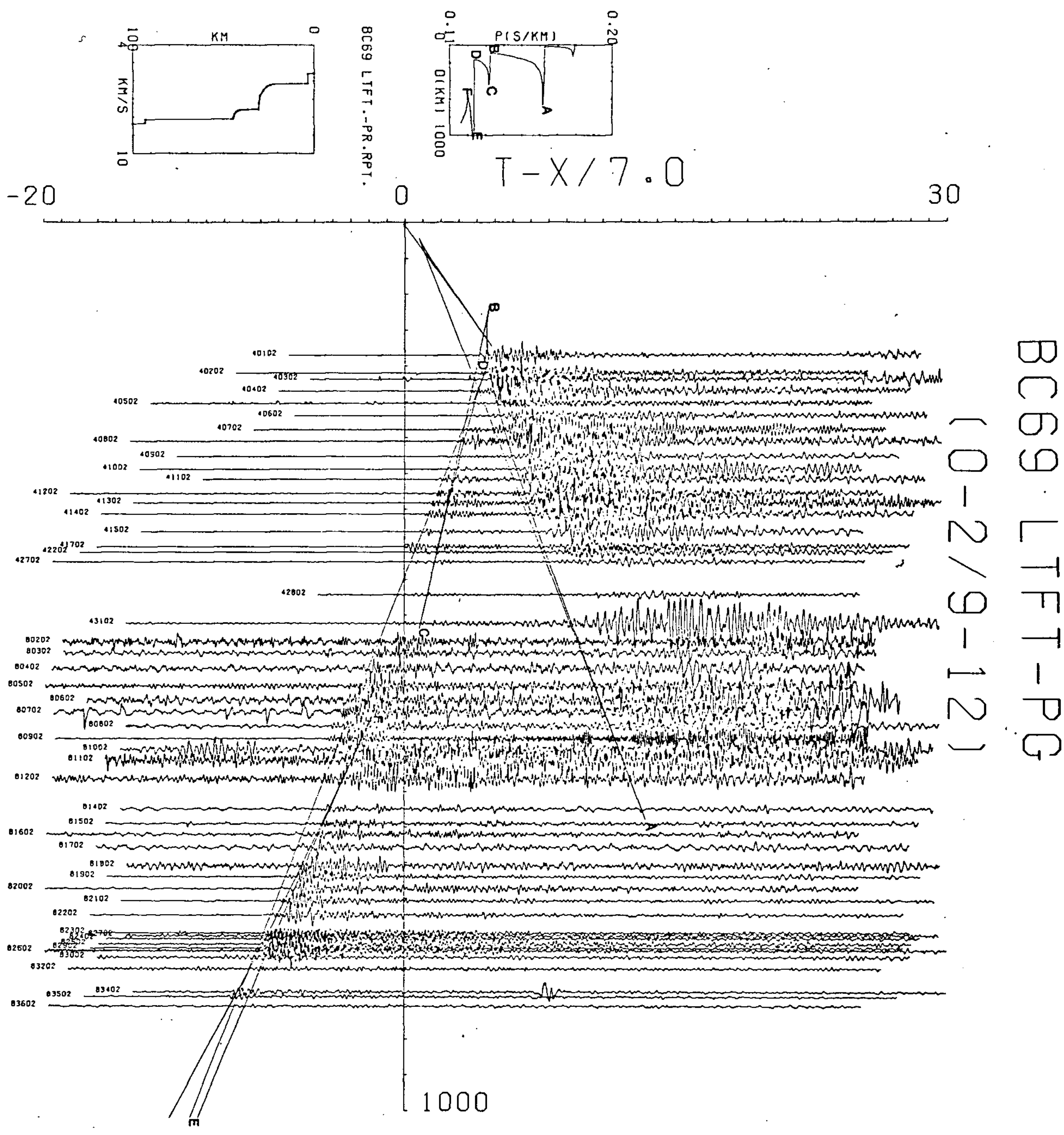

Fig. 10 The fit of Model 2 to the data of Fig. 5a.
Tics on x-axis are at 40 km. intervals.

(a) structural focusing by M topography of either P_n energy as described by Barr (1971), or P energy as described by Mereu (1969). Both effects could produce a triplication of the travel-time curve.

(b) a triplication of the travel-time curve due to a discontinuous velocity increase in the upper mantle.

These alternatives will be discussed after examining data from Bird Lake.

