THE STRUCTURE OF THE EARTH'S CRUST IN THE VICINITY OF VANCOUVER ISLAND AS ASCERTAINED BY SEISMIC AND GRAVITY OBSERVATIONS

By

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PUBLICATIONS

1. Milne, W.G. and W.R.H. White. A seismic investigation of mine "bumps" in the Crowsnest Pass Coal Field. The Canadian Mining and Metallurgical Bulletin, 51, No. 559, 1958.

2. Milne, W.G. and W.R.H. White. A seismic survey in the vicinity of Vancouver Island, British Columbia. Publications of the Dominion Observatory, XXIV, No. 7, 1960.

3. Scrimger, J.A., W.G. Milne and W.R.H. White. Sub-bottom velocities in the Esquimalt Lagoon, British Columbia. Report 61-4, Pacific Naval Laboratory, Esquimalt, B. C., 1961.

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ABSTRACT

A seismic explosion programme has been carried out in the Vancouver Island-Strait of Georgia area of Western Canada. The programme included a relatively intensive survey in the Strait of Georgia between Campbell River and the south end of Texada Island, as well as a number of longer range refraction lines extending from Kelsey Bay along the coast as far south as northern California, and east through the mountains to a distance of 700 km. Gravity readings were obtained at intervals of about ten km. along the east coast of Vancouver Island as well as for a number of east-west traverses. Readings were also obtained for a few locations on the British Columbia mainland. Except for a marked positive trend in the Victoria area, the regional value of the Bouguer anomaly for the Vancouver Island area is nearly zero.

The average structure for the area, derived from the seismic refraction observations consists of a layer of volcanic and granitic strata less than five km. in thickness, and an intermediate layer 46 km. thick with a constant velocity for compressional waves of 6.66 km/sec. A velocity of about 7.7 km/sec. for the mantle has been observed along unreversed refraction lines, both along the coast and east through the mountains. Interpretation of the refraction observations has been based mainly on first arrival phases. The observed regional gravity anomaly is compatible with the crustal model obtained from the seismic results.

GRADUATE STUDIES

Field of Study: The Crustal Structure of the Earth in Western Canada

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Advanced Dynamic Oceanography .... R.W. Stewart

Related Studies:

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Computational Methods .... C. Froese

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A seismic explosion program has been carried out in the Vancouver Island-Strait of Georgia area of Western Canada. The program included a relatively intensive survey in the Strait of Georgia between Campbell River and the south end of Texada Island, as well as a number of longer range refraction lines extending from Kelsey Bay along the coast as far south as northern California, and east through the mountains to a distance of 700 km. Gravity readings were obtained at intervals of about ten km. along the east coast of Vancouver Island as well as for a number of east-west traverses. Readings were also obtained for a few locations on the British Columbia mainland. Except for a marked positive trend in the Victoria area, the regional value of the Bouguer anomaly for the Vancouver Island area is nearly zero.

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1. INTRODUCTION

1.1 Definition of the Earth's Crust

Various definitions of the earth's crust have been suggested. For example, three concepts have been cited by Ewing and Press (1956) as follows:

(1) The division of the outer part of the earth into two zones, the outer shell being designated the lithosphere, characterized by the fact that the material possesses sufficient shear strength to support the topographic features in evidence at the surface of the earth. This is underlain by the asthenosphere, in which the shear forces are negligible and only hydrostatic forces are important. When surface elevations or depressions have lateral dimensions several times the thickness of the lithosphere, they are supported mainly by the hydrostatic forces of the asthenosphere.

(2) The division on the basis of the maximum depth at which earthquakes are observed. The material above such a boundary must be sufficiently rigid to allow shear strain energy to build up to values required to account for the observed magnitude of earthquakes. The question of the time scale over which strain energy is maintained must be considered. Earthquakes are known to have depths of focus in certain areas in excess of 700 kilometres.

(3) The division between the crust and the mantle as marked by the Mohorovičić discontinuity. This discontinuity in the velocity of elastic wave propagation and the inferred discontinuity in the physical constants

of the material, have been detected by refraction and reflection seismology. It may be considered to be the deepest abrupt velocity discontinuity in the upper 100 km. of the earth. The material below the discontinuity is referred to as the mantle and is characterized by a velocity of about 8 km/sec. for compressional elastic waves. Measurements of this velocity have been found to be remarkably consistent in most parts of the earth both for continental and oceanic areas. It has thus become customary to associate the Mohorovičić discontinuity with the upper boundary of the layer having this velocity. Recently velocities less than 8 km/sec. have been observed for some areas. These areas must be considered anomalous in view of the large amount of data presently existing which consistently indicate the 8 km/sec. velocity. The identification of these lower velocity measurements with the mantle, however, appears to be indicated. Confirmation by mapping from normal areas into anomalous ones is required.

The last of these definitions is adopted in this thesis, since the primary method of measurement is essentially a measure of velocity structure.

1.2 Methods of Investigation of Structure in the Earth's Crust

1.2.1 Seismic reflection and refraction surveys:

The most direct approach to the determination of structure in the earth's crust is that of reflection and refraction seismology. Elastic waves propagated from a disturbance within the crust or at the earth's surface are recorded with seismograph instruments having the appropriate frequency response, located at suitable intervals of distance from the disturbance. Travel times are measured for the various arrivals of wave energy and time-distance plots made from the reduced data. By an examination of these plots an attempt is made to associate the various arrivals of energy with certain ray paths of the propagation. When this has been done, statistical methods may be applied to groups of plotted points to obtain quantitative information as to the structure, including the depth of the velocity discontinuities and the velocities of propagation of the elastic waves in the proposed layers. In most investigations interpretation has been based on refraction rather than reflection data. In the past this has been the safest approach, since for most refraction data, the interpretation may be based on the first arrivals of seismic energy. That this is not always the case will be pointed out later. More recently the use of spreads of detectors, and more detailed observations, have made possible the correlation of secondary arrivals from one detector to adjacent ones. This has greatly enhanced the value of results from reflection observations as well as those of secondary refraction arrivals from intermediate layers. The existence of refraction and reflection arrivals, and the geometry of ray paths will be discussed in a later section.

A variety of energy sources has been used, including earthquakes, rock-bursts commonly found in mining areas, and man-made explosions. Quarry blasts, underwater explosions and underground nuclear test explosions have been used. The magnitude of some explosions has made it possible to record the radiated seismic energy well beyond the distances at which refracted rays from the mantle become first arrivals on the seismograms. An alternative to this procedure is to use smaller explosions, observed in greater detail at shorter ranges, and to base the interpretations partly on secondary arrivals of refracted and reflected energy.

Explosions used as energy sources are to be preferred to earthquakes and other naturally occurring seismic phenomena, in that location, depth of focus and origin time may all be accurately measured quantities. In addition, the precise time of occurrence of the disturbance may be provided through appropriate communication systems so that temporary stations may be set up for a minimum of time and high time resolution may be obtained by running recorders at high speed for short periods of time.

For the greater part of the investigation reported in this thesis underwater explosions were used as energy sources. Naval depth charges which had become obsolete for military purposes were positioned from a ship as single units and in packages of ten when greater ranges of recordings were required. The explosive was detonated at sufficient depth that, in almost all cases, the water cover confined the explosions and ensured efficient transformation of the energy released by the explosion into seismic energy.

1.2.2 Analysis of surface waves:

A consideration of solutions of the wave equations which apply for an elastic medium indicates the possibility of the propagation of surface waves. The application of various boundary conditions results in the prediction of surface waves of various types. Rayleigh waves may be propagated at a free surface in a homogeneous medium, in which case there is no wave dispersion. For a medium with velocity structure, Rayleigh waves are dispersed. The velocity structure may provide channels for guided waves of various types predicted by the theory. The dispersion observed for such waves may be examined from seismograms of earthquakes and used to infer the dimensions and physical constants of the structure. Extensive use of this method has been made by many investigators. Briefly, the technique is to compute dispersion curves of group and phase velocity for various crustal models and then to choose the one which best fits the observed data. Rayleigh waves and Love waves have been used to investigate the continental and oceanic crustal structure. Other surface waves known as Lg and Rg have been observed for purely continental paths. Various types of structure in the crust and upper mantle have been proposed to account for the efficient propagation of these waves. A summary is given by Byerly (1956).

The present investigation included a study of Rayleigh waves recorded at the permanent seismograph stations at Victoria, Alberni and Horseshoe Bay from earthquakes in the south-east Pacific. Because of inadequate information related to the constants of the instruments, an attempt to make corrections for the phase shifts in the heterogeneous recording systems was not successful. The lack of success was evidenced by the very large scatter in the phase velocity-wave period plots. The analysis is not reported in this thesis. It is hoped that with the instrumentation now in operation, a further attempt may be made to obtain dispersion curves.

1.2.3 Gravity measurements:

The analysis of gravity data does not lead to a unique crustal structure. However, if a relation between the velocity of propagation of seismic waves and the density of the material through which they propagate can be established, a quantitative comparison may be made between the structure determined by the direct measurements of refraction and reflection seismology and the observed gravity values. Such a relation has been found by Nafe and Drake (1958) by a statistical treatment of laboratory and in situ measurements of the physical properties of various media. A curve showing their results is found in Talwani (1959). It is of course necessary to set up a standard for comparison. This has been done by Press (1960) and Woollard (1959). Press has chosen a crustal structure for Africa, which agrees with the observed seismic data, as being typical of a continental crust and as one which gives a Bouguer gravity anomaly of -30 mgals. On some basis such as this, one may proceed to compare structures determined by seismic refraction and reflection studies with the observed regional gravity anomalies.

If a theory of isostasy is assumed, the crustal structure must provide for compensation for the variation in load imposed by variations in the regional land elevation or ocean depth. Two systems of compensation have been proposed, the Pratt-Hayford isostatic system involving compensation by variations in density, or the Airy-Heiskanen system involving variations in thickness of the lower density crustal materials.

In the present study, gravity readings have been obtained for the south part of the British Columbia coast, as well as along the east coastline of Vancouver Island and for some east-west profiles on the Island. A few readings obtained by other investigators are included and gratefully acknowledged.

1.2.4 Other methods:

The structure of the earth's crust must also be expected to be reflected in such measurements as heat flow and variations in the earth's magnetic field.

1.3 Some General Aspects of Crustal Structure Studies

1.3.1 History of the pioneer refraction studies:

A brief summary of the early refraction studies, and the notation which has developed, is presented here. Comprehensive accounts are given by Jeffreys (1959), Byerly (1956), and more recently by Steinhart and Meyer (1961).

The first evidence for structure in the earth's crust was observed by Mohorovičić in 1909. Seismograms obtained for an earthquake which occurred in Croatia on October 8 of that year indicated two compressional wave arrivals and two transverse wave arrivals. The P and S waves had been previously identified on seismograms of earthquakes. Mohorovičić concluded that the earthquake had occurred in the upper layer of the crust and that the two P waves represented propagation paths through the upper (granitic) layer and by refraction through a deeper layer of higher velocity. The former arrival was named $\overline{P}$ and the latter P. The corresponding transverse waves were named $\overline{S}$ and S. $\overline{P}$ and $\overline{S}$ have also been referred to as Pg and Sg, and P_1 and S_1. It was found that near the focus of the earthquake only $\overline{P}$ and $\overline{S}$ appeared, that at greater distances P and S were observed and became first arrivals on the seismograms. P and S are frequently referred to as P_n and S_n. The velocity discontinuity between the two layers has been named the Mohorovičić discontinuity.

Gutenberg observed similar features in records of earthquakes occurring in Europe in 1911 and 1913.

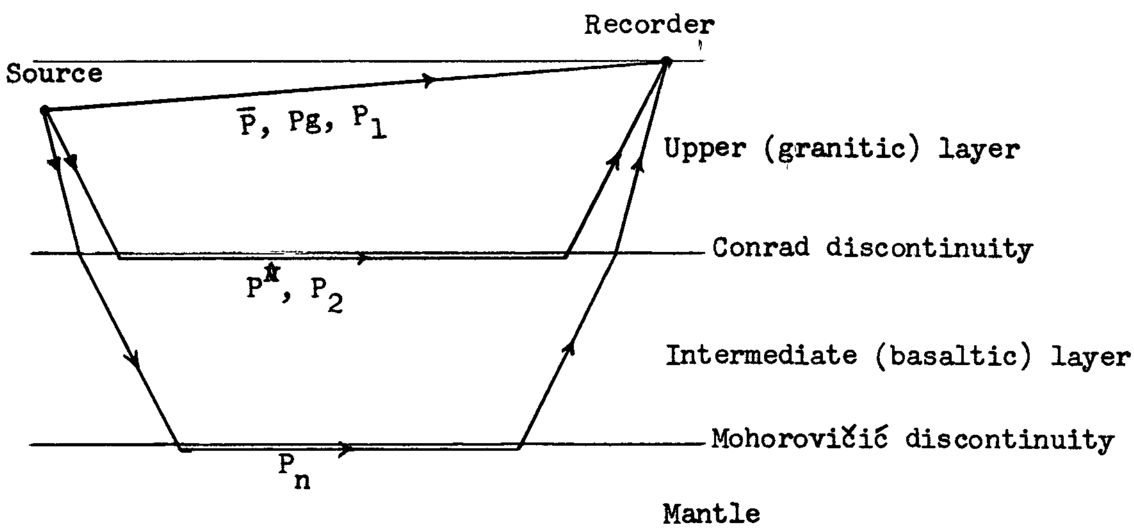


Figure 1. Notation for Refracted Rays in a Two Layer Crustal Model.

Conrad in 1925 and Jeffreys in 1926 found evidence for arrivals from an intermediate layer. These arrivals were characterized by velocities intermediate between the crustal and subcrustal values. They have been referred to as P^* and S^* and also as P_2 and S_2, and the layer as the 'basaltic layer'.

The various propagation paths and associated notation are shown in Figure 1. A similar diagram may be drawn for S waves.

Frequently the number subscripts are used with parameters referring to the sequence of layers beginning with the most surficial (i.e., P_0, P_1, P_2, ...).

1.3.2 Continental and oceanic crustal structure:

Following the pioneer observations of refraction arrivals from earthquakes, data have been obtained at many locations of the earth from earthquakes, other naturally occurring seismic disturbances and especially from explosions. Data have been obtained for both continental and oceanic areas. The results related to continental crustal structures have been summarized in detail by Byerly (1956) to the date of publication. Some of the more recent results will be summarized in a section to follow. Oceanic data have been obtained mainly by workers from Columbia, Cambridge and California.

A basic difference exists between continental and oceanic crustal structure. Because of the large variations in the proposed structure for the various continental areas, it is difficult to describe a typical continental crust. Most models indicate a crustal thickness of 30-40 km. in low lying continental areas, consisting of the granitic and intermediate layers, the lower boundaries of these layers being referred to as the Conrad and Mohorovičić discontinuities. Some doubt has been cast on the existence of the intermediate layer and as a result, single layered models have been proposed with or without an increase in velocity with depth. The thickness of the continental crust has been found to increase for mountainous and plateau areas. Thicknesses of up to 70 km. have been found to fit the observed data. A number of crustal structures have been proposed with more than two layers. Velocities for the granitic layer vary from about 5.6 to 6.4 km/sec. for compressional waves and those for the intermediate layer from about 6.6 to 7.2 km/sec. Mantle velocities of 7.5 to 8.4 km/sec. have been observed. Until recently the most consistent values were between 7.8 and 8.3 km/sec. The oceanic crustal structure consists typically of 5 km. of water, about 0.5 km. of unconsolidated sediments and about 1.0 km. of volcanic or granitic material. Underlying these layers is the intermediate layer with a typical compressional wave velocity of 6.8 km/sec. This layer varies in thickness from about 4 km. or less to 6 km. The granitic layer as it exists for the continental structure appears to be missing in oceanic areas. A typical crustal section for an oceanic area is shown in Figure 2.

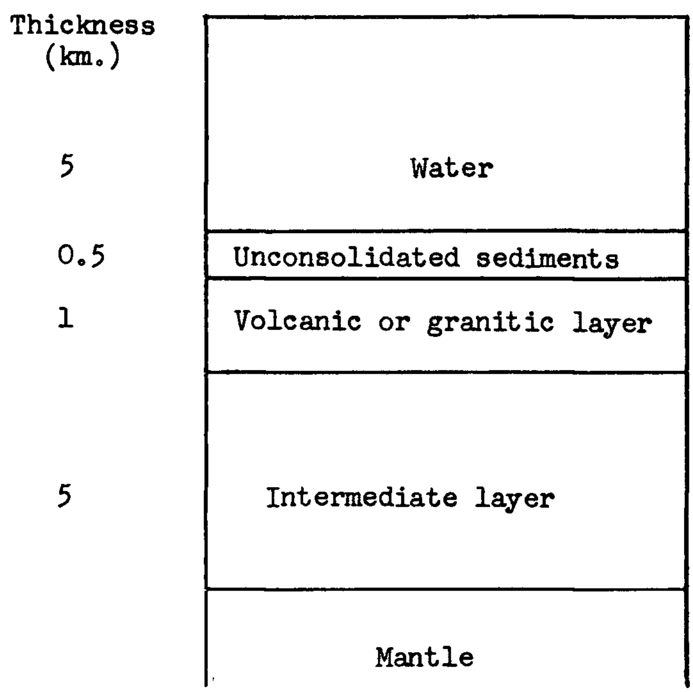


Figure 2. A Crustal Section Typical of Oceanic Areas.

1.3.3 The reality of the intermediate layer:

The evidence for the intermediate layer from seismic data is in the form of refracted arrivals. As will be shown later, the refracted arrival from an intermediate layer may not become a first arrival for any recording distance from the focus of a disturbance. Thus many of the refraction data for the intermediate layer have been based on secondary arrival phases. The reading of such a phase is often made difficult because of the background signal from an earlier arrival. It is also felt that if the Conrad discontinuity exists, seismic reflections should be observed at suitable recording distances in addition to the refracted arrivals.

These difficulties have led many workers to doubt the existence of the intermediate layer and to favor a single layered crust. This view is expressed, for example, by Press and Ewing (1956). Byerly (1956, page 146) suggests that the established existence of the layer for oceanic areas also points to its existence as a separate entity in continental structures.

More recent investigations with improved techniques and more detailed observations tend to confirm the existence of this layer in many continental areas. Its thickness, as well as the depth of the Conrad discontinuity varies over rather wide ranges from area to area. Richards and Walker (1959), reporting on a survey on the Alberta plains, interpret a strong arrival at a distance of about 120 km. as being a reflection from the Conrad discontinuity. Hales and Sachs (1959) have identified secondary arrivals as P_2 refractions from an intermediate layer in the eastern Transvaal area of South Africa. A number of other investigators also include the intermediate layer in their proposed crustal models.

1.3.4 Velocities of compressional waves in the mantle:

It has already been pointed out that most refraction studies have given compressional wave velocities of 7.8 to 8.3 km/sec. in the mantle. Recently somewhat lower velocities have been found for both continental and oceanic areas. These velocities (e.g., 7.5-7.6 km/sec.) are higher than would be expected for the intermediate layer, and there is a strong suggestion that they are associated with the mantle, since in some areas at least, a higher velocity is not observed. Menard (1961) has pointed out a correlation between the lower velocity and the proximity of the refraction line to the crest of the East Pacific Rise.

Velocities of about 7.6 km/sec. have been found by Press (1960) for eastern California and by Berg et al (1960) for the Eastern Basin and Range Province. Both, however, report arrivals indicating a velocity of about 8.0 km/sec. in a deeper layer. The upper boundary of the deeper layer is placed at about 50 km. for California and 70 km. for the Basin and Range Province.

1.3.5 Investigations of the earth's continental crustal structure:

No attempt is made in this section to summarize in detail the results of all of the crustal determinations which have been made. Rather, the results of a few surveys are briefly reviewed for various parts of this continent and other continental areas of the earth. In a section to follow, results of surveys carried out in areas adjacent to the area of the present investigation will be described in slightly greater detail.

Hodgson (1953) has used rockbursts as sources of energy in the Canadian Shield area of eastern Canada. He has found a single layered crust with velocities of 6.2 km/sec. above the Mohorovičić and 7.9-8.2 km/sec. below it. The thickness of the crust is 36 km. Katz (1955) has found a similar crustal model for the New York and Pennsylvania area.

Willmore (1949) recorded the Heligoland explosion to a distance of 1000 km. in Europe and from his analysis of the data, proposed a crustal structure consisting of a single layered crust, having a thickness of 28 km. His structure does not include an intermediate layer which has been proposed by some other workers in Europe.

Hales and Sachs (1959), using earth tremors of the Witwatersrand have carried out a study in the eastern Transvaal. They have found two possible structures for the plateau area, including an intermediate layer. They also conclude that early arrivals of P_n on records obtained in the coastal area of lower elevation indicated a decrease in the thickness of the crust.

Weizman et al (1957) have reported on surveys carried out from 1949-1955 in various areas of Russia, using methods in which the waves propagating from explosions were observed in great detail, and continuous correlation of arrivals was possible. In their report, crustal models for the various areas are presented. Crustal thicknesses ranged from 30 to 40 km. in 'platform' areas to more than 70 km. in the high mountain area of Northern Pamir.

The crustal structures proposed in these investigations are summarized in Figure 3.

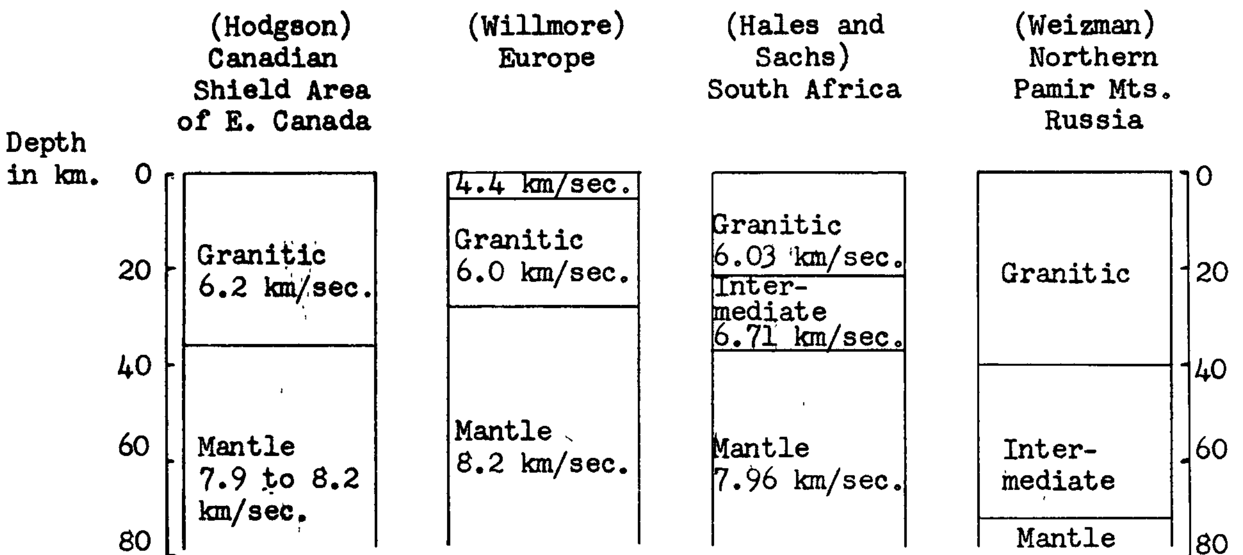


Figure 3. Crustal Sections for Various Continental Areas of the Earth.

The greater thicknesses of the continental crust in mountainous areas is in agreement with the idea of isostasy in that the load due to the elevated surface features is compensated for by the extension of the lower density crustal material to greater depths. Woollard (1959) has assembled in one diagram the measured crustal structures for a section extending from west to east beginning at the eastern Pacific and ending at the Indian Ocean and including the continents of North America, Europe and Africa. For comparison he shows also the observed Bouguer gravity anomaly values. This work has been cited also by Heiskanen and Vening Meinesz (1959) as strong evidence for the Airy-Heiskanen system of isostatic equilibrium. It may be remarked that the more recent refraction measurements in the Eastern Basin and Range Province (Berg, 1960) and the Colorado Plateau (Pakiser et al, 1962) have indicated somewhat greater crustal thicknesses than those shown in Woollard's diagram.

2. RESULTS OF SOME SURVEYS IN WESTERN NORTH AMERICA

Most of the explosions of the present study were located in the Strait of Georgia and Johnstone Strait between Vancouver Island and the British Columbia mainland, along a line paralleling the structure of the physiographic features. The recording stations were also distributed along the coast. The area investigated lies at a distance of about 200 km. east of the edge of the continental shelf, and may be expected to be transitional between oceanic and continental types of structure. In addition, data have been obtained from the Ripple Rock explosion in the Strait of Georgia as recorded at stations east through the mountains, as far as Banff, Alberta.

In this section, the results of a number of surveys carried out in the western part of this continent are summarized. Two refraction lines at sea, near the coast of British Columbia, are also included.

As a part of a program in which refraction and reflection studies were carried out in various parts of the United States, Tatel, Adams and Tuve (1953) and Tatel and Tuve (1955) have conducted a survey in the State of Washington. Explosions detonated in Puget Sound were recorded along lines in various directions from the explosion area, to a maximum distance of 290 km.

Although a relatively large number of observations at what was considered to be the correct range of distance was obtained, no secondary arrivals which could be interpreted as critical reflections from the Mohorovičić discontinuity were detected. This led the authors to suggest that the discontinuity does not exist in this area, or that it exists in a broken and irregular form.

The early arrival of a group of observations recorded at a range of distances of 110 to 140 km. to the west of the explosion area led the authors to postulate that the arrivals are refracted arrivals from the Mohorovičić discontinuity and that the crust becomes thinner as the edge of the continent is approached. A crustal thickness of 19 km. is calculated using a velocity of 8.1 km/sec. for P_n.

Neumann (1957) has analysed the data from a large number of seismograms obtained for earthquakes occurring in the State of Washington and in southwestern British Columbia. Arrival times of compressional waves at stations of the University of Washington network have been used as well as those for the western network of the Dominion Observatory. A best fit for the data has been obtained by adopting a structure with three layers having velocities for compressional waves of 5.8, 6.4 and 7.0 km/sec. With one exception, arrivals from earthquakes along the coast as far distant as southern California do not indicate propagation with a velocity reaching 8 km/sec. These observations have led Neumann to propose a very great depth to the Mohorovičić discontinuity, or non-existence of the discontinuity in the area of his observations.

A reversed profile program was carried out by A. R. Milne (1960) using the standard techniques of seismic refraction and reflection investigations at sea. The area of this survey is located between 135° and 136° W. longitude and at about 48° 20' N. latitude, the profiles running approximately east-west. Crustal sections obtained by treating the profiles independently show a typical oceanic crustal layer having a velocity of about 6.8 km/sec. underlain by material with typical mantle velocity slightly in excess of 8 km/sec. The basaltic layer is from 2.6 to 4.0 km. in thickness and is overlaid by 1.0 to 1.5 km. of sediment and material having a velocity typical of volcanics or granitics.

The structure found for the east end of the profile is shown in Figure 4.

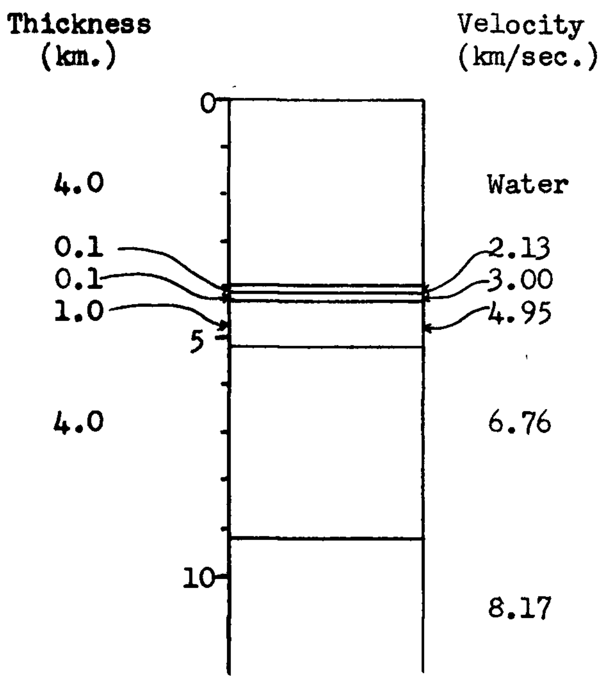


Figure 4. Structure for North Pacific Ocean Basin (A. R. Milne, 1960).

Among numerous other profiles, Shor (1962) has obtained a reversed profile running approximately east-west at the north end of the Queen Charlotte Islands in Dixon Entrance. This profile is on the continental shelf. Velocities of about 6.8 km/sec., typical of the oceanic structure, have been well established by the reversed profiles, with relatively long segments on the travel-time curves representing first arrivals. Based on secondary arrivals, which he interprets as possible refractions from the Mohorovičić discontinuity, a thickness of 26 km. has been suggested for the crust. The structure for this work is shown in Figure 5.

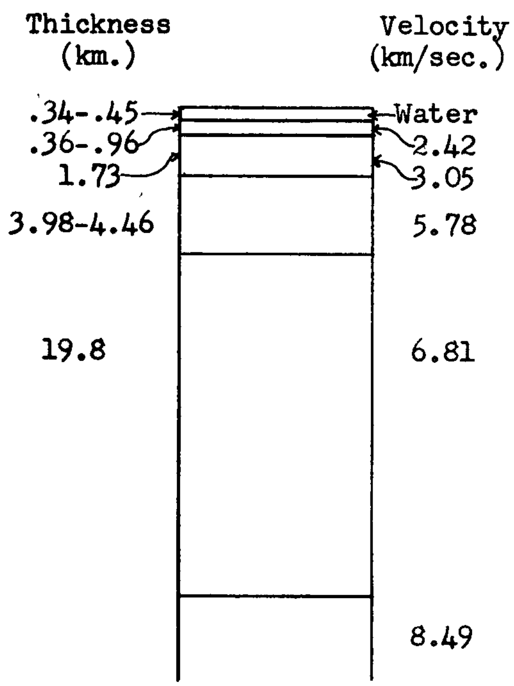


Figure 5. Structure for Dixon Entrance (Shor, 1962).

The results of earlier surveys carried out by Milne and White (1960) in the Vancouver Island area were based on records obtained for explosions detonated in the Strait of Georgia and a second profile of explosions in the Strait of Juan de Fuca and for some distance along the west coast of Vancouver Island. These events were recorded at the permanent seismograph stations at Victoria, Alberni and Horseshoe Bay. The results obtained by plotting the time distance data for all stations for each series of explosions indicated crustal velocities of 6.0 and 6.4 km/sec. for the two profiles. In addition to these longer range profiles, some very short range refraction work was done to measure velocities at the surface for the various geological structures outcropping in the Vancouver Island area.

Richards and Walker (1959) have carried out a seismic investigation of the crust on the plains of Alberta. The profile is 130 km. in length and parallels the Rocky Mountains. It is located approximately 100 km. to the east of the foothills. Fifteen prospecting units, using spreads up to 4 km. in length were stationed at intervals along the profile. The seismic energy was supplied by explosions at each end of the profile consisting of about 400 kilograms of conventional seismic explosive.

The interpretation is based on first arrivals in granitic or limestone strata having a velocity of about 6 km/sec. A slight increase in the apparent velocity across the spreads at greater distances appears to indicate an increase of velocity with depth in the granitic layer. Two discontinuities are proposed by interpretation of secondary arrivals. A decrease in apparent velocity across the spreads with an increase in range indicates that the arrivals are due to reflections.

