CRUSTAL STRUCTURE FROM A SEISMIC REFRACTION
PROFILE ACROSS SOUTHERN BRITISH COLUMBIA

by

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ABSTRACT

A partially reversed seismic refraction profile utilizing mine blasts as sources was recorded across southern British Columbia from Sparwood to the Highland Valley. The westwardly directed profile consisted of 32 short period seismograms covering 440 km, while the reversed line extended 330 km with 41 seismograms. The FM field tapes were digitized, filtered, and combined into vertical component record sections. Instrument and shot amplitude corrections were applied in order to display the true relative amplitude variation along the profile. As well as geometrical techniques, least squares delay-time methods and disc ray theory synthetic seismograms were used to interpret the data.

Where the profile crosses the Rocky Mountain Trench and the Okanagan Valley, the seismic data show arrival time and amplitude anomalies in the approximately 6.0 km/s upper crustal refraction arrivals. An intermediate crustal layer of velocity 7.05 km/s, depth 29 km, and thickness 9 km is defined by second arrival data recorded 100 to 200 km west of the Kaiser shot point. There is poorer evidence, based on data between 80 and 180 km from the Highland Valley shot point, for a layer with a velocity of 7.35 km/s, a depth of 15 to 24 km, and a thickness of 6 to 10 km. The M-

discontinuity generally dips to the east from an approximate depth of 33 km near the Highland Valley, to about 42 km just to the west of the Kaiser shot point. The upper mantle velocity is 7.8 km/s between the Okanagan Valley and Kootenay Lake. Delay time interpretations suggest that a 165 km wavelength anomaly in average crustal velocity and/or depth to the mantle occurs in the Eastern Metamorphic Belt. The anomaly is probably associated with a deep transition zone between the Arrow Lakes and Kootenay Lake. The results of the present study are applicable primarily to the eastern Interior Plateaux and the Eastern Metamorphic Belt south of 51°N.

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CHAPTER I

1. Motivation

A reversed seismic refraction profile between the Kaiser Resources strip coal mine near Sparwood, British Columbia, and the Lornex and Bethlehem open pit copper mines in the Highland Valley, was begun in 1973. It is a continuation of the University of British Columbia's seismic structural studies in the Canadian Cordillera utilizing mine blasts as energy sources. This work extends seismic coverage to the west of an earlier study which used the Kaiser shot point for a northwesterly profile along the Rocky Mountain Trench (Bennett et al., 1975). The profile of the present study crosses outstanding geological features that are poorly understood, especially at depth. Any deep expression of surface variability may be economically important in explaining the formation of major mineral deposits. For example, Cominco's Sullivan ore body has been related to a Precambrian rift (Kanasewich, 1968) and it is exactly in line with the profile. However, previous geophysical models of the upper mantle and crust across this region, based mainly on gravity evidence, have had very

little corroborating seismic data. The cooperation of the mining companies in obtaining shot statistics offered a relatively inexpensive opportunity to utilize the exceptionally large shots in a seismic investigation of a poorly understood region.

2. Regional Geology

The narrow region of southern British Columbia within which the profile is located crosses several geological zones (Figure 1). At the eastern end, the Kaiser shot point is in the Rocky Mountains. This area was once a stable platform of Hudsonian shield-type rocks overlain by miogeoclinal sedimentary sequences. In several pulses of activity, the first beginning in the Mesozoic, and the most recent ending in the Eocene, a series of low angle thrust sheets have been stacked progressively eastward. There is general agreement that, in the easternmost Front Ranges, a decollement separates the largely passive crystalline basement from the overthrust sediments. However, considerable debate has arisen over the degree of basement involvement in the thrusting in the Main and Western Ranges of the Rocky Mountains. The lateral shortening of the sedimentary section is partially controlled by basement deformation, and the degree of shortening will constrain the minimum westerly distance of the Proterozoic continental shelf-slope boundary from the present western margin of the

Figure 1. Geological and station location maps.

Upper map: The regionalized geological zone map is modified from Stacey (1973). The area of the lower map is outlined with heavy lines.

Lower map: The open and closed circles represent Highland Valley and Kaiser recording sites respectively. Alpha-numeric identification of recording sites is explained in the text. PNT is the location of the Canadian Standard Seismic Network station which was used for amplitude normalization.

Rocky Mountains. Campbell (1973) suggests that, to the north of latitude 55° at least, the basement has been deformed in the Main Ranges, in the Western Ranges, and in all of the mountains to the west of the Rocky Mountain Trench. A decollement would fit his interpretation only in the Front Ranges and the Foothills. However, the interpretations of Bally et al. (1966) and Price and Mountjoy (1970) are still widely accepted. They extend the decollement well to the west of the Rocky Mountains, into the Eastern Metamorphic Belt. This implies that as much as 200 km of shortening occurred in the thrust zone, which would place the original shelf slope assemblage west of the present day Arrow Lake. Campbell and Eislacher (personal communication, 1977) suggest that the shortening is less than half of this amount. The Western Ranges are terminated to the north of the area of this study, while the Main Ranges are physiographically truncated along a line approximately coincident with the profile. Therefore, it would be difficult to use the information from this study to resolve these models of the Rocky Mountains.

The Rocky Mountain Trench is an intermontane valley extending over 1600 km from Montana to northern British Columbia. It forms a sharp physiographic and geologic boundary between the generally imbricate structure of the Rocky Mountains to the northeast, and the more complex structure of the varicose ranges to the southwest. The Purcell Mountains are bounded by the trench at the latitudes

of this study. However, farther north, the trench truncates a series of ranges in the Eastern Metamorphic Belt in an "en echelon" fashion. The Rocky Mountain Trench has been a very enigmatic structure. In Montana it appears to be a graben, while in the north it has been interpreted by different authors as a half-graben, a transcurrent fault, a thrust fault structure, or a purely erosional feature. The linearity and persistence of the trench makes the last unlikely. Speculation as to the origin of the trench frequently reflects Leech's (1965) suggestion that, "the trench may mark an old, deep fracture zone that has reasserted itself through the allocthonous veneer." However, the complexity of the geology makes even a reconstruction of the "veneer" difficult. Any underlying vestigial tectonic feature may be detectable only by inference. More importantly, the proximity of such a boundary may be very indirectly related to the physiographic trench, and it may be only coincidence. Although the geological formations along the trench vary in structural detail, they do seem to be consistent with the extensional tectonics that have characterized this part of the eastern Cordillera since the Miocene. Therefore, the preferred interpretation is of a recent extensional feature expressing a late-Mesozoic to Eocene boundary between the brittle and ductile deformation to the east and west respectively. Deep structures may be indirectly involved.

The Purcell Anticlinorium is a thick sedimentary wedge

separating the Eastern Metamorphic Belt from the Rocky Mountain Trench in southern British Columbia. As a simplification, it is often included in the Eastern Metamorphic Belt as another truncated range (Wheeler and Gabrielse, 1972). The sediments of the Purcells are generally characterized as a continental slope assemblage, with the deeper water sediments in the west grading to shallow water deposits in the more easterly sections. The Proterozoic Purcell Group experienced mild deformation in the Racklan orogeny from 1000 to 800 mya, probably also involving the crystalline basement on which it was deposited. Unconformably overlain by the Windermere Group and Paleozoic rocks, the entire sedimentary section was then folded, thrust, intruded, and mildly metamorphosed during a series of phases in the Mesozoic. Despite the models of decollement structures (Bally et al., 1966), the basement in this area was almost certainly involved in the deformation.

The Eastern Metamorphic Belt, which forms the central region across which the profile was run, is distinguished from the Purcells by its high degree of metamorphism and widespread granitic intrusion. This area, often called the Omineca Crystalline Belt, is dominated, particularly in its southwestern sections, by the Shuswap Complex of intensely altered and deformed volcanic, sedimentary, and, perhaps, basement rocks. The region is usually referred to as the "core zone" of the late-Mesozoic deformation. The thermal activity appears to have occurred mainly in the Jurassic,

followed by a milder Tertiary event. Because of the intense metamorphism, the substructure of this zone has only recently become better understood.

Of particular interest is a belt of granitoid gneisses, approximately coincident with Arrow Lake, that apparently represent remobilized Hudsonian crystalline basement (Wanless and Resser, 1974). These rocks are probably not a simple extension of the shield-type rocks beneath the Rocky Mountains that have been brought to the surface. Duncan (personal communication, 1977) has suggested that a tectonic geometry with a major Paleozoic transcurrent (or transform) fault along an Arrow Lake "suture" zone better agrees with the structural evidence than previous models involving eastward dipping subduction zones (Monger et al., 1972). Although this considerably complicates the geological reconstruction of this region, the feature primarily considered in the interpretation of the present study, is the relatively simple pattern of more intense metamorphism in the western section of the Eastern Metamorphic Belt.

Another proposed tectonic "suture" zone, generally along the Okanagan Valley, separates the Eastern Metamorphic Belt from the Interior Plateaux. The nature of this "suture" is in considerable doubt, although it forms an obvious geological boundary. The Interior Plateaux is a heterogeneous, but relatively undeformed group of volcanic, plutonic, and volcanic sedimentary rocks. These rocks are typical of ocean basin, island arc, and successor basin

settings. By a complex process of eastward dipping subduction, some obduction, and probably some transcurrent movement, the rocks of the Interior Plateaux were brought into their present position relative to the Eastern Metamorphic Belt sometime during the early Mesozoic (Monger et al., 1972). The reactivation of old features in different modes probably causes much of the confusion in the interpretation of this area.