4-6. Record section from Bird Lake

The first arrival branches on the section recorded from Bird Lake are less clearly defined than on its reversed counterpart (Fig. 6). This is in part due to fewer stations and a correspondingly larger station spacing but also to the use of spreads. Since these arrays could feasibly be set up only along linear segments of roadway, there was little choice of seismometer site and hence background noise was relatively severe. Sites 840 to 849 fall on tertiary sediments and, like the reversed sites in the same area, are characterized by considerable background noise. Those recordings west of 849 where three components could be set on bedrock (850, 856, 857, 859) show relatively minor background noise. It is noted that where an array was used, all six seismograms were used in determining a first arrival time. Thus, the confidence of many of the picks is not as poor as the noise level on the chosen records might suggest.

On the Bird Lake section it is noted that, due to a thinner crustal section near the coast (P_n intercept of 5.5 seconds) than near Little Fort, the larger critical energy is effectively missing. From the coast eastwards, the main phases are identified as P_n and a larger coherent second arrival with a velocity of 6.4 km/s. The amplitude of the secondary phase drops abruptly at about 290 km (from trace 857 to 856). It is succeeded there by a slower, more emergent phase. The cessation of the larger amplitude phase coincides approximately with the western edge of the Hazelton mountains. The surface topography changes from an area characterized by seven thousand foot peaks in the west to the Bulkley ranges in the east where peaks reach nine thousand feet.

The question of phase identification arises again. Is the secondary phase, with a velocity less than 6.4 km/sec., simply the mantle reflection which has been perturbed by lateral structure in the region about site 857, or is it a separate arrival? Because of the distinct possibility of lateral structure effects and because the travel-time branches are so close at this distance, the cusp at A (Fig. 9) is not carried out to greater distances. The effect of this is only to make the final gradient above the M (lower left graph in Fig. 11) slightly less.

The velocity-depth structure for this section is shown in Fig. 9a. The first arrivals show no well-developed variations in velocity and deviations from the least square velocity (8.03 km/s) are plausibly indicative of topography. Thus, the presence of a significant intermediate layer is not suggested and M velocity is reached at a depth of 30 km.

4-7. <u>The anomaly at 820 km distance</u>

In an attempt to decide which of the suggested explanations of the phenomena at 820 km is more plausible, the following points are pertinent:

(a) Comparison of Fig. 5 and 5a shows that the application of a distance squared factor appears to restore P_n amplitude to an approximately constant level in the distance range from 0 to 800 km. The

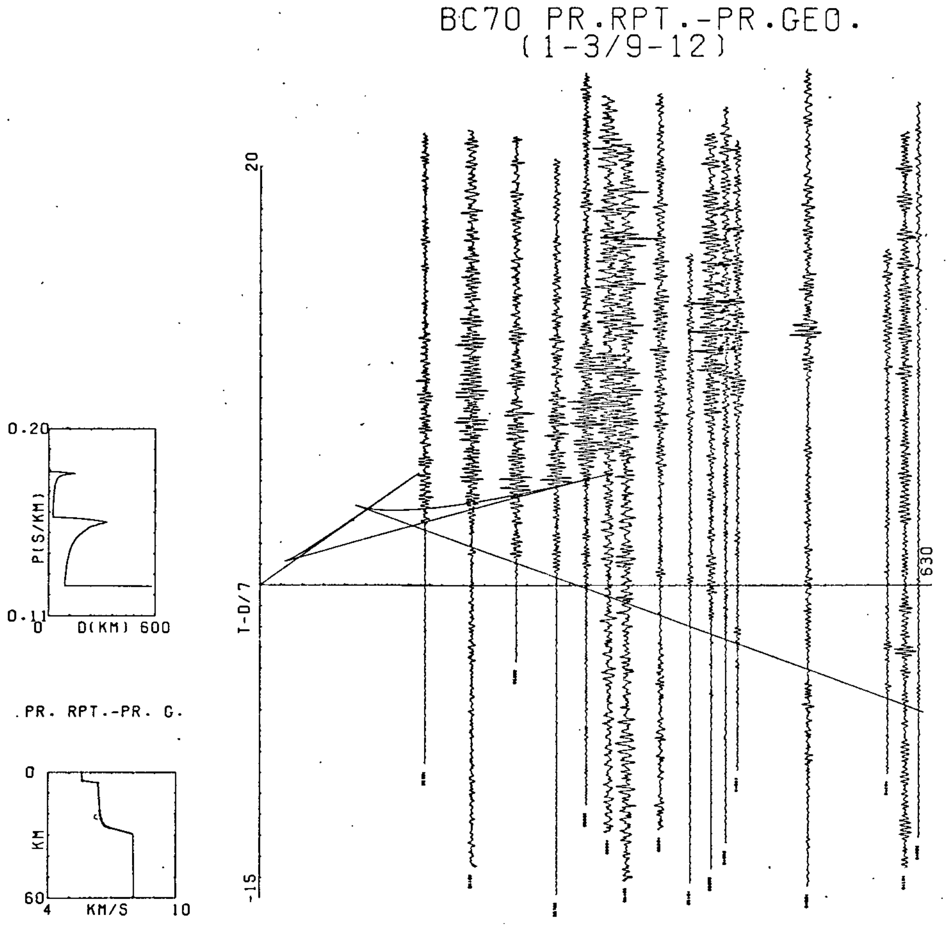

Fig. 11. The fit of the Bird Lake model to the record section. Tics on x-axis are at 20 km. intervals.