Real velocities of about 7.2 km/sec. and 8.2 km/sec. have been obtained for the intermediate layer and the mantle, respectively. Depths to the Conrad and Mohorovičić discontinuities are 29 km. and 43 km. These results are summarized in Figure 6.

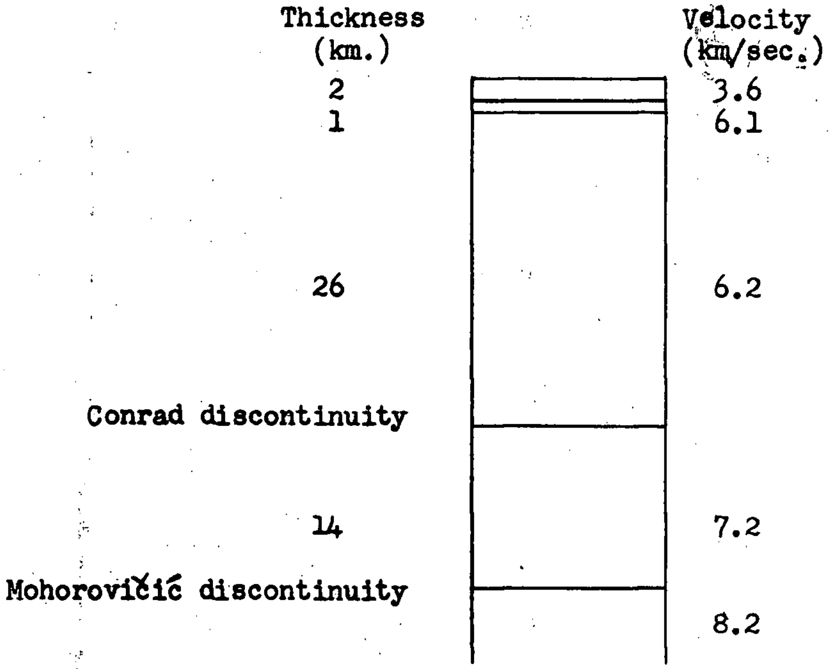


Figure 6. Structure for Alberta Plains (Richards and Walker, 1959).

The underground atomic tests conducted at the Nevada Test Site and more recently near Carlsbad, New Mexico, have provided energy sources for a number of refraction studies. Somewhat varying structures have been proposed for areas in Utah, Nevada, Colorado and California. These have been summarized by Berg (1960) to the date of his publication.

From a composite plot of arrivals for all events (including two nuclear explosions and other large quarry explosions) Berg has arrived at the velocity model shown in Figure 7 (page 19).

Press (1960) has discussed a crustal model for California from the point of view of the three methods outlined earlier. The refraction results are for records obtained from high explosive events at Corona and Victorville, and a number of nuclear events at the Nevada Test Site. The velocity model obtained is as shown in Figure 8 (page 19).

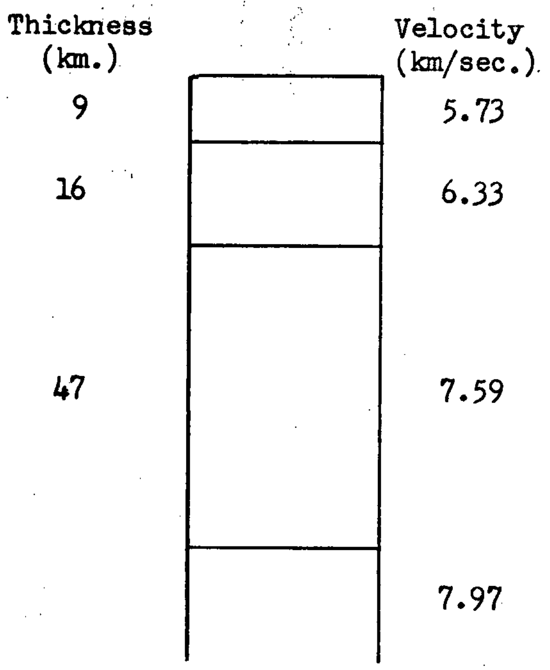


Figure 7. Average Structure for Area Surrounding Explosions in Northern Utah (Berg, 1960).

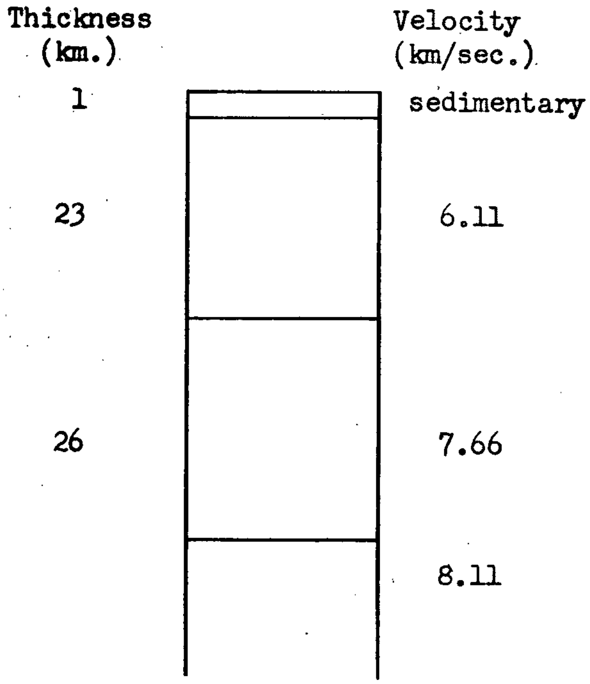


Figure 8. Structure for California-Nevada Region (Press, 1960).

More recent results obtained by the United States Geological Survey (Pakiser, et al, 1962) indicate the following approximate structure for a profile running north-south in Colorado, about 100 miles east of Denver (Figure 9).

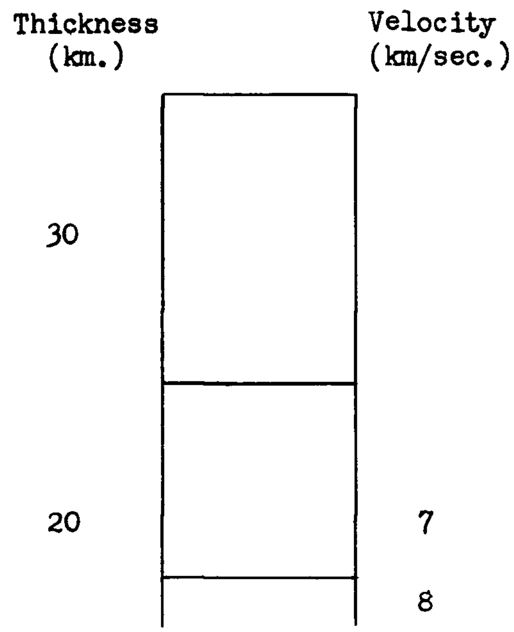


Figure 9. Structure for Colorado (Pakiser, 1962).

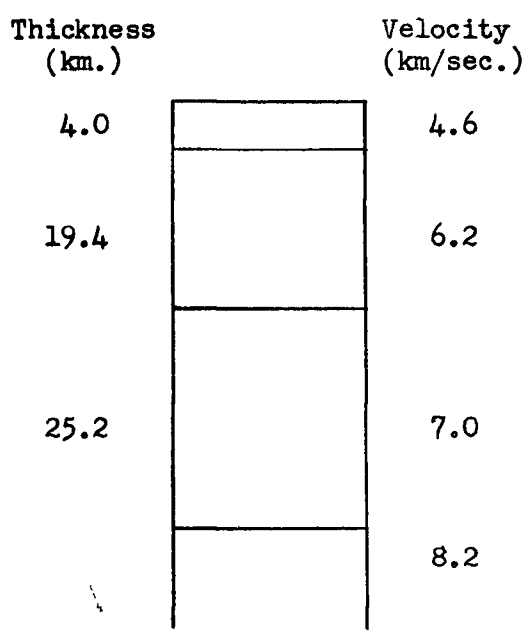


Figure 10. Structure for the Area North of Carlsbad, New Mexico (Pakiser, 1962).

A refraction line over a distance range of 70 to 430 km. in a direction north from the underground nuclear explosion Gnome, near Carlsbad, New Mexico, was observed by the United States Geological Survey and the Colorado School of Mines. The structure shown in Figure 10 (page 20), based on these data has been proposed by Pakiser (1962).

Healey (1962) has found the structure shown in Figure 11 for a refraction line from Santa Monica to San Francisco.

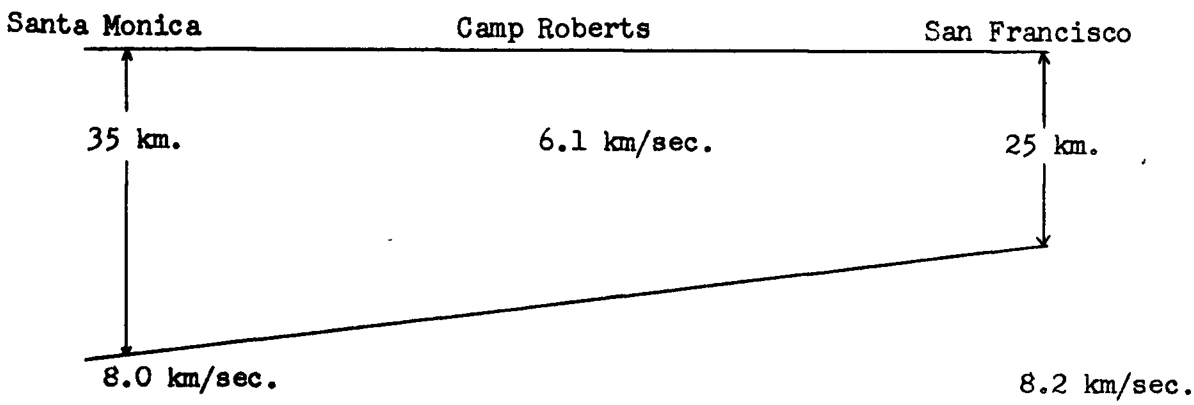


Figure 11. Structure along the Coast from Santa Monica to San Francisco.

By using the data obtained for this refraction line and additional reverse data from the Salinas explosion, Berg (1962) has proposed the structure shown in Figure 12 for the coastal area south of San Francisco.

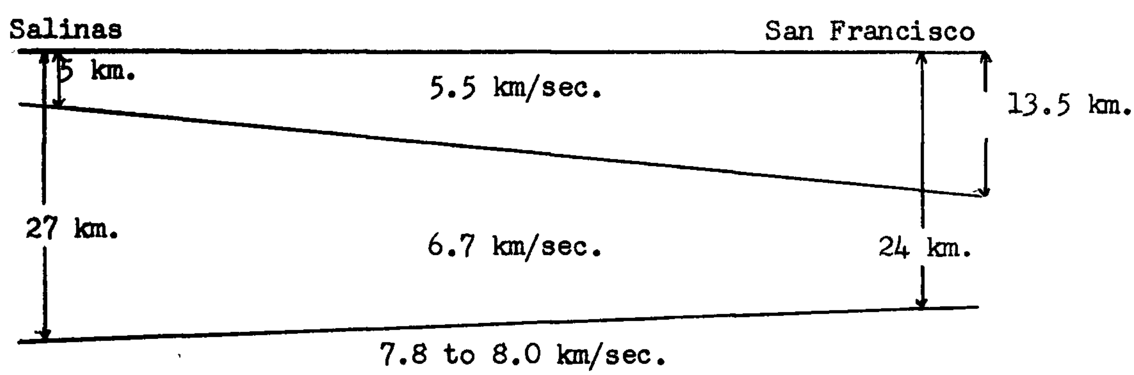


Figure 12. Structure for Coastal Area, Salinas to San Francisco (Berg, 1962).

Healy (1962) has obtained observations for the area east from San Francisco to Fallon and Eureka, Nevada. The structure shown in Figure 13 has been obtained.

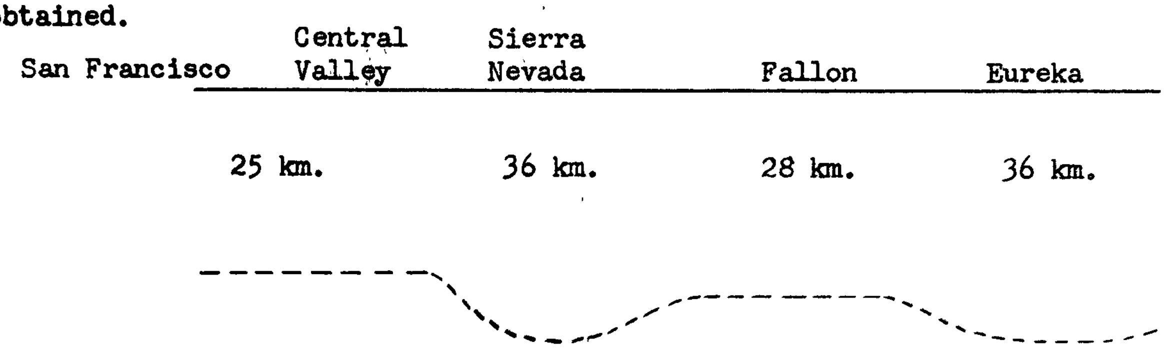


Figure 13. Structure East from San Francisco (Healy, 1962).

Herrin (1962) has mapped P_n velocities for the United States and has drawn velocity contours, which show a low value of about 7.6 km/sec. in the area of the Nevada Test Site, with values increasing radially to about 8 km/sec.

Healy (1962) reports the following significant variations in the velocity of P_n for the western United States:

Colorado	8.2 km/sec.
New Mexico	8.0 to 8.2 km/sec.
Northern Basin and Range Province	7.7 km/sec.
Santa Monica-Lake Meade	7.8 km/sec.
Santa Monica-San Francisco	8.0 to 8.2 km/sec.
Sierra Nevada Mountains	7.8 km/sec.

A brief summary such as the preceding serves to indicate the complexity of the earth's crustal structure in the coastal, mountain, and plateau areas of western North America. The need for detailed mapping rather than interpolation of structure between widely spaced areas of known structure is indicated.

3. THE SEISMIC PROGRAM

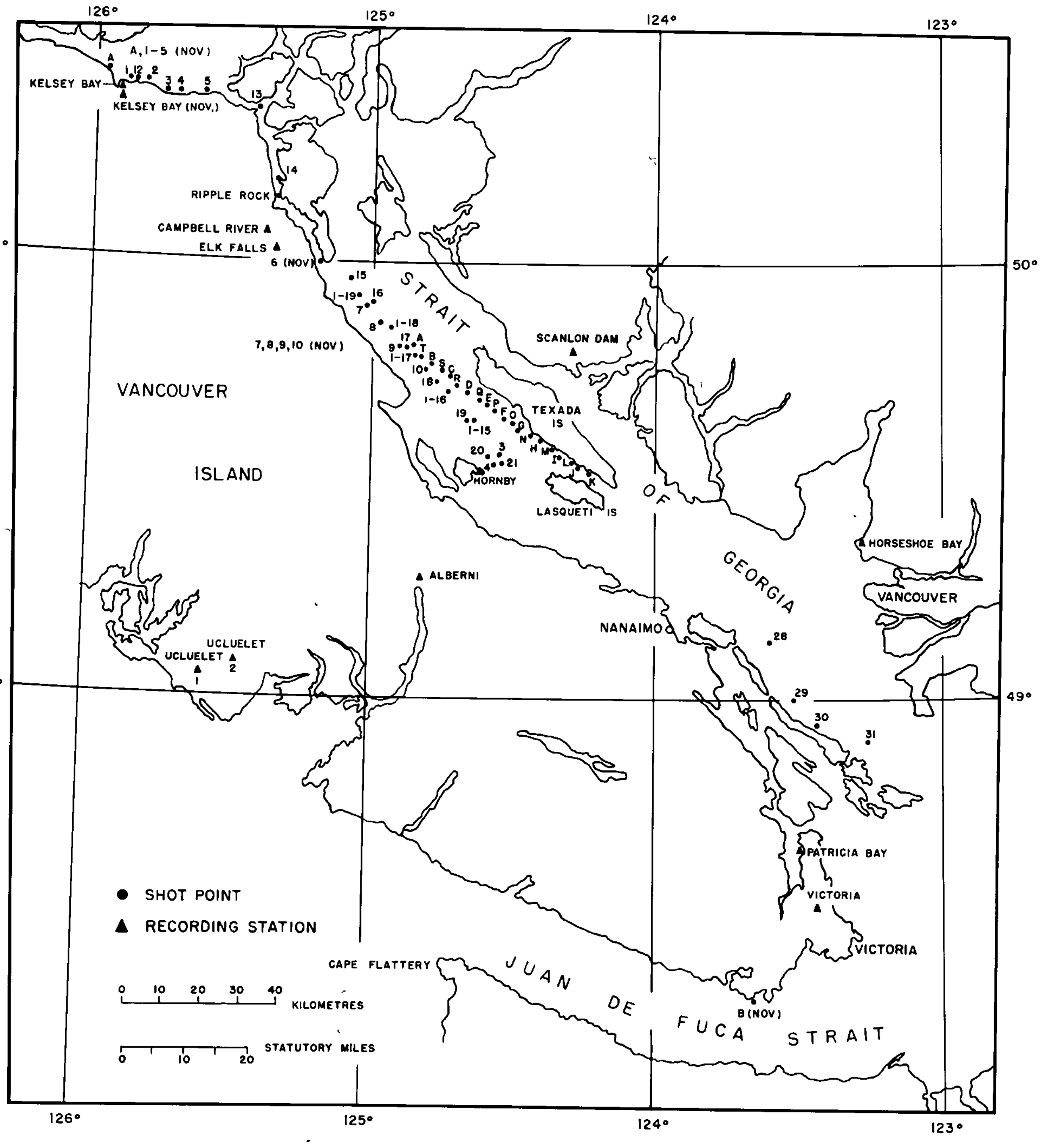
3.1 General Description

In May 1960 and June 1961, seismic explosion programs were carried out in the Strait of Georgia and Johnstone Strait areas of British Columbia. The seismic energy was supplied by 135-kilogram depth charges detonated at a depth of approximately 150 metres below the surface. The events of the 1960 program are referred to as shots 1 to 31. The events of the June 1961 program are referred to as shots A to T. In November 1961 a further program was carried out to obtain supplementary data. Two 1350-kilogram charges were detonated electrically and recorded at distances up to 510 km. from the shot points. In addition ten 135-kilogram charges were detonated separately. The events of this program are referred to as shots A (Nov.), B (Nov.) and 1 (Nov.) to 10 (Nov.)

For the 1960 program seismograms were obtained at the permanent seismograph stations at Victoria, Alberni and Horseshoe Bay. Temporary recording stations were also operated at Scanlon Dam, Hornby Island, Ucluelet, Bloedel and Kelsey Bay. For the 1961 programs seismograms were obtained at the permanent stations at Victoria and Alberni. Temporary stations were operated at Campbell River for the June program and at Elk Falls and Kelsey Bay for the November program.

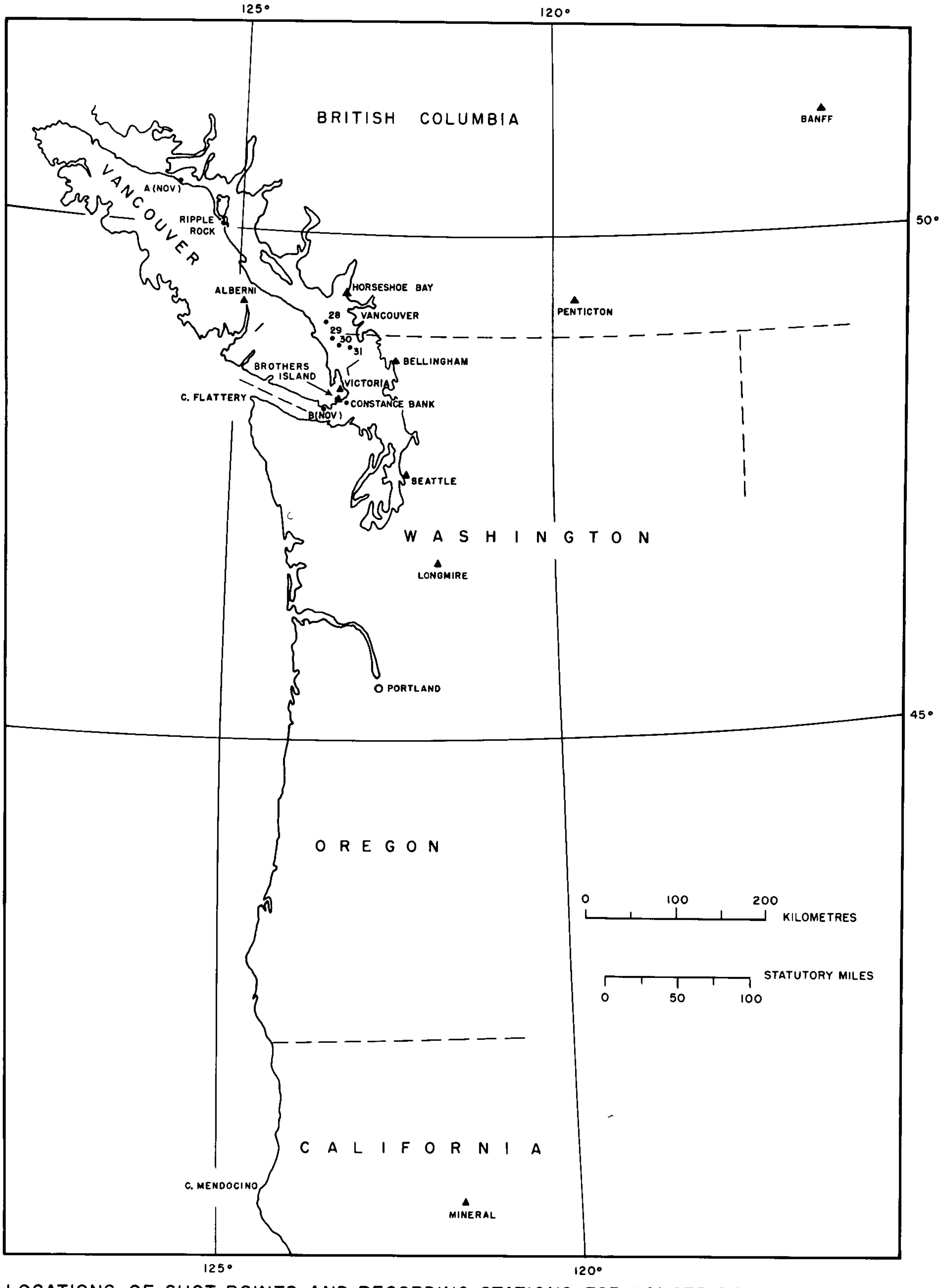
Some of the explosions were also recorded at Longmire, a station operated by the University of Washington, and at the Dominion Observatory station at Penticton.

The locations of the stations and shot points for the shorter range refraction work are shown in Figure 14 and for the longer range work in Figure 15. The coordinates are listed in Table 1 (page 24).



LOCATIONS OF SHOT POINTS AND RECORDING STATIONS FOR SHORTER RANGE REFRACTION PROFILES

FIGURE 14



LOCATIONS OF SHOT POINTS AND RECORDING STATIONS FOR LONGER RANGE PROFILES

FIGURE 15

Table 1. Locations of Explosions and Recording Stations

Station or Shot	Latitude	Longitude	Station or Shot	Latitude	Longitude
	° '	° '		° '	° '
Victoria	48 31.16	123 24.91	25	49 21.95	124 16.80
Alberni	49 16.23	124 49.30	26	49 18.12	124 02.40
Horseshoe Bay	49 22.65	123 16.55	27	49 11.40	123 41.30
Penticton	49 19	119 37	28	49 08.00	123 35.90
Ucluelet (1)	49 02.9	125 35.90	29	49 00.00	123 30.50
(2)	49 04.8	125 27.90	30	48 56.70	123 23.15
Kelsey Bay	50 23.82	125 57.55	31	48 53.40	123 15.55
Scanlon Dam	49 47.80	124 18.60	A	49 48.15	124 51.92
Bloedel	50 06.03	125 24.62	B	49 46.07	124 48.23
Hornby Island	49 37.60	124 27.26	C	49 44.17	124 44.50
Campbell River	50 03.37	125 24.47	D	49 42.37	124 40.55
Elk Falls	50 01.89	125 21.82	E	49 40.53	124 36.65
Kelsey Bay (Nov.)	50 21.38	125 55.28	F	49 38.61	124 33.11
Patricia Bay	48 38.94	123 28.83	G	49 36.79	124 29.02
Seattle	47 39.3	122 18.5	H	49 35.60	124 24.58
Longmire	46 45.0	121 48.6	I	49 33.91	124 20.31
Mineral	40 20.8	121 36.1	J	49 32.33	124 16.40
1	49 37.60	124 27.26	K	49 31.45	124 14.04
2	49 35.61	124 29.70	L	49 32.97	124 18.04
3	49 33.02	124 32.85	M	49 34.64	124 22.34
4	49 32.45	124 34.09	N	49 36.21	124 26.71
5	49 34.35	124 31.62	O	49 37.87	124 30.79
6	49 36.35	124 28.65	P	49 39.38	124 34.75
7	49 41.00	124 17.65	Q	49 41.38	124 38.60
8	49 43.88	124 18.21	R	49 43.19	124 42.46
9	50 33.55	126 51.35	S	49 45.12	124 46.26
10	50 30.20	126 31.27	T	49 46.95	124 50.32
11	50 28.20	126 10.40	A (Nov.)	50 24.47	125 58.27
12	50 23.74	125 53.00	B (Nov.)	48 18.6	123 37.7
13	50 20.22	125 25.70	1 (Nov.)	50 23.6	125 54.6
14	50 10.71	125 21.62	2 (Nov.)	50 23.4	125 50.0
15	49 57.30	125 05.55	3 (Nov.)	50 22.2	125 46.4
16	49 53.61	125 00.40	4 (Nov.)	50 22.4	125 42.3
17	49 48.92	124 54.08	5 (Nov.)	50 22.5	125 37.3
18	49 43.95	124 47.05	6 (Nov.)	49 59.6	125 12.1
19	49 38.10	124 40.90	7 (Nov.)	49 53.8	125 02.7
20	49 33.27	124 35.70	8 (Nov.)	49 51.1	124 58.8
21	49 32.20	124 32.10	9 (Nov.)	49 48.9	124 55.3
22	49 27.72	124 38.47	10 (Nov.)	50 21.4	125 55.3
23	49 25.75	124 31.10	Ripple Rock	50 07.9	125 21.2
24	49 23.82	124 23.55			

3.2 Instrumentation and Recording Techniques

The instrumentation for the May 1960 program is summarized in Table 2.

Table 2. Summary of Instrumental Constants

Station	Seismometer	Recorder	Seismometer Period (sec.)	Galvanometer Period (sec.)	Paper Speed (mm/sec)
Victoria	Benioff	Benioff	1.0	0.2	1.0
Alberni	Willmore	Sprengnether	1.0	0.03	1.0
Horseshoe Bay	Willmore	Sprengnether	1.0	0.25	1.87
Penticton	Benioff	Benioff	1.0	0.20	1.0
Ucluelet (1)	Willmore	Willmore	1.0	0.25	0.89
Ucluelet (2)	Willmore	Willmore	1.0	0.25	0.89
Kelsey Bay	Willmore	Willmore	1.0	0.25	0.89
Scanlon Dam	Willmore and Geophone Spread	Electro-tech ER-101	0.222	0.005	60.0
Bloedel	Willmore	Heiland	1.0	0.025	9.4
Hornby Island	Willmore and Geophone Spread	Century	1.0	0.06	90.0

The recording equipment at Victoria consisted of 3 component instruments. The other stations were equipped with vertical components only. The stations at Scanlon Dam, Bloedel and Hornby Island all had spreads of detectors. The June 1961 explosions were recorded at the permanent stations at Victoria and Alberni with the same instrumentation as indicated above, and also at the temporary station at Campbell River near the John Hart Dam. This station was equipped with a spread of geophones recording into an Electro-Technical ER-101 recorder mounted in a truck. The spread was approximately 1050 metres in length with geophones at intervals of 150 metres. The geophones had a natural frequency of 4.5 cycles per second and were critically damped. Included also were two low impedance Willmore seismometers having a natural frequency of 1 cycle per second. The outputs were amplified with conventional amplifiers and recorded on channels 1-10 of the photographic paper recorder. All geophones were located near bedrock. A paper speed of about 75 mm/sec. was used. For the November 1961 program this equipment was operated at Kelsey Bay. The site did not permit the use of the whole spread of geophones. The layout for this operation is further described in a later section. In addition to this station and the permanent stations at Victoria, Alberni and Penticton, two other temporary stations were operated at Elk Falls Forestry Lookout and at Patricia Bay. At Elk Falls a short spread of three Willmore seismometers spaced at 75-metre intervals recorded through low frequency amplifiers into a Century recorder. The paper speed used was 26.5 mm/sec. The Pacific Naval Laboratory of the Defence Research Board at Esquimalt operated the instrument at Patricia Bay, which recorded the output of a hydrophone. Well recorded events were obtained at this station from the smaller explosions up to a distance of 195 km.

Time control at the recording sites was provided by Times chronometers in practically all cases. These chronometers are operated by a synchronous motor which is driven by an electronically generated power supply. The frequency of the power is controlled by a tuned vibrator. At Scanlon Dam a Mercer self-winding chronometer was used and at Hornby Island a Dent chronometer with 2-second contacts was used. WWV and Dominion Observatory time signals were used to correct and rate the chronometers. The accuracy of time control at the temporary stations and on the ship was sufficient to detect a delay of a few hundredths of a second in the Dominion Observatory time signal as broadcast from the Canadian Broadcasting Corporation station in Vancouver.

The delay is presumably introduced by the transmission system between Eastern Canada and the West Coast.

Shot times were recorded on the ship on a two-channel tape recorder. A Times chronometer was used to trigger pulses at intervals of one second and these were recorded on one channel of the tape recorder. WWV signals were recorded with the chronometer pulses almost continuously throughout the program. The shock from the explosion was detected by a microphone fastened to the hull of the ship and recorded on the other channel of the tape recorder. For the 1960 program communication was carried on between the ship and those recording stations which used high paper speeds by means of a 60-watt shortwave transmitter on the ship. Communication provided the recorder operator with a warning signal at an appropriate time for switching on the recording equipment. In some cases the communication was intermittent. For the June 1961 program, in addition to the shortwave equipment, communication was maintained between the ship and the Elk Falls Forestry Lookout near Campbell River through British Columbia Telephone lines. The ship's radio was used to patch into the telephone circuit. The communication link to the seismic truck was completed by V.H.F. Pye transmitter-receiver sets located at the truck site and at the Forestry Lookout. The telephone lines were again used, supplemented by an f-m telephone unit on the ship for the November 1961 program to provide communication from the ship to the stations at Elk Falls and Kelsey Bay. From all areas in which the ship operated it was possible to work into one of the telephone company's coastal stations with the f-m unit installed on the ship. Telephones were installed conveniently in the Elk Falls Lookout and the seismic truck at Kelsey Bay and connected to local lines of the Campbell River exchange. The only difficulty with transmission was experienced in the case of shot B (Nov.) as a result of elevated topography between the ship and the telephone land station.

Shot times for the two large explosions of the November 1961 program were obtained in two ways. The shock wave detected by the hull microphone was recorded with time reference signals on a two-channel tape recorder. Also a gating circuit was triggered by the current in the detonator circuit. This turned on an audio tone for a duration of about one second, and this was transmitted from the launch from which the charge was detonated to the ship, where it was recorded by a second tape recorder with the same time reference signals.