Near the western margin of the Interior Plateaux, the Highland Valley shot points lie around the core zone of the Mesozoic granodiorite Guichon Creek batholith which intrudes volcanics and volcanic sediments. The gross structure of the batholith has been determined from gravity data (Ager et al., 1973). It appears to be a tilting funnel shaped intrusion. Its various phases roughly encase each other, with the most recent emplacement approximately in the centre or "core zone" (Northcote, 1969). The disseminated copper mineralization is apparently associated with the core zone. In order to investigate the batholith, and the Nicola volcanics on its eastern margin, a greater density of recording sites was used near the Highland Valley shot points.

3. Geophysical Review

The Cordillera in British Columbia has been the subject of considerable geophysical investigation much of which is summarized in Berry et al. (1971). They pointed out that there are few mantle depth determinations from seismic data in the Eastern Metamorphic Belt, although an average crustal thickness of 30 to 35 km was implied by gravity data (Stacey, 1973). Stacey developed a gravity model with a slightly more dense mantle, and a less dense crust in the central Cordillera west of the Rocky Mountain Trench, than in adjacent regions. A vague mantle depth-velocity-density boundary based on the gravity data was suggested in southern British Columbia running southwest to northeast. It was placed between 49°N and 51°N. To the south, the M-discontinuity sloped from 33 km in the Interior Plateaux to 45 km beneath the Rocky Mountains, and to the north the mantle dipped from 33 km to 53 km. A deep mantle between 50 and 60 km in the northern Rocky Mountain Trench is confirmed by Bennett et al. (1975) and Spence et al. (1977) .

At the western end of the profile of this study, White et al. (1968) found a three layer crust: a 5.2 km/s layer over a 6.1 km/s crust that apparently directly overlies the mantle. A mantle discontinuity near 50° with an east-west strike was proposed. One model had a velocity change from 7.8 km/s in the south to 8.1 km/s to the north in a mantle 30 km deep. The alternate model had the mantle depth

changing from 33 km in the north to 28 km in the south, with a uniform Pn velocity of 8.0 km/s.

The nature of the crust-mantle transition in British Columbia has been studied by Berry and Forsyth (1975), primarily in the western Cordillera, but with limited data as far east as the Eastern Metamorphic Belt. In the southwest, a mantle velocity of 7.8 km/s increases to 8.1 km/s north of 51°. Time-term interpretations reveal a shallower upper mantle boundary in the south, with a less complex topography than profiles north of 50° 30'N. Regional amplitude studies suggest that the M-discontinuity becomes less distinct to the southwest of Kamloops, than to the northwest.

Using surface wave data, Wickens (1976) confirmed a tendency to a sharper crust-mantle transition to the north and east of the Highland Valley shot point. A low velocity layer 40 to 50 km thick and about 15 to 20 km beneath the M-discontinuity in the Interior Plateaux, was found to become thicker and deeper to the north and east. Wickens also confirmed the generally low mantle velocities previously suggested for the region investigated by the present study. A general synthesis of previous studies suggests that a gently dipping upper mantle boundary, perhaps of varying character lies along the profile, with a velocity of about 7.8 to 8.0 km/s and an average depth of 35 km.

Although the upper crust is extremely complex at the surface, it is reasonable to assume that it has relatively

smooth anomalies near mantle depths (Berry and Forsyth, 1975). Fairly simple models have accounted for most of the crustal refraction results, with a 6.5 km/s average crust west of the Interior Plateaux grading to a 6.1 km/s average crust in the eastern Cordillera. Wickens (1976) suggested that the seismic refraction experiments were unable to detect a crustal low velocity zone that was evident from surface wave studies. In the region of this study, this low velocity zone apparently bottomed at the M-discontinuity. Although such a feature would tend to give anomalously shallow M-depths from refraction results, as Wickens pointed out, it would be difficult to detect with refraction data.

The correlation between the major geological divisions and magnetic anomalies was described by Haines et al. (1971). The Rocky Mountain Trench forms the major magnetic boundary with a sharp contrast between the broad smooth anomalies characteristic of the Canadian Shield to the east, and the magnetically quiet Eastern Metamorphic Belt to the west. The Interior Plateaux is relatively quiet with patches of small scale anomalies. The Rocky Mountain Trench discontinuity has been extensively investigated by Caner et al. (1971) using geomagnetic depth sounding data. The vertical magnetic component, Z, has a marked discontinuity just to the west of the trench, with high Z to the east, and low Z to the west. This feature apparently runs parallel to the trench from the north until it reaches the north end of

the Purcell Anticlinorium where it follows the Kootenay Arc along the western margin of the Purcells. A deep crustal high conductivity layer 15 to 40 km deep to the west of the transition was proposed. It would consist of thermally hydrated rock. Caner et al. (1971) also proposed an east-west trending anomaly just north of 49° and suggested that this marked either the northern margin of the highly conductive upper mantle region in the U.S.A. (Reitzel et al., 1970), or an offset in the crustal conductive layer. Using new data, Dragert (1973) altered the interpretation of Caner et al. He put the conductivity layer deeper, and increased the complexity of the structures, particularly in the west. He also suggested that an extension of the Precambrian rift zone of Kanasewich et al. (1969) from southern Alberta into the Purcell Anticlinorium might explain some of the data. Using the extension of the rift zone of Kanasewich et al. (1969) to allow for the magnetic and geological anomalies in the Purcells, Berry and Forsyth (1975) reaffirmed the suggestion of Berry et al. (1971) and Law and Riddihough (1971) that the Rocky Mountain Trench did, in fact, mark the cratonic margin.

However, the magnetic anomalies may be more closely related to heat flow observations than to structural models (Camfield and Gough, 1975). The area from the Rocky Mountain Trench to the eastern margin of the Coast Metamorphic Belt appears to experience moderately high heat flow, compared to low values found to the east and west (Jessop and Judge,

1971). A.M. Jessop has suggested that the southern Eastern Metamorphic Belt and Purcells are an extension of the northern U.S.A. Rocky Mountain thermal anomaly (Blackwell, 1969). Because this area, particularly the Eastern Metamorphic Belt, has undergone intensive thermal alteration since the middle Mesozoic, it seems that the magnetic data is more likely to be directly related to relatively recent thermal anomalies, than to Proterozoic tectonic features. The preferred interpretation of the Rocky Mountain Trench previously described agrees with this, although a coincidentally or indirectly related ancient tectonic feature is not unlikely.

Bally et al. (1966) interpreted detailed reflection seismic work through the Rocky Mountains, and across the Rocky Mountain Trench, at approximately the latitudes of the profile of this study. In the Front Ranges they found a high velocity Paleozoic sequence (6.1 km/s), covered by Mesozoics (4.0 to 4.6 km/s) in the east, and overlying Precambrian Purcell or Windermere sediments (5.5 km/s) in the west. These sequences are thrust into imbricate sheets with an older layer often overthrusting a younger sequence. The relatively passive basement (6.5 km/s) slopes gently about 2° to the west. This information was important in the interpretation of the arrivals from stations near the Kaiser shot point. The extension of their results to the northwest in the Main and Western Ranges, and across the Rocky Mountain Trench where the data was poor, was doubtful.

Integrating the geophysical and geological interpretations is difficult, since the geological models are rapidly evolving, and it is not clear what the geophysical data represent in tectonic terms. The most prominent geophysical anomalies to the west of the Rocky Mountain Trench should be relatable to fairly recent events (since the mid-Mesozoic). The tendency to rely on invoking ancient structures to model the data should be approached with care; two billion years of tectonic activity with several intense orogenic episodes might allow little direct evidence to survive. Tectonic reconstructions are also misleading, since there is growing evidence that lateral movements parallel to the tectonic strike are as geologically important as subduction and other compressional movements perpendicular to the strike. Long range seismic refraction can be used to define large scale lateral and vertical crustal features with the previously described constraints on the interpretation. In order to successfully resolve these structures, Berry and Forsyth (1975) prescribed a signal-to-noise ratio of better than 2, and a regular station spacing of less than 20 km.

CHAPTER II

1. Data Acquisition

The seismic systems used in this survey are described in detail by Bennett(1973). Three systems designated A, B and C were deployed. Each system amplified and recorded signals from vertical, radial, and transverse Willmore Mark II seismometers with a natural frequency of one Hertz. In order to extend dynamic range, the Geotech AS330 seismic amplifiers have low and high output gain levels separated by 18 to 30 dB, with a maximum gain of 100 dB. Both gain levels for the vertical and radial components, the high gain transverse component, and two time signals were recorded on seven channel FM tape. A crystal clock synchronized with the WWV radio time signal, and the WWVB binary coded decimal time signal provided timing. The shot point system consisted of a geophone placed within 50 m of the blast site, and a two channel chart recorder monitoring it and the WWVB time signal. The paper speed of 4 cm/s allowed a determination of origin time to within 20 ms.

For some of the shots, no operator was at the blast site and timing was achieved by reducing arrival times from

the FM tapes of the MICA seismic array to the north of Revelstoke, or from the Penticton (PNT) Canadian Standard Seismic Network station. Table 1 gives the complete shot statistics. The shot point system timing error of .02 s was based on reading capability and the variable distance of the geophone from the exact blast location. The MICA and PNT timing errors of .04 s and .1 s to .4 s respectively, were assigned on the basis of the ability to match arrivals from timed and untimed blasts. Traces with a large timing uncertainty are marked appropriately on the record sections and the first arrival travel times were not used.