suggestion is that to this distance the first arrival travels as a head wave, probably connected with the M boundary. Beyond 800 km the amplitude of the first distinct arrival increases uniformly to a maximum at about 815 km and subsequently decays (Fig. 12). The length of the section precludes determination of the exact nature of the decay. However, this pattern is very similar to that calculated by Mereu (1969) using ray theory to analyse the focusing effect of M topography on P energy.

(b) Topographically, the phenomena occurs in the region characterized by the highest mountains in the coast range at this latitude. Culbert (1971) points out that a line between Douglas Channel and Nass River (at a distance of approximately 810 km on the record section) marks a prominent scarp line in the summit envelope. Geologically, the phenomenon occurs at the eastern edge of the Coast Plutonic Complex in the region of the Skeena Arch (Wheeler, 1970; Monger et al., 1972).

(c) The magnitude of the velocity discontinuity required to produce a travel-time triplication which might account for the amplitude anomaly is approximately 0.2 km/s at a depth of 95 km. However, this raises the question of upper mantle homogeneity. Assuming this model is true, the inference is that no similar velocity discontinuity occurs between the M and 95 km, since no effect similar to that at 820 km distance is observed on the record section. Construction of synthetic seismograms for this model would aid in deciphering data from below the M.

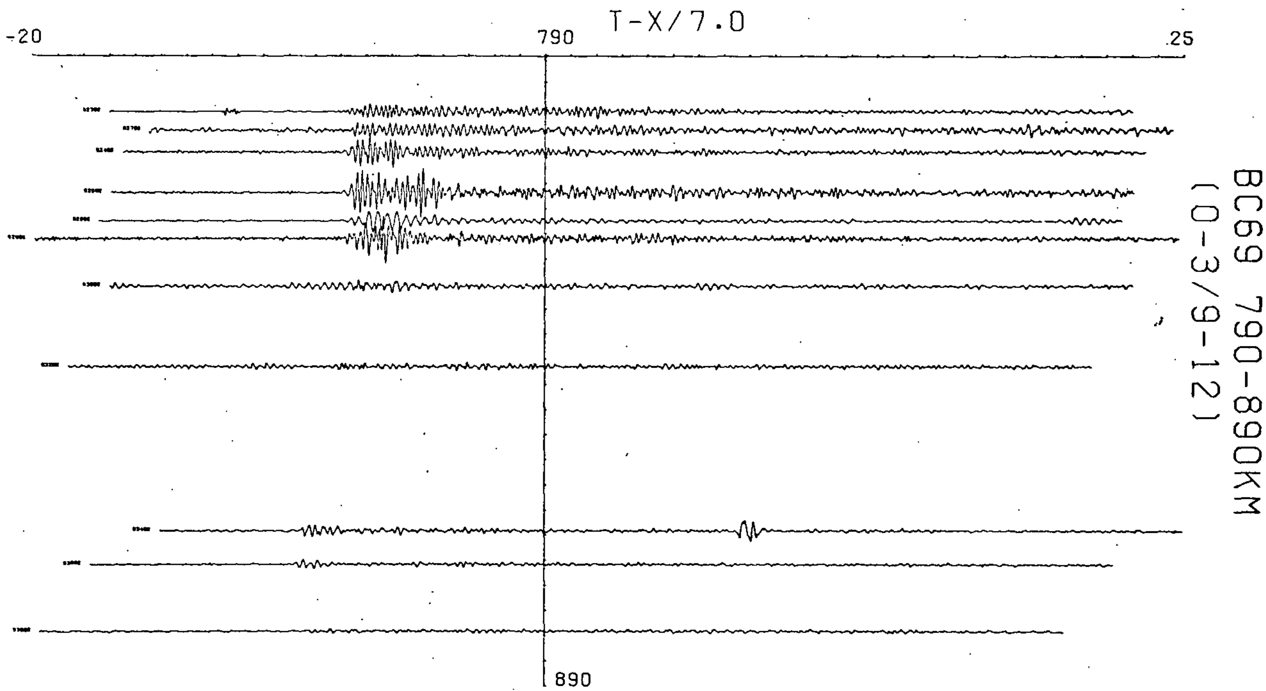

Fig. 12 Part of the Greenbush record section expanded to show the amplitude increase near 820 km. Tics on x-axis are at 4 km. intervals.