Some of the tape recordings were played back into a two-channel brush recorder and others, into the Century photographic paper recorder. Examples of the visual records of shot times are shown in Figure 19.

Navigation was carried out by members of the crews of the CNAV Laymore and CNAV Whitethroat. Bearings were taken at the time the charges were dropped into the water, on land marks which were well defined on the Hydrographic Survey Charts. The ship's gyro was used to obtain the reference direction. For shots 1 to 6 of the 1960 program some extra control on the shot positions was obtained by readings taken with land-based theodolites on Lasqueti and Hornby Islands.

3.3 Reduction of Data

Origin times (defined as the times of arrival of the shock waves at the bottom below the charges) were obtained by making appropriate corrections to the recorded shock instants. The pressure detonating mechanism on the depth charges was set to trigger at a depth of about 150 metres. In some cases the depth setting varied from this figure, but a record was kept of the actual setting. A rate of descent of the depth charge in the water was assumed to be 3 m/sec. An average speed of the ship was calculated. The depth of water under each charge was obtained with sufficient accuracy from the soundings marked on a Hydrographic Survey chart, published by the Federal Department of Mines and Technical Surveys. For the explosions of the 1960 program, depth soundings were supplied by the ship's echo sounder. The two large charges of the November 1961 program, shots A (Nov.) and B (Nov.), were detonated on the bottom in water depths of 194 m. and 102 m., respectively.

The data for obtaining the origin times of the explosions are shown in Tables 3 (page 30) and 4 (page 31).

Coordinates were obtained for the temporary stations by plotting the positions on 1:50,000 scale topographic maps. Distances between shot points and stations were calculated using the Richter short distance formula (1943).

Arrivals of seismic energy were read for all stations at which events were recorded. Drift curves were drawn up for each chronometer based on the recorded standard radio signals. Corrections to each arrival time were then made by referring to the drift curves. In many cases it was possible to record WWV signals on the ship and at the land-based stations, through the recording time of the explosion.

3.4 Accuracy of Measurements

The error in the origin time is due to the following uncertainties in the data used in its calculation.

(1) The correction to the time of arrival of the shock at the ship for travel time in the water is calculated on the basis of an average velocity of the shock or sound wave in the water. The sinking rate of the depth charge was taken as 3 m/sec. with a depth setting of 150 metres, approximately, giving a delay of about 50 seconds. A figure of 364 m. (1200 ft.) with an uncertainty of about 30 m. (100 ft.) was taken as the distance from the ship to the charge at the time of detonation. The effect of the uncertainties in distance and velocity is shown by the relation

Table 3. Reduction of Recorded Shock Time at the Ship to O-Time for Explosions of the June 1961 Program

	Recorded Shock Instant	Correction for Filter in Play-back Circuit (+.05 sec.) and Travel Time to Ship (-.25 sec.)	Depth of Water (metres)	Correction for T.T. to Bottom (sec.)	O-Time (Pacific Daylight Time)
A	1105 09.97	1105 09.77	218	+ .05	1105 09.82
B	1121 59.20	1121 59.00	290	.10	1121 59.10
C	1138 25.00	1138 24.80	326	.12	1138 24.92
D	1152 40.18	1152 39.98	302	.10	1152 40.08
E	1209 39.67	1209 39.47	326	.12	1209 39.59
F	1227 06.92	1227 06.72	272	.08	1227 06.80
G	1245 38.40	1245 38.20	290	.10	1245 38.30
H	1303 08.18	1303 02.98	326	.12	1308 03.10
I	1320 31.69	1320 31.49	218	.05	1320 31.54
J	1337 13.29	1337 13.09	326	.12	1337 13.21
K	1415 41.42	1415 41.22	326	.12	1415 41.34
L	1429 51.66	1429 51.46	326	.12	1429 51.58
M	1444 21.09	1444 20.89	290	.10	1444 20.99
N	Not recorded				
O	1514 40.86	1514 40.66	290	.10	1514 40.76
P	1528 04.14	1528 03.94	272	.08	1528 04.02
Q	1544 31.24	1544 31.07	272	.08	1544 31.12
R	1556 01.68	1556 01.48	326	.12	1556 01.60
S	1611 04.74	1611 04.54	326	.12	1611 04.66
T	1625 38.94	1625 38.74	208	.04	1625 38.78

Table 4. Reduction of Recorded Shock Time at the Ship to O-Time for Explosions of the November 1961 Program

Shot	Corrected Detonation Time	Correction for Travel Time to Bottom (sec.)	Correction for Travel Time to Ship (sec.)	O-Time (Pacific Standard Time)
1 (Nov.)	No shot time.	+ 0	- .17	
2 (Nov.)	0750 16.19	0	.15	0750 16.04
3 (Nov.)	0810 01.56	.01	.18	0810 01.39
4 (Nov.)	0830 04.61	.03	.18	0830 04.46
5 (Nov.)	0850 06.80	.07	.18	0850 06.69
6 (Nov.)	1329 29.80	0	.12	1329 29.68
7 (Nov.)	1410 07.78	.02	.24	1410 07.56
8 (Nov.)	1429 59.65	.04	.24	1429 59.45
9 (Nov.)	1450 09.86	0	.23	1450 09.63
10 (Nov.)	1510 11.89	.03	.17	1510 11.75
A (Nov.)*	1729 59.30			1729 59.30
B (Nov.)*	1044 59.68			1044 59.68

*These times were obtained from the pulse triggered by the detonating circuit.

$$\frac{\delta t}{t} = \frac{\delta D}{D} + \frac{\delta v}{v}$$

to be about .02 sec. where a variation of one per cent is allowed in sound wave velocity.

(2) The depth of water as interpolated from the Hydrographic Survey Charts has an uncertainty of 45 m., introducing an uncertainty of 0.03 sec. into the correction for travel time from charge to bottom. In the case of shots Q to M, the uncertainty may be as large as 90 m.

These and other uncertainties are summarized in Table 5.

Table 5. Uncertainties in Time Distance Data

	Corr. due to travel time in water (sec.)	Corr. for filter delay	Measurement errors on brush recording	Combined correction to absolute time	Reading errors on seismograms	Position	Probable error
High Paper Speed Recorders with Spreads	.05	.01	.05	.04	.05	.02	.10
Continuous Operating Recorders	.05	.01	.05	.10	.2	.02	.23

Positions were obtained from bearings taken on land markers. This work was done by experienced navigators who had become accustomed to accurate positioning in laying mines. The bearings were taken relative to the ship's gyroscope. Assuming an accuracy of better than 0.5° in the bearings, it is reasonable that the uncertainty in position is limited to 0.1 km.

3.5 Additional Data

On April 5, 1958, about 1.5 kilotons of high explosive were detonated in a single explosion in Seymour Narrows in order to remove the twin pinnacles of Ripple Rock which had in the past presented a navigational hazard. The Dominion Observatory operated a number of seismograph stations temporarily at points traversing the mountains as far east as Banff. Other stations were operated in the Calgary area by a number of oil prospecting crews. A station was operated by the University of Alberta, near Edmonton. The explosion was also recorded by permanent seismograph stations at Spokane, Longmire, Seattle and Mineral. Data from the recordings of this explosion have also been included in this thesis.

Data from a few explosions recorded during depth charge programs carried out in October of 1957 and July of 1959 are also included. The 1957 program has been described in a previous publication (Milne and White, 1960).

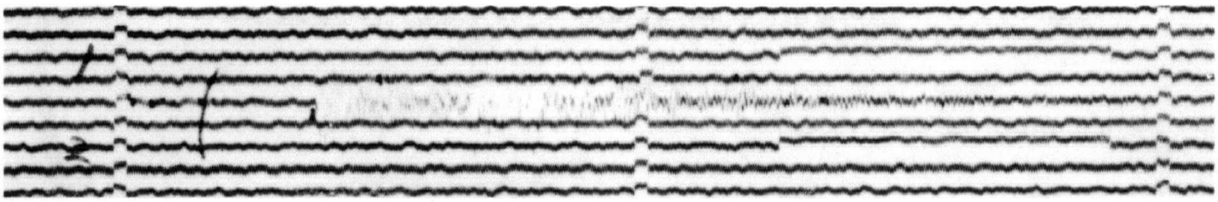
3.6 Seismograms

Examples of seismograms are shown in Figures 16 to 19. Most of the interpretation has been based on first arrival phases. A few secondary arrivals which were considered to be well defined were used on the long range time-distance plots.

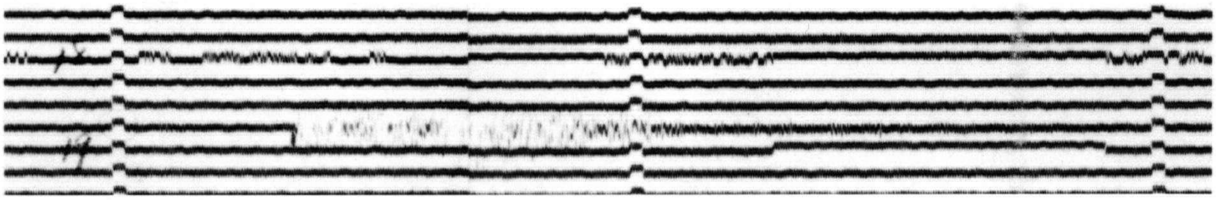
3.7 Amplitudes of Recorded Energy

A quantitative analysis of the relation of trace amplitudes and maximum distances of recording to size of explosion, amplitude of background noise, depth of detonation and other factors has not been made in this thesis. However, a brief discussion is in order. The observations will be useful in setting up future programs.

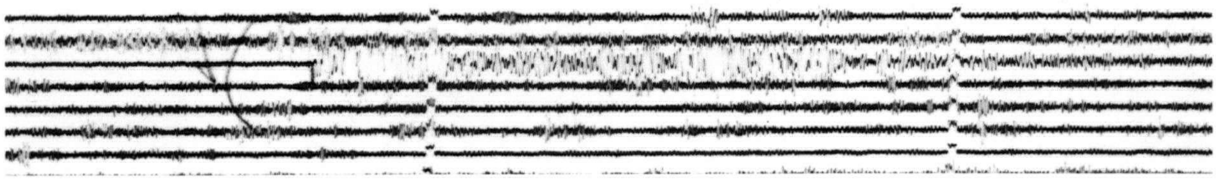
The two large charges, A (Nov.) and B (Nov.), were detonated in order to obtain records for distances beyond the point where P_n becomes a first arrival. The greatest distance for which these charges were recorded was from shot A (Nov.) to Longmire (510 km.). The amplitude of the disturbance on this seismogram is small, but differs in frequency from the background noise so that the onset may be recognized with some certainty. Stations along the coast record a rather high level of microseismic background during the winter months. This reduces the signal to noise ratio for these stations. The frequency of the recorded seismic energy is, however, considerably higher



a SHOT A(NOV.), 1350 Kilograms Explosive, Water Depth - 194 Metres
Recorded at Alberni, Δ = 151·11 Kilometres



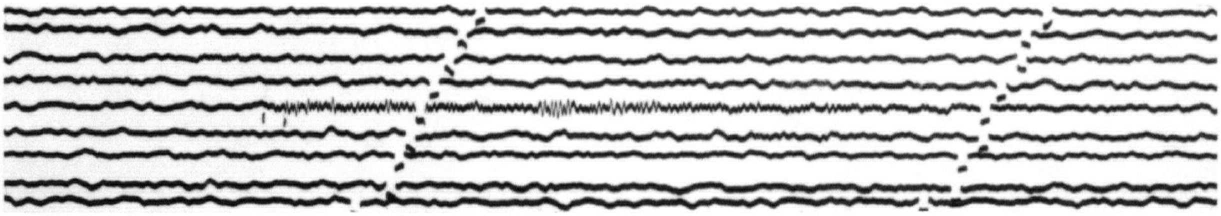
b SHOT B(NOV.), 1350 Kilograms Explosive, Water Depth - 102 Metres
Recorded at Alberni, Δ = 138·89 Kilometres



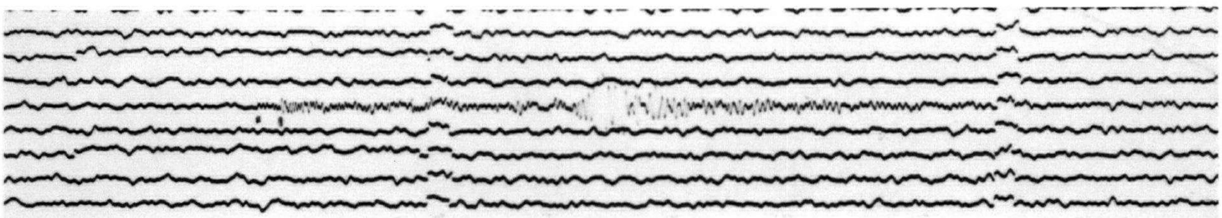
c SHOT B(NOV.), Recorded at Penticton, Δ = 315·0 Kilometres

SEISMOGRAMS OBTAINED AT PERMANENT STATIONS

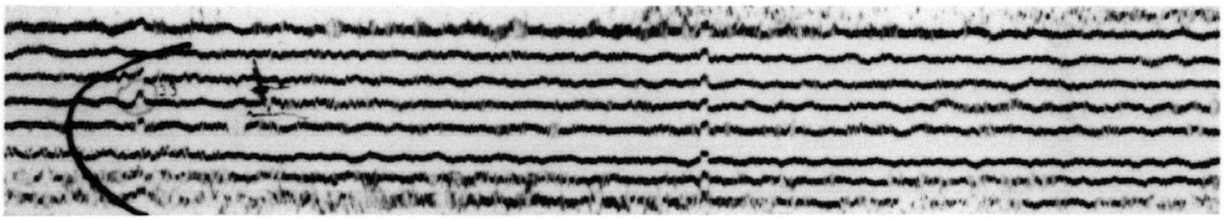
FIGURE 16



a SHOT B (NOV.), Recorded at Longmire, Δ = 220·97 Kilometres



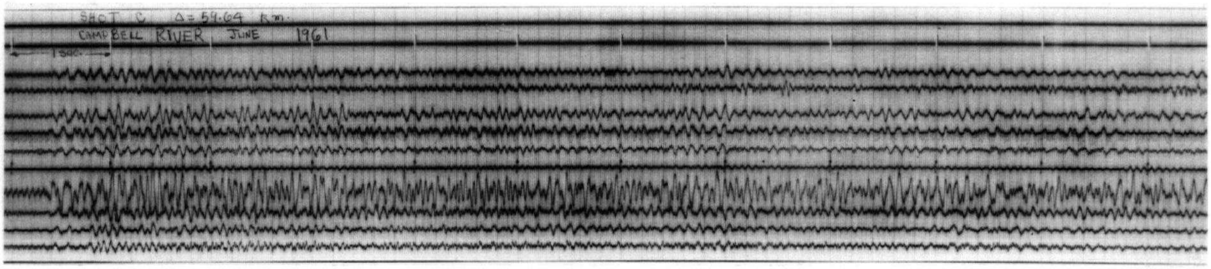
b SHOT A (NOV.), Recorded at Victoria, Δ = 280·1 Kilometres



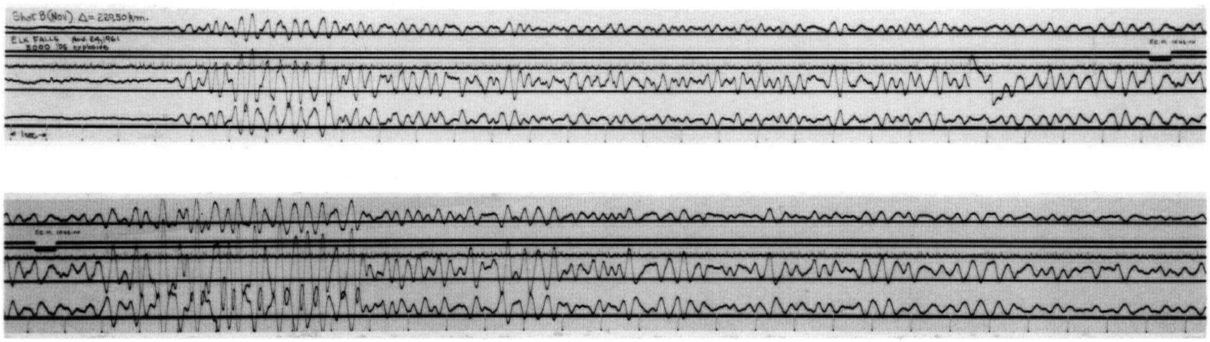
c RIPPLE ROCK, 1·5 Kilotons Explosive
Recorded at Mineral, Δ = 1126·6 Kilometres

SEISMOGRAMS OBTAINED AT PERMANENT STATIONS

FIGURE 17



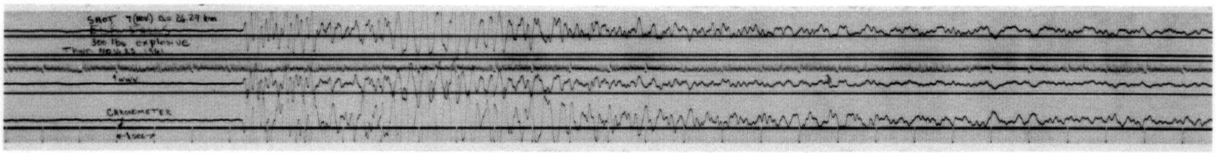
a SHOT C, 135 Kilograms Explosive
Recorded at Campbell River, $\Delta = 59{\cdot}64$ Kilometres
Geophone Spacing 145 Metres



b SHOT B (NOV.), Recorded at Elk Falls, $\Delta = 229{\cdot}50$ Kilometres
Geophone Spacing 75 Metres

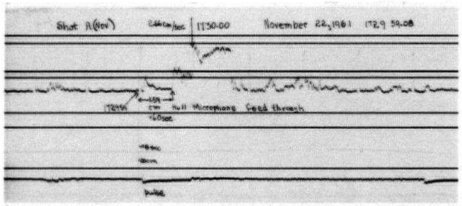
SEISMOGRAMS OBTAINED AT TEMPORARY STATIONS

FIGURE 18

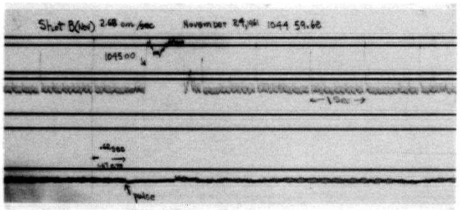


SHOT 7 (NOV.), 135 Kilograms Explosive, Recorded at Elk Falls, $\Delta = 26{\cdot}29$ Kilometres

SEISMOGRAM OBTAINED AT ELK FALLS



SHOT A (NOV.)



SHOT B (NOV.)

VISUAL RECORDS OF DETONATION TIME FOR SHOTS A(NOV.) AND B(NOV.)

FIGURE 19

than the frequency characteristic of the microseismic background. This is best illustrated in the Victoria record of shot A shown in Figure 17b. A precise time of arrival may be read for the initial disturbance on the seismogram.

It is of interest that a first arrival at Victoria has been recorded for shot 12, a shot which was detonated at approximately the same distance from Victoria as shot A (Nov.) but contained only 1/10 the amount of explosive. That the first arrival of energy has been chosen is indicated by the good correspondence of the travel times of these two explosions. The amplitude for shot 12 is very small. A considerably higher signal to noise ratio has been obtained at Penticton for shot B (Nov.), as compared with that for shot A (Nov.) as recorded at Victoria. The distance is slightly greater (315 km.) than for the shot A-Victoria distance (280 km.). A comparison of the amplitudes recorded for shots A (Nov.) and B (Nov.) at Alberni may be made by referring to the seismograms shown in Figure 16a and b. It will be noted that the overall amplitude for shot A is somewat greater. The weight of explosive used in each case is the same and shot A is at a slightly greater distance from the recording station. It should be noted that shot A was detonated on the bottom in 194 m. of water as compared with 102 m. for shot B. Other factors which may account for the variations are the bottom conditions, and the possible existence of major discontinuities in the surficial structure in the propagation path of the seismic energy.

An examination of the seismograms for other events indicates an overall amplitude variation from one explosion to another. A cursory analysis would indicate that the variation is observed at all stations and is a result of the conditions local to the charge and not, for example, a function of the azimuth of the recording station.

The necessity for finding a 'quiet' site was emphasized by an examination of the seismograms obtained at Kelsey Bay during the November 1961 program. The spread of detectors was laid out on the alluvium at the mouth of the Salmon River. This uncompacted sediment had the effect of transmitting with rather large amplitude the ground noise set up by logging operations and electrical generating equipment, even though the site was located at what was expected to have been a safe distance from the latter. Local industrial noise of this nature gives rise to background of about the same frequency as the seismic energy radiating from the explosions and makes precise reading of onsets difficult.

It would appear that the 1350 kilogram charges supply sufficient seismic energy to carry out refraction studies to distances where P_n is a first arrival, provided that quiet sites are chosen for recording. This condition is better realized for stations located some distance away from the coast.

3.8 Shorter Range Refraction Data for the 1960 and 1961 Programs

In this section the layout of the shot points and recording stations is described for each profile of the shorter range data. In the two following sections a similar description is given for the Ripple Rock data and for the longer range data obtained for the 1960 and 1961 programs. The time-distance data are presented in tabular form together with the plots, and the least squares equations for the various segments of the time-distance relations. General features of the travel time curves are observed. Discussion and interpretation of the time-distance plots in the form of suggested structures follow in section 3.12.

The data are presented for the various profiles which are suggested by the geographical locations of the shot points and stations. In most cases the profiles consist of a spread of shots recorded at a single station. In a few cases the profile is for a single shot recorded on a spread of stations.

The observations have been treated in a manner conventional in seismic refraction studies. Time-distance plots have been made and the various segments treated by least squares to obtain equations of the form

$$t = T_0 + \frac{\Delta}{v}$$

where t = travel time in sec.

T_0 = zero distance intercept on the time axis in sec.

Δ = distance between shot and recording station in km.

v = velocity in km/sec. for the refracting layer being considered.

The following assumptions are inherent in this approach.

(1) The layers of the crustal model are assumed to have plane, but not necessarily horizontal, boundaries.

(2) The velocity in each layer is constant.

(3) The travel time is not affected by the interchange of a shot and a recording station.

3.8.1 Profile I:

The time-distance data used for profile I, and consisting of events recorded at Campbell River and at Elk Falls Forestry Lookout, are shown in Tables 6 (page 37) and 7 (page 38). Since these two stations differ only slightly in location and are underlain by the same geological structure it was considered justifiable to plot the data for both on the same plot. The locations for shots 6 (Nov.) to 10 (Nov.) were laid out to fill in the short range part of the profile.

The data are plotted in Figure 20. The arrival times for this profile with the exception of shot 6 appear to fall along two lines with a discontinuity between shots P and F. This suggests a discontinuity in the structure such as a buried fault with vertical displacement, the high side underlying shot P. Events C and R show late arrivals which may be due to deep deposits of low velocity sediment below the shot positions. A shot located between 6 (Nov.) and 7 (Nov.) had to be omitted due to local marine traffic. Shot 6 (Nov.) shows some evidence of a layer having a typical granitic velocity underlying the lower velocity Cretaceous sediments.

Table 6. Time-Distance Data for Elk Falls used for Profile I

Shot	t (sec.)	Δ (km.)
6 (Nov.)	2.32	12.41
7 (Nov.)	4.80	26.29
8 (Nov.)	5.96	34.01
9 (Nov.)	7.00	39.88
10 (Nov.)	8.32	49.78

It may be noted that these shots were detonated in two stages, during the June 1961 program. Ten were dropped while the ship made a traverse in one direction and the second group of ten were dropped at staggered positions on the return traverse. This procedure gave the ship's crew more time for handling the explosives and it is also felt that errors in timing and position would tend to cancel out since each event is independent of the errors in the immediately preceding and following event.

A summary of the time-distance relations, in the form of least squares equations is given in Table 8 (page 39) for each profile. The uncertainties are probable errors.

Table 7. Time-Distance Data for Campbell River used for Profile I

Shot	t (sec.)	Δ (km.)
A	8.02	48.10
B	8.85	53.95
C	9.85	59.64
D*	Not recorded*	65.45
E	11.37	71.25
F	12.54	76.79
G	13.22	82.76
H	14.02	88.38
I	14.91	94.37
J	15.60	99.91
K	16.20	103.21
L	15.31	97.64
M	14.48	91.60
N*	Not recorded*	85.63
O	12.84	79.87
P	11.74	74.36
Q	10.89	68.43
R	10.31	62.71
S	9.18	56.90
T	8.44	50.97

*The recorder was not operating at the correct time due to a breakdown in the communications at the time of shot D and in the case of shot N, to an unusual delay in the detonating mechanism associated with the depth charge.

Table 8. Least Squares Equations Representing Time-Distance Relations

Profile	Uncompacted Sediments	Cretaceous Sediments	Granitic or Volcanic	Intermediate	Mantle
I (Campbell River, Elk Falls)				$t = 1.10 \pm .21 + \frac{\Delta}{6.94 \pm .20}$	
				$t = 1.48 \pm .15 + \frac{\Delta}{7.04 \pm .07}$	
II (Alberni)				$t = .70 \pm .10 + \frac{\Delta}{6.85 \pm .08}$	
				$t = 2.51 \pm 9 + \frac{\Delta}{7.19 \pm 3}$	
				$t = .38 \pm .56 + \frac{\Delta}{3.61 \pm .16}$	
III (Elk Falls)				$t = .47 \pm 1.28 + \frac{\Delta}{6.66 \pm 1.20}$	

Table 8 (Continued)

Profile	Uncompacted Sediments	Cretaceous Sediments	Granitic or Volcanic	Intermediate	Mantle
IV (Kelsey Bay)			$t = .10 + \frac{\Delta}{5.41}$	$t = .60 + \frac{\Delta}{6.70}$	
V (Kelsey Bay)	$t = \frac{\Delta}{1.58 \pm .02}$				
VI (Hornby Island)		$t = .05 \pm .04 + \frac{\Delta}{3.81 \pm .16}$		$t = .95 + \frac{\Delta}{6.67}$	
VII (Scanlon Dam)				$t = .56 \pm .86 + \frac{\Delta}{6.45 \pm 1.00}$	
VIII (Victoria)				$t = 1.55 \pm .49 + \frac{\Delta}{6.76 \pm .13}$	
				$t = .92 \pm 3.11 + \frac{\Delta}{3.62 \pm .24}$	
IX (Ucluelet)				$t = 1.13 \pm .60 + \frac{\Delta}{6.63 \pm .30}$	

Table 8 (Continued)

Profile	Uncompacted Sediments	Cretaceous Sediments	Granitic or Volcanic	Intermediate	Mantle
X (Kelsey Bay 1960)				$t = .03 \pm .49 + \frac{\Delta}{7.22 \pm .23}$	
XI (Horseshoe Bay)				$t = 1.69 \pm .41 + \frac{\Delta}{6.74 \pm .16}$	
XII (Ripple Rock)					$t = 4.81 \pm .64 + \frac{\Delta}{7.66 \pm .07}$ $t = 6.0 \pm 1.3 + \frac{\Delta}{7.78 \pm .15}$ $t = 2.00 \pm 2.49 + \frac{\Delta}{3.64 \pm .06}$
XIII (Ripple Rock)				$t = .11 \pm .53 + \frac{\Delta}{6.60 \pm .10}$	$t = 7.93 \pm .19 + \frac{\Delta}{7.75 \pm .02}$
XIV				$t = .97 \pm .28 + \frac{\Delta}{6.71 \pm .06}$	$t = 09.5 + \frac{\Delta}{7.97}$

Table 8 (Continued)

Profile	Uncompacted Sediments	Cretaceous Sediments	Granitic or Volcanic	Intermediate	Mantle
XV				$t = \frac{\Delta}{6.66}$	$t = 7.17 \pm 2.5 + \frac{\Delta}{7.68 \pm .35}$
XVI				$t = .22 \pm .08 + \frac{\Delta}{6.64 \pm .03}$	
XVII				$t = 1.31 \pm .26 + \frac{\Delta}{6.66 \pm .09}$	
Composite Plot				$t = 0.63 \pm .30 + \frac{\Delta}{6.66 \pm .07}$	

3.8.2 Profile II:

The time-distance observations for profile II, consisting of events recorded at Alberni, are listed in Table 9. It will be noted by reference to Figure 14 that although the Alberni station is not collinear with the line of shots, this profile is an approximation to a reversal of profile I. The profile includes the Ripple Rock event which has also been included in the least squares reduction of the data. It also includes shots A (Nov.) and 1 (Nov.) to 5 (Nov.) which are shown in the distance range 135 to 151 km. on the plot of the data shown in Figure 21. These arrivals are late and have been treated separately to obtain a least squares segment of the travel time curves.

Table 9. Time-Distance Data for Profile II as Recorded at Alberni

Shot	t (sec.)	Δ (km.)
4	5.7	35.25
3	6.3	36.94
20	6.1	35.61
21	5.9	35.19
P	7.4	46.37
Q	7.8	48.38
D	7.9	49.59
C	8.2	52.11
S	8.4	53.68
B	8.6	55.33
T	9.1	56.96
A	9.4	59.18
16	11.0	70.57
15	12.1	78.61
R.R.	15.7	103.10
A (Nov.)	23.75	151.11
1 (Nov.)	22.61	147.40
2 (Nov.)	22.52	144.21
3 (Nov.)	22.49	140.14
4 (Nov.)	21.59	138.13
5 (Nov.)	21.19	135.65
6 (Nov.)	13.29	84.95
7 (Nov.)	11.17	71.54
8 (Nov.)	10.40	65.34
9 (Nov.)	9.32	59.07
10 (Nov.)	8.40	53.00

3.8.3. Profile III:

The time-distance data for profile III are shown in Table 10. The data are for shots A (Nov.) and 2 (Nov.) to 5 (Nov.) as recorded at Elk Falls.

Table 10. Time-Distance Data for Profile III, Events Recorded at Elk Falls

Shot	t (sec.)	Δ (km.)
A (Nov.)	9.74	60.03
1 (Nov.)	8.74	56.24
2 (Nov.)	8.19	52.26
3 (Nov.)	7.69	47.68
4 (Nov.)	7.21	45.16
5 (Nov.)	6.91	42.42

The plot for this profile is shown in Figure 22. The points do not fit the line obtained for profile I.

3.8.4 Profile IV:

The data for profile IV were obtained from records at Kelsey Bay of shots 2 (Nov.) to 5 (Nov.). The plot is interpreted as having two segments with two points on each segment. It is shown in Figure 23 and the data are shown in Table 11. A third low velocity segment taken from profile V has been drawn in.

3.8.5. Profile V:

Profile V (Figure 24) is for a short range refraction shot. It was obtained by detonating a small charge (about one kilogram) of nitrone in several metres of water at one end of the geophone line and recording the explosion across the spread of geophones laid out at Kelsey Bay (Nov.). The purpose of the profile is to obtain the velocity in the sediments at the mouth of the Salmon River, on which this station was located. The observed data* are shown in Table 12.