The shot points at both ends of the profile are scattered over a small area. The various pits of the Kaiser coal mine are up to one km apart, while the Lornex and Bethlehem mines are about 5 km apart. The Kaiser shots typically consisted of a 200 by 100 m grid of 15 to 20 m drill holes spaced about 30 m apart and filled with explosive slurry. The explosions were not impulsive since time delays between the detonation of each section of holes gave typical total time delays of 70 to 200 ms. Some multiple blasts were spread over more than one second. The Lornex and Bethlehem shots were smaller in charge size and areal extent, but had similar delays. The centre of the blast zone and the elevation of the base of the drill holes were precisely determined through cooperation of the mining companies. The uncertainty associated with shot location errors in the distance calculations was assumed to be less

Table 1. Shot statistics. Some of the shots had no corresponding stations. The locations and elevations were determined from data supplied by the mining companies. Most timings were determined at the site, but some shots were timed remotely and have estimated timing errors greater than .03 s.

SHOT STATISTICS

SHOT#	DATE	MINE-PIT	SIZE ¹	LATITUDE	LONGITUDE	ELEV ²	TIME (U.T.)	PNT AMP. ³
1-73	JULY 26/73	KAISER-ADIT29	150	49.7525	114.8105	6370	19:58:08.93±.02	4.1
2-73	JULY 27/73	KAISER-HARMER1	150	49.7773	114.8303	6370	18:15:10.01±.02	2.9
1-74	MAY 21/74	KAISER-HARMER2	261	49.7848	114.8367	6370	18:33:08.67±.02	2.9
2-74	MAY 22/74	KAISER-ADIT29	230	49.7582	114.8165	6270	20:58:02.96±.02	4.9
3-74	MAY 24/74	KAISER-ADIT29	250	49.7503	114.8083	6220	18:12:10.85±.03	4.5
4-74	JUNE 6/74	KAISER-ADIT29	160	49.7607	114.8178	6220	21:03:03.28±.02	3.9
5-74	JUNE 7/74	KAISER-HARMER2	255	49.7888	114.8328	6370	18:38:48.13±.02	5.6
6-74	AUG 12/74	KAISER-HARMER2	203	49.7885	114.8342	6295	18:19:23.47±.02	4.0
7-74	AUG 13/74	KAISER-ADIT29	467	49.7598	114.8150	6220	20:58:47.73±.04	6.5
8-74	SEPT 4/74	BETHLEHEM-HUESTIS	9	50.4970	120.9946	4400	19:02:12.94±.02	4.5
9-74	SEPT 4/74	LORNEX	43	50.4583	121.0440	4672	22:54:28.48±.02	2.0 **
10-74	SEPT 5/74	BETHLEHEM-HUESTIS	28	50.4958	120.9949	4333	19:02:32.99±.04	1.1 *
11-74	SEPT 5/74	LORNEX	31	50.4552	121.0463	4752	22:55:54.87±.04	2.1 *
12-74	SEPT 6/74	KAISER-HARMER2	100	49.7905	114.8355	6320		
12-74-2 ⁵			300	49.7893	114.8377	6320	18:12:25.81±.04	5.3
13-74	SEPT 6/74	BETHLEHEM-JERSEY	41	50.4962	120.9826	4967	19:08:31.31±.02	1.9
1-75	MAY 6/75	LORNEX	60	50.4548	121.0418	4632	22:55:55.22±.04	6.0
2-75	MAY 7/75	BETHLEHEM-HUESTIS	27	50.4957	120.9971	4267	18:59:50.09±.04	3.8
3-75	MAY 8/75	KAISER-HARMER2	300	49.7878	114.8362	6320	NO TIMING	
4-75	MAY 9/75	BETHLEHEM-HUESTIS	24	50.4958	120.9981	4267	19:05:22.35±.02	2.5
5-75	MAY 9/75	KAISER-ADIT29	600	49.7563	114.8153	6170	21:02:18.57±.04	1.0
6-75	MAY 27/75	KAISER-HARMER2	220	49.7837	114.8353	6270		
6-75-2			215	49.7878	114.8322	6270	20:01:18.42±.04	0.8
7-75	MAY 27/75	LORNEX	19	50.4537	121.0400	4672	22:58:27.44±.02	1.6
8-75	MAY 28/75	LORNEX	19	50.4580	121.0479	4752	22:57:58.85±.02	6.1
9-75	MAY 29/75	KAISER-ADIT29	250	49.7507	114.8148	6170	21:01:17.14±.10	0.8
10-75	MAY 29/75	LORNEX	27	50.4557	121.0418	4632	22:53:17.52±.02	5.3
11-75	MAY 30/75	KAISER-ADIT29	200	49.7612	114.8183	6120	21:07:49.54±.40	0.5
12-75	MAY 30/75	LORNEX	10	50.4530	121.0397	4672	22:57:27.45±.02	0.8
13-75	JUNE 17/75	KAISER-#6 SEAM	50	49.7548	114.8363	6150	18:15:38.05±.02	0.8
14-75	JUNE 17/75	LORNEX	OMITTED					
15-75	JUNE 18/75	LORNEX	OMITTED					
16-75	JUNE 19/75	KAISER-HARMER2	115	49.7878	114.8322	6150	18:16:33.51±.02	0.5
17-75	JUNE 24/75	KAISER	?	49.7608	114.8181	6150	20:59:55.95±.04	1.0
18-75	JUNE 24/75	LORNEX	37	50.4545	121.0414	4632	22:57:46.32±.02	4.8
19-75	JUNE 25/75	BETHLEHEM-HUESTIS	?	50.4953	120.9943	4433	19:06:51.22±.02	5.8
20-75	JUNE 25/75	LORNEX	38	50.4553	121.0483	4712	22:58:35.36±.02	6.3
21-75	JUNE 26/75	LORNEX	17	50.4527	121.0445	4712	22:54:43.31±.02	2.5
22-75	JUNE 27/75	BETHLEHEM-IONA	26	50.4937	120.9787	5033	19:29:55.54±.02	2.3
23-75	JUNE 27/75	KAISER	?	49.7557	114.8367	6150	20:51:42.67±.04	0.5
24-75	JUNE 27/75	LORNEX	41	50.4582	121.0484	4752	22:53:38.57±.02	8.8

¹SIZE - THE TOTAL SHOT WEIGHT IN THOUSANDS OF POUNDS²ELEV - THE ELEVATION OF THE BOTTOM OF THE SHOT HOLE IN FEET ABOVE SEA LEVEL³PNT AMP. - THE PEAK TO PEAK AMPLITUDE OF THE P-ARRIVAL

MEASURED IN CM. FROM PNT PAPER RECORDS (CORRECTED FOR INSTRUMENT RESPONSE)

** DENOTES SCALE AMPLITUDES DETERMINED FROM MICA ARRAY

*MULTIPLE BLAST (TIMING GIVEN FOR FIRST BLAST)

than .1 km.

The recording sites were preferably located on bedrock outcrops found near access roads, as close to the profile line as possible. Figure 1 illustrates the line, with the closed circles indicating stations which recorded Kaiser shots, and with open circles showing those which recorded Highland Valley shots. Tables 2a and 2b give the statistics of those stations used in the interpretation. The station labels are derived from the system identification (A, B or C), the shot number, and the year of the field season. The sites were located using 1:50000 topographic maps, aerial photographs, and Provincial Forest Inventory Maps. The resulting errors in the calculation of distances were generally less than .2 km with a few exceptions as noted later.

The seismic stations were corrected to an elevation datum of one km above sea level by assuming a 5.3 km/s near-surface velocity, and a 6.0 or 8.0 km/s inferred refractor velocity.

System and environmental noise contamination, poor timing, system malfunction, logistical problems, and duplication resulted in a severe reduction in the total number of recordings actually used in the interpretation. Fifteen of a total of nineteen Kaiser shots were used for 34 successful recordings. Eighteen of a total of twenty Highland Valley shots were used for 41 successful recordings.

Table 2a. Kaiser station statistics. The locations and elevations were mainly determined from 1:50000 topographic maps. The first arrival times were determined from the analog output. The column PICT indicates whether the trace was included in the final record section and whether the analog travel time information was used in the delay time and first arrival time analysis. Many travel time picks on noisy traces were considered erroneous.

