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AN ABSTRACT OF THE THESIS OF David John Nazy for the Master of Science in Geology presented July 17, 1987.

Title: A Seismic Refraction Study of a Portion of the
Northeastern Margin of the Tualatin Valley,
Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

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Ansel G. Johnson, Chairman

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The Tualatin Valley is a well defined elliptical basin centered at Hillsboro, with a major axis trending roughly N65°W. The valley is bordered on the northeast by the Tualatin Mountains (Portland Hills) which are a faulted, northwest-trending asymmetrical anticline. Topographic and geophysical evidence have defined the Portland Hills fault, which occurs along the northeast side of the Tualatin Mountains. The possibility that a fault or fault zone occurs along the southwest side of the Tualatin Mountains was investigated in this study.

Boring Lavas, occurring on the southwest side of the Tualatin Mountains and having been erupted through the Columbia River basalt, may define zones of fracture or faulting in the Columbia River basalt. An exposed "window" of sediment is located near the town of Bonny Slope on the southwest side of the Tualatin Mountains. This sedimentary unit is presumed to be marine in origin, stratigraphically below the Columbia River basalt. Exposure of this unit at this location may be the result of landsliding, faulting, or paleotopographic highs during the deposition of the Columbia River basalt.

Seismic refraction methods were used to produce shallow (0 - 50 meters) geologic models near the areas of the proposed fault zone. The refraction models indicate that Columbia River basalt roughly parallels the surface topography at an average depth of 15 meters and is overlain by a weathered zone ranging in thickness from 5 to 15 meters. The basalt is broken up into blocks, mainly in the southeastern half of the study area. Data collected through this study indicate that the sedimentary unit at Bonny Slope is not underlain by Columbia River basalt. This provides further evidence that this unit is part of the Scappoose Formation although it is uncertain as to whether this feature is related to faulting or paleotopographic highs.

A SEISMIC REFRACTION STUDY
OF A PORTION OF THE NORTHEASTERN MARGIN
OF THE TUALATIN VALLEY, OREGON

by
DAVID JOHN NAZY

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
GEOLOGY

Portland State University

1987

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of David
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TABLE OF CONTENTS

	PAGE
ACKNOWLEDGEMENTS	iii
LIST OF FIGURES	vi
INTRODUCTION	1
PURPOSE	1
LOCATION	1
PREVIOUS WORK	9
GEOLOGIC SETTING	11
STRATIGRAPHY	11
STRUCTURE AND TECTONICS	15
METHODS OF INVESTIGATION	18
INTRODUCTION	18
PROCEDURES	18
Field Techniques	
Data Reduction	
Equipment Used	
GEOPHYSICAL MODELING	23
SEISMIC REFRACTION	23
RESULTS AND DISCUSSION	27
Thompson Road Line	
Bonny Slope Line	
Laidlaw Road Line	
Bronson Creek Line	
Springville Lane Line 1	
Springville Lane Line 2	
Germantown Road Line	
Kaiser Road Line	

Rock Creek Line
Cornelius Pass Line

SUMMARY AND CONCLUSIONS	51
REFERENCES CITED	61
APPENDIX A. REFRACTION DATA AND FORMULAS	66
APPENDIX B. FORTRAN PROGRAMS TO REDUCE DATA	75

LIST OF FIGURES

FIGURE	PAGE
1. Regional Map	2
2. Study Area	3
3. Thompson Road and Bonny Slope Refraction Lines	5
4. Laidlaw Road, Bronson Creek, and Springville Lane Refraction Lines	6
5. Germantown Road, Kaiser Road, and Rock Creek Refraction Lines	7
6. Cornelius Pass Refraction Line	8
7. Earthquake Epicenters near the Tualatin Valley	10
8. Formations in Study Area	12
9. Typical Refraction Line Layout	20
10. Example of a Seismic Field Record	21
11. Diagram Showing Paths of Seismic Waves Leaving Source at Time of Impact	24
12. Thompson Road Refraction Line, Time-Distance Plot and Generalized Cross Section	28
13. Bonny Slope Refraction Line, Time-Distance Plot and Generalized Cross Section	30