Table 11. Data for Profile IV, Events Recorded at Kelsey Bay

Shot	t (sec.)	Δ (km.)
2 (Nov.)	1.45	7.29
3 (Nov.)	2.07	10.64
4 (Nov.)	2.91	15.44
5 (Nov.)	3.80	21.42

Table 12. Data for Profile V, for Explosion Detonated near the South End of the Geophone Line at Kelsey Bay

Geophone Number	t (sec.)	Δ (km.)
1	.000	0.000
2	.033	0.061
4	.138	0.247
5	.206	0.348
6	.282	0.456
7	.344	0.556
8	.400	0.625

Onsets for shots A (Nov.) (Δ = 6.70 km.) and 2 (Nov.) recorded at station Kelsey Bay were sharp and velocities were read across the geophone spread for these two events. An apparent velocity of 5.85 km/sec. was obtained for shot 2 (Nov.). The apparent velocity obtained for shot A was very high, as a result of refraction from the high velocity rock of the wall of the river valley. The geophone line was orientated at an angle of approximately 30° with the valley wall.

3.8.6 Profile VI:

The time-distance data for profile VI, events recorded on Hornby Island, are shown in Table 13. Hornby is the only station located on the Cretaceous sediments.

Table 13. Time-Distance Data for Profile VI, Events Recorded at Hornby Island

Shot	t (sec.)	Δ (km.)
3	1.1	4.42
4	0.6	2.60
15	9.8	59.12
19	2.9	13.09
20	0.7	2.75
21	1.2	4.76

The plotted points shown in Figure 25 appear to fall along two lines intersecting at a distance of 8.03 km. The low velocity segment is associated with the low velocity sediments of Cretaceous age. There is no indication of a layer having velocity of the order of 6 km/sec. above the layer having velocity 6.67 km/sec. The data, however, are sparse, and the refraction from a thin layer between the Cretaceous layer and the higher velocity layer would not become a first arrival.

3.8.7 Profile VII:

The data for records from Scanlon Dam used in the plot for profile VII are shown in Table 14.

Table 14. Time-Distance Data for Profile VII, Events Recorded at Scanlon Dam

Shot	t (sec.)	Δ (km.)
17	7.2	42.61
18	6.0	34.92
19	5.8	32.29
20	5.5	33.89

A plot of the data is shown in Figure 26. The uncertainties are very large.

3.8.8 Profiles VIII to XI:

The data obtained at a number of stations at greater distances from shots detonated in the same area are also presented. The data for Victoria, Patricia Bay, Ucluelet, Kelsey Bay and Horseshoe Bay are shown in Tables 15 to 19.

The time-distance data for Patricia Bay for events 6 (Nov.) to 10 (Nov.) are combined with those for Victoria for profile VIII (Figure 27) and were also used in the least squares determination. Included also, but not used in the least squares, are Ripple Rock, shot 12 and shot A (Nov.), observed travel times to Victoria. Patricia Bay and Victoria are located on the same geological formation. The points plotted as solid circles are probably all located on Cretaceous sediments. The open circles at the short distances represent charges detonated on the Fraser River deposits. Ripple Rock, 12, and A (Nov.) plotted at distances greater than 230 km. were all detonated close to a competent basement rock.

Table 15. Time-Distance Data for Profile VIII, Events Recorded at Victoria

Shot	t (P) (sec.)	t (Lg) (sec.)	Δ (km.)
3	22.4	40.5	141.43
4	22.7		141.49
20	22.7	39.7	143.85
P	24.4		152.39
Q	25.3		158.06
D	25.4		160.91
C	25.8		166.39
S	26.1	47.8	169.07
B	26.3		171.88
T	27.1	50.4	174.71
A	27.8	51.6	177.63
15	31.5	56.1	201.03
17	28.6		181.66
1-18*	29.4		186.36
1-19*	30.8		196.58
6 (Nov.)	32.52		209.22
7 (Nov.)	30.44		194.04
8 (Nov.)	28.76		187.00
9 (Nov.)	27.78		181.14
10 (Nov.)	27.72		171.42

*Shots from the explosion program of October 25, 1957 (Milne, 1960).

Table 16. Time-Distance Data for Profile VIII, Events Recorded at Patricia Bay

Shot	t (P) (sec.)	t (Lg) (sec.)	Δ (km.)
6 (Nov.)	30.5	54.5	194.97
7 (Nov.)	28.5	47.8	179.56
8 (Nov.)	27.5	48.3	172.66
9 (Nov.)	26.3	45.4	166.79
10 (Nov.)	25.1		157.05

Lg arrivals are included of events for which they were well defined.

The data for both Ucluelet stations are plotted together for profile IX (Figure 28). The location of the shotpoints tend to lie along a line at right angles to the line joining them to the stations.

The Ripple Rock arrival time is plotted with the Horseshoe Bay data on profile XI (Figure 30) but is not included in the least squares.

Table 17. Time-Distance Data for Profile IX, Events Recorded at Ucluelet Stations (1) and (2)

Shot	t (sec.)	Δ (km.)
20 (2)	13.5	82.33
19 (2)	14.0	83.93
18 (2)	14.5	87.78
20 (1)	15.0	92.15
4 (1)	15.7	92.82
19 (1)	15.5	93.23
3 (1)	15.8	94.04
21 (1)	15.2	94.50
18 (1)	15.8	96.33
17 (1)	16.1	99.14
16 (1)	16.6	103.30
15 (1)	17.6	107.27

The number in brackets identifies the two Ucluelet stations.

Table 18. Time-Distance Data for Profile X, Events Recorded at Kelsey Bay

Shot	t (sec.)	Δ (km.)
15	10.93	79.06
16	11.71	88.16
17	14.08	99.56
18	15.73	111.97
19	17.65	124.77
20	18.54	135.49
21	19.10	139.99
13	4.50	38.36
14	7.37	49.11

however that this chronometer had a low drift rate and that the velocity across the spread of shots is reasonably reliable but that the zero distance time intercept has little meaning. The time-distance plot is shown in Figure 29.

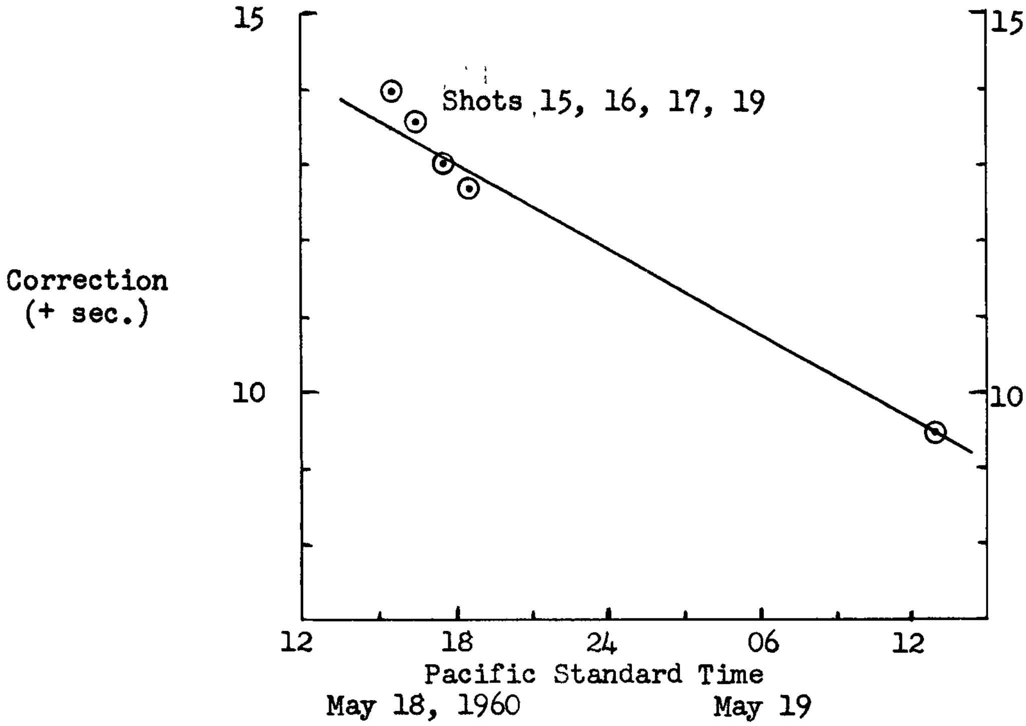


Figure 31. Drift Curve for Horseshoe Bay Chronometer

3.9 Ripple Rock Data

3.9.1 Profile XII and Profile XIII:

Temporary stations were operated eastward from the Ripple Rock explosion, through the Rocky Mountains at the geographical locations listed in Table 20 (page 52). The data from this program were kindly supplied by Dr. P. L. Willmore who coordinated the seismic program of the Dominion Observatory at the time of the Ripple Rock explosion.

Table 20. Time-Distance Data for Profile XII for Ripple Rock Recorded at Stations East through the Mountains

Station	t (P) (sec.)	t (Lg) (sec.)	Δ (km.)
Cache Creek	43.8	86.5	296.1
Deadman	47.4	87.7	336.8
Cherry Creek	50.0	96.1	345.8
Knutsford	53.3	102.2	362.0
Chase	56.7	111.6	401.2
Revelstoke	71.8	143.2	514.8
Glacier	79.6	155.6	568.3
McMurdo	85.3	172.1	617.8
Banff	96.3		702.3
Edmonton		252.2	896.3

No adjustment has been made to travel times for height above sea level. Events A (Nov.) and B (Nov.) as recorded at Penticton are shown on this plot, but not included in the least squares calculation (Figure 32).

Data for stations along the Coast south-east from Ripple Rock are shown in Table 21. The data are plotted in Figure 33 for profile XIII.

Table 21. Time-Distance Data for Profile XIII, Ripple Rock Recorded at Stations South East along the Coast

Station	t (sec.)	Δ (km.)
Alberni	15.69	103.10
Horseshoe Bay	26.29	171.52
Victoria	34.5	228.1
Brother's Island	35.9	235.5
Bellingham	39.8	259.6
Seattle	54	358.2
Longmire	67.0	458.5
Mineral	153.1	1126.6

The Ripple Rock explosion was recorded at two of the University of Washington stations at Seattle and Longmire, and at Bellingham, Washington. It was also recorded at a University of California station at Mineral. The data from these stations are included in the plot. The seismogram of this event recorded at Mineral is shown in Figure 17c.

3.10 Longer Range Data

The data presented in this section are for the larger explosions which were capable of recording at distances for which P_n becomes a first arrival, i.e., Shot A (Nov.), B (Nov.), Ripple Rock and Constance Bank.

3.10.1 Profiles XIV to XVII:

The data for the longer range profiles are shown in Table 22 (Page 54). The plots for the four profiles are shown in Figure 34. The data for profile XIII are also replotted. In plotting these observations it has been assumed that the interchange of a shot point and a station does not affect the travel time between them. Profile XIV is obtained from records of Shot A (Nov.) along a spread of stations running southeast on Vancouver Island and the Puget Sound area as far south as Longmire near Mt. Rainier. A well-defined secondary P arrival has been read for Victoria. Data for profile XV are for events recorded at Longmire. The line representing the relation $t = \frac{\Delta}{6.66}$ has been drawn in by assuming zero intercept, and using the time-distance data for shot B (Nov.) recorded at Longmire as a point on the line. The open circles plotted on this profile represent data for shots 28, 29, 30 and 31 detonated on the low velocity sediments associated with the depositions of the Fraser River. They have not been included in the least squares analysis. Their position on the plot suggests that if properly corrected for sediments, they would lie on the $t = \frac{\Delta}{6.66}$ line rather than the $t = 7.17 + \frac{\Delta}{7.68}$ line.

Table 22. Time-Distance Data for Longer Range Profiles

Profile XIV

Shot A - Recorded at Stations Southeast to Longmire

Station	t (sec.)	Δ (km.)
Elk Falls	9.74	60.03
Alberni	23.75	151.11
Victoria	42.56 44.6	280.1
Longmire	73.4	509.7

Profile XV

Events Recorded at Longmire

Shot	t (sec.)	Δ (km.)
B (Nov.)	33.2 35.9	220.97
28	45.3	296
29	46.0	280.4
30	41.7	271.1
31	40.8	261.5
Ripple Rock	67.0	458.5
A (Nov.)	73.4	509.7

Profile XVI

Shot B (Nov.) Recorded at Stations Northwest to Elk Falls; Ripple Rock and Shot A Recorded at Victoria

Station or Shot	t (sec.)	Δ (km.)
Victoria	4.34	28.29
Patricia Bay	6.2	39.13
Alberni	21.34	138.89
Elk Falls	34.52	229.50
Ripple Rock	34.5	228.1
A (Nov.)	42.56	280.1

Table 22. Time-Distance Data for Longer Range Profiles (Cont.)

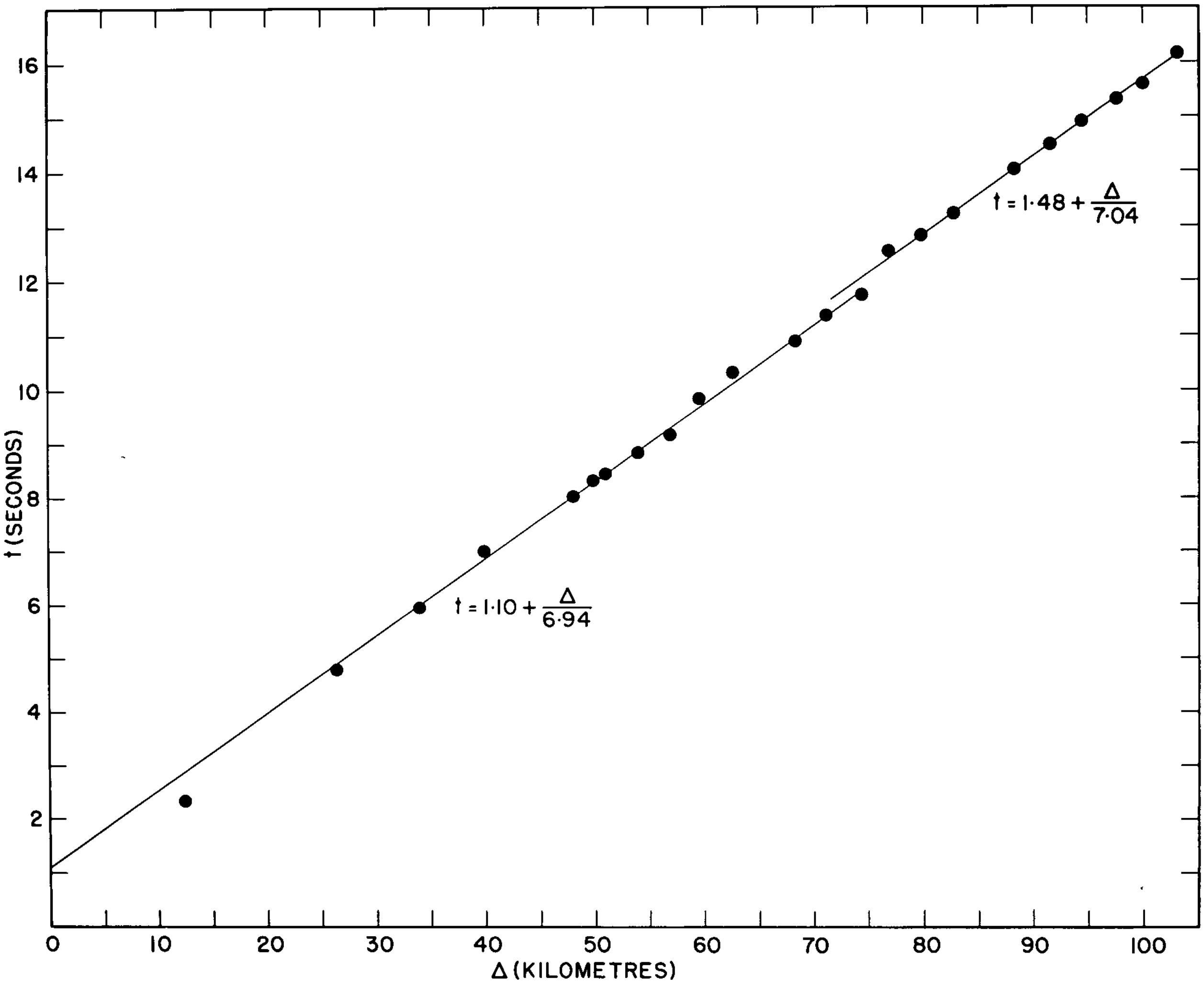
Profile XVII

Constance Bank Recorded at Stations Northwest to Ripple Rock Camp

Station	t (sec.)	Δ (km.)
Victoria	4.18	19.93
Alberni	24.28	150.86
Ripple Rock Camp	38.31	247.3

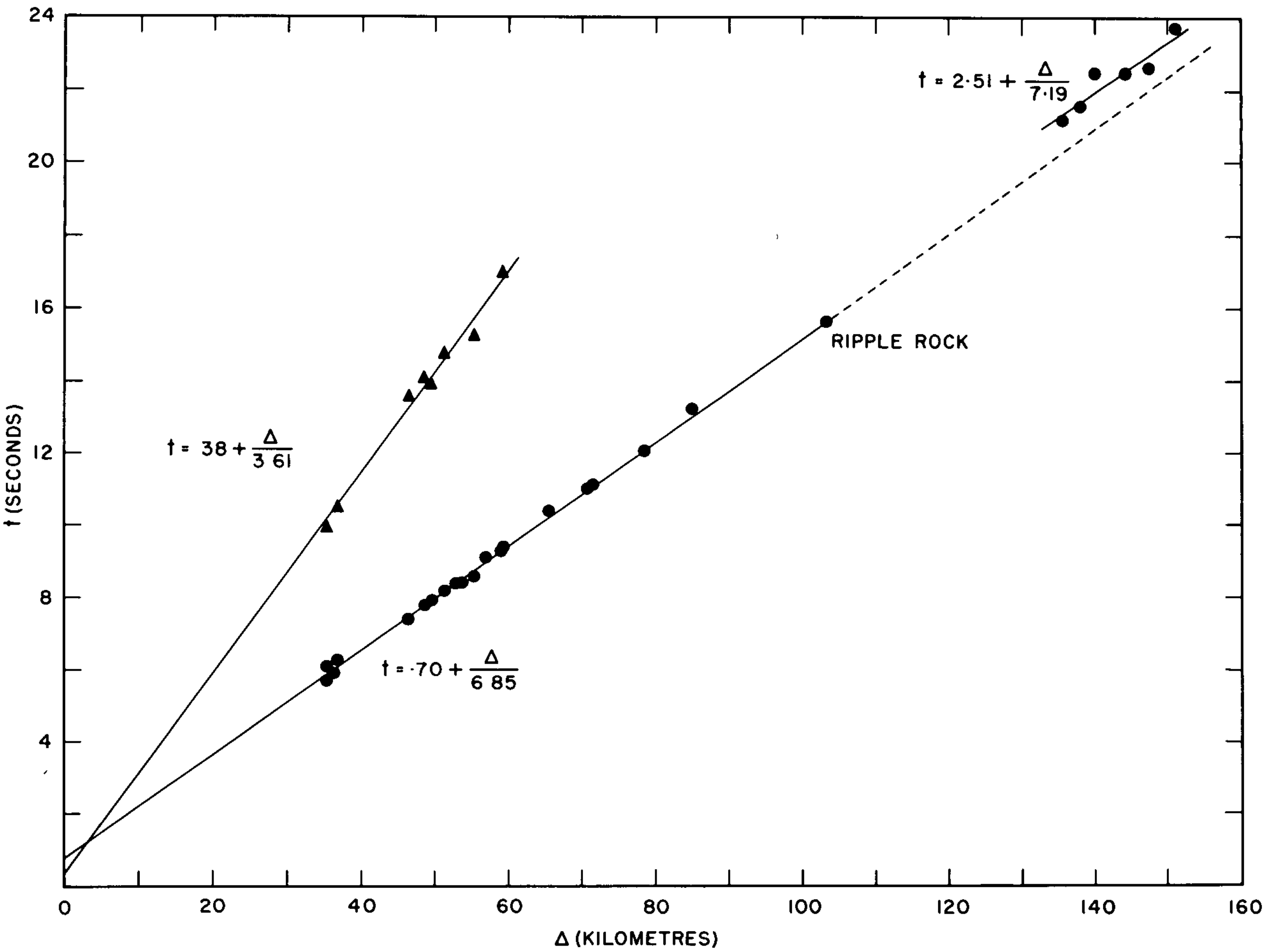
Profile XVI represents the data from stations recording Shot B to the north-west as far as Elk Falls, as well as events A (Nov.) and Ripple Rock recorded at Victoria. The assumption regarding interchange of shot point and recording site has also been made here in plotting the data for both spreads of shots and spreads of recording stations. The justification for plotting data for Victoria and shot B on the same plot is indicated by the good correspondence between travel times of Ripple Rock to Victoria and Shot B to Elk Falls.

Profile XVII represents data obtained from the explosion at Constance Bank as recorded at stations to the north-west as far as Ripple Rock Camp. The good correspondence of the velocities obtained for this profile with that of profile XVI is indicated. The discrepancy in the intercepts indicates either the presence of low velocity material below the Constance Bank explosion or the possibility of an error in the shot instant obtained. The latter possibility is favoured, since no geological evidence for a low velocity layer of the required depth is indicated. The shot instant was obtained by recording the explosion with a hydrophone at a location several kilometres from the shot point and correcting for the delay on the basis of an assumed velocity.



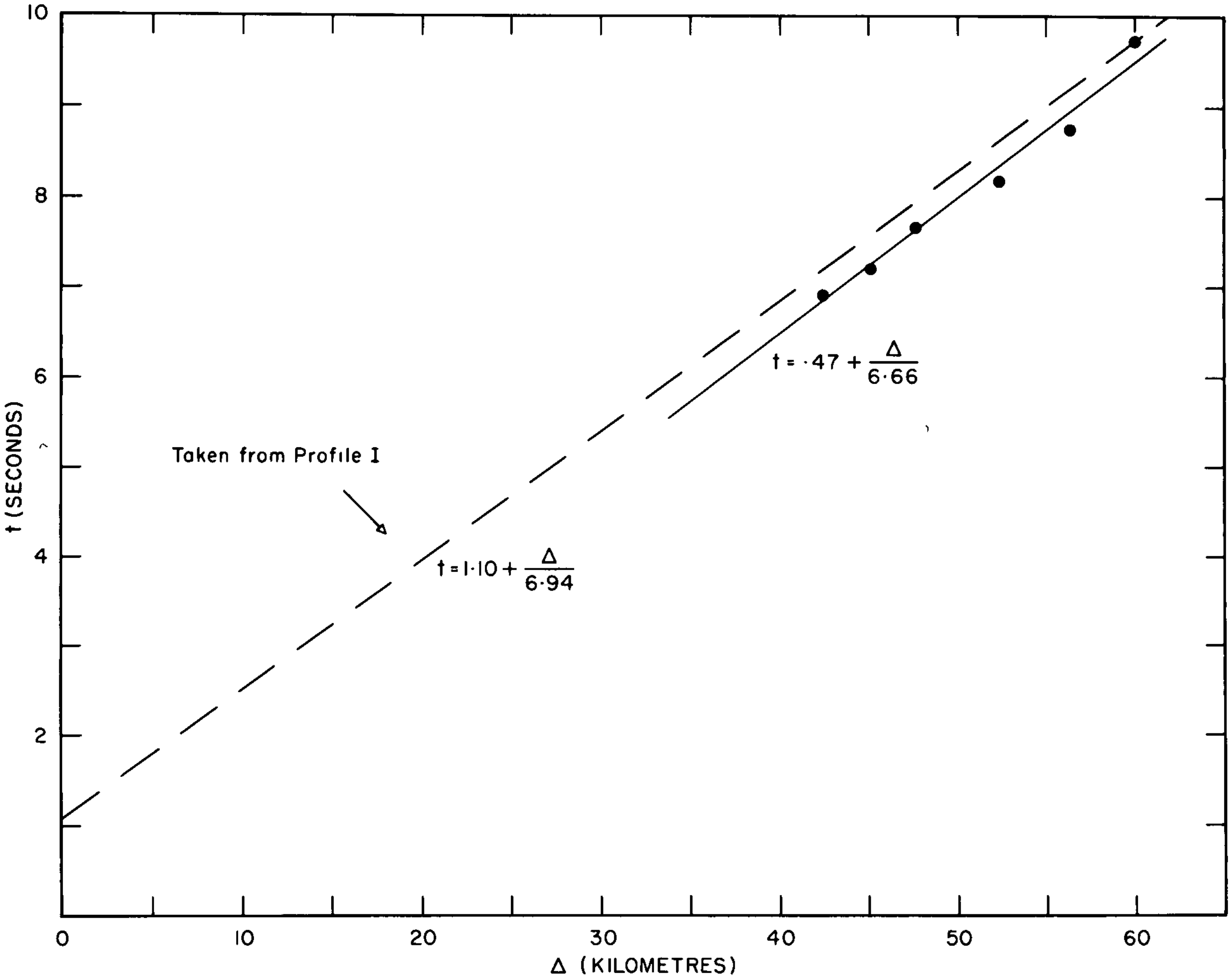
PROFILE I EVENTS RECORDED AT CAMPBELL RIVER AND ELK FALLS

FIGURE 20



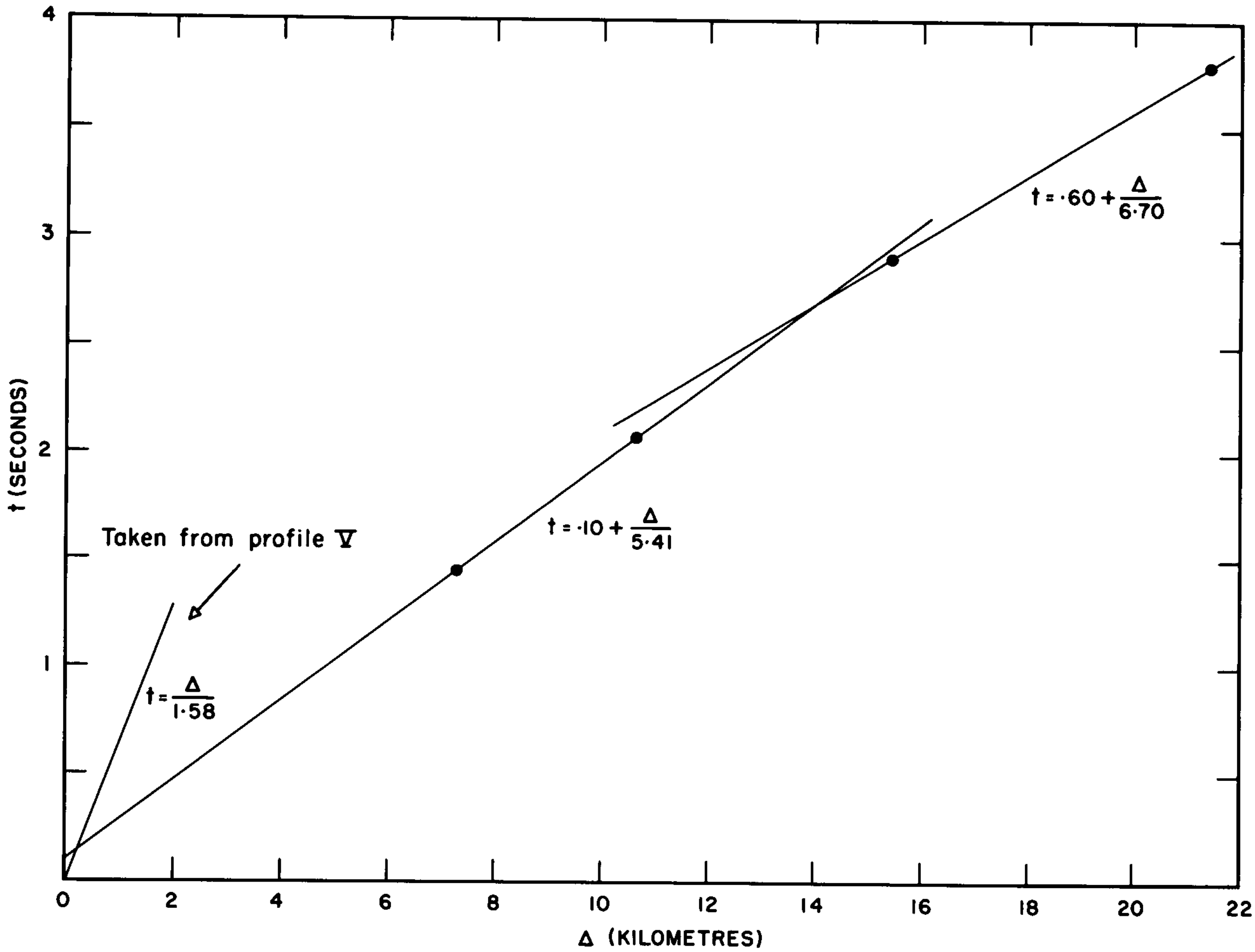
PROFILE II EVENTS RECORDED AT ALBERNI

FIGURE 21



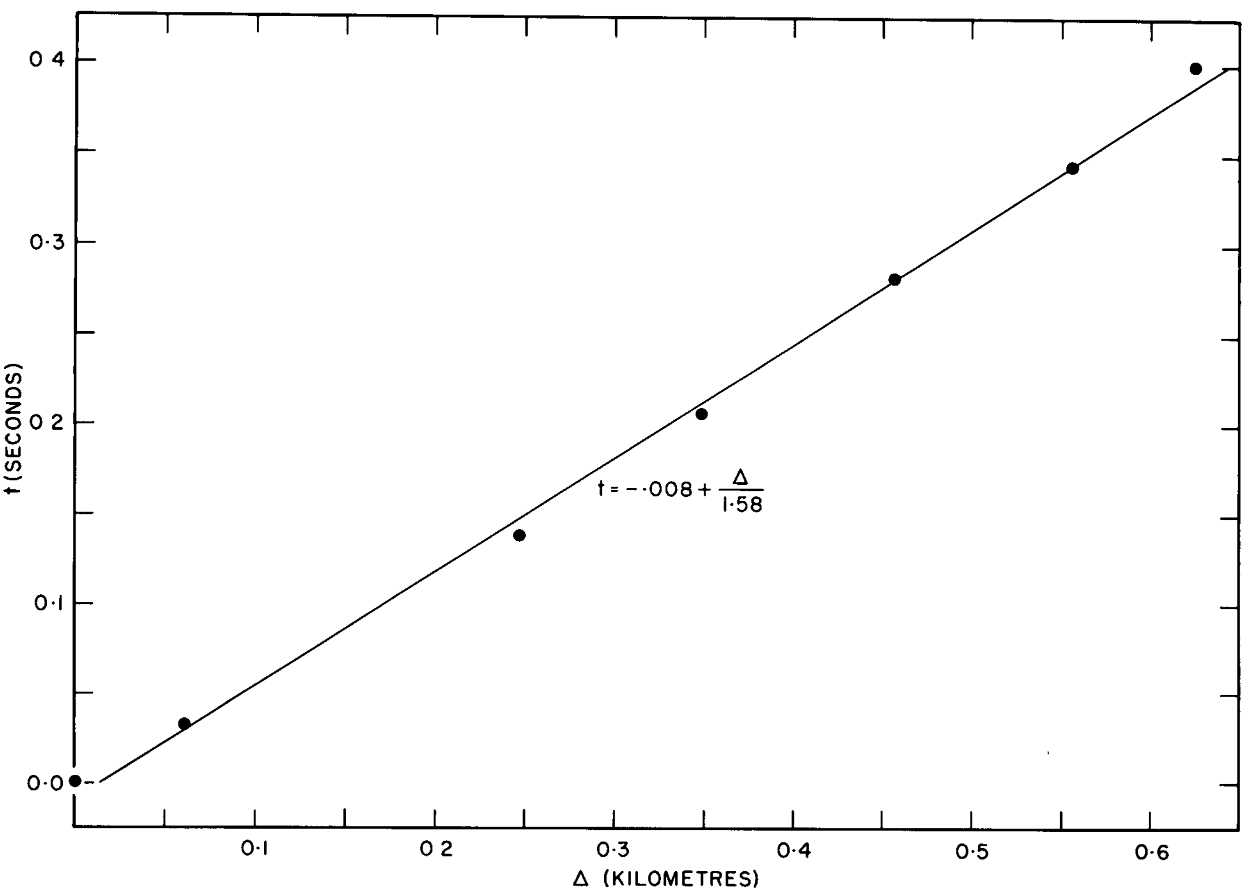
PROFILE III EVENTS RECORDED AT ELK FALLS

FIGURE 22



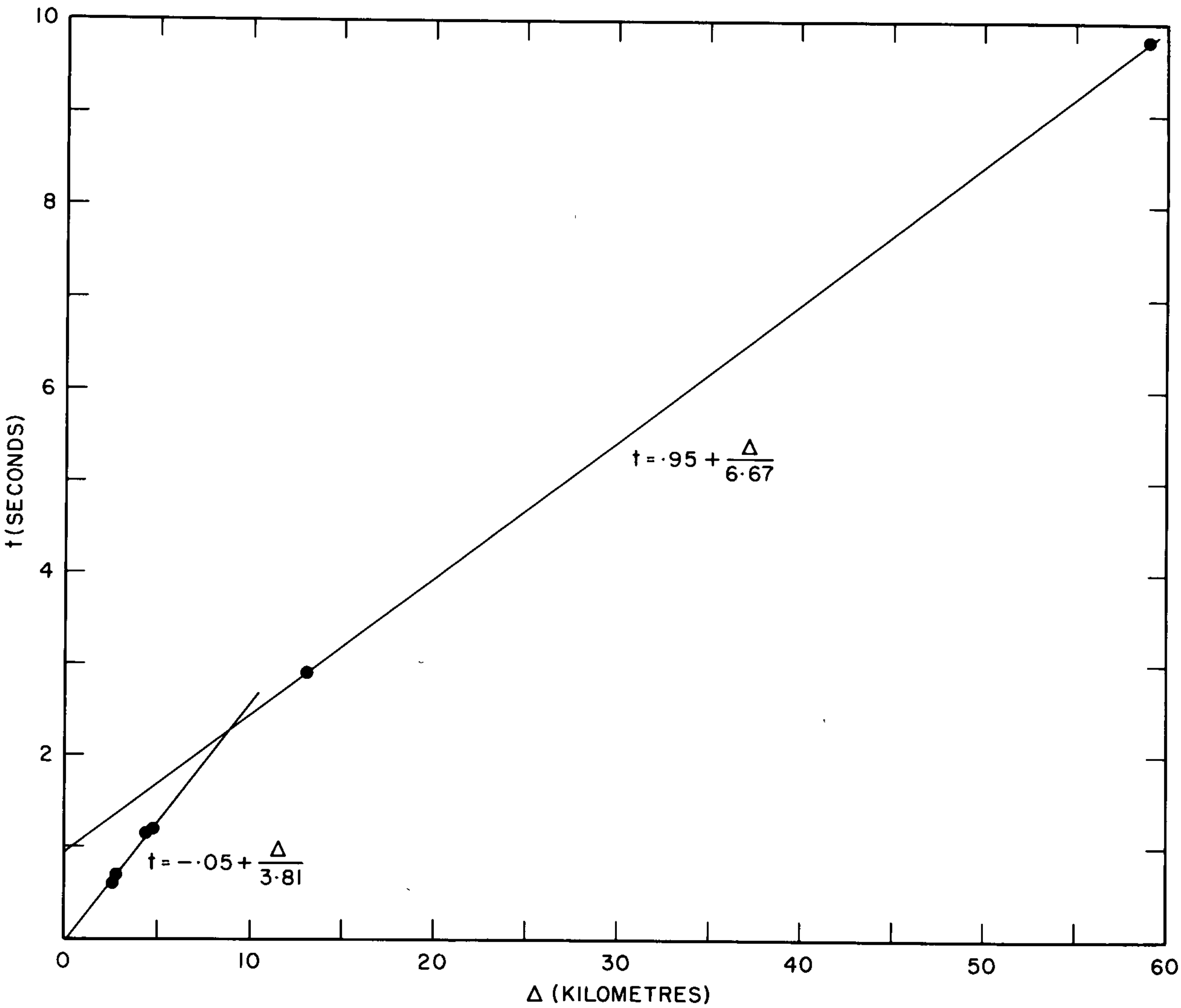
PROFILE IV EVENTS RECORDED AT KELSEY BAY (NOV.)