KAISER PROFILE STATISTICS

SITE	LATITUDE	LONGITUDE	DISTANCE	TIME ¹	ELEV ²	P-COR ³	LO-CUT ⁴	HI-CUT	PLOT ⁵	TITLE	SCIDLE
C1375	49.77177	114.94044	7.296	1.62	4050	-.11	0.75	12.50	Y Y	-.15	1.00
A774	49.81351	115.13933	24.197	4.32	4000	-.11	0.75	12.50	Y Y	-.10	1.00
C774	49.84550	115.24583	32.553	5.65	4400	-.13	0.75	12.50	Y Y	-.18	1.00
C1675	49.75793	115.38705	40.141	6.99	5100	-.15	0.75	12.50	Y Y	0.0	0.50
A474	49.78017	115.51666	50.402	8.62	5100	-.15	0.75	12.50	Y Y	0.0	1.00
C674	49.78416	115.67767	60.801	10.33	2900	-.08	0.75	12.50	Y Y	0.0	1.00
A674	49.83701	115.80434	70.115	11.88	2950	-.08	0.75	7.00	Y Y	0.0	1.00
A1375	49.73546	115.98280	82.754	13.00	5500	-.16	0.75	7.00	Y Y	0.0	1.00
A1675	49.70584	116.22334	100.780	17.09	5600	-.16	1.50	6.00	Y Y	0.0	0.50
A574	49.73167	116.40568	113.664	18.88	3800	-.11	0.75	10.00	Y Y	-.30	1.00
A2375	49.70648	116.62277	130.324	0.0	4900	-.14	0.80	8.00	Y N	0.70	1.00
B774	49.71334	116.70000	135.993	22.82	5900	-.17	0.75	12.50	Y Y	0.0	1.00
B1675	49.71776	116.82384	143.877	24.39	3700	-.10	0.75	6.00	Y Y	0.0	1.00
C2375	49.76463	116.90974	150.791	0.0	1900	-.05	0.80	8.00	N N	0.0	1.00
A173	49.92817	116.94733	155.203	26.07	6262	-.19	0.75	8.50	Y Y	0.0	1.00
C173	50.04008	117.12743	169.653	28.72	3750	-.11	0.75	12.50	Y Y	0.0	10.00
B674	49.98734	117.35201	182.435	30.44	2900	-.12	0.75	8.00	Y Y	0.0	1.00
A273	50.12106	117.50882	196.176	32.34	2450	-.10	0.75	12.50	Y Y	0.0	1.00
C273	50.12300	117.76134	214.015	34.64	2100	-.09	0.75	7.50	Y Y	0.0	10.00
B273	50.11633	118.00917	231.441	36.54	2950	-.12	0.80	7.00	Y Y	0.0	1.00
A1775	49.90125	118.08612	234.578	0.0	1700	-.06	0.80	7.50	Y N	0.0	0.25
C1775	49.93036	118.23447	245.326	0.0	3950	-.16	0.75	7.50	Y N	0.0	0.25
A374	49.81551	118.30434	252.071	39.47	3150	-.13	0.75	6.00	Y Y	0.0	1.00
A274	50.09175	118.47334	265.409	40.99	4100	-.17	0.75	6.00	Y Y	0.0	1.00
A975	50.19400	118.56824	273.943	41.91	2700	-.10	0.80	8.00	Y Y	0.0	0.25
C274	50.24150	118.63628	279.297	0.0	1950	-.07	0.75	6.00	Y N	0.0	1.00
B274	50.26500	118.82283	292.866	44.24	2300	-.09	0.75	6.00	Y Y	0.0	1.00
C975	50.26500	118.82283	293.164	0.0	2300	-.09	0.80	6.00	N N	0.0	1.00
C174	50.35468	119.09801	311.837	46.73	5050	-.22	0.75	7.50	Y Y	0.0	2.00
B374	50.35001	119.51666	343.997	50.83	3200	-.13	0.75	5.20	Y Y	0.0	1.00
C374	50.33968	119.95982	375.023	54.93	3150	-.13	0.75	7.50	Y Y	0.0	1.00
C474	50.38100	120.30133	398.842	57.67	2900	-.11	0.75	5.00	Y N	0.0	1.00
B474	50.48927	120.47021	412.502	59.90	4200	-.17	0.75	5.00	Y N	0.0	1.00
C574	50.47569	120.95039	442.742	64.00	4050	-.17	0.75	5.00	Y N	0.0	1.00

¹TRAVEL TIME IN SECONDS IS DETERMINED FROM ANALCG PLAYBACKS

A ZEAC IMPLIES THAT NO TIME COULD BE DETERMINED

²ELEVATION OF THE RECORDING SITE IN FEET ABOVE SEA LEVEL (FROM 1:50000 MAPS)

³ELEVATION CORRECTION IN SECONDS TO A ONE KM DATUM (APPLIED TO PLOTS FOR DISTANCES OVER 80 KM)
THE CORRECTION IS NOT INCLUDED IN THE TRAVEL TIMES REPORTED IN THIS TABLE

⁴LO-CUT AND HI-CUT ARE THE LIMITS IN HERTZ OF THE BANDPASS FILTER USED ON THE FILTERED RECORD SECTIONS

⁵THE FIRST COLUMN OF PLOT SPECIFIES WHETHER OR NOT (Y OR N) THE TRACE IS INCLUDED IN THE FINAL SECTION
THE SECOND COLUMN SIMILARLY SPECIFIES IF THE ANALCG TRAVEL TIME INFORMATION WAS USED

Table 2b. Highland Valley station statistics.

The locations and elevations were mainly determined from 1:50000 topographic maps. The first arrival times were determined from the analog output. The column PLOT indicates whether the trace was included in the final record section and whether the analog travel time information was useful. Many travel time picks on noisy traces were considered erroneous.

HIGHLAND VALLEY PROFILE STATISTICS

SITE	LATITUDE	LONGITUDE	DISTANCE	TIME ¹	ELEV ²	E-COR ³	LO-CUT ⁴	HI-CUT	PLOT ⁵	TITLE	SCIDLE
A874	50.47569	120.95042	4.399	0.70	4050	-.06	0.75	12.50	Y Y	0.0	1.00
A974	50.47569	120.95042	7.296	1.07	4050	-.07	0.75	12.50	Y Y	-.20	1.00
C874	50.48560	120.88460	8.519	1.42	3900	-.05	0.75	12.50	Y Y	0.05	1.00
C974	50.48560	120.88460	12.048	2.07	3900	-.06	0.75	12.50	Y Y	-.22	1.00
B874	50.47029	120.81161	13.560	2.53	3300	-.04	0.75	12.50	Y Y	0.0	1.00
B974	50.47029	120.81161	16.896	3.11	3300	-.04	0.75	12.50	Y Y	0.0	1.00
A1074	50.48151	120.73000	19.050	3.29	3850	-.05	0.75	12.50	Y Y	0.0	0.25
A1174	50.48151	120.73000	22.860	3.86	3850	-.06	0.75	12.50	Y Y	0.0	1.00
C1074	50.46667	120.64999	24.887	4.39	4000	-.06	0.75	12.50	Y Y	0.05	1.00
C1174	50.46667	120.64999	28.341	4.90	4000	-.07	0.75	12.50	Y Y	0.0	1.00
B1074	50.45000	120.53333	33.287	5.62	4500	-.07	0.75	12.50	Y Y	-.05	1.00
B1174	50.45000	120.53333	36.610	6.10	4500	-.08	0.75	12.50	Y Y	-.05	1.00
A1374	50.43805	120.39127	42.540	7.23	3600	-.06	0.75	12.50	Y Y	0.92	1.00
C1374	50.38100	120.30133	50.161	8.64	3100	-.05	0.75	12.50	Y Y	0.05	1.00
A275	50.34550	120.28320	53.521	9.64	3800	-.05	0.75	12.50	Y Y	-.02	1.00
A175	50.34550	120.28320	55.387	9.88	3800	-.06	0.75	12.50	Y Y	0.10	1.00
B1275	50.32458	119.99663	75.627	12.60	3350	-.05	0.75	12.50	Y Y	0.0	1.00
C275	50.33968	119.95982	75.882	12.71	3150	-.03	0.75	12.50	Y Y	0.0	1.00
C1275	50.39452	119.82585	86.603	0.0	2300	-.01	0.75	12.50	Y Y	-.08	1.00
A1275	50.42976	119.62729	100.467	16.45	3400	-.05	1.00	5.20	Y N	0.0	0.50
B475	50.35739	119.51070	106.953	17.85	3200	-.03	0.75	12.00	Y Y	0.0	0.50
C475	50.38300	119.34067	118.520	19.65	2050	0.01	0.75	5.50	Y Y	0.0	1.00
A775	50.34575	119.20061	131.433	22.26	3200	-.04	0.75	9.50	Y Y	0.0	1.00
B875	50.34575	119.20061	132.039	22.35	3200	-.04	0.75	10.60	Y Y	0.0	1.00
C875	50.34354	119.11406	138.199	23.30	4500	-.08	2.70	10.00	Y Y	0.0	1.00
A875	50.35809	118.92316	151.591	25.00	2500	-.02	2.70	10.00	Y Y	0.0	1.00
C1075	50.26500	118.82283	159.463	26.07	2300	-.01	0.75	10.00	Y Y	0.0	1.00
A1075	50.19400	118.56824	178.697	28.78	2700	-.02	0.75	12.50	Y Y	0.0	1.00
B2175	50.06657	118.43533	191.102	0.0	4200	-.10	1.00	5.50	Y N	0.0	1.00
C1875	49.93036	118.23447	208.923	32.58	3950	-.09	0.75	12.00	N N	0.0	1.00
A2175	49.93036	118.23447	209.073	32.84	3950	-.09	0.75	12.00	Y Y	0.0	1.00
A1875	49.90125	118.08612	220.069	34.07	1700	0.01	0.75	5.50	N N	0.0	1.00
C2175	49.90125	118.08612	220.222	34.32	1700	0.01	0.75	5.50	Y Y	0.0	1.00
A1975	50.06081	117.79668	233.191	0.0	2500	-.02	1.50	4.00	Y N	0.0	1.00
A2075	50.06081	117.79668	236.182	38.69	2500	-.03	0.75	12.00	Y N	0.0	1.00
C1975	50.13155	117.53307	250.057	0.0	2450	-.01	1.50	4.00	Y N	0.0	1.00
C2075	50.13155	117.53307	253.278	40.24	2450	-.03	0.75	5.50	Y N	0.0	1.00
B2075	49.98633	117.34902	269.400	0.0	2900	-.05	0.80	5.50	Y N	0.0	1.00
C2275	49.76463	116.90974	302.260	0.0	1900	-.02	1.50	5.00	Y N	0.0	1.00
A2275	49.70648	116.62277	323.958	47.01	4900	-.15	1.00	5.50	Y N	0.0	1.00
A2475	49.70648	116.62277	327.850	0.0	4900	-.14	1.00	6.00	Y N	0.0	1.00

¹TRAVEL TIME IN SECONDS IS DETERMINED FROM ANALOG PLAYBACKS

A ZERO IMPLIES THAT NO TIME COULD BE DETERMINED

²ELEVATION OF THE RECORDING SITE IN FEET ABOVE SEA LEVEL (FROM 1:50000 MAPS)