(d) The reversed data from Bird Lake is rather inconclusive with respect to either alternative. Since the seismograms are only obtained out to 630 km from Bird Lake, effects from a depth of 95 km are not recorded.

If the amplitude behaviour at 820 km on the Greenbush section is due to the focusing of P energy by M topography, a similar effect, suitably offset to about the area of trace 852 on the reversed section, might then be expected. Unfortunately, the lack of reversed data in this region leaves the question open. Part of the reason for the apparent lack of focussed energy may be because the distance range from Bird Lake is too small to witness significant P energy return from below the M.

However, there are two features of the Bird Lake section which may indicate that the lower crust and perhaps the M transition is different in the region of the Hazelton Mountains. It was noted in describing the seismic arrivals from Bird Lake that the amplitude of the phase reflected from the M transition dropped abruptly at about 290 km. This could indicate a major discontinuity extending to the M in the area roughly coincident with the scarp line in the summit envelope reported by Culbert (1971). The other feature is a strong secondary wavelet on traces 856 to 851 (Fig. 11) similar to the large amplitude secondary arrival on records 816 to 822 from Greenbush (Fig. 10). Both wavelets are characterized by a frequency of 4-5 Hz, an amplitude approximately four times that of P_n and a velocity of 7.7 km/s. Assuming the two wavelets are related, it suggests that the M transition beneath the Skeena Arch has the rather unique property of producing this reverberation.

4-8. Time-term study

In an effort to see what structure is implicit in interpreting P_n arrivals as indicating depths to the M and whether the reversed travel-times are compatible, a time-term study was undertaken. Although the experiment was not designed to exploit this type of study, the small difference between reversed, least-square velocities and the fact that at least one site had observed both shot points while many sites from each survey lie within a few kilometers of each other are points in favour of its application. The rather limited areal distribution of sites means that the resulting model may only be valid in a zone trending west-northwest, coincident with the general line of recordings.

To determine the general topography on the M between Little Fort and Prince Rupert, a simplified version of the "Delay-Time-Function" method outlined by Morris (1972) was used. Conventionally, the refractor surface is determined by calculating a time term for every site. The delay-time method assumes that the time-term surface may be represented by a simple mathematical function of position. In doing so, the procedure eliminates the necessity of determining the arbitrary constant which may be subtracted from all shot time-terms and added to the recording site time-terms (Scheidegger and Willmore, 1957). In addition, the degree of smoothing of the data can be controlled somewhat by specifying the form of the function to be fitted. In the present study the time-term surface is described as a function of only one parameter - the distance from an arbitrary reference point.

Since the sites are restricted to a zone trending to the north-west, the present data were used to construct a time-term profile, rather than a surface, along a line coincident with an approximate centre-line of the zone of sites. Polynomials in x - the distance from the mid-point of the line - were fitted to the data to determine the profile.

In detail, a line centered near the midst of the survey area with an azimuth coincident with the trend of the sites was chosen. Secondly, the distances from the mid-point of this line to the sites were projected onto the line and offset a distance equal to the step-out of the critical ray in the appropriate direction. The set of points determined by the offset distances and the travel-times was then least-square fitted by polynomials of increasing order. Initially, a P_n velocity, an average crustal velocity and a single shot (recording) site time term were input to determine the offset distances. Subsequent fits used previous estimates of time-terms and P_n velocities to compute new offset distances and hence new profiles. An average crustal velocity of 6.4 km/s determined from the travel-time models was used throughout.

Herein the travel time from shot i to station j is given by the usual formula

$$T_{ij} = \frac{\Delta_{ij}}{V} + t_i + t_j \qquad ,$$

where Δ_{ij} is the horizontal shot-station distance, t_i and t_j are shot and station time terms and V is the refractor velocity, assumed constant for the profile zone. It is assumed that the time-term t at distance x can be adequately described by $t(x)$ where

$$t(x) = \sum_{k=0}^{n} a_k x^k \qquad ,$$

and n is the degree of the polynomial. Then the travel-time is given by

$$T_{ij} = \frac{\Delta_{ij}}{V} + \sum_{k=0}^{n} a_k x_i^k + \sum_{k=0}^{n} a_k x_j^k \quad \text{, or}$$

$$\sum_{k=0}^{n} a_k (x_i^k + x_j^k) + \frac{\Delta_{ij}}{V} = T_{ij} \quad .$$

Applying the principle of least squares, the quantity

$$\sum_{m=1}^{M} R_{ij}^2 = \sum_{m=1}^{M} \{ \sum_{k=0}^{n} a_k (x_i^k + x_j^k) + \frac{\Delta_{ij}}{V} - T_{ij} \}^2$$

(where M is the number of observations) is minimized. This operation yields the normal equations which may be solved for the coefficients a_k and V.