FIGURE 23



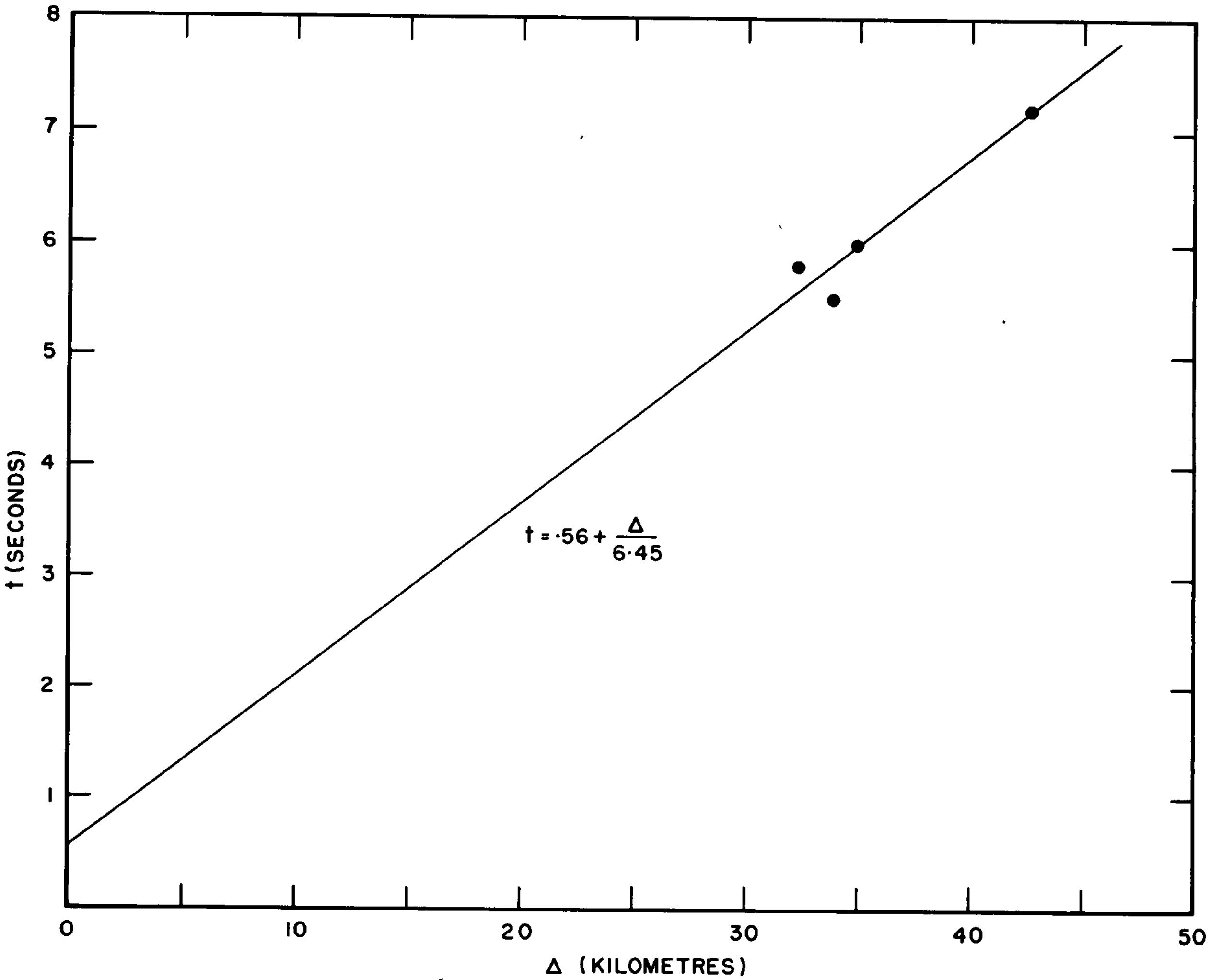
PROFILE V TIME-DISTANCE PLOT FOR ALLUVIUM AT MOUTH OF SALMON RIVER

FIGURE 24



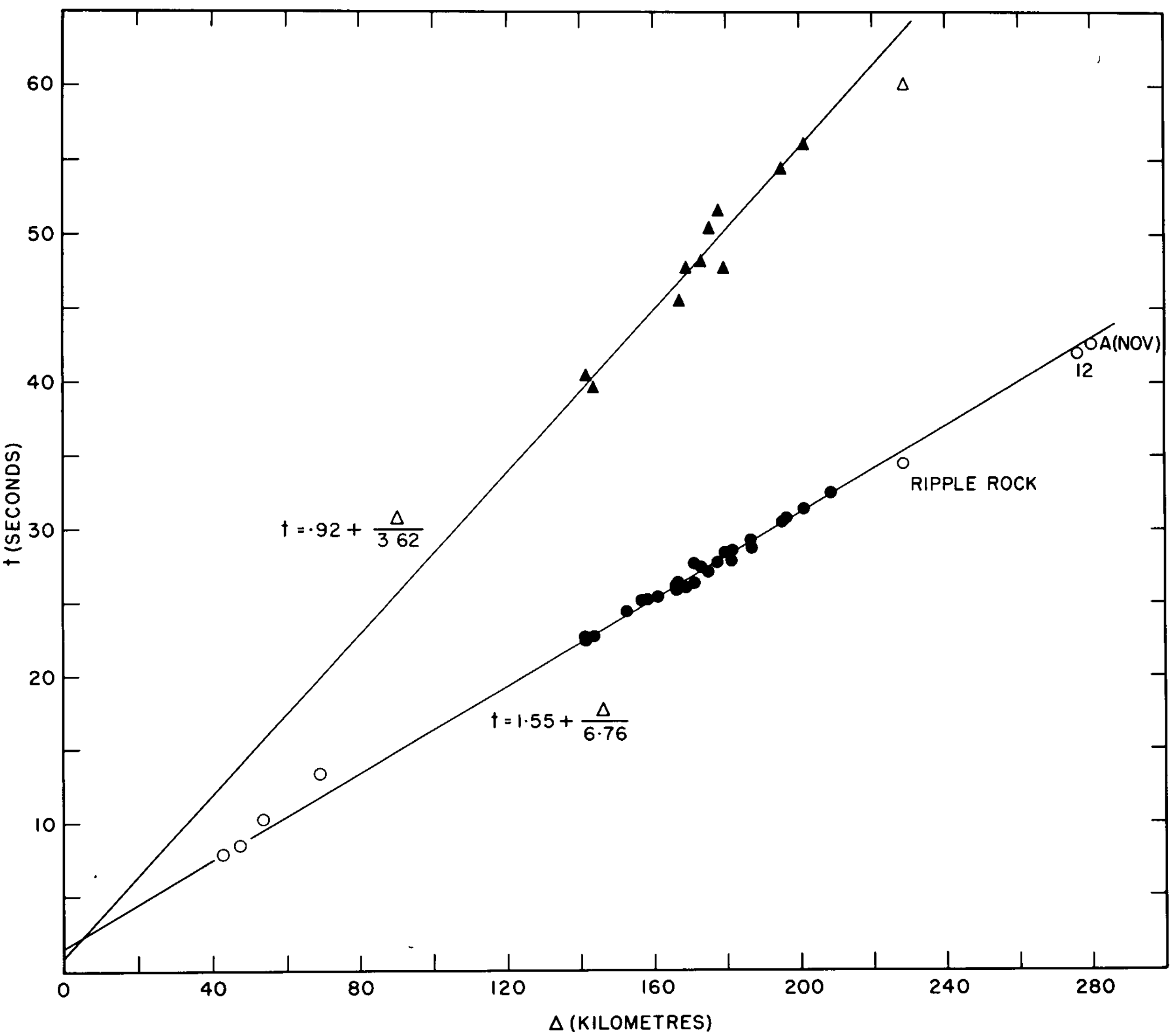
PROFILE VI EVENTS RECORDED AT HORNBY ISLAND

FIGURE 25



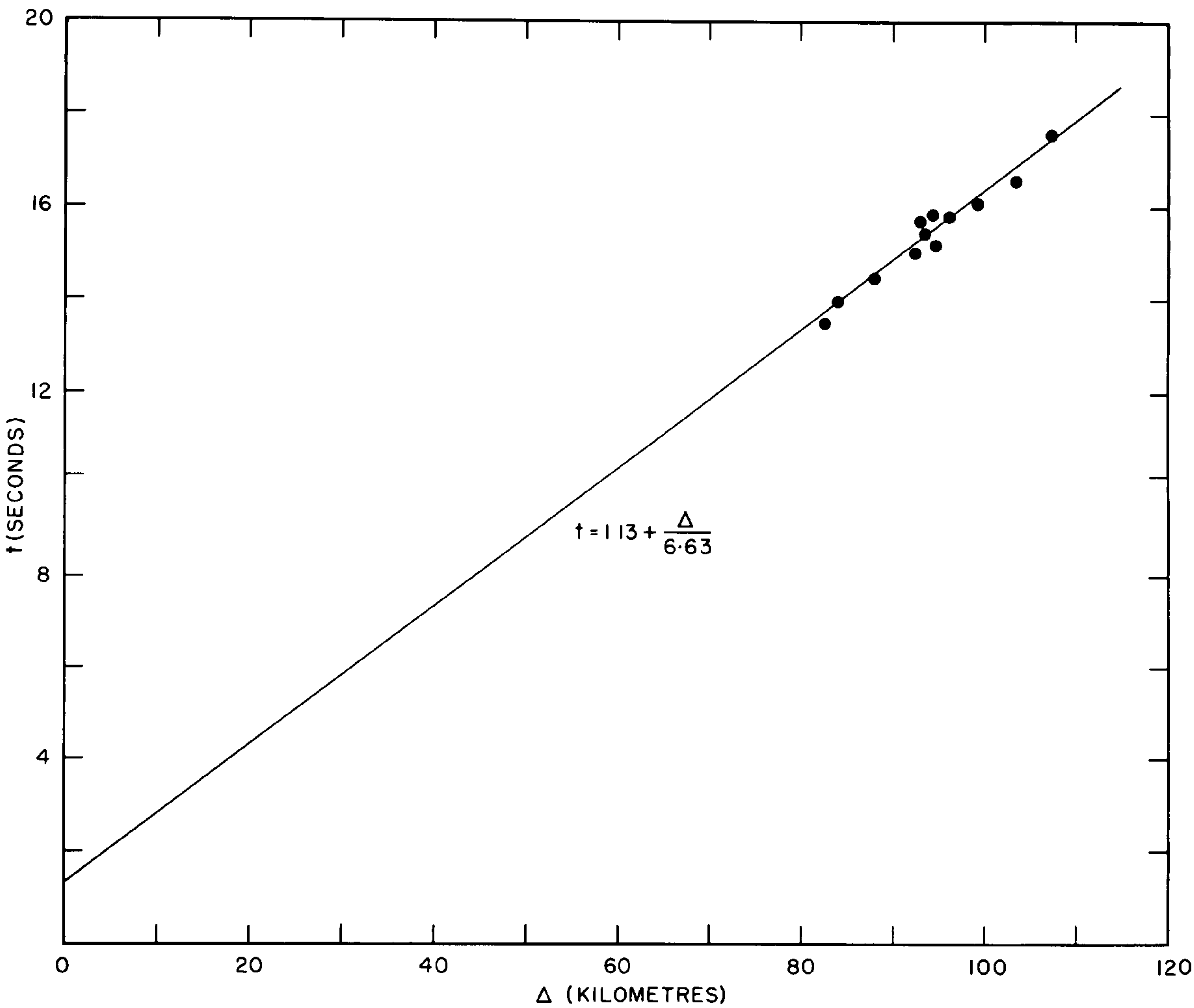
PROFILE VII EVENTS RECORDED AT SCANLON DAM

FIGURE 26



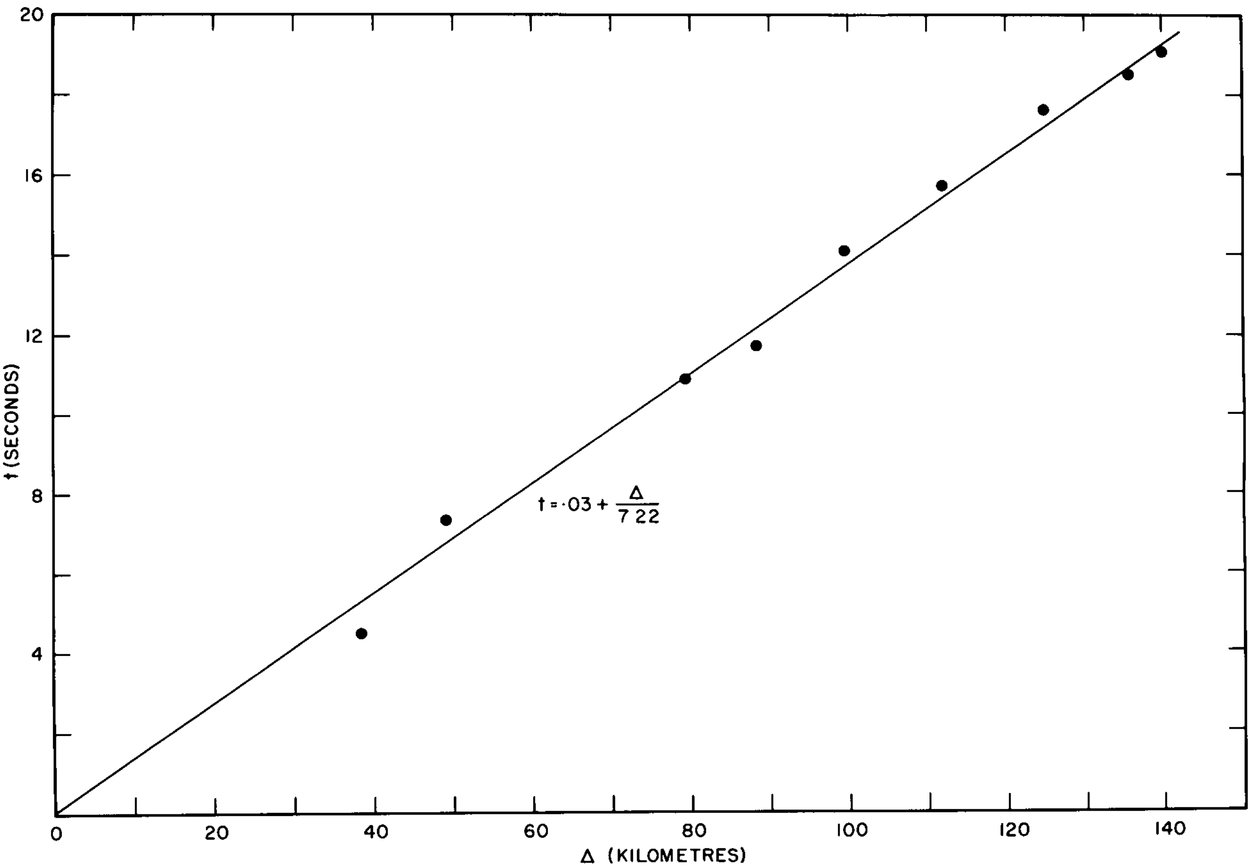
PROFILE VIII EVENTS RECORDED AT VICTORIA AND PATRICIA BAY

FIGURE 27



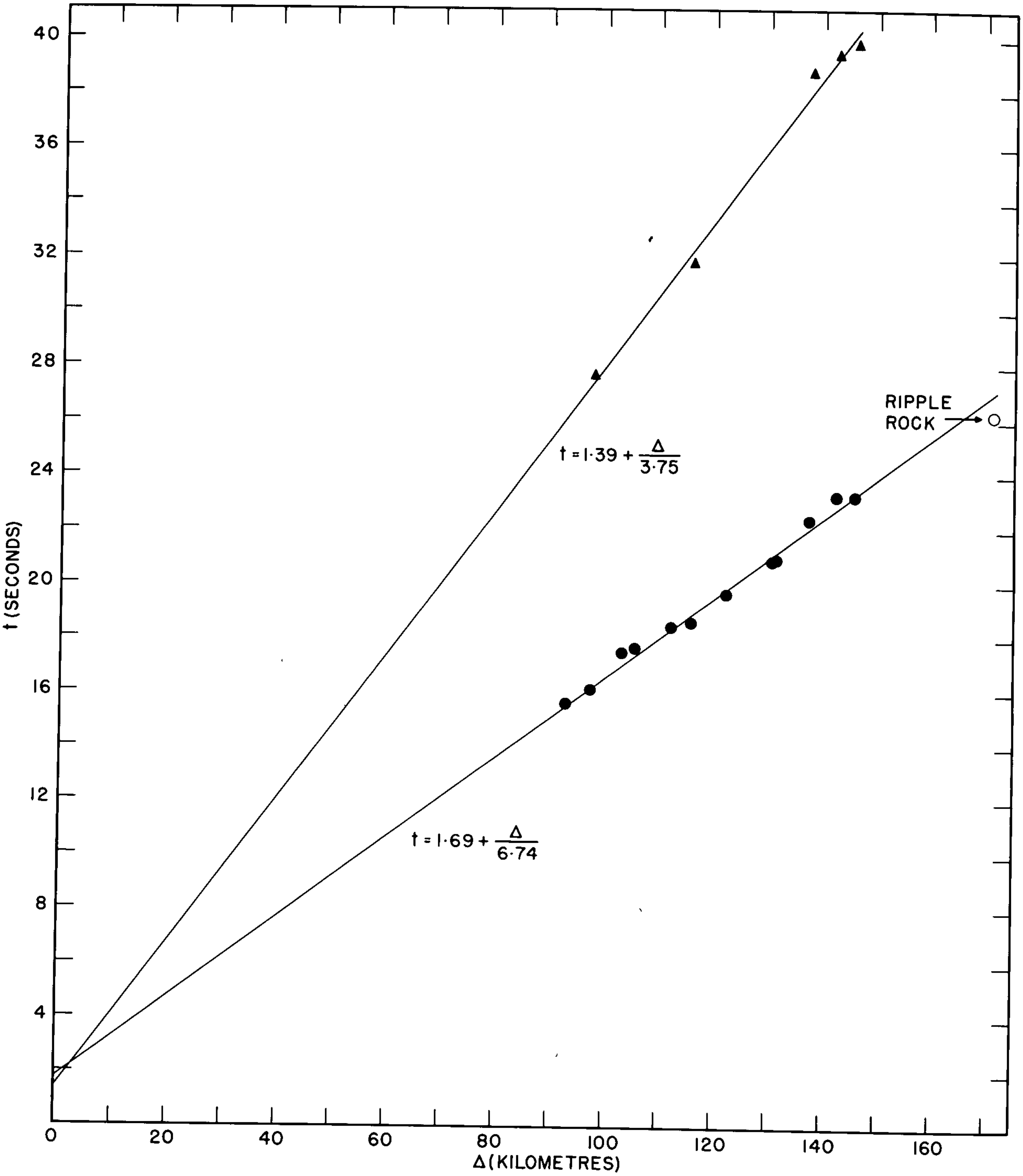
PROFILE IX EVENTS RECORDED AT UCLUELET (1) and (2)