³ELEVATION CORRECTION IN SECONDS TO A ONE KM DATUM (APPLIED TO PLOTS FOR DISTANCES OVER 80 KM)

THE CORRECTION IS NOT INCLUDED IN THE TRAVEL TIMES REPORTED IN THIS TABLE

⁴LO-CUT AND HI-CUT ARE THE LIMITS IN HERTZ OF THE BANDPASS FILTER USED ON THE FILTERED RECORD SECTIONS

⁵THE FIRST COLUMN OF PLOT SPECIFIES WHETHER OR NOT (Y OR N) THE TRACE IS INCLUDED IN THE FINAL SECTION

THE SECOND COLUMN SIMILARLY SPECIFIES IF THE ANALOG TRAVEL TIME INFORMATION WAS USED

2. Preliminary Analysis

The FM field tapes were edited onto a master tape and subsequently digitized. Four channels (three seismic plus time) were input to a 14 bit analog-to-digital convertor system with magnetic tape output. The system included a Hewlett Packard FM playback unit, a modified Analogic Corp. AN5800 A-D convertor, a Kennedy 8108 9-track digital tape transport with a Kennedy 8230 buffered formatter, and control-interface logic circuits. The effective digitization rate was 62.5 Hz with minor variations due to FM tape speed fluttering and tape stretching. An average sample rate was determined from the first 24 seconds of data and used in the analysis. The average digitizing rate was not exact, and in order to improve the appearance of the final record action, a time correction included in Table 2 as TTIDLE was used. It was determined by matching the analog and digital arrival times and its effect is primarily aesthetic.

Power spectral analysis, using a truncated autocorrelation power estimate, showed that most of the seismic energy, on the majority of traces, was between 2 and 4 Hz. There was considerable signal outside of this pass band, however, so that to preserve the quality of the first break, only traces that showed significant noise were band passed. For unfiltered traces the field system amplifier cutoffs of .75 and 12.5 Hz at the -6 dB level are quoted in

Table 2. The digital filter limits were set to eliminate the noise spectrum determined from the five seconds of noise preceding the first arrival. A fourth order zero-phase Butterworth filter (Kanasewich, 1975) was used to bandpass the traces.

In some cases cross-talk between the time channels and the seismic channels caused considerable noise contamination within the frequency limits of the signal. Maximum Entropy (MEM) spectral analysis (Ulrych and Bishop, 1975) was used to closely resolve the noise and signal spectra in order that a notch filter might be applied. However, the signal-to-noise ratio was not improved by the notch filter and the arrivals were distorted. As a compromise, a narrow bandpass with a width of a few Hertz was applied to these traces.

Amplitude correction factors due to the system amplifier responses were calculated from the field gain settings. The energy yield of the blasts was also estimated by determining the amplitude of the first arrival on the PNT records. This station is south of the profile, but the azimuths relative to the shot sites were judged to be close enough to the profile direction that the amplitude estimate would be reasonable. No other permanent station could give equivalent data. However, because the PNT station was inoperable for a short time during the field work, some of the shots were scaled from MICA array arrivals as indicated in Table 1. Although charge sizes were included in Table 1 for comparison, they were not used directly in the scaling,

but they did help indicate some difficulties.

The scale adjustment factor SCIDLE in Table 2 was used to correct possible errors in field amplifier settings, and to allow for inappropriate shot yield factors. It was assumed that, after scaling, the amplitudes should vary more or less smoothly along the profile, and that they should be independent of the shot. Using this criterion, recordings of shots 9-75, 12-75, 16-75 and 17-75 were amplitude corrected by the additional factor SCIDLE. These qualitatively justifiable adjustments are similar to the TTIDLE factor in that their effect is more aesthetic than substantial.

The traces were digitally edited and compiled into the final filtered record sections, shown in Figures 2, 3 and 4. Question marks placed after the trace label imply that the timing for the trace was only approximate, so that only the amplitude information is relevant. The small horizontal ticks on the traces correspond to the first arrival times as picked from the seven channel FM playbacks. The analog records were generally easier to pick than the digital tracks. Only the picks which were reasonably clear were plotted; the full set of data was included in Table 2. Figures 2 and 3 are full record sections of Kaiser and Highland Valley shots, while Figure 4 is an enlargement of the near source traces in Highland Valley, with a 6 km/s reducing velocity. In order to enhance the head waves relative to the body waves, an R^2 geometrical spreading

factor was included in the amplitude scaling. A few apparently unreasonable discrepancies, that could not be corrected, are mentioned as they appear in the interpretation. The remaining amplitude and travel time information was assumed to be related to geophysical structure along the profiles.

Figure 2. Kaiser record section. The filtered traces are amplitude corrected and have a R^2 factor applied to emphasize arrivals at large distances. The horizontal tic marks on the traces mark the first arrival picks from the analog output. Question marks appearing beside trace names imply that those traces had poor timing and provide only amplitude information.

Figure 3. Highland Valley record section. The filtered traces are amplitude corrected and have a R^2 factor applied to emphasize arrivals at large distances. The horizontal tic marks on the traces mark the first arrival picks from the analog output. Question marks appearing beside trace names imply that those traces had poor timing and provide only amplitude information.

Figure 4. Near source Highland Valley section. The first seventeen traces of Figure 1 are displayed with a reducing velocity of 6 km/s. The filtered traces are amplitude corrected and have a R^2 factor applied to emphasize arrivals at large distances. The horizontal tic marks on the traces mark the first arrival picks from the analog output.

CHAPTER III

1. Preliminary Interpretation

Several factors encouraged a relatively simple approach to the interpretation. The profile has obvious lateral discontinuities with few other geophysical constraints. More sophisticated approaches to seismic modelling of these structures are not readily available. In any event, the very non-impulsive nature of the sources, together with the low frequency of the recordings, limits the resolution to a few kilometers at depths corresponding to the M-discontinuity. Timing equipment malfunctions, inclement weather, interfering seismic arrivals from other unidentified blasts, and uncertain site location in poorly mapped and rapidly changing areas all contributed to make much of the data of indifferent quality. Despite these difficulties, several interesting features are defined or suggested by this experiment.

Common assumptions about observed arrivals were used in the interpretations. Arrivals with an apparent velocity of 7.5 km/s or greater were interpreted kinematically as critical refractions from the M-discontinuity. Amplitude

modelling required the more correct dynamic representation of these waves as interference or diffraction head waves (Braile and Smith, 1975; Cervený, 1966). Phases with apparent velocities of 4.5 to 6.1 km/s were assumed to be kinematically behaving like sub-critically and critically refracted waves in the upper crust. Dynamically they may be a group of arrivals corresponding to the sum of multiple reflections in the crustal wave guide (Berry and Forsyth, 1975). Intermediate layers with velocities from 7.0 to 7.4 km/s were tentatively identified, although only second arrivals were observed on the Kaiser record section. The preliminary determination of the velocities and depths of these layers was made from least squares fits to the first arrival travel times.

Simple models from straight line fits to the arrivals suggested the basic structure and identified interpretational difficulties. The first arrival times picked from the analog records are plotted in Figure 5 along with the topography and a cross-section of the near-surface geology. The lines were fitted using a weighted generalized least squares program adapted by Ahern (1975) from a program described by York (1969). Weights were computed from estimates of the errors in distance and time associated with each observation. The usual error assigned to the distance was .2 km, and the assumed timing error was normally .05 s. Exceptions are noted in the detailed discussion below.

The Highland Valley data can be fitted reasonably with

Figure 5. Travel times, topography, and geology.

Upper: Reduced travel time curves were determined from least-squares fits to the data. Crosses are Highland Valley observations and squares are data from Kaiser shots.

Middle: The topographic variations along the profile were measured on 1:250000 maps.

Lower: The schematic geological cross-section was adapted from Campbell (1973) and Wheeler and Gabrielse (1972).

Intrusives-

Volcanics-

Sediments and Volcanic Sediments-

Sediments-

Hudsonian Basement-

Paleozoic Sediments-

a two layer model, although a three layer version with three travel time branches is displayed in Figure 5. The difference is in the assumption that the three points past 178 km represent a separate travel time branch from the five previous points. The intercept of the near surface crustal refraction is non-zero, but this is a vestige of the systematic scatter in the points that is discussed below. The branch has a least squares apparent velocity of $6.04 \pm .04$ km/s. The two layer assumption (actually one layer and a half-space) gives a lower layer velocity of $7.35 \pm .05$ km/s with an intercept of $4.41 \pm .12$ s. A horizontally layered model calculation yields a depth of 14.6 ± 1.4 km for the interface. With this velocity structure, a Pn arrival with apparent velocity 7.6 km/s and apparent depth of 30 km, would not be observed as a first arrival on a profile of this length. If the three arrivals past 178 km are interpreted as a separate branch, then the velocities and intercepts plotted in Figure 5 give a $7.36 \pm .02$ km/s layer at a depth of 23.4 ± 1.0 km with a thickness of $6.1 \pm .5$ km. The half-space below has an apparent velocity of $7.49 \pm .02$ km/s. This can be interpreted as an upper mantle branch, using the criterion of associating apparent velocities of 7.5 km/s or over with Pn arrivals.

The Kaiser travel time curve has two well defined branches plotted in Figure 5. The first has an apparent velocity of $6.11 \pm .03$ km/s. Because the six points within 70 km of the shot have less scatter, the intercept, $.39 \pm .03$ s,

was calculated using only them. The arrival at the recording site closest to the shot implies an average first layer velocity of 4.5 ± 0.02 km/s with a maximum probable thickness of 1.3 ± 1 km. The second layer has a thickness of 33.2 ± 1.1 km putting the 7.93 ± 0.04 km/s half-space at a depth of about 35 km.