4-9. Discussion of time-term study

To examine the effect of arbitrarily choosing the line of profile, solutions were obtained for the position of the line entered at 54° latitude, 125° longitude (azimuth of 310°); 54° latitude, 125° longitude (azimuth of 282°) and 53.5° latitude, 124° longitude (azimuth 293°). The general topography of the time-term profile changed insignificantly; however, the last mentioned line gave the best fit numerically.

The statistical F test was used to test the significance of each solution. It was found that a polynomial including terms to the fourth order gave a significant fit. Subsequent solutions with higher order terms showed little improvement. Unexpectedly, the eleventh order polynomial gave a markedly improved RMS residual. Since this polynomial is still not an interpolative fit, the suggestion is that the inclusion of the eleventh order term, which introduces a wavelength of about 200 km, is significant. A plot of the time-terms (Fig. 13) shows that the smoothing effect of the fourth order polynomial is an over-simplification. In fact, the consistent deviation of the residuals from the fourth order profile depicts a shorter ($\approx$200 km) wavelength which is not matched until the eleventh order polynomial is fitted. Perhaps most notable is the fact that the profile points from Bird Lake are compatible with the points from Greenbush. The reversed profile is thus characterized by lateral elements with at least two significant wavelengths. The broader structure has a wavelength of about 800 km and an amplitude of about 5 km, while the shorter structure has a wavelength of about 200 km and an amplitude of about 10 km.

4-10. Limitations

Elevation corrections were not applied to the data since it is doubtful that any survey points differ in elevation by more than 2500 feet. Recording sites were not greatly distant from the main access routes which follow the river valleys in regions where corrections might be significant.

The validity of the time-term method is indicated by the behaviour of the residuals. In preliminary profile solutions, data were re-examined if residuals were anomalously large. Only four observations out of 62 could be rejected on the basis of large uncertainties assigned to them in the least-square analysis. Of the remaining 58 observations, 49 are shown to have a total estimated uncertainty of less than 0.2 seconds.

The profile shown in Fig. 13 and Fig. 14 is in reality a projection of the structure on either side of a line centered at 53.5°

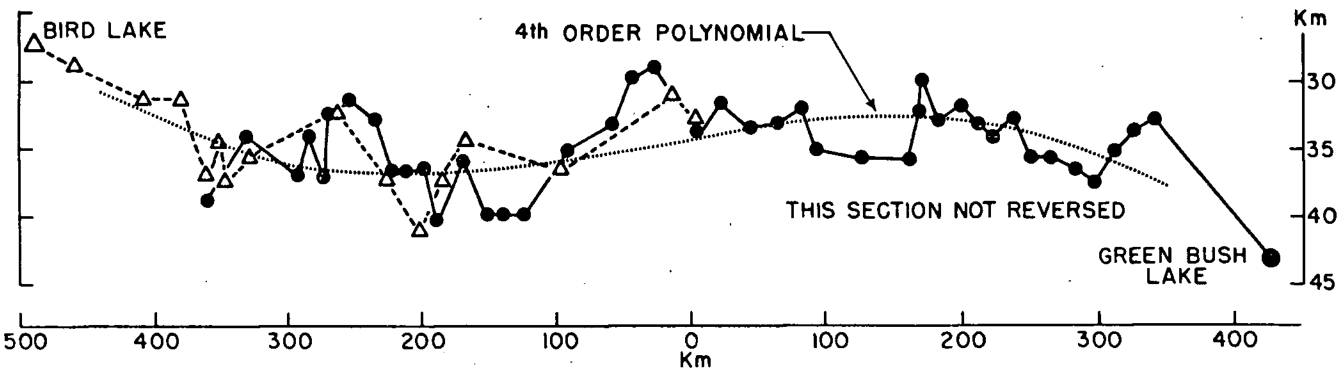

Fig. 13 The plot of time-terms converted to depth. The origin of distance scale is at 33.5°N latitude, 124°E longitude. The profile is along a line with an azimuth of 293°. Note the deviations from the fourth order polynomial are consistent in outlining a wavelength of about 200 km.

latitude, 124° longitude with an azimuth of 293°. Inherent in this projection are two types of distortion. The first is the unknown effect of forcing onto the profile structure which is laterally displaced. However, since 80 per cent of the stations are within 60 km of the line of profile and the reversed data are consistent, the profile is probably a good average picture. The second type of distortion is a shortening (<10%) of the profile introduced by projecting the inter-station distance onto the line with an azimuth of 293°. The effect shrinks the true inter-site distance by an amount dependent upon the cosine of the angle between the line of sites and the profile line. Examination of this effect in detail shows that significant shortening occurs locally in the areas where the profile crosses the line of sites. In these areas the apparent dip between local pairs of profile points may be considerably in error; however, the general shape of the profile remains the same.