FIGURE 28



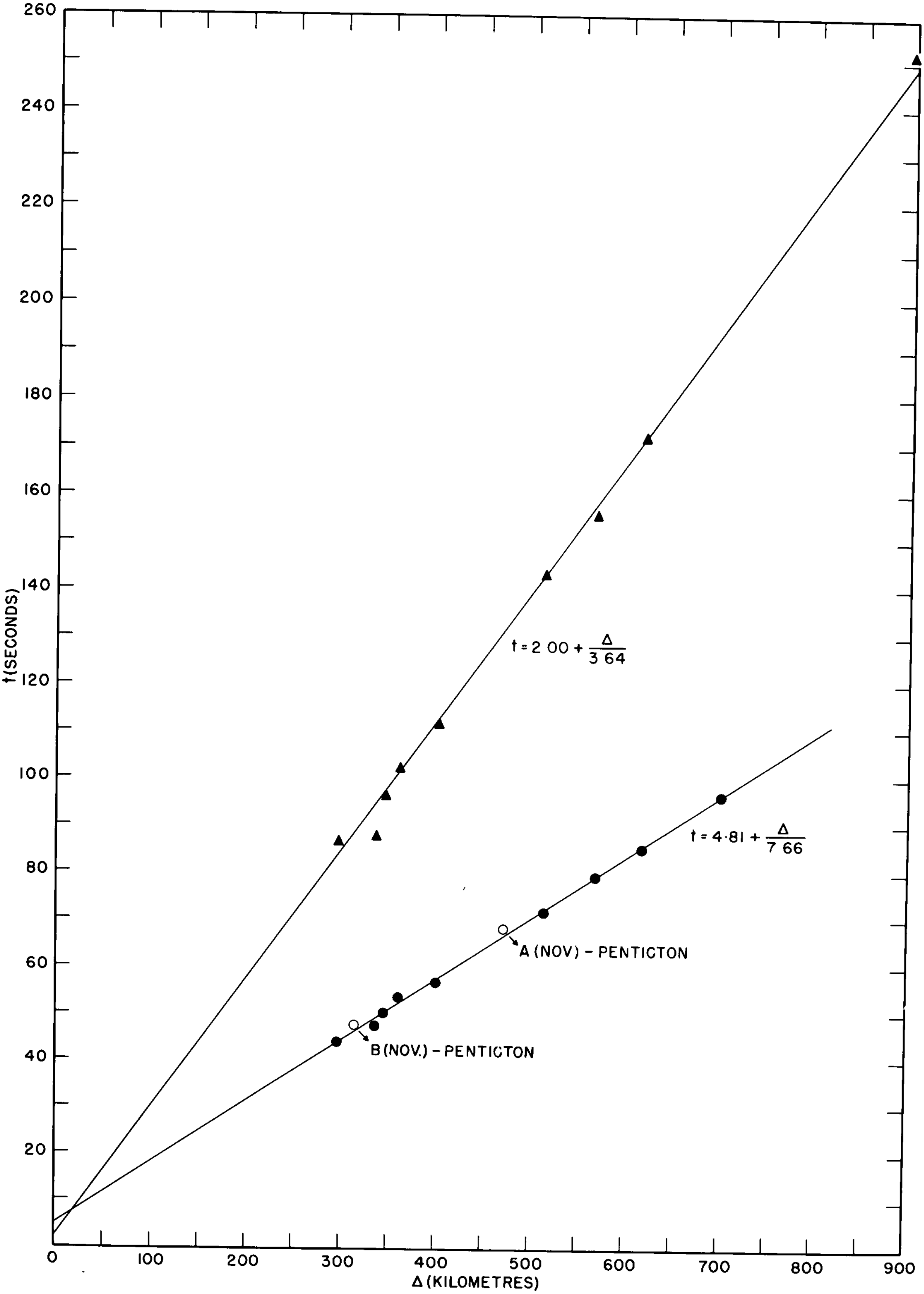
PROFILE X EVENTS RECORDED AT KELSEY BAY

FIGURE 29



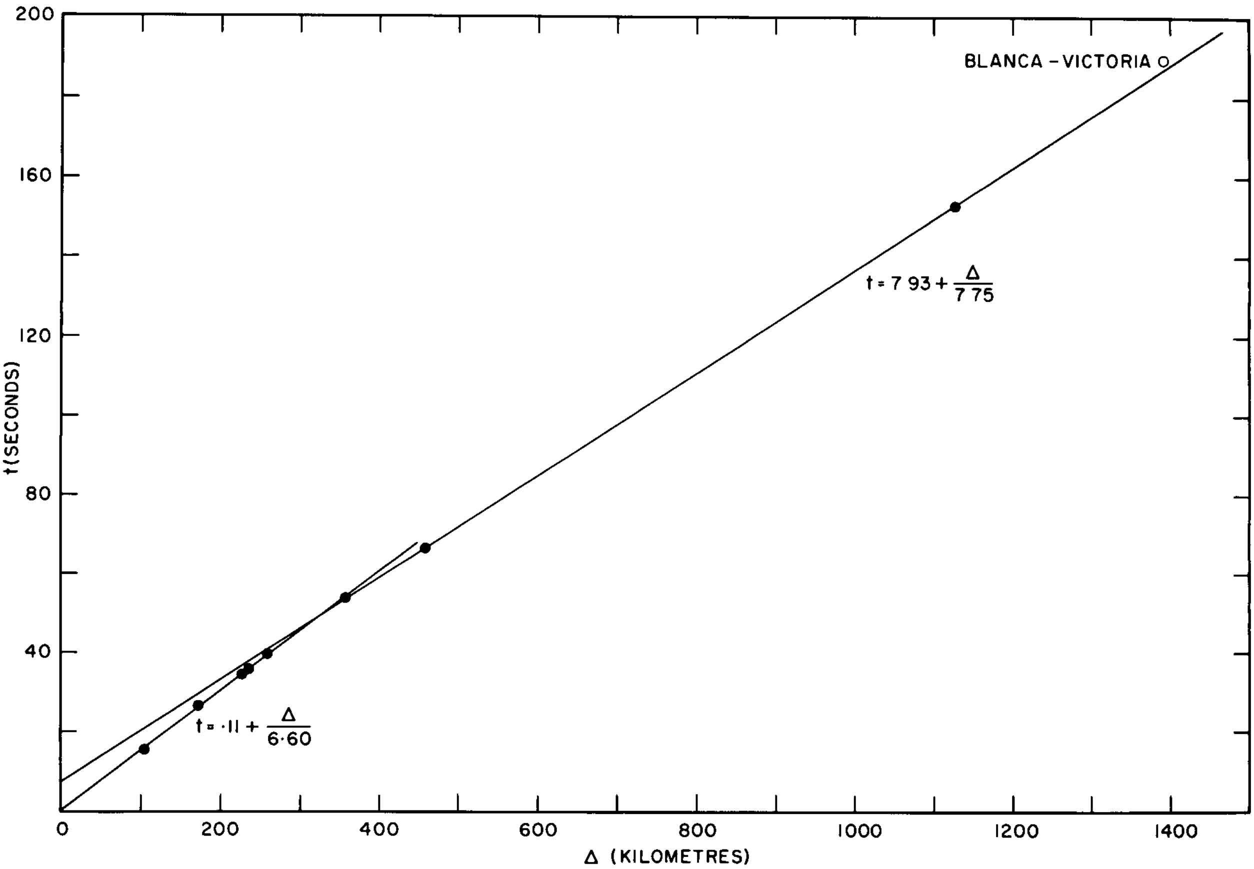
PROFILE XI EVENTS RECORDED AT HORSESHOE BAY

FIGURE 30



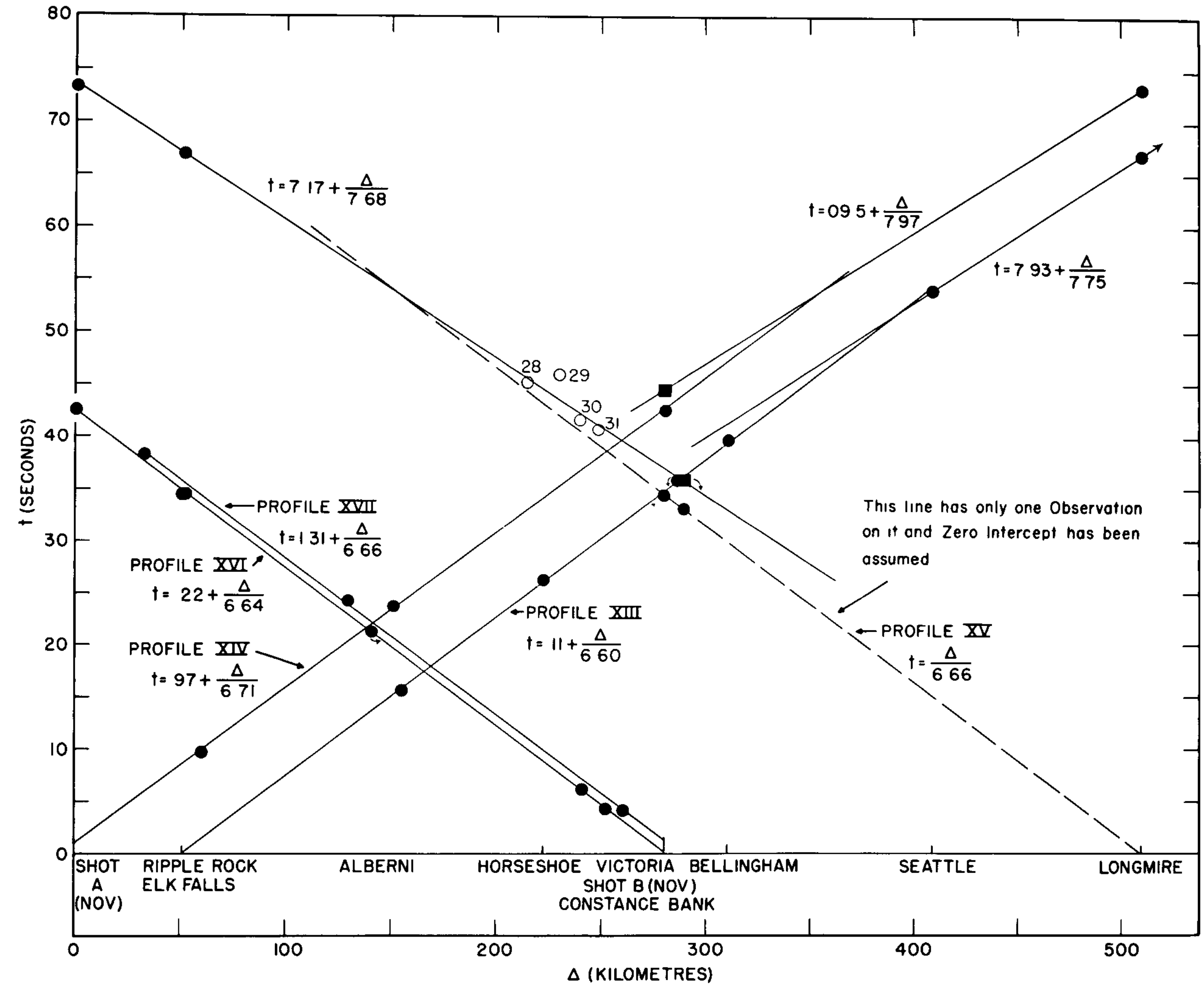
PROFILE XII RIPPLE ROCK RECORDED AT STATIONS EAST THROUGH MOUNTAINS

FIGURE 32



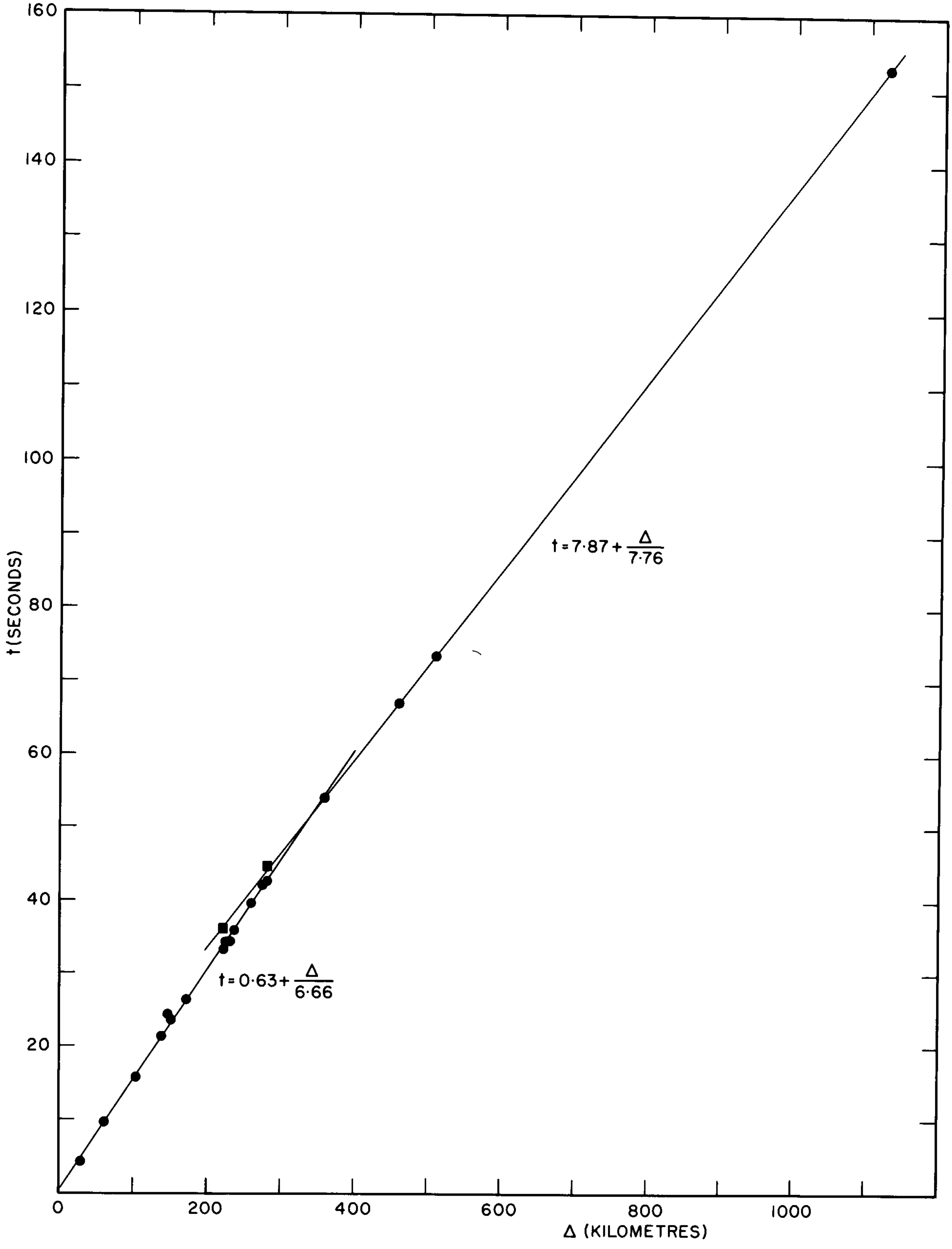
PROFILE XIII RIPPLE ROCK RECORDED AT STATIONS SOUTH-EAST ALONG THE COAST

FIGURE 33



PROFILES XIII, XIV, XV, XVI, XVII

FIGURE 34



COMPOSITE PLOT OF ALL LONG RANGE DATA

FIGURE 45

3.11 Methods of Interpretation

The existence of a refraction arrival has been treated theoretically by a number of authors. Ewing, Jardetzky and Press (1957) have shown that for an explosive source and a receiver on the lower velocity side of a discontinuity between two semi-infinite media in contact there is an arrival at a time,

$$t = \frac{r}{v_2} + (z + h)\ \frac{\cos \theta c}{v_1}$$

The parameters of this equation are illustrated in Figure 35,

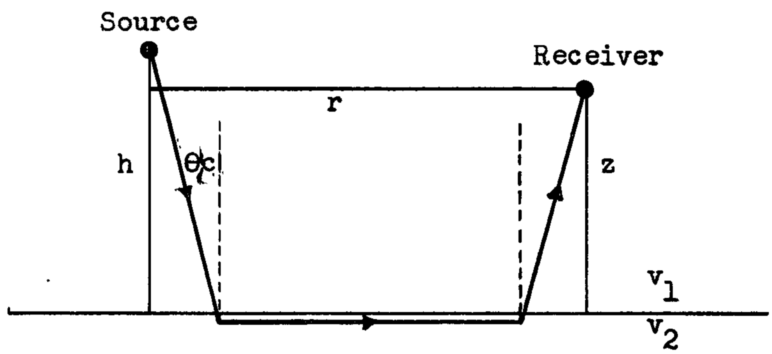


Figure 35. Refraction from an Interface between Two Semi-Infinite Media where $v_1 < v_2$.

where v_1 and v_2 are the compressional wave velocities in the two media and $v_1 < v_2$, and where θc is the critical angle such that $\sin \theta c = \frac{v_1}{v_2}$. This is the expected time of arrival for a wave propagated over the path shown by the broken line.

This result has been obtained for the case of two liquids in contact. The theory of refracted arrivals has also been developed by these authors for the case of two solid media in contact.

The interpretation of the refraction data obtained in the present investigation is based on the following geometrical considerations, where the seismic energy radiating from the explosive source is considered in terms of ray paths.

The diagram of Figure 36 represents the case of refraction from a layer of velocity v_2, underlying a layer of velocity v_1, where $v_1 < v_2$. The layers are separated by a plane interface, dipping from the horizontal at an angle ϕ. A and B are shot point and recording station, and are interchangeable. H_a and H_b are taken as the thicknesses of the layer below points A and B. θc is the critical angle defined by the relation,

$$\theta c = \sin^{-1} \frac{v_1}{v_2}$$

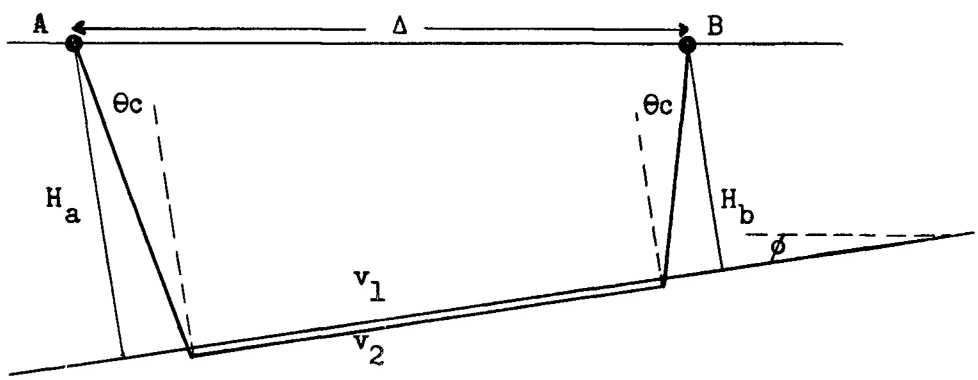


Figure 36. Refracted Rays in a Dipping Structure with Plane Interface.

The following relation gives the travel time from A to B or B to A,

$$t = \frac{(H_a + H_b) \cos \theta c}{v_1} + \frac{\Delta \cos \phi}{v_2} \qquad (3\text{-}11\text{-}1)$$

For the case of horizontal layering where $\phi = 0$ the relation reduces to

$$t = \frac{2H \cos \theta c}{v_1} + \frac{\Delta}{v_2} \qquad (3\text{-}11\text{-}2)$$

Conventional procedure is to plot the observed data and obtain by a least squares analysis an equation relating t and Δ in the same form as 3-11-2:

$$t = T_o + \frac{\Delta}{v_2}$$

for the direct and refracted arrivals, v_2 being the inverse of the slope of the line obtained for refracted arrivals.

Thus from the value of T_o obtained from the observational data, together with the velocities v_1 and v_2, the depth of the layer is determined.

The following relation may also be shown to hold

$$H = \frac{\Delta_{12}}{2}\left[\frac{v_2 - v_1}{v_2 + v_1}\right]^{\frac{1}{2}} \qquad (3\text{-}11\text{-}3)$$

where Δ_{12} is the distance at which the direct and refracted arrivals arrive at the same time.

For the general case of a structure with m - 1 layers it may be shown that

$$t_m = 2 \sum_{n=1}^{m-1} H_n \frac{\cos \theta c_{nm}}{\Delta_n} + \frac{\Delta}{v_m} \qquad (3\text{-}11\text{-}4)$$

where t_m is the travel time of the ray refracted in the m^{th} layer; H_n is the thickness of the n^{th} layer, θ_{nm} is the critical angle, such that,

$$\sin \theta_{nm} = \frac{v_n}{v_m}$$

v_n, v_m are the velocities in the n^{th} and m^{th} layers respectively.

This follows directly if the geometry of Figure 37 is considered, and it is shown that $\theta_n = \theta c_{nm}$.

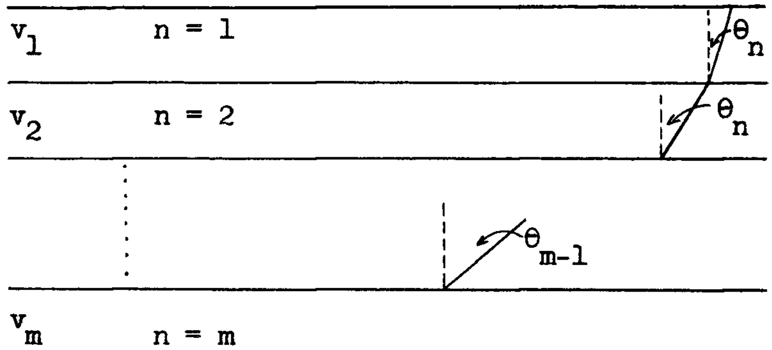


Figure 37. Geometry of Refracted Ray in Multi-Layered Structure.

The first arrival data for the multi-layered case may be expected to define m segments of the travel time curve. This assumption will hold only for the cases where an appropriate relation exists between the thicknesses and velocities of the layers; e.g., in a case where m = 2, first arrivals of energy refracted in the second layer will only be observed when the thickness of this layer exceeds a certain value. Leet (1938) has shown the criterion (after Maillet and Bazerque) for determining the minimum thickness for refracted first arrivals from an intermediate layer. A quantity Y is formed,

$$Y = \frac{\cos \theta_{12} - \cos \theta_{13} + \sin(\theta_{12} - \theta_{13})}{\sin \theta_{12} \cos \theta_{23} (1 - \sin \theta_{12})}$$

where $\sin \theta_{13} = \sin \theta_{12} \sin \theta_{23}$.

Then the line for v_2 passes above the point Δ_{13}, t_{13} if $\frac{h_2}{h_1} < Y$.

The geometrical relationships have been derived for the case of dipping interfaces (Leet - pages 138, 139), and these will be cited in interpreting the observed data.

3.12 Interpretation and Discussion of the Refraction Data

The Strait of Georgia is underlain by sediments of Cretaceous age throughout most of the area where explosions have been located. These sediments consist mainly of sandstones, shales and loosely cemented conglomerate. The formation outcrops on Vancouver Island and on the adjacent islands in the Strait of Georgia. Small patches of the outcrop are also found on Lasqueti and Texada Islands.

Hornby Island was the only recording station located on the Cretaceous formation. The other stations in the Vancouver Island area were located on outcrops of granitic or volcanic rock, with the exception of Kelsey Bay (Nov.)

This station was located on the alluvium at the mouth of the Salmon River. The shot points A (Nov.), B (Nov.), 1 to 5 (Nov.), Ripple Rock and Constance Bank were also located on volcanic or granitic type formations.

Short range refraction surveys indicate the average velocity of compressional waves for the Cretaceous formation to be 4.05 km/sec. Velocities of 5.4 to 6.0 km/sec. have been found for the more competent volcanic and granitic formations (Milne and White, 1960).

Figure 38 shows the form of model which represents the results of the refraction data, along a line from Kelsey Bay to Victoria.

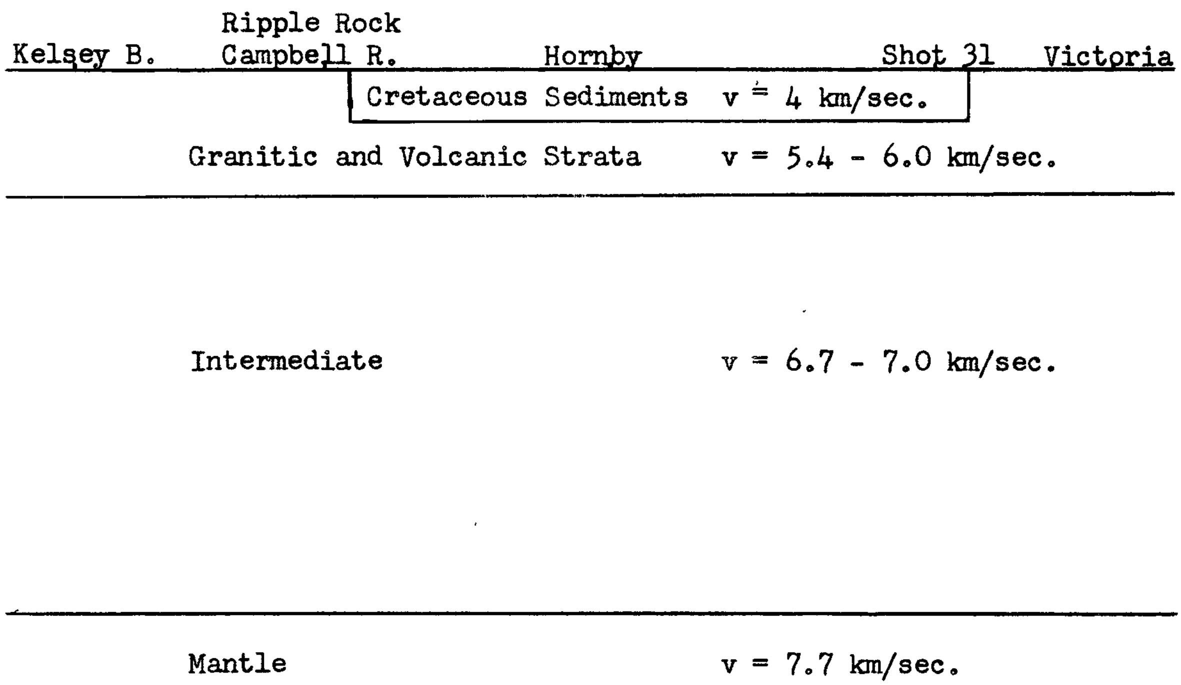


Figure 38. Form of Model Representing Structure from Kelsey Bay to Victoria.

Reference to Table 8 (page 39) indicates that most of the refraction arrivals are from the intermediate layer with apparent velocities varying from 6.6 to 7.0 km/sec., except for two extreme values of 6.5 and 7.2 km/sec.

for profiles VII and X. The data for the shorter ranges which give the structure of the Cretaceous and volcanic layers are rather sparse. Data for which P_n is a first arrival have been obtained by extending the line of observations into the coastal area of the State of Washington and Northern California.

3.12.1 Results for the Strait of Georgia Area:

Profile VI is an unreversed profile for which the recording station (Hornby Island) and the six shot points are located on the Cretaceous formation. The thickness of the Cretaceous structure, found from the data of Figure 25 by the relation expressed in equation (3-11-3), is 2.33 ± .43 km. The uncertainty has been found by placing reasonable limits on the accuracy of travel time measurements for shots 15 and 19 and using the probable errors of the low velocity segment of the travel time curve derived from least squares. On the basis of the few data obtained, there is no evidence for first arrival energy from a layer with a velocity near 6 km/sec. The lack of evidence may be due to the absence of events at the appropriate range of distances, or it may be due to the fact that the second layer is not sufficiently thick to give rise to first arrivals. If we assume the following numerical values,

$$v_1 = 3.81 \text{ km/sec.}$$
$$v_2 = 6.00 \text{ km/sec.}$$
$$v_3 = 6.70 \text{ km/sec.}$$

and refer to Leet's curve to obtain a value for Y, we obtain a minimum ratio for h_2:h_1 of about 0.3.

If a segment representing the 6 km/sec. layer is proposed which would give the greatest thickness of the layer, with first arrivals starting at Δ_{12} = 7.16 km. and ending at Δ_{23} = 13.09 km. we obtain the results

$$H_1 = 1.69 \text{ km.}$$
$$H_2 = 1.06 \text{ km.}$$

The total thickness of the two layers is 2.75 km. as compared with 2.33 km. obtained by assuming a single layer case. It appears that further observations in the range below 13.09 km. could reveal the presence of a 6 km/sec. layer. The maximum thickness of this layer is 1.06 km. The alternative structures for the area of profile VI are shown in Figure 39.

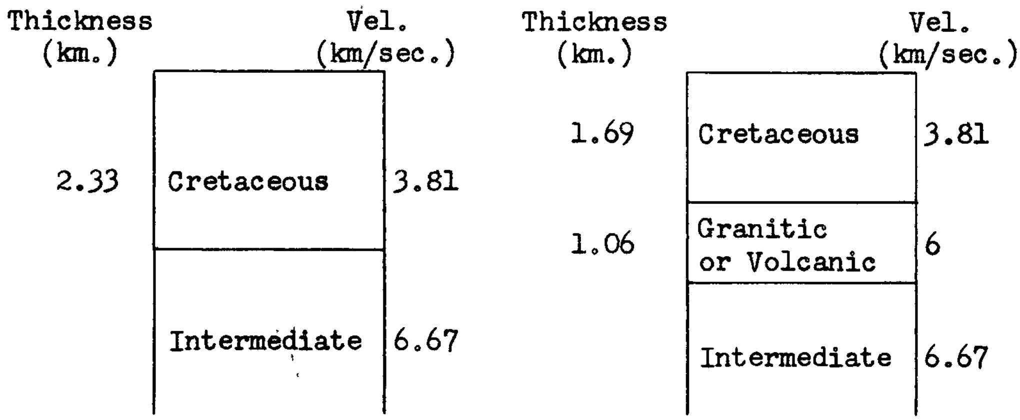


Figure 39. Alternative Structure of Upper Crustal Layers for Profile VI.

The only direct evidence for a 6 km/sec. basement layer overlying the 6.8 km/sec. material is shown by profile I. the plot for event 6 (Nov.) falls below the velocity curve $1.10 + \frac{\Delta}{6.94}$. The calculated travel time for the direct ray, propagated near the surface, first in the Cretaceous sediments and then in the volcanic strata near Elk Falls, is 3.10 sec. The propagation path includes 10.41 km. of Cretaceous and 2.00 km. of volcanics. The observed travel time is somewhat less (2.32 sec.). It is thus indicated that the plot for 6 (Nov.) is on a velocity line characteristic of the higher velocity volcanic rock. Unfortunately a shot planned for the interval between 6 (Nov.) and 7 (Nov.) had to be cancelled.

The discontinuity between the time-distance segments for profile I between events P and F is indicative of a fault structure with the vertical displacement being up on the side represented by shot P. The same effect may be the result of a rapid increase in the thickness of the Cretaceous strata along the profile between these two events. In either case the displacement of about 0.3 sec. in the time-distance curve requires a change of path length of the seismic energy in the Cretaceous strata of about 1 km.

The variation in travel time for shots C and R is in excess of the expected errors of measurement and probably indicates thicker deposits of Cretaceous or lower velocity materials under these events.

The apparent velocities obtained for the two segments of this profile agree, within the uncertainties as shown in Table 8.

The same series of shots, as far along profile I as shot P has been plotted for Alberni in Figure 21. The data for Ripple Rock and some other explosions are also included. The apparent velocity obtained is 6.85 km/sec. Profile II forms an approximate reversal to profile I.

The calculation of the angle of dip of interfaces which would give rise to the apparent velocities of profiles I and II is somewhat complicated by the fact that two layers may be overlying the intermediate velocity layer. The geometry and related formulas for a three-layer case, where the two interfaces are dipping in opposite directions, are given by Leet (1938). The ambiguity in the interpretation of the data presented here is that no apparent velocity has been obtained for a layer between the low velocity Cretaceous sediments and the layer having velocity near 7 km/sec. If a constant thickness of Cretaceous sediments underlying the area of the explosions used for profile II and the shorter range segment of profile I is assumed, an angle of dip may be computed for the interface between a 6 km/sec. layer and the 6.9 km/sec. layer.

We have that

$$\sin(\theta_{12} + \phi_2) = \frac{v_1}{v_{2-}} \text{ and } \sin(\theta_{12} - \phi_2) = \frac{v_1}{v_{2+}}$$

where $v_1 = 6$ km/sec.

$v_{2-} = 6.85$ km/sec.

$v_{2+} = 6.94$ km/sec.

where $\theta_{12} = \sin^{-1}\frac{v_1}{v_2}$ and ϕ_2 = angle of dip.

The angle of dip obtained is 42 minutes toward the Elk Falls end of the spread of shots. The real velocity v_2 is found to be 6.90 km/sec.

If profile VIII for the data obtained at Victoria is used as a reversal of profile I, the dip is 1 degree 19 minutes and a real velocity of 6.86 km/sec. is obtained. These results are subject to the uncertainties associated with the apparent velocities obtained for the profiles.

3.12.2 Results for the Kelsey Bay and Johnstone Strait Areas:

The data for the area near Kelsey Bay and east in Johnstone Strait are presented in Figures 23 and 24 for profile IV and V. From a consideration of profile IV, a calculated thickness for the alluvium and volcanic strata may be obtained. The equations for the three segments are:

$$t_1 = \frac{\Delta}{1.58}$$

$$t_2 = 0.10 + \frac{\Delta}{5.41}$$

$$t_3 = 0.60 + \frac{\Delta}{6.70}$$

The average thicknesses obtained are 0.08 km. (280 ft.) of alluvium and 1.5 km. of volcanic strata. The thickness of the alluvium may be greater under the recording station since rather high velocity tidal currents occur in the area of the shot points. That this is the case is indicated in that for the data of profile V, no break is observed in the arrival times within a distance of 0.6 km. The data for this profile were obtained for a short range refraction measurement on the alluvium at the site of the recording truck.

If shot A is plotted on profile IV (Δ = 6.70 km.), it is late by 0.23 sec. This indicates a variation in the thickness of river deposited silt of about 0.4 km. (1320 ft.) if a velocity of 1.58 km/sec. is used. An error in position for shot A could also account for the late arrival at the Kelsey Bay recorder. In any case it is to be noted that the origin time and location for shot A are well controlled for use on the longer range profiles.

An examination of the time-distance plots for profiles II and III reveals a change in structure between the Ripple Rock - Campbell River area and the Kelsey Bay - Johnstone Strait area. The arrivals of shots A (Nov.) and 1 (Nov.) to 5 (Nov.), shown in the upper right hand corner of Figure 21, are late by about 1 sec. relative to the velocity line fitting the other data at shorter ranges. This requires a somewhat greater depth to the upper boundary of the intermediate layer than that obtained from the results of profile IV. The existence of a layer of 5.6 km/sec. strata about 10 km. in thickness in the Kelsey Bay area would explain the delay of the arrivals for profile II. Direct arrivals (propagated in the 5.6 km/sec. strata) at Elk Falls from the same group of shots, however, would be later for such a structure than the observations shown in Figure 22 would indicate. An increase in the velocity of the upper layer to about 6 km/sec. and an increase in the thickness of the layer at Kelsey Bay could explain the results from both profiles II and III. The proposed structure is shown in Figure 40 (page 66).

A low velocity plug in the Kelsey Bay - Alberni path of propagation but not in the Kelsey Bay - Elk Falls path would also introduce the observed effect. The early arrivals on profile III would then be due to the absence of the Cretaceous formation in the Kelsey Bay area.

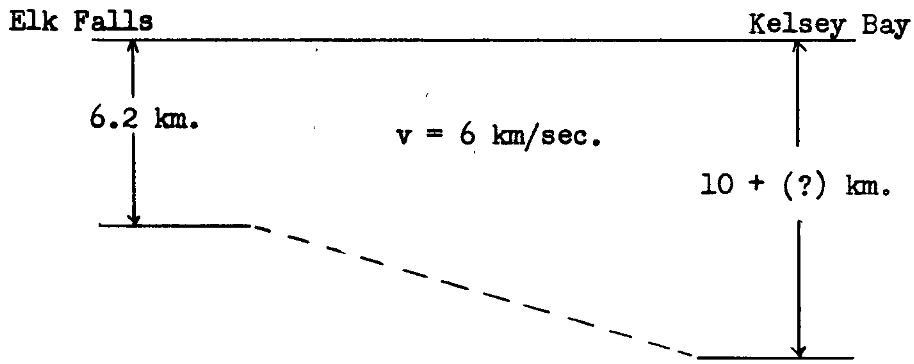


Figure 40. Proposed Structure for Elk Falls - Kelsey Bay Area.

Profile X for shots recorded at Kelsey Bay during the 1960 program do not contribute to a definition of the structure in the Kelsey Bay area since the time-intercept is not known with any degree of precision and most of the events recorded are south of Campbell River. The high apparent velocity obtained may be attributed to a small drift rate for the chronometer as the program proceeded. A drift of 0.2 sec. in the four hours during which the program was in progress would raise the apparent velocity from 7.0 km/sec. to the observed value (7.2 km/sec.).

3.12.3 Estimated thickness of granitic and volcanic strata:

The least squares equations obtained for profiles VII, VIII, IX, X and XI tend to strengthen the evidence for the intermediate layer with a relatively thin layer of surficial strata above it. If the second structure for profile VI is assumed and used as a starting point, the thickness of the strata above the intermediate layer may be computed for the various other profiles. This has been done for profiles I, II, VIII and XI. The velocity in the surficial layer at Alberni and Elk Falls - Campbell River has been taken as 5.6 km/sec., an average velocity for volcanic strata as obtained by Milne and White (1960). The velocity at Victoria and Horseshoe Bay has been taken as 6.0 km/sec. where the surface bedrock is granitic in character. In making these calculations, the angle of dip has been neglected. The resulting structure at each station is shown in Figure 41.

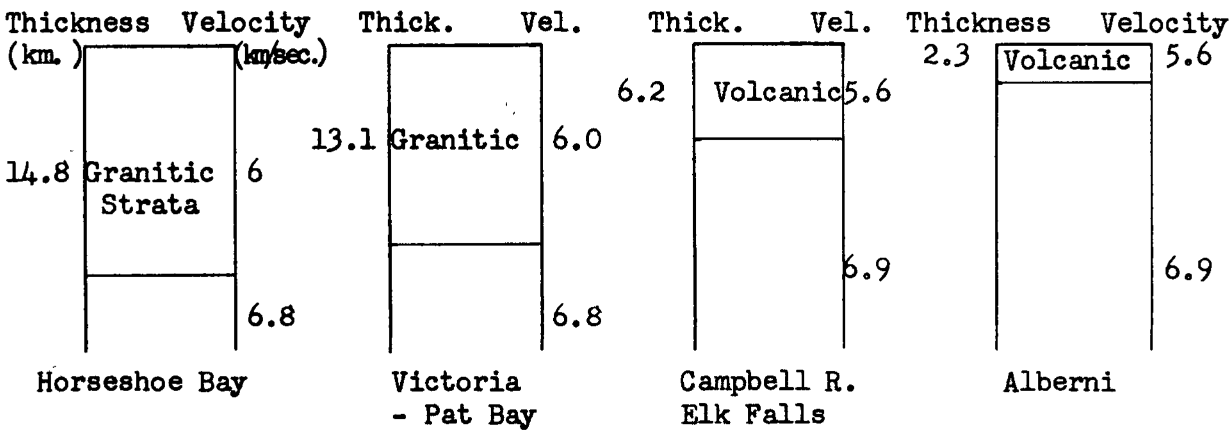


Figure 41. Estimated Thicknesses of Volcanic or Granitic Layer.