It is immediately obvious that there are considerable changes along the profile, and that a simple horizontally layered model is inadequate. The simplest alternative is a dipping layer model. Using formulae from Dobrin (1960), and assuming an average upper crustal velocity of 6.1 km/s, a model was computed with a mantle velocity of 7.7 km/s, and a M-discontinuity gently dipping 2° to the east from a depth of about 25 km under Highland Valley to a depth of 37 km under the Kaiser shot point. Based on the previous discussion of the travel time curves, the assumption for the average crustal velocity may be too low, particularly for the Highland Valley three layer model, so that the depth is likely to be greater than the one calculated at that end of the profile.

The crustal models derived from the first arrival data are very vague averages. To extend the interpretation, second arrivals and later phases on the record section were identified using ray tracing and synthetic seismogram programs. A delay time approach was finally used to separate upper mantle topography from lateral variations in the upper crustal velocity. The considerable near-source

variations from the crustal travel time curves are described in detail in the following sections.

2. Near Source Crustal Profile from Highland Valley

The concentration of sites near the Highland Valley shot points reflects an attempt to get seismic information about the local geology. The averaging nature of a refraction profile and the complexity of the geology makes the evaluation necessarily qualitative. Figure 6 displays the near source traces out to 80 km with a 6.04 km/s travel time curve plotted. The least squares intercept of $.12 \pm .05$ s can be best explained as due to varying surficial thicknesses of lower velocity rocks. The near-source first arrivals are sharp with four or five cycles in the first phase. Bethlehem arrivals tend to have higher frequencies of 3 to 10 Hz while Lornex arrivals are in the 3 to 7 Hz range. The more rapid attenuation of the higher frequency Bethlehem arrivals may explain an apparent slight overcompensation of Bethlehem amplitudes from the PNT scaling. The Lornex blasts also generate much larger Rayleigh waves (ground roll). The surface wave arrivals are often sharp (C1174, A1374) but they were not well correlated between traces, resulting in the poorly defined 3.4 km/s branch in Figure 6.

The traces are paired. For example, the records A874 and A974 were recorded from the Bethlehem and Lornex shot

Figure 6. Near source Highland Valley section with travel time curves. The first 6.04 km/s curve is a near source crustal refraction. The 3.4 km/s curve through the second arrivals corresponds to the surface wave (ground roll) primarily produced by Lornex blasts. Shots 8-74, 10-74, and 2-75 were Bethlehem shots and 9-74, 11-74, 13-74, and 1-75 were Lornex shots.

points respectively, using the same site. The ray paths are similar near the receiver, but they are very different close to the shot points. Therefore, the apparent velocity between first arrivals detected at the same site from two separate shots is assumed to be related to the geology within a few kilometers of the shot points, and is relatively independent of the local geology of the site. The apparent velocities between adjacent station locations, if they are consistent for Lornex and Bethlehem shots separately, reflect lateral variations in acoustic properties between the sites. Using the above assumptions, reasonable explanations can be found for most of the observed travel time anomalies.

The deviations from the least-squares travel time curve along the near source profile are small, but if they are consistent, then some geological feature may be correlated with them. The average velocity between the first site, A874 and the Bethlehem mine is $6.2 \pm .2$ km/s while the average velocity from A974 to the Lornex pit is $6.7 \pm .2$ km/s. The Bethlehem mine is on the east side of the Bethlehem Phase of the Guichon Creek Batholith (Northcote, 1969). The Lornex mine is on the western margin, so that the ray paths of the waves travelling from Lornex blasts go through this phase of the batholith, while the ray paths from Bethlehem shots avoid it. The two ray paths are similar to each other for the rest of their course in the Highland Valley Phase. This implies that the Bethlehem Phase near the core zone of the

batholith has an average velocity of 6.7 km/s, while the surrounding Highland Valley Phase has a velocity near 6.1 km/s, the average for the Interior Plateaux near-surface crust. Gravity studies of the batholith seem to conflict with this data since the density generally decreases toward the core zone (Ager et al., 1973). The changing azimuths of stations farther away from the shot locations result in small variations in the apparent velocities between Bethlehem and Lornex arrivals at the same sites. Different proportions of Lornex ray paths are in the Bethlehem Phase for different azimuths. This characteristic can be observed as far as 55 km from the sources.

The arrivals C874 and C974 were in the outer "Hybrid" zone of the batholith and suggest that most of the outer phases have velocities near 6.0 km/s. The times at B874 and B974 are late relative to the travel time curve, perhaps caused by a lateral low velocity zone at the outer margin of the batholith. However, the site was actually off of the batholithic outcrop, on unconsolidated sediments of unknown thickness that may have delayed the arrival.

The stations from A1074 to B1174 are located on the Nicola Group of volcanics. The scattered arrival times appear to reflect an inhomogeneous zone, with velocities near 6.0 km/s. Unknown thicknesses of glacial drift might make the arrivals at C1074 and C1174 appear late, thus exaggerating the apparent magnitude of the inhomogeneity.

The arrivals at A1374 and C275 suggest that, although

the formations between them are very inhomogeneous, the average 6.0 km/s velocity is well determined. The late arrival at C1374 could be attributed to the unconsolidated sediments on which the site was located, or it may reflect further inhomogeneity in the Nicola Group, presumably underlying the detritus. The arrivals at A275 and A175 are .6 s late. The traces are very "ringy," probably due to acoustic qualities of the site, but there is no reasonable explanation on seismic grounds for the delay. However, due to inadequate mapping, there is some doubt as to the exact location of the site, so that these traces were assigned 3 km errors and were weighted accordingly in the least squares calculations. An arrival at -.5 s on A175 appears to correlate with energy on traces closer to the shots. This arrival on A175 is probably due to an unidentified source not related to the Highland Valley shots, and the apparent correlations are erroneous since they are only observed on the noisiest traces.

The crustal arrivals at distances greater than 80 km are displayed in Figure 10 (page 59). The arrival at A1275 in Figure 10 is early. This is a very unusual trace with its high frequency large amplitude later arrivals, and low amplitude crustal phase. The next traces, B475 and C475, confirm an average crustal velocity of 6.04 km/s out to 120 km. Past 120 km, the crustal phase is either delayed or severely attenuated, since the observed arrivals at A775 and B875 are late. This may be due to a major lateral

geological boundary correlated with the Okanagan Valley, which is located at about 125 km.

3. Near Source Crustal Profile from Kaiser

The interpretation of the near source arrivals of the Kaiser profile presents a more tractable problem than that of the Highland Valley profile. There is considerable upper crustal geophysical information over at least the first 80 km. Although they are very complex, the geological structures are less heterogeneous than those of the Interior Plateaux. Also, they have a more obvious geophysical expression, that is, greater density, acoustic and magnetic contrasts.

The previously described 6.1 km/s crustal refraction is very consistent for the first 80 km on the Kaiser section in Figure 8. A gradual increase in amplitude with very sharp 2 to 4 Hz arrivals is the general pattern. However, the trace just past 80 km, A1375, has an anomalous first arrival time and amplitude.

The arrival time at A1375 is approximately one second early. The crustal phase arrival times of traces past 85 km are scattered, but are roughly along the 6.1 km/s line. The only reasonable model for the early arrival on A1375 would be an abrupt lateral upper crustal velocity increase. This is not reflected in arrivals at greater distances. As well, A1375 is on the west margin of the Rocky Mountain Trench and

the work of Bally et al. (1966) suggests that a velocity decrease in this area is more likely. Therefore, the arrival is probably a seismic event unrelated to the timed blast. This is quite probable since a number of other recordings experienced interference from background seismic events.

The attenuation of arrivals after the trench is real. The crustal phases beyond 80 km are very low amplitude and emergent and the travel times are scattered around the 6.1 km/s line. A1675 has a crustal arrival late by .1 s, reflecting the lower velocity Proterozoic sediments in the Purcells. The first arrival at A574 is .2 s early. This could be explained by inaccurate site location, or by local high velocity Paleozoic carbonates. It is interesting to note that the 6.5 km/s basement at a depth of 8 km at Kaiser could be extended to the west as in Bally et al. (1966). With a westward slope of 2° , this layer would produce a first arrival branch with an apparent velocity slightly less than 6.5 km/s at about 115 km from the Kaiser shot point (Dobrin, 1960). The A574 early arrival is at an appropriate distance. However, this interpretation is unlikely since arrivals at greater distances do not show similar characteristics, and there are no corresponding second arrivals. The first arrivals in four traces from B774 to C173 are high frequency very emergent phases. B774 and A173 agree well with the 6.1 km/s line. The trace B1675, which appears to be of lower frequency because of severe digital

filtering, has a arrival time .3 s late. However, it was very noisy with an uncertain pick of the arrival. The upper crustal phase at C173 may have been missed because it was below the noise level. In support of this, the first arrival picked for C173 was abrupt, while the arrival at A173, 8 km nearer the shot, was very emergent, suggesting that the correct first arrival time for C173 was not picked.

The crustal model needed to explain the kinematic characteristics of this profile is a simple 6.1 km/s block with small inhomogeneities. However, the dynamic characteristics, specifically the amplitude attenuation beyond 80 km, necessitate a more complex solution. Using the results of Bally et al. (1966), the average upper crustal model in Figure 7 was synthesized. The 6.1 km/s layer is composed of Paleozoic strata. The underlying low velocity Proterozoic rocks have an unknown extent. The crystalline basement velocity of 6.5 km/s was taken from a study done 100 km to the north by Chandra and Cumming (1972). The geological discontinuity at the Rocky Mountain Trench could attenuate crustal amplitudes using any number of reasonable geometries for the structure.