The tendency to make the topography more dramatic may not be incorrect. If the M topography follows the strike of the structural elements, which is about North 30° West in the area between 52° and 56° latitude (Fig. 1), then the profile line striking North 67° West crosses the structure obliquely. This would result in an apparent cross-section with lower dips than a section normal to the structural elements. Thus, any effect which enhances the topography may present a more accurate picture. The significance of the time-term profile will be outlined in Chapter 5.

CHAPTER 5

SUMMARY

5-1. Travel-time models

Acknowledging some of the basic shortcomings of ray theory with respect to published wave solutions, the models shown in Fig. 7a, Fig. 8a and Fig. 9a have been derived for the end regions of the survey. The earth's curvature has been taken into account in the manner described by Mereu (1969). Alternative interpretations are presented for the data within 360 km of Greenbush. The velocity of 5.6 km/s for the surface layer was chosen on the basis of recordings made from Nazko to Barkerville of a shot in Punchesakut Lake. The velocity of first arrivals at Sandspit from Bird Lake shots and the velocity log of a well drilled near Nazko (J.A. Mair, personal communication) are in close agreement with this figure.

In the simpler model (Fig. 7a), the velocity between 3.5 km and 24 km is near 6.2 km/s. At this depth a gradient is introduced which produces the cusp at 550 km (similar to cusp A in Fig. 8). Between 24 km and 36 km, the velocity gradient is varied in the manner shown to produce the necessary curvature to the reflected branch and the cusp at 110 km (similar to cusp B in Fig. 8). The upper mantle velocity is 8.0 km/s.

The alternate model from Greenbush (Fig. 8a) introduces a layer at the base of the crust with a velocity of 7.5 km/s and a velocity discontinuity at 95 km in an effort to explain variations in P_n velocity and significant energy immediately following the P_n arrivals. These same observations may also be explained in terms of topography on the M. On the basis of the present study, the two effects cannot be separated.

The Bird Lake model is shown in Fig. 9a. Using 5.6 km/s as a surface layer velocity, the required thickness is 4.5 km. Between 4.5 km and 20.5 km, the velocity is near 6.4 km/s. From 20.5 km to 29.5 km, the velocity gradients shown in Fig. 9a are required to produce the travel-time curve of Fig. 11. The upper mantle velocity is 8.0 km/s.

5-2. Time-term model

Assuming the velocity of the refracting horizon and the crustal velocity within the critically refracted ray cone remain nearly constant and the slope and curvature of the refracting surface are not too great (Berry and West, 1966), the time-term method may be applied. The wavelength of energy observed in the present data would limit vertical resolution to about 2 km. The station spacing would restrict lateral structure resolution to features with a wavelength greater than about 20 km. Consistent with these limitations, the present study has delineated an M transition characterized by two prominent wavelengths (Fig. 14). The larger feature with an apparent wavelength of about 800 km and an amplitude of about 5 km is depicted by the fourth order polynomial. On the surface, this feature has as correlatives the distribution of metamorphic terrains (Monger and Hutchison, 1971) and, not surprisingly, the physiographic regions of the Canadian Cordillera. The low grade metamorphic terrain overlies the thinner central crustal section. The "half wavelength" point has recently been depicted as the boundary between the Pacific and Columbian Orogens (Wheeler and Gabrielse, 1972). It is also noted that the 800 km wavelength is similar to the dimension