It must be pointed out that the thicknesses of these surficial strata depend on the velocities chosen for them and also on the structural column obtained for profile VI for the shot point area. The latter is based on a small number of observations. An increase in thickness of the surficial layers in the shot point area of the Strait of Georgia would result in a decrease in the computed thicknesses of the strata above the intermediate layer for the structures in Figure 41.

It has been assumed that the velocity across the spread of shots is also the velocity between the spread of shots and the recording stations. That this is a good approximation is shown by the velocities obtained for the longer range profiles.

3.12.4 Results of the longer range data:

These data are plotted in Figures 32, 33 and 34. The interpretation is based mainly on first arrival P phases. Two well-defined secondary phases (designated by solid squares on the time-distance plots) are used. The events designated by open circles are not included in the least squares analysis.

The least squares equation for the first segment of the data for profile XIII along the coast south-east from the Ripple Rock explosion indicates a velocity of 6.60 km/sec. with a small intercept. This is in agreement with the velocities obtained for the shorter range profiles. This lower velocity line represents the arrivals to a distance of 340 km. The higher velocity segment of this profile is based on the data from three recording stations: Seattle, Longmire and Mineral. The velocity of 7.75 km/sec. obtained is considerably lower than the value 8 km/sec. commonly found for the upper mantle. No records of the explosion are available in the distance interval between Longmire and Mineral. The first detectable arrival of energy for the Mineral record does not indicate refraction from a higher velocity layer. The arrival read is well defined and time control is good. It is of course possible that an earlier weak arrival is not detected. The seismogram for this reading is shown in Figure 17.

The structure determined from this unreversed profile is shown in Figure 42 (page 69). The thin layer inferred by the small intercept has been omitted.

The five profiles of Figure 34 display all of the longer range data along the coast for explosions A (Nov.), B (Nov.), Ripple Rock and Constance Bank. Four smaller explosions (28 to 31) as recorded at Longmire are also included. Two reversed profiles are obtained by treating the data as explained in 3.10. Profiles XIV and XV represent a reversal for the area between shot A (Nov.) and Longmire. These may be compared with profile XIII which is for essentially the same area, except that it is extended to Mineral and the north-west end of the profile is displaced from the location of shot A, a distance of about 50 km. to the Ripple Rock location. Profiles XVI and XVII form reversals for both XIII and XIV from Victoria and shot B. The arrivals shown for profiles XVI and XVII do not appear to indicate a transition to a higher velocity segment in the distance represented (280 km.) This result is not inconsistent with the three other longer range profiles for which the cross-over distance is at approximately 350 km.

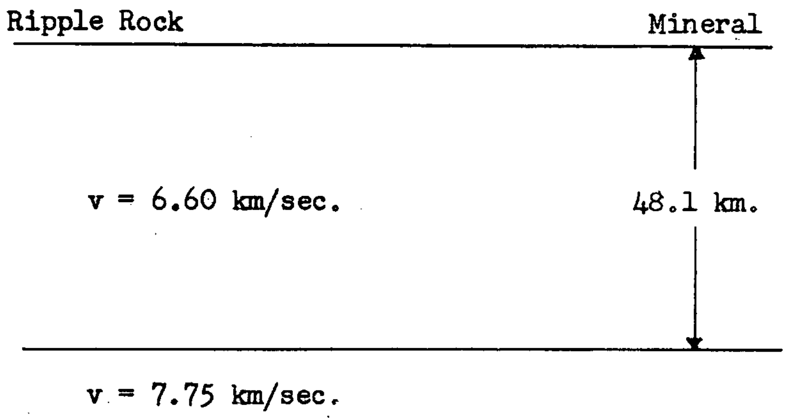


Figure 42. Crustal Structure Determined from Data for Profile XIII.

The data represented by the open circle plots for events 28 to 31 were not used in the least squares solution for profile XV. The events are for arrivals read at Longmire. The lateness of their arrival with respect to the low velocity segment may be the result of the low velocity sediments underlying the area of these explosions. The apparent velocity represented is an indication that the arrivals read are possibly secondary ones, and are associated with the higher velocity segment. Including these arrivals in the least squares would lower the velocity (7.68 km/sec.) slightly.

The arrival time for the underground nuclear explosion Blanca, at the

Nevada Test Site, as recorded at Victoria (Δ = 1390 km.) is shown on profile XIII. It is late by approximately 3 seconds relative to the velocity line $t = 7.93 + \frac{\Delta}{7.75}$. It is possible that the first arrival of seismic energy has not been detected. In this regard Romney (1959) has observed that P_n decreased to very small amplitudes at distances beyond about 1000 km. and is not often detected as the first arrival, a later phase being picked. An examination of Romney's published seismograms indicates that the P_n arrival is missing at a distance of about 1200 km. and is again present at about 1400 km. The distance from Ripple Rock to Mineral is 1127 km. and from Blanca to Victoria is 1390 km.

The crustal model computed for the reversed profiles XIV and XV is shown in Figure 43.

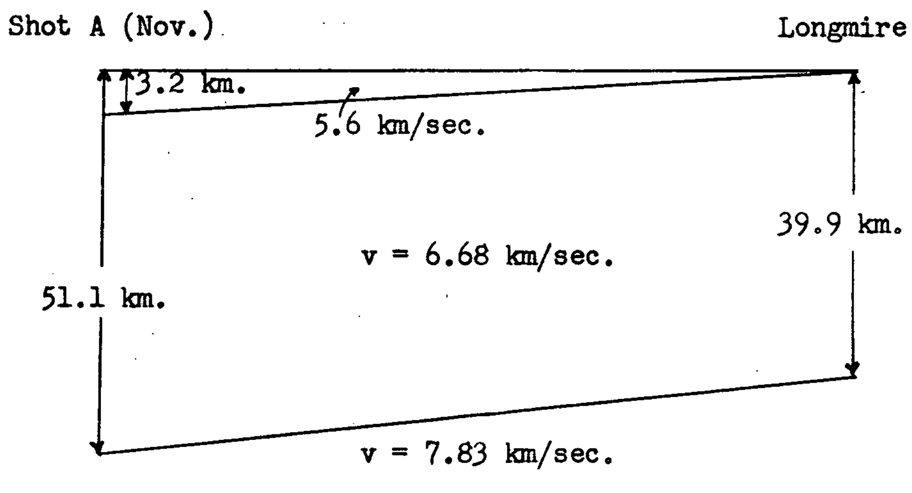


Figure 43. Crustal Structure Determined from the Reversed Profiles XIV and XV.

It is to be observed that the high velocity segment of profile XIV is based on only two observations, one of which is a secondary arrival. The velocity obtained is considerably higher than that for profile XIII. Also, the low velocity segment of Profile XV has been obtained from one observation and the assumption of zero time intercept. The form of the 5.6 km/sec. layer is subject to the validity of this assumption. The average thickness of the 6.7 km/sec. layer is consistent with the results obtained from the other profiles of Figures 42 and 44.

The dipping lower boundary of the 6.7 km/sec. layer is a result of the high apparent velocity (7.97 km/sec.) observed for profile XIV.

The crustal model computed from the results for the composite plot of long range data (Figure 45) is shown in Figure 44.

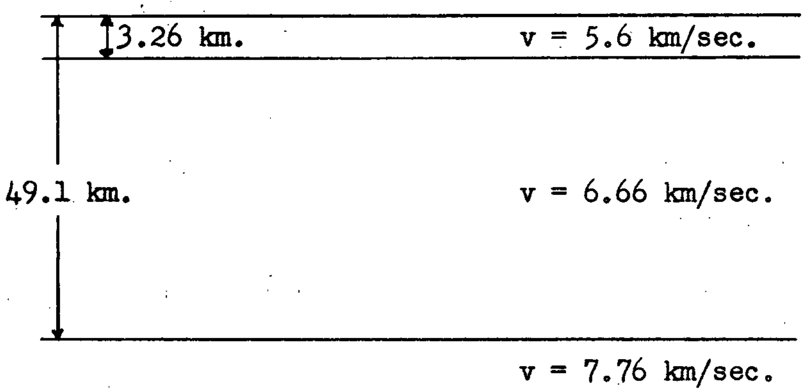


Figure 44. Crustal Structure Determined from Composite Plot of Longer Range Data.

A velocity of 5.6 km/sec. has been chosen to represent the average velocity of the thin surface layer. This is based on measurements made on basement type rocks in the Vancouver Island area.

3.12.5 Ripple Rock - east data:

The data for Ripple Rock recorded at stations east through the mountains, as plotted in Figure 32, indicate an apparent velocity of 7.66 km/sec. No observations have been obtained for distances smaller than about 300 km. There is thus no first arrival data for arrivals in the upper crustal layers. A depth of 30.6 km. to the upper interface of the layer having velocity 7.66 km/sec. is obtained if the velocity for the short range data along the coast is used. No arrivals may be interpreted as refractions from an 8.2 km/sec. layer, if the 7.66 km/sec. velocity is accepted as a real velocity. The absence of refracted arrivals from an 8.2 km/sec. layer may be due to the fact that Banff is not at a great enough distance from the explosion to make the refraction a first arrival. This infers a thickness exceeding 55 km. for the 7.66 km/sec. layer. A second possibility is that sufficient energy is not refracted through the 7.66 km/sec. layer to record as a refraction from an 8 km/sec. layer. The third and most preferred possibility is that the 7.66 km/sec. layer is the mantle.

3.12.6 Lg waves:

A later arriving phase (designated by the solid triangles on the time-distance plots) has been read in cases where it is well defined. These arrivals have been plotted for profiles II, VIII, XI and XII. The zero distance time intercept is small for each profile. Except for profile XI, the velocity is about 3.6 km/sec., even for the longer ranges represented in profile XII. The arrivals have been identified as the Lg phase which is propagated over paths of continental crustal structure. The velocity is higher than 3.5 km/sec. reported by other investigators for this wave. (Ewing, Jardetzky and Press, 1957, page 219)

4. THE GRAVITY SURVEY

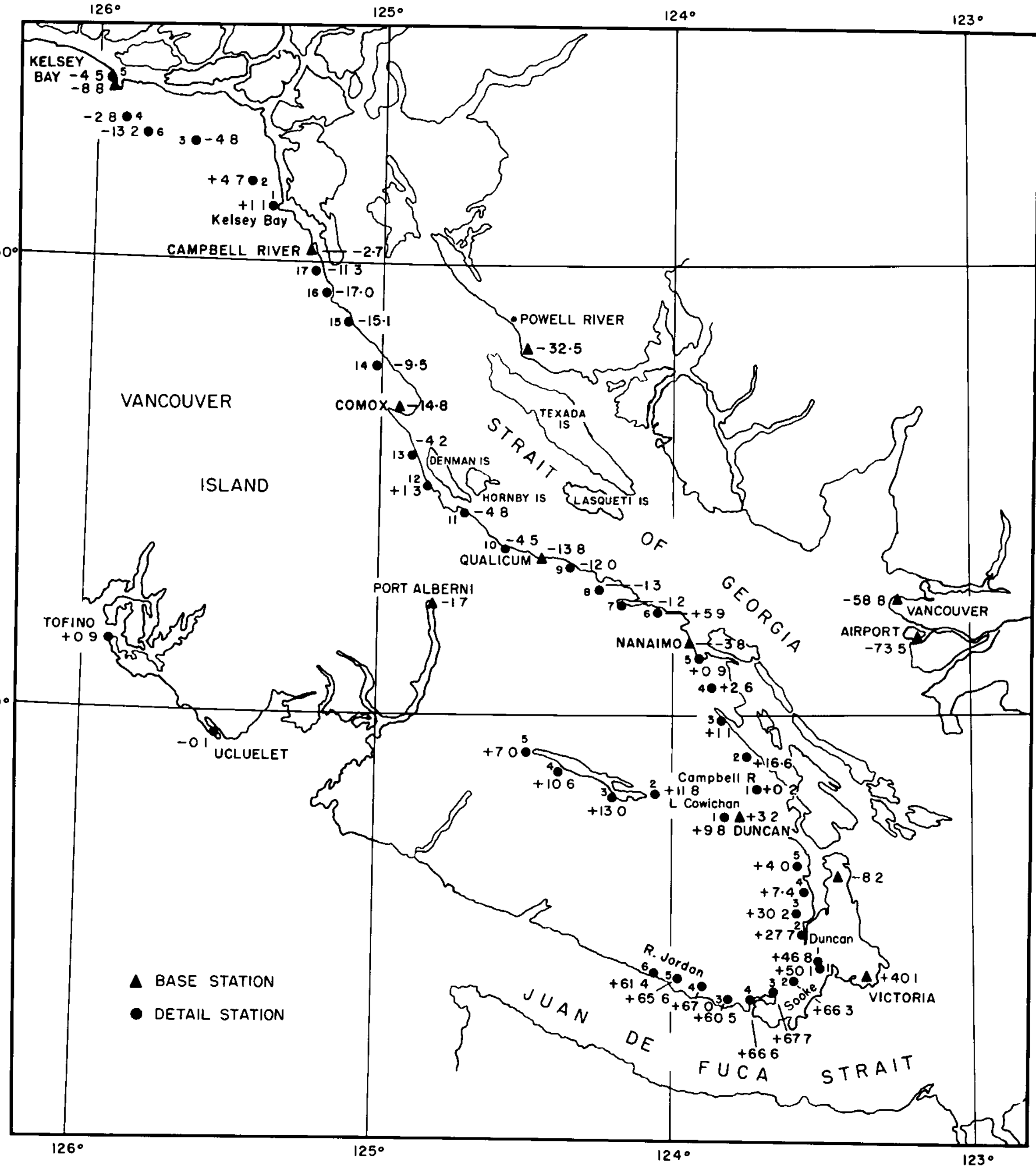
4.1 General Description of Program

The gravity survey was carried out in two parts. A network of base stations was first established at the locations shown in Figure 46. This part of the survey was carried out during the month of December 1960 by Mr. A. K. Goodacre of the Gravity Division of the Dominion Observatory. The author accompanied Mr. Goodacre for the greater part of this operation and readings were taken on two Worden gravimeters. This procedure afforded an opportunity to check the performance of the gravimeters and to arrive at a revised calibration constant for the Worden No. 35 instrument used on the subsequent part of the survey. The base station readings were referred to absolute datum by including the pendulum station at the University of British Columbia in the network.

During the month of January 1961, detailed readings at intervals of about 10 km. were obtained. These readings were taken on Vancouver Island along the highway between Victoria and Kelsey Bay. Some observations were also obtained along two east-west lines from Victoria to River Jordan and from Duncan to the west end of Cowichan Lake. In May 1961 the observations were extended from Port Alberni to Ucluelet and Tofino. These gravity stations are shown in Figure 46.

4.2 Instrumentation

The observations used in establishing the base network of stations were obtained with a Worden No. 546 gravimeter with a temperature control unit incorporated. This instrument had a calibration constant of .39881 mgal/ division. It had recently been calibrated by taking readings for a



BOUGUER ANOMALIES FOR GRAVITY STATIONS IN VANCOUVER ISLAND AREA

FIGURE 46

network of stations in Eastern Canada for which gravity values had been established. During a part of the program for the establishing of a base network, readings were also taken on the Worden No. 35. It thus seemed advisable to calibrate the Worden No. 35 against the Worden No. 546. A calibration constant of 0.416 mgal/div. was obtained for the Worden No. 35.

Elevations for almost all of the base stations were obtained from geodetic bench marks. A pair of altimeters was used to obtain elevations for most of the detail stations.

4.3 Procedures Used in the Survey

A 'base looping' procedure was followed in obtaining readings for the base network. In extending the observation of the gravity value from station A to station B, readings were taken in the order A B A B. It was then possible to construct two drift curves for the instrument and to obtain an estimate of the uncertainty of the readings. In almost all cases the uncertainty was not greater than 0.1 scale divisions. If a deviation from the mean of more than ±0.2 occurred, the loop was repeated. The distance between base stations varied from 40 to 70 km. and it was thus possible to keep the delay between readings to within about an hour. The total time for carrying out one looping operation was three to four hours. A typical drift curve for the Worden No. 35 is shown in Figure 47 (page 75). Loops were done by aircraft from the Vancouver International Airport to the Victoria International Airport, from Vancouver to Powell River, from Campbell River to Vancouver and from Vancouver to Comox. Also loops were made from the airports to stations which were part of the land based survey. It was then possible to form circuits from the data for most of the base station network. Closure errors are shown in Figure 48 (page 75) together with the reading differences between the stations of the base network.

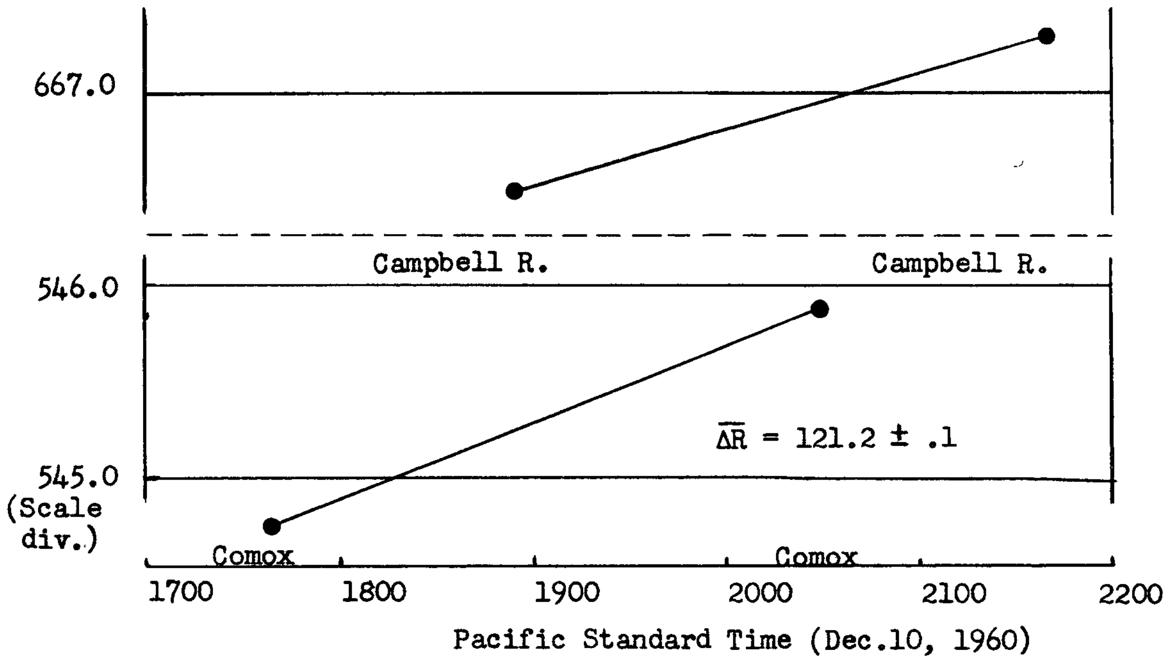


Figure 47. Typical Drift Curve for the Worden No. 35.

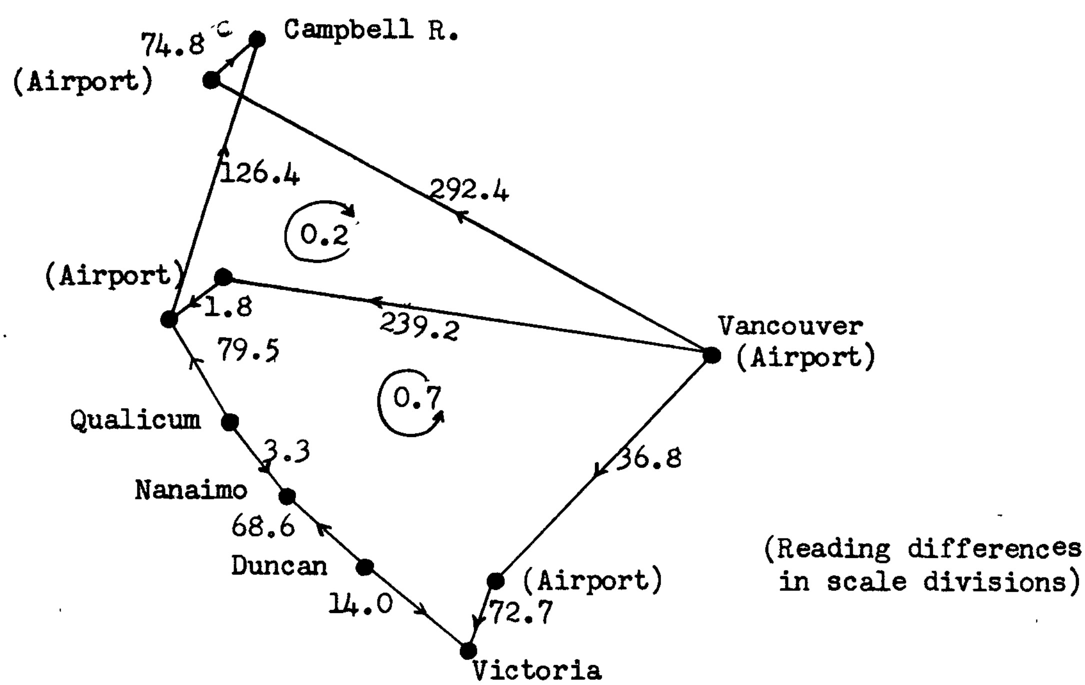


Figure 48. Closure Errors in Base Looping Circuits.

Detail readings were made with the Worden No. 35 gravimeter at intervals of about 10 km. between base stations. The base stations were included in the observations and drift curves were drawn up for the instrument by converting back from the gravity differences at base stations to instrumental reading differences using the calibration constant k = 0.416 mgal/div. There was no check on irregularities in the instrumental drift between the base stations. In the case of the observations made from Victoria to River Jordan, Duncan to Cowichan Lake, and Port Alberni to Ucluelet and Tofino, readings were taken at the base station at the beginning and end of the observations. Drift curves were drawn from these readings. For the Port Alberni to Ucluelet and Tofino profile, observations were taken at six intermediate points both on the outward traverse and the return traverse. An average drift curve was drawn from these observations.

4.4 Elevations and Positions

Elevations for most of the base network stations were obtained from bench marks placed by the Geodetic Survey of Canada. For stations located at air terminals, elevations were obtained from the Department of Transport. The elevation for the pendulum station at the University of British Columbia was obtained by correcting the elevation given by the University Department of Buildings and Grounds to geodetic datum, a correction of -93 feet.

Elevations for almost all of the detail stations were obtained by the use of a pair of altimeters. Drift curves were drawn for the altimeters by taking readings at all bench marks. Temperature and humidity observations were made at each station and corrections applied to altimeter readings. Coordinates were obtained from 1:50,000 scale maps compiled by the Surveys and Mapping Branch of the Department of Mines and Technical Surveys.

4.5 Reductions

The gravity values obtained at each station were used to obtain the values of the Bouguer anomaly. This was done by applying the Bouguer correction to the observed gravity values and comparing the reduced value with the gravity value given by the International Gravity Formula:

$$\gamma = \gamma_E(1 + \beta \sin^2 \phi + \varepsilon \sin^2 2\phi) \qquad (4\text{-}5\text{-}1)$$

where γ_E = 978.0490, the gravity value at the equator, in gal.

β = 0.0052884

ε = .0000059

ϕ is the latitude.

The Bouguer reduction consists of a correction to the observed value for the effect of elevation above sea level of the observing station and the effect of the attraction of the mass of material between the observing point and sea level on the vertical component of gravity. If the mass is considered to be in the form of an infinite plate, its effect may be shown to be

$$z = 2\pi k\rho h \qquad (4\text{-}5\text{-}2)$$

where z = vertical component of the attraction

k = gravitational constant

ρ = density of material

h = thickness of plate (i.e., elevation above sea level)

The second part of the correction is that due to the effect of height of the observing point above sea level, the free air correction. It is given by the following relation

$$g_f = 2 \frac{g_m}{R_o} h \left(1 - \frac{3}{2} \frac{h}{R_o} + \ldots.\right) \qquad (4\text{-}5\text{-}3)$$

where g_m = average gravity value in gal

R_o = average radius of curvature of the earth in cm.

Making the substitution

$$k = g\frac{R^2}{M} \quad \text{where } M = \text{mass of the earth}$$

in (4-5-1) it follows that the Bouguer correction has the form

$$g_B = 2\frac{g}{R}h\left(1 - \frac{3}{4}\frac{\rho}{\rho_m}\right) \qquad (4\text{-}5\text{-}4)$$

where ρ_m = mean density of the earth and the second term of the free air correction has been neglected. For the reduction made on this data the values $\rho = 2.67$ gm/cm.^{3} and $\rho_m = 5.576$ gm/cm.^{3} were used. The correction then takes the form

$$g_B = 0.1978\ h \quad \text{where h is in m.}$$

No terrain correction has been made to the data. In this connection it may be noted that no extreme variations in topography occur near most of the stations, and it is assumed that the correction is small. The total Bouguer correction in many cases is only a few mgal. The greatest elevation of the survey is 310 m. The data and reductions are presented in Tables 23 and 24.

Table 23. Locations and Gravity Data for Stations of the Base Network

Station	B.M. No.	Latitude		Longitude		Elevation (m.)	Observed Gravity	Bouguer Corr.	Calculated Gravity	Bouguer Anomaly (mgal.)
Vancouver*		49°	16.'0	123°	15.'0	87	980.9370	+17.4	981.0132	-58.8
Victoria	776J	48	25.2	123	22.1	10.1	980.9756	2.0	980.9375	+40.1
Duncan	762J	48	46.7	123	42.4	15.0	980.9700	2.8	980.9696	+ 3.2
Nanaimo	772J	49	10.0	123	56.1	16.3	980.9974	3.2	981.0044	- 3.8
Qualicum	809J	49	21.0	124	26.8	52.4	980.9961	10.3	981.0202	-13.8
Port Alberni		49	14.5	124	48.3	38.1	981.0037	5.6	981.0110	- 1.7
Comox	831J	49	40.5	124	56.2	36.3	981.0278	7.2	981.0498	-14.8
Campbell River	843J3	50	02.0	125	15.0	2.7	981.0782	.6	981.0815	- 2.7
Kelsey Bay		50	22.8	126	57.5	5	981.1030	.9	981.1124	- 8.5
Vancouver Airport		49	10.7	123	10.0	3	980.9316	.6	981.0057	-73.5
Victoria Airport		48	38.8	123	25.3	16.5	980.9463	3.3	980.9578	- 8.2
Powell R. Airport		49	49	124	30	119.5	981.0063	23.6	981.0623	-32.5

* U.B.C. Physics Bldg. - Pendulum Station.

Table 24. Locations and Gravity Data for the Detail Stations (Cont.)

Station Name	Latitude		Longitude		Elevation (m.)	Observed Gravity	Bouguer Corr.	Calculated Gravity	Bouguer Anomaly
(Campbell River) Kelsey Bay Leg									
	°	'	°	'					
Kelsey Bay 1	50	07.2	125	23.1	24	981.0852	4.7	981.0888	+ 1.1
2	50	10.0	125	27.9	264	981.0457	52.2	981.0932	+ 4.7
3	50	15.3	125	39.7	112	981.0739	22.1	981.1008	- 4.8
4	50	18.3	125	53.8	20	981.0986	4.0	981.1054	- 2.8
5	50	23.8	125	57.6	9	981.1074	1.8	981.1137	- 4.5
6	50	16.5	125	49.8	66	981.0765	13.0	981.1027	-13.2
(Duncan) Lake Cowichan									
Lake Cowichan 1	48	46.6	123	49.8	140	980.9517	27.7	980.9696	+ 9.8
2	48	49.7	124	03.0	175	980.9511	34.6	980.9739	+11.8
3	48	49.2	124	10.6	175	980.9517	34.5	980.9732	+13.0
4	48	53	124	22	181	980.9536	35.8	980.9788	+10.6
5	48	55.0	123	29.5	192	980.9509	38.0	980.9819	+ 7.0
(Port Alberni) Tofino Leg									
Ucluelet	48	56.8	125	31.9	0	980.9846	0	980.9847	- 0.1
Tofino	49	09.1	125	56.3	0	981.0037	0	981.0028	+ 0.9

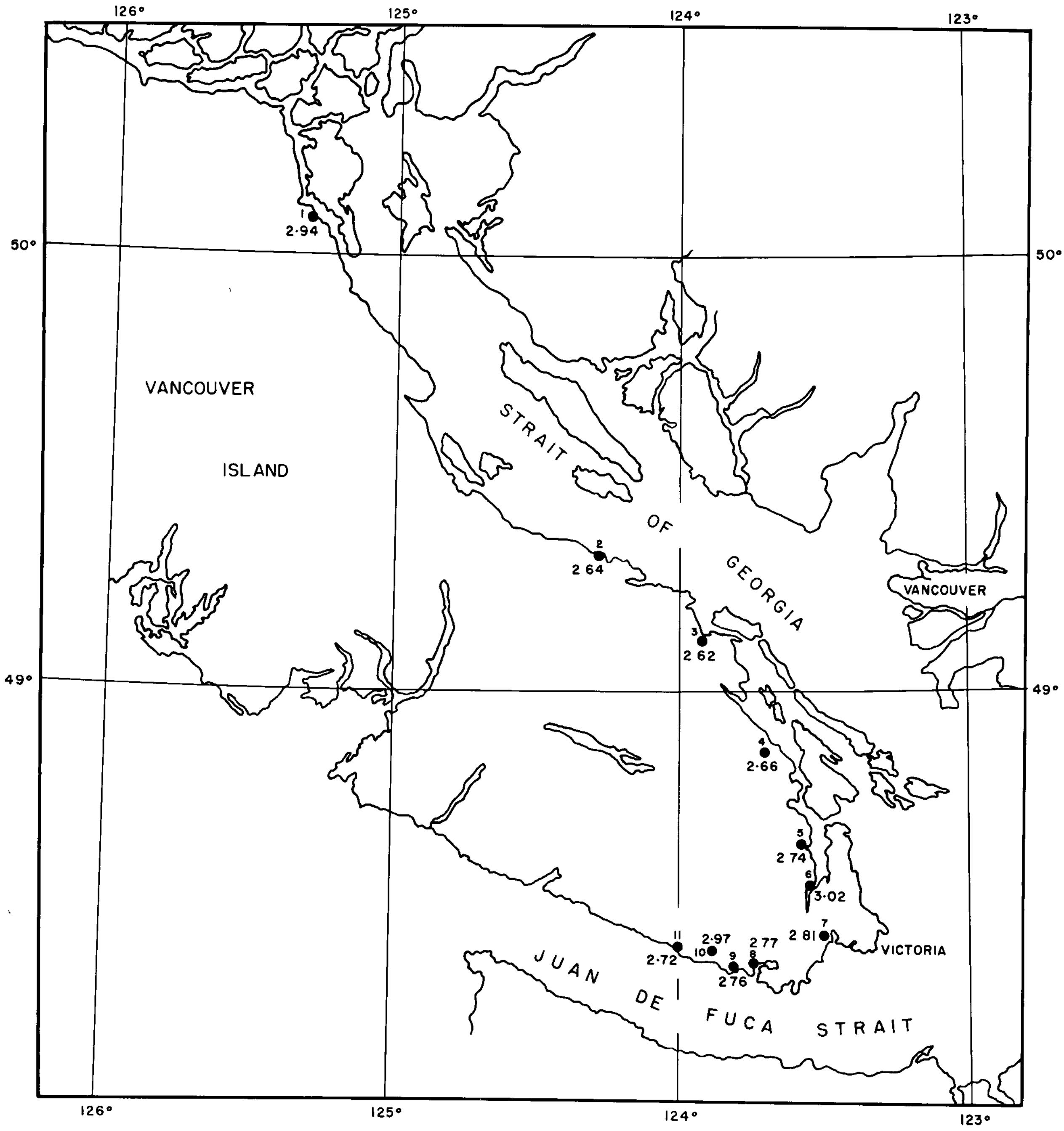
Note - The station in parenthesis is the base station at the beginning of each leg. The one following is the station at the end of the leg.