Figure 7. Schematic of near source Kaiser seismic structure. It is a compilation from Bally et al. (1966) and is not defined by the data set of this study. The poorly determined discontinuity at the Rocky Mountain Trench and the sedimentary low velocity zone probably contribute to the low amplitudes observed on the Kaiser record section beyond 80 km.

4. Synthetic Seismograms

Synthetic seismogram computations offer a method of verifying seismic models. Phases more complex than the critical refractions that appear as first arrivals can be included in the interpretation. However, no generally applicable program is available to compute the seismic response of a laterally heterogeneous medium. Therefore, the computed synthetics corresponding to the record sections of the present study are useful only as a general indication of the correctness of the interpretation. The models can not be treated as definitive.

The Disc Ray Theory (DRT) method of computation of the synthetic seismograms is described by Wiggins (1976). Chapman (1976) has provided a theoretical derivation of DRT. The program used was the HRGLTZ routine developed by Wiggins. Besides constraining the model to that of laterally homogeneous media, the computational procedure also has difficulty with models that have thick, homogeneous layers with large velocity contrasts. The corresponding head wave amplitudes are exaggerated. This problem can be obviated by using the more expensive but exact Generalized Ray Theory (Wiggins and Helmberger, 1974). For the present study, the Disc Ray Theory approach was used since only the identification of phases and a suggestion of amplitude trends was expected.

The output from the HRGLTZ routine includes travel time

curves and synthetic seismograms. Figures 8 and 10 are the Kaiser and Highland Valley record sections, respectively, with the travel time curves for the models in Figures 9 and 11 superimposed. Figures 9 and 11 also include the corresponding computed seismograms. Numerous models were computed: those displayed are the simplest, and they demonstrate most of the difficulties.

The interpretation of the Kaiser record section is more complex than the simple travel time model previously described. The major change is the addition of a 9 km thick 7.05 km/s intermediate layer at a depth of 29 km. The wide angle reflections from this layer match the large amplitude phases about 1 s after the Pn arrival on B674, A273, and C273. They correlate well with arrivals beyond 120 km. The interference effect near 125 km, due to reflections and refractions from the mantle and the intermediate layer, produce very large amplitudes on the synthetics, corresponding with the observations on B774, A2375, and B1675. The lower amplitudes at distances less than 120 km are supported by the DRT calculations as well. The computed upper crustal refraction branch and the reflection branch from the intermediate layer converge at the upper right. There is a generally good correlation with seismic energy along these lines out to 440 km. However, the amplitudes computed are far too large. This would be expected from this model, despite the problems with the DRT method. An attempt to use low velocity zones or velocity gradients to

Figure 8. Kaiser section of Figure 2 with travel time curves. The travel time curves were calculated from the velocity-depth model given in Figure 9 using the program HRGLTZ.

Figure 9. Synthetic seismogram section and velocity model for Kaiser profile. In comparison with Figure 8, the amplitudes of the near-surface crustal phase and the wide angle reflection from the 7.0 km/s layer are excessive.

reduce these amplitudes seems futile, since the most prominent crustal amplitude change at A1375 near the Rocky Mountain Trench is certainly related to lateral changes. There is evidence for a crustal low velocity zone in the disappearance or delay of the crustal phase on C173. However, with the present data set, this complex area on the record section cannot be resolved.

The Highland Valley profile was more difficult to model than the Kaiser profile. A first approximation provided by the simple model determined from the first arrival data previously described was used to produce the synthetic section in Figure 11. The fit of the corresponding travel time curve to the actual data is displayed in Figure 10.

At distances beyond 90 km, the Highland Valley profile has large amplitude phases arriving at about 5.5 s. They are especially evident on A1275 and B475. These probably correspond to post-critical constructive interference between reflected and critically refracted phases from the deep crustal interface (Cerveny, 1966). Apparently the sub-critical reflections are of very small amplitude, suggesting an abrupt but not first order interface (Braille and Smith, 1975). Since the synthetic seismogram program HRGLTZ will have the same difficulties with the model depicted in Figure 9 as was previously mentioned, a comparison of amplitudes is difficult. The excessive head wave amplitudes that the program predicts at large distances may be erroneous. However, several obvious shortcomings of the model can be

Figure 10. Highland Valley section of Figure 3 with travel time curves. The travel time curves were calculated from the velocity-depth model in Figure 11. The lack of definition of the three layer model is particularly evident. The model is also unsatisfactory in that the upper crustal refraction and lower crustal wide angle reflection branches do not consistently correlate with the large amplitude arrivals appearing past 150 km.

Figure 11. Synthetic seismogram section and velocity model of Highland Valley profile.

Although the generally poor fit of the amplitudes to Figure 10 can be improved, many of the most reasonable alternatives could not be modelled by DRT.

verified. The existence of the interface at 30 km is tenuous. A two-layer model gives similar results. The sharp phases arriving at approximately 5 s on A1275 and C475 and showing correlations on C275 and C1275 have no expression in the model. Most importantly, there are unaccounted sharp phases arriving at 7 s and later on C1075, A1075, A2175 and less obviously on C2175 and A2075. They arrive about 2 s after the first arrival, and apparently become emergent after 220 km. It is also after this distance that first arrival data become too indistinct to pick. Although the arrivals correlate generally with the near surface crustal refraction and the wide angle reflection from the deep crustal layer, the agreement is inconsistent. After 220 km, the arrivals are earlier than the travel time curve predicts for either phase. This effect may be due to lateral changes, but the appearance of the section suggests a deep crustal low velocity zone. The large arrivals would correspond to wide angle reflections from the top of the low velocity zone. This hypothesis is untested, but the Generalized Ray Theory synthetic seismogram programs will be applied to this problem in future studies.

The present study does not define the deep structure in the distance range of 80 to 180 km on the Highland Valley profile as well as might be accomplished from the data. Perhaps, with more sophisticated interpretation techniques and additional geophysical control, the interpretation can

be improved. However, it is apparent from synthetic modelling that there may be a high velocity deep crustal layer between 80 and 200 km from both shot points. It is shallower, probably thicker, and of higher apparent velocity at the Highland Valley end of the profile than at the Kaiser end (assuming that the Highland Valley deep crustal arrivals are not Pn phases). In this interpretation, the average crustal velocity would increase towards the west from Kaiser. A low velocity zone included in the Highland Valley model would not alter this situation. Since the Kaiser and Highland Valley interpretations differ considerably, the crustal structures determined from the synthetics assuming lateral homogeneity are not generally valid.

5. Least-Squares Delay Times

The obvious lateral changes along the profile made a term-term method attractive for interpreting the Pn first arrivals. A simplified version of the "Delay-Time-Function" method described by Forsyth et al. (1974) was used. A delay-time surface composed of linear and Fourier terms (as a function of position) was fitted to the travel time data using least-squares. The first fit used a preset average offset distance and lower layer velocity. In subsequent iterations, an offset distance proportional to the time-term was applied and the lower layer velocity was updated. This method requires that there not be a high correlation between

shot/receiver distance and position (Morris, 1972). Also, the upper layer average velocity should not change since this affects the correspondence between the delay times and the depth to the refracting interface. Because only three uncertain Pn travel times from the Highland Valley sources are available, the first requirement is very nearly unfulfilled. The different crustal structures previously determined for opposite ends of the profile may make the time terms only indirectly indicative of mantle depths.

The average crustal velocity at the Highland Valley end, as suggested in the model of Figure 11, is near 6.5 km/s. It is near 6.3 km/s for the Kaiser model. A range of average velocities were used to fit the data, but higher velocities gave a lower standard deviation for the solutions. Therefore, a 6.5 km/s average upper crustal velocity was assumed. The results of constraining the delay-time surface to a dipping plane resulted in the third iteration solution given in Figure 12a. The travel time observation corresponding to B273 (Figure 8) was not used in the final delay time solutions because of its large residual in the preliminary work. The least squares mantle velocity was $7.82 \pm .04$ km/s with a standard deviation of .14 s for the solution. There is an apparent oscillation, with a 165 km wave length, of the observations about the line. An additional Fourier term of this wavelength was included in the solution of Figure 12b. The least squares mantle velocity for this solution, which had a standard deviation

Figure 12a. Delay time solution for a plane. The Highland Valley and Kaiser shot points are located at -225 and 225 km. Crosses (Highland Valley) and squares (Kaiser) denote observations from each source. The average crustal velocity was assumed to be 6.5 km/s. This is a third iteration resulting in a least-squares refractor velocity of $7.82 \pm .04$ km/s. The standard deviation of the solution is .14 s. Note the apparent oscillation (of one cycle) with a 165 km wave length.

Figure 12b. Delay time solution with one Fourier term. The assumed average crustal velocity was 6.5 km/s, giving a third iteration solution with a .08 s standard deviation. The calculated refractor velocity was $7.80 \pm .03$ km/s. Note the disagreement in the slopes of the Highland Valley and Kaiser data set about the solution.

of .08 s, was $7.80 \pm .03$ km/s. The peak to peak amplitude of the oscillation was approximately .5 s. The calculated delay times range from 3.0 to 3.6 s. It is important to note that the solution is valid only where data points exist.