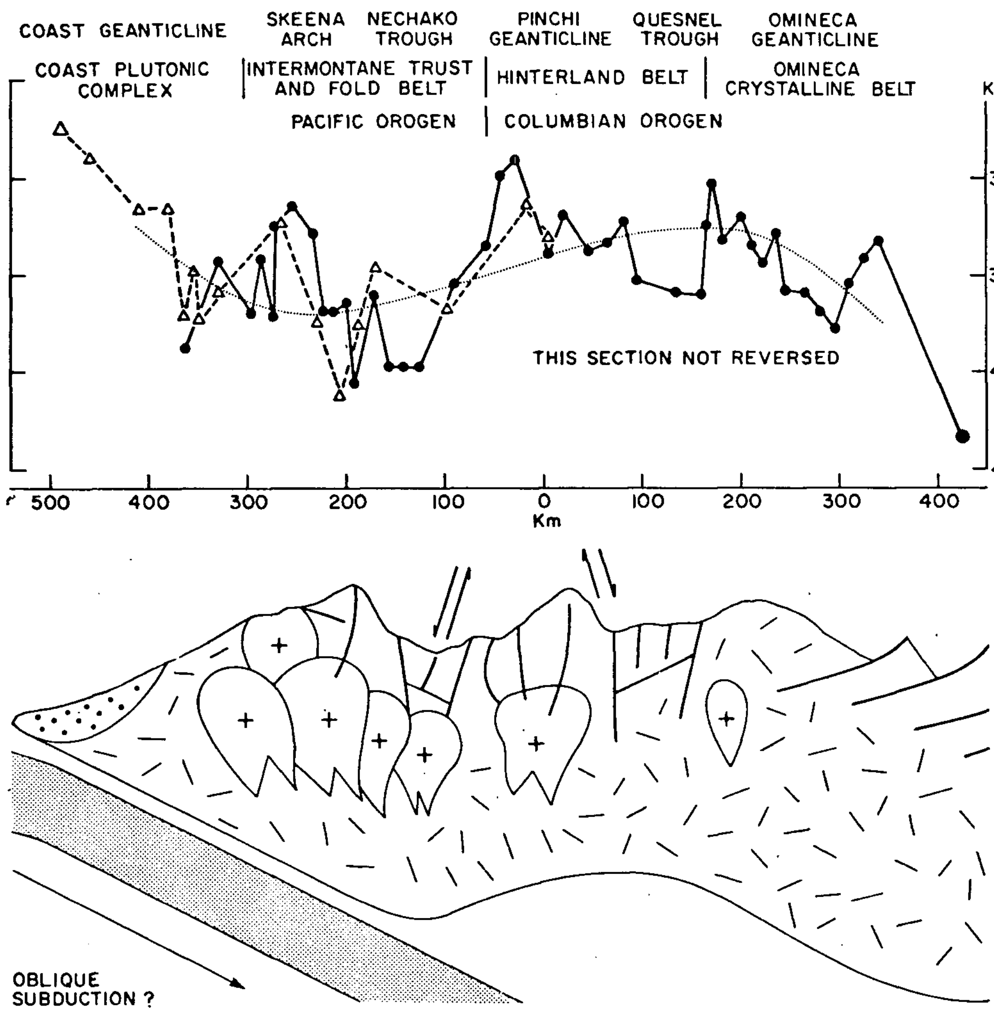

Fig. 14 The correlation of the time-term structure with Geology (Cordillera model after Wheeler and Gabrielse, 1972). The triangles are data from Bird Lake, the dots are data from Greenbush.

of topography at the lithosphere interface as depicted in the plate tectonic model for the evolution of the Canadian Cordillera (part c, Mid-Cretaceous (100 MY) to Oligocene (25 MY), ibid.). Assuming that the profile section is actually a projection of the true structure onto a vertical plane which crosses the strike of the structure at 40° to the West, then the true wavelength would be about 640 km. In terms of presently envisaged plate models (Isacks et al., 1968) and wavelengths for continental lithospheric flexure (Walcott, 1970), this number appears quite reasonable. The long wavelength structure, of course, may also be explained by a regional variation in velocity.

The smaller feature with an apparent wavelength of about 200 km and an amplitude of about 10 km, is outlined by the consistent residuals to the fourth order polynomial. The feature suggests that the Cordilleran structure elements and their subdivisions, the tectonic elements, have a topographic expression on the M transition. If this is so, then the M transition beneath southern British Columbia should differ considerably from the area presently under study. This is already suggested by the different pattern of aeromagnetic Z component residuals (Haines et al., 1971) between the two regions and the fact that the M discontinuity may be at least 50 km deep beneath Vancouver Island (Tseng, 1968).

5-3. Conclusions

On the basis of the present study and the work of Shor (1962), the presence of typical oceanic crust is not suggested until west of Graham Island (Queen Charlotte fault?). From a depth of 26 km beneath Graham Island (Fig. 14), the M transition deepens slightly beneath the coastal mountains and then rises beneath the Hazelton Mountains in the region of the Skeena Arch (Fig. 14). This area is characterized by peaks which reach 9000 feet. The crustal section then thickens immediately to the east of these mountains. The major aeromagnetic anomaly also occurs just to the east of the major elevations at this latitude. The records from Greenbush which are characterized by anomalously large amplitude first energy could originate from this region between $126^\circ30'$ and $127^\circ30'$ longitude. The M transition then rises to the area separating the Pacific and Columbian Orogens (Fig. 1). South of Prince George the section is unreversed with the exception of the Nazko to Barkerville profile. This short profile agrees with the unreversed data in suggesting an M structure which rises from the east to the vicinity of the Fraser River.

The present study is in good agreement with the results of White et al. (1968). The apparent velocities for profiles 01, 02 and 03 of the 1968 study, reinforce the present interpretation in terms of M topography for the area east of the Fraser.