4.6 Density Measurements

Representative rock samples were collected for various locations in the area of the survey. Density measurements were made on these samples. The density measurements and locations are given in Table 25 (page 80) and are also shown in Figure 49.

4.7 Precision of Measurements

A statistical treatment has not been applied to these data in order to obtain precision indices. However, some estimate of the accuracy of the



SPECIFIC GRAVITY MEASUREMENTS OF SURFACE ROCKS

FIGURE 49

Table 25. Data for Collected Rock Samples

Sample No.	Latitude	Longitude	Density (gm/cm.^{3})
	° '	° '	
1	50 05	125 19	2.94
2	49 19	124 16	2.64
3	49 07	123 55	2.62
4	48 52	123 42	2.66
5	48 39	123 34	2.74
6	48 33	123 32	3.02
7	48 26.0	123 29.7	2.81
8	48 21.9	123 44.1	2.77
9	48 21.8	123 48.2	2.76
*10	48 23.8	123 52.6	2.97
11	48 24.2	123 59.2	2.72

*It is thought that sample 10 may not be representative.

measurements may be made. Two standards of precision exist in the survey and these are discussed separately.

(1) The base network:

The drift curves for the Worden No. 546 indicated an uncertainty of $<|0.1|$ scale division or $<|.04|$ mgal in the measured difference in the value of gravity between any two stations. It may be assumed that the calibration constant k = .39881 is determined to within ± .0001. The greatest reading difference for this instrument occurs between Vancouver (g = 980.9370) and Kelsey Bay (g = 981.1030), a difference of 166.0 mgal or 416.24 scale divisions. This leads to an uncertainty of ± .04 mgal for the extreme range of measurement. The probable error in the observed gravity for any station is thus ± 0.06 mgal.

The closure errors in the two large circuits are shown in Figure 48 to be 0.2 and 0.7 scale divisions or 0.07 and 0.28 mgal.

The Bouguer reduction is dependent on the value assumed for ρ. It would appear that the conventional value ρ = 2.67 is somewhat low for this area.

(2) The detail stations:

The standard of accuracy for the detail stations is not well determined. The calibration constant for the Worden No. 35 used in this part of the survey has been obtained by comparing reading differences obtained with it for some of the base network stations and taking an average value for the conversion factor. It may be assumed that the value of 0.416 for k has an uncertainty of ± .002. This would lead to an uncertainty of about ± 1 mgal over the range of about 180 mgal used in this survey.

It has been pointed out that except in a few cases, there is no check on irregularities in the drift between base stations, or between base station readings taken at the beginning and end of a leg. In some instances, readings were taken at stations on the return trip for a particular leg. An examination of the drift curves would indicate that errors arising from irregularities in drift are probably less than 2 scale divisions, or about 1 mgal.

Elevations were obtained for the detail stations by the use of two altimeters. The uncertainty of these elevations is probably not greater than ± 2 metres. This would give rise to an uncertainty in the Bouguer correction of 0.4 mgal.

4.8 Discussion of Data

The base network stations and the detail stations are shown in Figure 46, with the Bouguer anomalies for each station.

An attempt to draw isoanomalies has not been made since most of the observations were made along a line paralleling the line of the refraction profiles in the Strait of Georgia. Some of the stations lie along east-west lines. However, to draw isoanomalies would require greater detail in the observations.

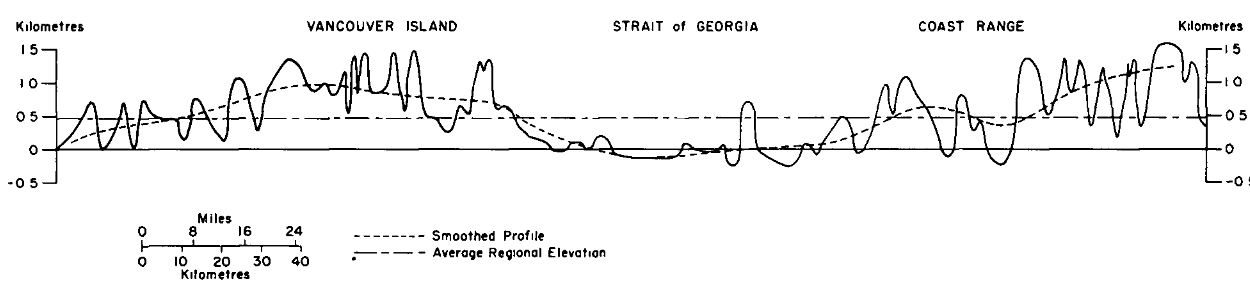
The general features of the data are as follows:

(1) The anomaly values along the east coastline of Vancouver Island (except for the Victoria area) as far north as Kelsey Bay do not differ much from zero. The same may also be said of the east-west legs from Duncan to Lake Cowichan and from Qualicum west to Port Alberni, Ucluelet and Tofino.

(2) The negative anomaly at Vancouver and the smaller negative anomaly at Powell River are to be expected due to the effect of compensation in the mountainous area, if isostatic equilibrium exists. Garland and Tanner (1957) have carried out a gravity survey across the southern Canadian Cordillera and have found an isostatic anomaly of - 4.2 mgal for a measurement made at Vancouver (Brockton Point).

(3) There is an area of positive Bouguer anomaly in the Victoria area which becomes even more positive to the west along the shoreline of the Strait of Juan de Fuca toward River Jordan. This value of from +40 mgal to +70 mgal is in contrast with an anomaly of nearly zero at Port Angeles on the opposite side of the Strait, and with the large negative anomaly in the Puget Sound area.

In Figure 50 a section of the topography is shown for a line taken at approximately 49° 30' latitude and traversing the area for which gravity values are being discussed. The average elevation along this section is found to be 0.48 km. Since the features of low elevation, such as the Strait of Georgia, included by this section have dimensions smaller than, or of the same order as, the minimum dimension for local compensation as given by Heiskanen and Vening Meinesz (1958) (about 100 km.), we may assume that the compensation exists on a regional basis. Woollard (1959) cites the general rule that local compensation exists only for features which have horizontal



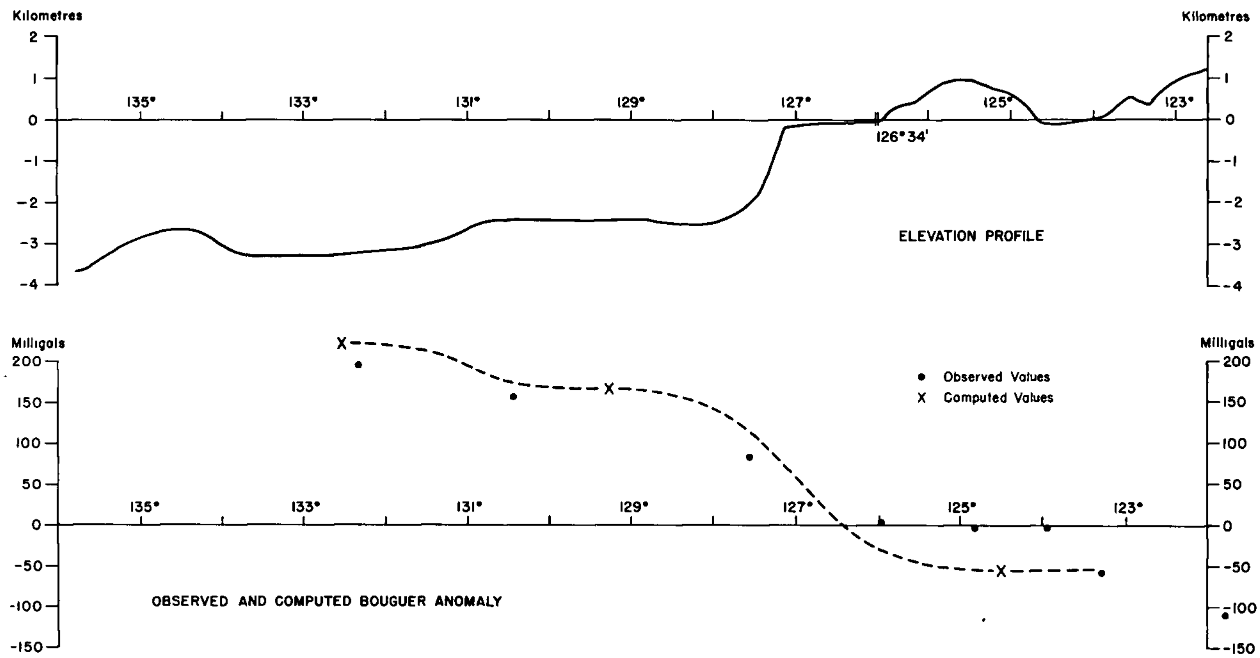
CROSS SECTION OF ELEVATIONS TAKEN NEAR $\phi = 49^\circ 30'$ FROM $\lambda = 122^\circ 35'$ TO $\lambda = 126^\circ 34'$

FIGURE 50

dimensions exceeding three times the regional crustal thickness. The expected Bouguer anomaly is -55 mgal. This is close to the observed value obtained for the Vancouver station. The difference between this value and the average value obtained for the profile along the east side of Vancouver Island appears as an isostatic anomaly of about 50 mgal and requires an explanation.

Sufficient gravity data are available to draw a gravity profile along a line from Vancouver across the Strait of Georgia, Vancouver Island and out for some distance into the Pacific Ocean. The submarine observations are taken from measurements made by Worzel and Ewing (1952). The profile of Bouguer anomalies is shown in Figure 51 together with the elevations. The elevations taken for the continental part of the profile are along the same line as that shown in Figure 50. This profile is displaced about 20° north in latitude from the gravity profile. This was done in order to obtain a more representative figure for the average elevation of the land mass for the region, since a cross section taken through Vancouver would follow the Fraser River Lowlands. The oceanic part of the profile is taken along a line west from the Tofino gravity station at latitude 49° 10'. The gravity reading included to the east of Vancouver is for Agassiz and is taken from the results of a survey carried out by Garland and Tanner (1957). The data obtained from this source as well as those from the submarine measurements are shown in Table 26 (page 84). The Bouguer anomaly reductions do not include terrain corrections for any of the data given.

The deviation of the observed anomaly from the calculated curve for the Vancouver Island area is about +50 mgal. For the oceanic observations the deviation is about -20 mgal.



ELEVATION AND BOUGUER ANOMALY PROFILES

FIGURE 51

Table 26. Additional Data Obtained from Other Observers

Station No.	Observer	ϕ		λ		Observed Gravity (gal)	Elevation (m.)	Reduced Gravity (gal)	Gravity from International Gravity Formula (gal)	Bouguer Anomaly (mgal)
157	Garland and Tanner	49°	14.1'	121°	46'	980.8977	20			109.7
7	Worzel and Ewing	49	12	127	33	980.963	-1906	981.092	981.007	85
8	Worzel and Ewing	50	05	130	26	981.086	-2282	981.241	981.086	155
120	Worzel and Ewing	49	43	132	21	981.034	-3216	981.252	981.033	197

The Bouguer reduction as given by Heiskanen and Vening Meinesz (1958) for submarine observations requires that the following correction be made to the observed value of gravity:

$$-.3086\ (1 - \frac{3}{4}\frac{\rho_w}{\rho_m})\ d + .3086\ (\frac{3}{4}\frac{\rho - \rho_w}{\rho_m})\ t' + 2\ \omega \cos \phi\ v$$

where ρ = density of rock with which the water is replaced and is taken as 2.67 gm/cm.^{3}

ρ_w = density of water, 1.027 gm/cm.^{3}

d = depth of observation in m.

ρ_m = mean density of the earth in gm/cm.^{3}

t' = depth of water in m.

v = east-west velocity in m/sec.

The final term is the Coriolis force which results from the east-west component of the submarine velocity and has not been considered.

In computing the Bouguer anomaly values for the three submarine readings, the observed gravity values as received in a communication from Worzel and Ewing were corrected only for the second term of the above expression. The effect due to the depth at which the observations were taken was neglected. If a depth of 50 m. is taken as the maximum expected depth of the submarine, the error in correction is limited to about 10 mgal.

The small variations in the gravity anomaly values observed along the profiles shown in Figure 46 may be easily accounted for by the variations in depth and density of the surficial geological structures. As may be noted from Table 25 and Figure 49 there is a considerable density contrast between the sedimentary rocks of the Cretaceous strata and the volcanic rocks and basic and granitic intrusives underlying the gravity stations at the north and south ends of the profile. A variation of 20 mgal. may be due to a layer of thickness 2.4 km. if a density contrast of 0.2 gm/cm.^{3} is assumed.

The rather large positive anomaly at the south end of Vancouver Island requires further observations to define the boundaries. It may be assumed from the high horizontal gradient in the gravity values that the anomaly is the result of a high density body at rather small depth. If the highest value of the gradient indicated in the observations is considered, i.e., 3.9 mgal/km. taken between station Sooke-2 and Duncan-2, an estimate of the maximum depth to the upper surface of the anomaly producing body may be made. A formula given by Bancroft (1960) has been used:

$$d_o = \frac{1}{\pi}\left(\Delta g_t / U_{xz}\right)$$

where d_o = maximum possible depth to the top of the anomaly producing body in km.

Δg_t = total anomaly in mgal

U_{xz} = maximum horizontal gradient in mgal/km.

Using the value 3.9 mgal/km. as the gradient and the total anomaly of 60 mgal, one obtains an estimate of 4.9 km. as the maximum possible depth to the top of the anomaly producing body.

5. DISCUSSION AND COMPARISON OF REFRACTION AND GRAVITY RESULTS

The locations of the Alberni and Victoria stations relative to the spread of shots in the Strait of Georgia are convenient for testing the variation of velocity with depth in the 6.8 km/sec. layer.

Observations from a layer with velocity increasing with depth would result in a non linear time-distance curve. The equation representing the time-distance relation for a layer in which the velocity increases linearly with depth for the case of zero time intercept has the form:

$$t \doteq a\Delta + b\Delta^3 \tag{5-1}$$

where $a = \frac{1}{v_o}$ and $b = -\frac{g^2}{24v_o^3}$

g is the velocity gradient with depth and v_o is the surface velocity. For the case of constant velocity which has been assumed in the analysis of this study, the constant b reduces to zero and the relation to the linear form

$$t = a\Delta \tag{5-2}$$

From (5-1) we have that

$$\frac{dt}{d\Delta} = a + 3b\Delta^2 \tag{5-3}$$

$\frac{dt}{d\Delta}$ is the reciprocal of the apparent velocity for any value of Δ. An increase in apparent velocity is indicated for an increase in Δ. A continuous increase in velocity with depth of another form yields a similar result. The observational results for Alberni and Victoria as shown for profiles II and VIII give $\left.\frac{dt}{d\Delta}\right|_{\Delta \doteq 70 \text{ km.}}$ and $\left.\frac{dt}{d\Delta}\right|_{\Delta \doteq 170 \text{ km.}}$

Reference to Table 8 indicates values for these slopes as follows:

$$\left.\frac{dt}{d\Delta}\right|_{\text{Alberni}} = \frac{1}{6.85 \pm .08}$$

and

$$\left.\frac{dt}{d\Delta}\right|_{\text{Victoria}} = \frac{1}{6.76 \pm .13}$$

Since the observed velocities are about equal, an increase in velocity with depth is not indicated. The small variation in the apparent velocities may be due to slightly different orientation of the profiles in an area with dipping structures.

If the gravitational field associated with an infinite plate of density and thickness h is considered, we have from Poisson's equation that,

$$\nabla^2 \phi = 0 \qquad (5\text{-}4)$$

for all space external to the plate, where ϕ is the potential. Since ϕ is presumably not a function of x and y, we have

$$\frac{\partial^2 \phi}{\partial z^2} = 0$$

and

$$\phi = Az + B.$$

The gravitational force is

$$-\frac{\partial \phi}{\partial z} = -A$$

The gravitational force due to an infinite plate is thus a constant, in the space above the plate, and not a function of the z coordinate.

The vertical attraction due to an infinite plate may be shown to be:

$$\bar{z}' = 2\pi k \rho h \qquad (5\text{-}5)$$

(Heiskanen and Vening Meinesz, 1958) where k is the gravitational constant.

This result facilitates the comparison of various crustal models in terms of the expected differences in regional gravity anomalies. It is a simple process to insert a layer of positive or negative density, $\pm\Delta\rho$, and thickness h into a model at any crustal depth and to calculate its effect on the gravity value, as long as the assumption of the infinite plate is considered to be a good one.

Press (1960) has assumed a regional Bouguer gravity anomaly of -30 mgal for an average continental crust. He adopts the crustal model for South Africa which is consistent with the explosion data as determined by Hales and Sachs (1959) and the surface wave dispersion data (Figure 52).

Thickness (km.)	Density (gm/cm^3)	Velocity (km/sec.)
21	2.78	6.03
15	3.00	6.71
	3.37	

Figure 52. Structure Found by Hales and Sachs (1959) for South Africa.

If this model is adopted as a standard for a comparison with the structure of this study, a depth for the 6.7 km/sec. layer may be calculated from the measured regional Bouguer gravity anomaly. In making this calculation the effect of the surface layers of lower velocity, for the area of this study, has been neglected. Also the variation in the velocities obtained for the sub-crustal material between the two models has not been taken into account.

The value of $\rho = 3.00$ gm/cm.^{3} for the 6.7 km/sec. material has been obtained, as in the analysis by Press, from the empirical relation arrived at by Nafe and Drake (1958) between the velocity of compressional waves and density. The value of the depth obtained is 46 km., a result which compares well with the seismic models obtained in 3.12.4.

It may be stated that the expected effect on the gravity values is very sensitive to the values of density chosen for the different layers of the structure. For example, a change in the assumed value of ρ for the 21 km. layer of 0.10 gm/cm.^{3} would lead to a difference in the expected gravity value of 100 mgal.

6. COMPARISON WITH OTHER SURVEYS

A brief comparison of the results of the present investigation with other investigations in adjacent areas is presented.

The plot of the data given by Tatel, Adams and Tuve (1953) for the Puget Sound area has been examined. The plot represents the data obtained from about 60 observations from 17 explosions in Puget Sound. The refraction lines run in directions radial from the explosion area. The data of Figure 10 of the above publication have been plotted separately for each of these lines, in order to compare the results with those of the present study. The refraction lines to the south-east and east of the explosion area extend to distances of about 280 and 290 km. respectively. The velocity line $t = \frac{\Delta}{6.66}$, obtained for the composite plot of the data of the present study with a somewhat larger time intercept fits the data for these profiles reasonably well. The refraction profile to the southwest of the explosion area indicates an apparent velocity of about 6 km/sec. The early arrivals recorded on a line to the west of the explosion area, have been interpreted by the authors as refractions from the Mohorovičić discontinuity which they suggest is rising toward the surface as the continental margin is approached. The spread of recording stations (110 - 140 km.) is rather short for the determination of a reliable apparent velocity. However, the plot of the points does appear to fall along a line parallel to $t = \frac{\Delta}{6.66}$.

A quotation from Steinhart and Meyer (1961) refers in part to the work of Tatel and Tuve in the Puget Sound area. "An interpretation with a uniform crust gives 24 km. to the M. Woollard finds a much greater depth indicated to the west but there are not enough data to compute a structure. Hodgson (National report for Canada 1959-60, Contributions Dominion Observatory, Ottawa) gives about 32 km. for this area."

The following values are also given in the same reference:

Velocity in the crust:	6.0 increasing to 7.0 km/sec. at base of crust
Mean crustal velocity:	6.5 km/sec.
Mantle velocity:	8.0 km/sec.
Depth to mantle:	30 km.

The reversed profile observed by Shor on the continental shelf in Dixon Entrance at the north end of the Queen Charlotte Islands has indicated an intermediate velocity for this area. The equations for the segments of the velocity lines with a conversion of units are approximately,

$$t = 1.47 + \frac{\Delta}{6.80}$$

$$t = 2.17 + \frac{\Delta}{7.15}$$

where Δ is in km. These results are quite comparable with those of the short range profiles of the present investigation.

Shor has interpreted some secondary arrivals as possible refractions from the mantle and has calculated a depth of 26 km. for the crust in the area of the profile. The present investigation requires a thicker intermediate layer for the Vancouver Island area.

The reversed profiles observed by A. R. Milne (1960) seaward from the edge of the continental shelf indicate velocity segments on the time-distance plots of 6.78 km/sec. and 6.76 km/sec., typical for the intermediate layer which forms the greater part of the oceanic crustal section. The thickness of the layer varies from about 2.5 km. at the west end of the profile to 4.0 km. at the east end. The present investigation requires a thickening of the intermediate layer at the continental margin.

A previous investigation by Milne and White (1960) based on a smaller number of observations in the Vancouver Island area gave a somewhat lower velocity for the upper crustal strata. It was pointed out that the Alberni recording of the Ripple Rock explosion showed an earlier than expected arrival. This observation is accounted for by the present interpretation.

The observations of Neumann (1957) include the use of a 7.0 km/sec. velocity in epicentral determinations of local earthquakes, the proposal of a very thick crustal section in the Seattle area, and the failure to observe velocities approaching 8 km/sec. from earthquakes along the coast as far as southern California. These are in general agreement with the conclusions from the present investigation.

7. CONCLUSIONS

The crustal model which has been derived from a composite plot of all longer range refraction data, is shown in Figure 44 (page 71) and consists of the following structure (Table 27, page 92).

Structures determined by treating the data in the form of refraction profiles do not differ much from this model. Considerable variations in the thickness and character of the granitic and volcanic layer are detected in the results of the shorter range refraction data.

Table 27. Average Crustal Structure for Coastal Area

Layer	P-wave Velocity (km/sec.)	Thickness (km.)
Volcanic and granitic strata	5.6 - 6.0	3.26
Intermediate	6.66	45.8
Mantle	7.76	

The shorter range profiles obtained from closely spaced explosions in the Strait of Georgia area extending from Campbell River about 100 km. southeast, show strong evidence for the intermediate layer at shallow depth. Variations of 0.7 km/sec. have been found in the observed apparent velocities across this spread of explosions. Except for two profiles, the variation is limited to 0.3 km/sec. The variations may be explained in part by the existence of dipping interfaces. This explosion area is underlain by a layer of Cretaceous sediments having a compressional wave velocity of about 4 km/sec. There is some evidence for major faulting in the area.

An anomalous situation exists north of Campbell River which gives rise to earlier than expected arrivals from the explosions A (Nov.) and 1-5 (Nov.) at Elk Falls and later arrivals at Alberni. Alternative structures have been proposed to explain these data consisting of a considerable thickening of the upper crustal layer toward Kelsey Bay or the existence of a low velocity plug in the path of propagation between Alberni and the Kelsey Bay - Johnstone Strait area.

Except for the case of one profile, where the velocity segment is based on only two observations, a velocity approaching 8 km/sec. has not been observed. The velocity obtained for observations along the coast from the Ripple Rock explosion as far distant as 1127 km. is 7.7 km/sec. This velocity has also been found for a profile in the reverse direction, of events recorded at Longmire from a distance of 510 km. The possibility that the arrival read at Mineral (Δ = 1127 km.) is a secondary arrival has been considered. Unfortunately an opportunity to follow the character of P_n with increasing distance is not afforded in the data because of the gap in the observations between Longmire and Mineral. An apparent velocity of 7.66 km/sec. has been obtained for observations along a line east from Ripple Rock for the distance range 300-700 km. It is suggested that these velocities are associated with the mantle.

Since no observations have been made east from Ripple Rock in the distance range 0-300 km. the data are not complete enough to determine a structure. It is to be noted, however, that the time intercept of 4.8 seconds is somewhat smaller than for the P_n curve for the coast data.

A test for a possible increase in velocity with depth in the intermediate (6.7 km/sec.) layer has shown that no appreciable increase exists.

The results of the gravity observations, taken between Victoria and Kelsey Bay on Vancouver Island, show that except for the south end of the Island, the regional Bouguer gravity anomaly is about zero. A pronounced positive anomaly of about 40-65 mgal has been found in the Victoria area and west along the south shore of Vancouver Island. The horizontal gradients observed indicate that the positive anomaly is due to dense material near the surface. An east-west gravity profile starting on the British Columbia mainland, traversing Vancouver Island and extending out into the Pacific Ocean indicates a positive isostatic anomaly of about 50 mgal in the Vancouver

Island area. The isostatic anomaly at Vancouver and seaward from Vancouver Island appears to be small.

If the seismic model, requiring an intermediate layer at shallow depth is accepted, then in order to explain the observed regional gravity results, this layer must be assumed to be relatively thick. The positive effect on the gravity value resulting from the existence of the intermediate density material near the surface must be compensated for by extending the intermediate densities to greater depths. Some of the higher density material of the mantle must be replaced with intermediate density material. The density of the intermediate layer has been inferred from the compressional wave velocity. A comparison of the structure of the Vancouver Island area with that of a standard model gives a thickness of 46 km. for the intermediate layer based on the gravity observations.

8. BIBLIOGRAPHY

Bancroft, A.M. 1960. Gravity anomalies over a buried step. J. Geophys. Research, 65, No. 5, pp. 1630-1631.

Berg, Eduard, Bob Hamilton, and Alan Ryall. 1962. Travel times and crustal structure from blast near Salinas, California. Program, meetings of the Seismological Society of America, April 16-18, 1962.

Berg, Joseph W., Jr., Kenneth L. Cook, Harry D. Narans, Jr., and William M. Dolan. 1960. Seismic investigations of crustal structure in the eastern part of the Basin and Range Province. Bull. Seism. Soc. Am. 50, No. 4, pp. 511-535.

Birch, F. 1958. Interpretation of the seismic structure of the crust in the light of experimental studies of wave velocities in rocks. Contributions in Geophysics, 1, Pergamon Press, New York, pp. 158-170.

Byerly, Perry. 1956. Subcontinental structure in the light of seismological evidence. Advances in Geophysics, Vol. 3, Academic Press Inc., New York.

Ewing, Maurice, and Frank Press. 1956. Handbuch Der Physik, 47, Springer-Verlag, Berlin, Gottingen, Heidelberg, pp. 246, 248.

Garland, G.D., and J. G. Tanner. 1957. Investigations of gravity and isostasy in the southern Canadian Cordillera. Publications of the Dominion Observatory, 19, No. 5, pp. 169-208.

Gutenberg, B. 1950. Structure of the earth's crust in the continents. Science, 111, pp. 29-30.

Hales, A. L., and I. S. Sachs. 1959. Evidence for an intermediate layer from crustal structure studies in Eastern Transvaal. Geophysical Journal, 2, pp. 15-33.

Healy, J. H., S. W. Stewart, and W. H. Jackson. 1962. Crustal studies in the western Cordillera. Program, meetings of the Seismological Society of America, April 16-18, 1962.

Heiskanen, W. A., and P. A. Vening Meinesz. 1958. The earth and its gravity field. McGraw Hill, New York, pp. 138, 159, 208-209.

Herrin, Eugene. 1962. Interpretation and adjustment of regional travel times and phase velocities using high speed computers. Program, meetings of the Seismological Society of America, April 16-18, 1962.

Hodgson, J. H. 1953. A seismic survey in the Canadian Shield, I: Refraction studies based on rockbursts at Kirkland Lake, Ontario. Publications of the Dominion Observatory, 16, No. 5, pp. 111-163.

Jeffreys, Sir Harold. 1959. The Earth (Fourth Edition). Cambridge University Press, Chapter III.

Katz, Samuel. 1955. Seismic study of crustal structure in Pennsylvania and New York. Bull. Seism. Soc. Am., 45, No. 4, pp. 303-325.

Leet, L. D. 1938. Practical seismology and seismic prospecting. Appleton-Century-Crofts, Inc., New York, Chapter 4.

Menard, H. W. 1961. The East Pacific Rise. Scientific American, December 1961, pp. 52-61.

Milne, A. R. 1960. A reversed seismic refraction profile, North Pacific Ocean Basin. Report 60-10, Pacific Naval Laboratory, Esquimalt, B. C.

Milne, W. G., and W.R.H. White. 1960. A seismic survey in the vicinity of Vancouver Island, British Columbia. Publications of the Dominion Observatory, 24, No. 7, pp. 145-154.

Nafe, J. E., and C. L. Drake. 1958. Physical properties of crustal materials as related to compressional wave velocities. Abstr. in Geophysics, 23, p. 403.

Neumann, Frank. 1957. Crustal structure in the Puget Sound area. Publications du Bureau Central Seismologique International, Serie A, Travaux Scientifiques, Fascicule 20 (Memoires presentes a la Conference de Toronto 1957).

Pakiser, L. C., J. H. Healy, W. H. Jackson, and S. W. Stewart (U. S. Geological Survey, Denver, Colorado). 1962. Seismic refraction exploration of the continental crust in eastern Colorado and the Basin and Range Province. Abstract, J. Geophys. Research, 67, No. 4.

Press, Frank, and Maurice Ewing. 1952. Two slow surface waves across North America. Bull. Seism. Soc. Am., 43, pp. 219-228.

Press, Frank. 1960. Crustal structure in the California-Nevada region. J. Geophys. Research, 65, No. 3, pp. 1039-1051.

Richards, T. C., and D. J. Walker. 1959. Measurement of the thickness of the earth's crust in the Alberta Plains of Western Canada. Geophysics, 24, No. 2, pp. 262-284.

Richter, C. F. 1943. Calculation of small distances. Bull. Seism. Soc. Am., 33, pp. 243-250.

Romney, Carl. 1959. Amplitudes of seismic body waves from underground nuclear explosions. J. Geophys. Research, 64, pp. 1489-1498.

Shor, George G., Jr. 1962. Seismic refraction studies off the coast of Alaska. Bull. Seism. Soc. Am., 52, No. 1, pp. 37-57.

Steinhart, J. S., and R. P. Meyer. 1961. Explosion studies of continental structures. Publication 622, Carnegie Institute of Washington, D. C.

Talwani, Manik, George H. Sutton, and J. Lamar Worzel. 1959. A crustal section across the Puerto Rico Trench. J. Geophys. Research, 64, No. 10, pp. 1545-1555.

Tatel, H. E., L. H. Adams, and M. A. Tuve. 1953. Studies of the earth's crust. Proceedings of the American Philosophical Society, 97, No. 6, pp. 658-669.

Tatel, H. E., and Tuve, M. A. 1955. Seismic exploration of a continental crust. Geol. Soc. Am. Special Publs. 62, pp. 35-50.

Weizman, P. S., Kosminskaja, I. P., Risnichenko, J. V. 1957. New deep seismic sounding data on the structure of the earth's crust and on mountain roots. 11th General Assembly of I.U.G.G. at Toronto.

Willmore, P. L. 1949. Seismic experiments on the north German explosions, 1946 to 1947. Phil. Trans. Roy. Soc., A 242, pp. 123-151.

Woollard, G. P. 1959. Crustal structure from gravity measurements. J. Geophys. Research, 64, No. 10, pp. 1521-1544.

Worzel, J. L., and Maurice Ewing. 1952. Gravity measurements at sea, 1948 and 1949. Transactions, American Geophysical Union, 33, No. 3, pp. 453-460.