The interpretation of the delay time solutions involves the separation of crustal velocity variation from mantle topography. Lateral velocity changes in the upper mantle are also possible, but the stability of the delay time solutions for a 7.8 km/s velocity suggests that this is not a major consideration. The previously determined upper crustal models would result in a delay time increase from Highland Valley to Kaiser. The magnitude would be from .2 to .4 s if there were no lateral changes in the M-discontinuity. This would account for most of the cosine term of the delay time solution. Assuming that most of the cosine term is related to average crustal velocity, then a sudden decrease in velocity apparently occurs between 0 to 60 km on the scale of Figure 12. This corresponds to the area from just east of the Arrow Lakes to Kootenay Lake on Figure 1. Because of the lateral velocity change, the delay time conversion to depths is too large at the Kaiser end of the profile. Taking the velocity variations into consideration in a subjective fashion, the delay time solution indicates a 7.8 km/s M-discontinuity dipping from about 33 km near the Highland Valley to a poorly defined 40 km at the Kaiser end.

The alternative would be to assume that the delay times reflected mantle topography directly. This may imply that at least part of the 7.35 km/s travel time branch interpreted as being from the lower crust is actually associated with critical refractions from a steeply dipping M-discontinuity. In this case, the mantle boundary would dip steeply to the east locally beneath the region adjacent to Okanagan Lake and the previously described area between the Arrow Lakes and Kootenay Lake. This interpretation is encouraging since lateral changes in velocity do not seem to compensate for all of the short wavelength character of the delay time curve. Also, the delay times match well with the delay time solutions determined for areas immediately to the west (Berry and Forsyth, 1975). However, as Berry and Forsyth (1975) note, the lack of improvement of a solution with an increased number of iterations, together with a systematic disagreement between reversed points on a delay time curve, suggest that there are significant lateral average crustal velocity variations. Both of these indications are evident in this study. Therefore, it is likely that both horizontal velocity gradients and relatively short wavelength crust-mantle topography are present.

6. Discussion

The interpretation of this profile as described is in general agreement with previous studies of the region. The primary feature is a 7.8 km/s M-discontinuity dipping to the east, with an average depth near 35 km. Although the resolution of this study is limited, it does confirm previous models derived from gravity data (Stacey, 1973). The near source information was also not definitive, although it indicated some interesting features. The most interesting results were the short wavelength but very smooth variations in the delay time interpretation, the deep crustal layers, and the undeveloped possibility of a low velocity zone interpretation for the Highland Valley profile.

A deep crustal layer from the Kaiser data was not surprising since Chandra and Cumming (1972) suggested a similar 7.0 km/s layer immediately to the east of Kaiser, with a gradual taper to the west. The thickness calculated in this study was greater than was previously suggested. Allowing for offset distances, the layer apparently exists at least as far west as Kootenay Lake. The arrivals become indistinct at greater distances, and, considering the other complications in this area, this is very reasonable.

The deep crustal layer in the Highland Valley interpretation is more tenuous. The possibility of a steep eastward dip in the mantle, suggested by the delay time

study, complicates the problem of separating deep crustal branches from Pn sections of the travel time curve. Also, the data is of poorer quality. From a profile directed westward from a shot point approximately 90 km east of the Highland Valley, Berry and Forsyth (1975) found an intermediate crustal layer of velocity from 6.5 to 7.0 km/s (increasing with depth). Since it has not been found elsewhere in British Columbia, this may indicate that such a layer exists only south of 51°. Therefore, the east-west striking upper mantle boundary near this latitude that is described in the Geophysical Review of Chapter I, may have a general expression in the deep crust as well.

Because of the geological complexity of the Cordillera, and because of its uncertain tectonic history, a definitive correlation can not be made between the present study and hypothetical tectonic models. Berry and Forsyth (1975) extensively discussed possible tectonic implications of seismic refraction interpretations in British Columbia. The tectonic complications that they considered can be simplified by relating geophysical features primarily to structures that would have formed since the Cretaceous. The region considered in this study has not undergone subduction or transcurrent type activity since then. Vertical tectonics have probably characterized the deep crust and upper mantle, and it is probably this activity that has the greatest effect on present geophysical parameters. The interpretation of the observations using this viewpoint,

reduces the speculative possibilities considerably.

The Cordilleran Thermal Anomaly Zone, which probably includes most of the Interior Plateaux and all of the Eastern Metamorphic Belt and Purcell Anticlinorium, is probably an effect of Tertiary subduction of the East Pacific plate and the Farallon (now Juan de Fuca) plate at the latitudes of the present study (Berry et al, 1971; Atwater, 1970). The late-Mesozoic thermal events may be associated with a more complex system of imbricate high angle subduction zones (Godwin, 1975). The relatively shallow and low velocity upper mantle beneath the Eastern Metamorphic Belt may be related to the heating and associated upward mobility of these thermal regimes.

The intensity of surface metamorphism used as a measure of late-Mesozoic to recent anomalous thermal activity allows a direct association of the delay time discontinuities with thermal boundaries. The most intense metamorphism along the line of the Highland Valley to Kaiser profile occurs between Okanagan Lake and the Arrow Lakes. The region between the Arrow Lakes and Kootenay Lake experienced somewhat less severe metamorphism, while the Purcell Mountains were only mildly affected. Therefore, east of Okanagan Lake, the increasing delay times are well correlated with decreasing metamorphism. The lateral changes previously described in either the lower crust or the mantle could be consistent with this view. Mechanisms that might explain the apparent correlation of more severe metamorphism with either a higher

average velocity in the crust or a shallower and perhaps lower velocity upper mantle are highly speculative.

The shallow, high velocity lower crustal layer postulated beneath the west section of the Eastern Metamorphic Belt could be formed by a differentiation process suggested by R.L. Armstrong (personal communication, 1976). Under intense heating with partial or full melting, the heavier gabbroic rocks could separate downward from the lighter, lower velocity granitic rocks which would form the surface layer. If the degree of this activity was related to the rate of uplift, then surface erosion and lateral movement of the near surface layers could accomplish a net lateral change in average crustal velocity and, presumably, density (Price and Mountjoy, 1970). However, this density increase contradicts the findings of Stacey (1973).

The only other evidence in the Eastern Metamorphic Belt for a deep crustal or upper mantle boundary associated with thermal effects was the conductive, hydrated lower crust proposed by Caner (1971). The depth of 10 to 15 km, later modified to 20 to 40 km, could be identified with either a crustal anomaly in the former case, or a deep crust/upper mantle anomaly in the latter case. Also, the magnetic transition zone marking the eastern boundary of the conductive layer is near Kootenay Lake, the eastern boundary of the rapid increase in the delay times. These observations are certainly related, although the precise nature of the association is obscured by poor resolution.

Anomalous behaviour in the upper mantle would also be expected near major lateral thermal boundaries. Wickens (1976) has suggested that the low upper mantle velocity determined within the Cordilleran Thermal Anomaly Zone indicates that the Gutenberg low velocity zone is at or near the base of the crust. Since smaller scale thermal features observed at the surface probably have their origins below the M-discontinuity as well, the depth to this already anomalous mantle boundary may vary laterally in a fashion analogous to the metamorphic variations in the surface features.

While the general features of the deep crust and mantle of the central Cordillera probably relate to late-Mesozoic to recent events, the details may have a much older history. The possible increase in average crustal velocity between Kootenay Lake and the Arrow Lakes could also be explained in terms of horizontal tectonic movements. I. Duncan (personal communication, 1977) suggests that the Eastern Metamorphic Belt west of the Arrow Lakes was a separate crustal block early in the Paleozoic, although its position had not changed relative to the craton, probably since the Proterozoic. When such ancient lateral variations are taken into account, a much better understanding of the geophysical and geological situation than has been accomplished is necessary to relate geophysical parameters to the pre-Mesozoic geology and tectonics.

7. Conclusions

1. In order to obtain upper crustal resolution in heterogeneous areas such as the Interior Plateaux an areal plan for the experiment (such as fan profiling) could be used with a station spacing less than 1 km. The present study suggests that interesting velocity contrasts do exist; for example in the high velocity core zone of the Guichen Creek Batholith.

The Kaiser profile results show that the Rocky Mountain Trench is a major lateral boundary, but without reversed seismic control, the nature of this discontinuity is speculative. It may be that refraction methods do not have the necessary resolution to delineate this feature.

2. There are major lateral changes, in both the average crustal velocity and the mantle depth, at short wavelengths in the Eastern Metamorphic Belt.

3. Besides possible shorter wave length depth variations, the upper mantle of velocity close to 7.8 km/s generally dips to the east from an approximate depth of 33 km near the Highland Valley to about 42 km just to the west of the Kaiser shot point.

4. The short wavelength delay time anomalies can be correlated with the thermal history and vertical tectonic events since the Jurassic.

5. There is strong evidence for an intermediate crustal

layer of velocity 7.05 km/s, depth 29 km, and thickness 9 km between 100 and 200 km from the Kaiser shot point. Based on the interpretation of poorer data, a 7.35 km/s layer may exist between 80 and 180 km from the Highland Valley shot point at a depth of 15 to 24 km and a thickness of 6 to 10 km.

6. This study confirms suggestions by others (Berry and Forsyth, 1975) that lateral structure and low velocity channels can only be defined well with a signal-to-noise ratio of 2 or better and a regular station spacing of less than 20 km. The uniqueness of an interpretation could be tested by varying shot points as well as station locations along a profile. A number of stations recording multiple shots that are separated by at least the average station spacing would make a delay time approach more valid. For the immediate future, seismic experiments would be most successful in delineating lateral anomalies (which are often the most interesting and significant features), if the experiment was adapted to time-term analysis. Recent work by Bamford (1976), suggests that time-term and profiling approaches are compatible, particularly if they are designed to be used in conjunction with each other.

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