For the Prince Rupert area, the model obtained by Johnson et al. (1972) for the coast crustal section is rather more complex than the present data would indicate. The two studies concur in suggesting an average crustal velocity of approximately 6.4 km/s; however, the evidence for a strong refracted event with a velocity of 6.7 km/s in the Prince Rupert area is missing in the present data. This may, of course, be explained in terms of the different azimuths of recording lines and M topography, or the considerably greater station spacing in the study by Johnson et al. However, it is observed that the major geomagnetic anomaly which extends northwest from Ripley Bay terminates in the area of Prince Rupert. This may suggest a rather different crustal section in detail for the area approximately mid-way between Ripley Bay and Prince Rupert.

The analysis of gravity data over the general area of the survey has not been completed. However, a preliminary interpretation for the area between Little Fort and the Fraser River is in good agreement with the present suggestion of M topography (R. Stacey, personal communication).

In addition to the structural pattern described above, the following general points are considered pertinent.

(A) Careful consideration of systems' responses and the monitoring of all shots at one location enables construction of record sections which show a coherent energy pattern. The main effects of poor seismometer sites are, apparently, an amplification of background noise, but only rare amplification of the entire record by more than a factor of about two.

(B) The passband of the recorded seismic energy is naturally restricted to the range from about 3 to 6 Hz. The monochromatic nature of the energy is not readily explained. Other puzzling features of the record sections which remain unexplained are:

1. the regional levels of background noise,
2. the anomalous variation in amplitude of the crustal phase with respect to P_n energy.

(C) The Bird Lake and Greenbush Lake shotpoints, although greatly separated and with different water depths, apparently differ little in response.

(D) P_n is well recorded as a first arrival northwest from Greenbush Lake to at least 800 km, and east from Bird Lake to 610 km. Restoration of P_n energy to an approximately constant level by the application of a distance squared factor suggests that the wave travels as a head wave connected with the M transition and, tentatively, that upper mantle gradients are extremely small over this region of the Cordillera (Hill, 1971a).

(E) The rather complex energy patterns which follow the major events (P_n and crustal reflections) suggest the models derived herein are simplified versions of the true picture. Construction of synthetic seismograms for comparison with the record sections and examination of the data recorded along lines from Little Fort to McLeod Lake and from Williams Lake to Bella Coola may help to distinguish between the effects of topography and velocity depth structure.

Appendix A

Travel-Time Curves

The distance and travel time along a ray can be expressed in terms of the angle of inclination of the ray and depth z by the equations

$$x = \int_o^z \tan\theta dz \qquad \text{and} \qquad t = \int_o^s \frac{ds}{c} = \int_o^z \frac{dz}{c\cos\theta} \quad ,$$

where s is length along the ray and v is velocity.

Using the ray parameter $p = \dfrac{\sin\theta}{c}$

$$x = \int_o^z \frac{\sin}{\cos} dz$$

$$= \int_{\theta_o}^{\theta} \frac{\sin\theta}{pc'(z)} d\theta$$

$$= \frac{1}{pc'(z)} \int_{\theta_o}^{\theta} \sin\theta d\theta = \frac{1}{pc'(z)} \{\cos\theta_o - \cos\theta\}$$

where $c'(z)$ is the gradient.

The travel time is then

$$t = \int_{\theta_o}^{\theta} \frac{d\theta}{c'(z)\sin\theta}$$

$$= \frac{1}{c'(z)} \{\log \frac{\tan^{\theta/2}}{\tan_o^{\theta/2}}\}$$

and since $\tan\theta/2 = \sin\theta/_{(1 - \cos\theta)}$

$$t = \frac{1}{c'(z)} \{\log \frac{\sin\theta}{1-\cos\theta} \cdot \frac{1-\cos\theta_o}{\sin\theta_o}\}$$

$$= \frac{1}{c'(z)} \log \{(\frac{V_o}{V_{\theta_o}}) (\frac{1-\cos\theta_o}{1-\cos\theta})\}$$

using a linear gradient within each layer such that

$$c'(z) \approx (V_{i-1} - V_i)/h_i$$

where h_i is the thickness of the i^{th} layer.

Then for the layer in which the ray bottoms

$$p = 1/V_{i+1}$$

and the time and distance are given by

$$t = \left(\frac{V_{i+1}-V_i}{h_i}\right)^{-1} \log\left\{\frac{1-\cos\theta_i}{V_i P}\right\}$$

$$x = \left(\frac{V_{i+1}-V_i}{h_i}\right)^{-1} \frac{\cos\theta_i}{P}$$

A program based on the above equations was used to produce travel-time graphs. The program effectively sums the time and distance contribution from a specified number of rays per layer, for as many layers as desired, to produce a travel-time plot. The program, in its original form, was written by Dr. Gerhard Mueller.

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