FIGURE	PAGE
14. Laidlaw Road Refraction Line, Time-Distance	
Plot and Generalized Cross Section	33
15. Bronson Creek Refraction Line, Time-Distance	
Plot and Generalized Cross Section	35
16. Springville Lane Refraction Line 1, Time-	
Distance Plot and Generalized Cross	
Section	38
17. Springville Lane Refraction Line 2 Time-	
Distance Plot and Generalized Cross	
Section	40
18. Germantown Road Refraction Line, Time-Distance	
Plot and Generalized Cross Section	42
19. Kaiser Road Refraction Line, Time-Distance	
Plot and Generalized Cross Section	45
20. Rock Creek Refraction Line, Time-Distance	
Plot and Generalized Cross Section	47
21. Cornelius Pass Refraction Line, Time-Distance	
Plot and Generalized Cross Section	49
22. Comparison and Interpretation of Cornelius	
Pass, Rock Creek, Germantown Road, Kaiser Road,	
and Laidlaw Road Refraction Lines	52
23. Comparison and Interpretation of Springville	
Lane Refraction Lines 1 and 2	54
24. Comparison and Interpretation of Thompson Road, Bonny	
Slope, and Bronson Creek Refraction Lines	57

INTRODUCTION

PURPOSE

The Tualatin Mountains (Portland Hills) are an expression of deformation of the Miocene Columbia River basalt. This study was undertaken to examine the shallow (0 - 50 meters) subsurface geology along the border of the Tualatin Mountains and the Tualatin Valley. The paucity of outcrops and the thick vegetative cover in the Tualatin Mountains makes a geophysical study the most reasonable method of investigating the structure in the area. This study has three main objectives: 1) to determine local thickness of the sediment or soil (weathered zone) overlying the Columbia River basalt; 2) to gain information about the upper surface of the Columbia River basalt and how it relates to the topography; 3) to look for displacement of refracting surfaces.

LOCATION

The study was conducted in Washington and Multnomah counties, Oregon (Figure 1). Ten seismic refraction lines were conducted along the western margin of the mapped surface exposure of the Columbia River basalt. The refraction surveys are spread out over 8.8 kilometers along the southwestern edge of the Tualatin Mountains. Figure 2 shows the location of the ten seismic lines and the mapped pattern of the major rock units in the study area.

Figure 2. Study area (from USGS 7.5' Linnton quadrangle map, 1961).
(Modified from Trimble, 1963).

Figure 1. Regional map (from USGS map of Oregon, 1966, 1:500,000).

Geology and refraction line locations are shown in more detail in Figures 3 - 6. The Thompson Road and Bonny Slope refraction lines are shown in Figure 3. The Thompson Road line, 90 meters long, was conducted along NW Thompson Road in T1N, R1W, Sec. 23. The Bonny Slope refraction line, 350 meters in length, was run along the northern side of NW Laidlaw Road (T1N, R1W, Sec. 22 and 26).

Figure 4 shows the location of four seismic lines. The Laidlaw Road line was run a distance of 90 meters along NW Laidlaw Road. The Bronson Creek line, 360 meters in length, was run along NW 124th street. Both lines are located in T1N, R1W, Sec. 22. Two 180 meter lines were run perpendicular to each other along NW Springville Lane in T1N, R1W, Sec. 16.

Another set of lines were run perpendicular to each other at the intersection of NW Kaiser Road and NW Germantown Road in T1N, R1W, Sec. 8 (Figure 5). A 180 meter line was run along the east edge of NW Kaiser Road and a 90 meter line was run along the south edge of NW Germantown Road. Rock Creek line, also shown in Figure 5, was run a distance of 145 meters along the north edge of NW Germantown Road in T1N, R1W, Sec. 7.

Two 90 meter lines run along Cornelius Pass Road are shown in Figure 6. The lines were run on either side of the intersection with NW Kaiser Road in T1N, R1W, Sec. 6.

Figure 3. Thompson Road and Bonny Slope refraction lines. (From USGS 7.5' Linnton quadrangle map, 1961). (Modified from Trimble, 1963).

Figure 4. Laidlaw Road, Bronson Creek, and Springville Lane refraction lines. (From USGS 7.5' Linnton quadrangle map, 1961). (Modified from Trimble, 1963).

Figure 5. Germentown Road, Kaiser Road, and Rock Creek refraction lines. (From USGS 7.5' Linnton quadrangle map, 1961). (Modified from Trimble, 1963).

Figure 6. Cornelius Pass refraction line. (From USGS 7.5' Linnton quadrangle map, 1961). (Modified from Trimble, 1963).

PREVIOUS WORK

Regional studies of the geology of the Tualatin Valley have previously been published by Warren, Norbistrath, and Grivetti (1945), Tresher (1942), Trimble (1957, 1963), Hart and Newcomb (1965), and Schlicker and Deacon (1967). The origin of the Willamette Silt deposits on the valley floors has been discussed by Allison (1933, 1935, 1936), Glen (1965), and Bretz (1925, 1928). The petrology and stratigraphy of the Portland Hills Silt was described by Lentz (1977). Lowry and Baldwin (1952), Theisen (1958), and Trimble (1963) discussed the genesis of the Upland Silt in the Tualatin Mountains. The subsurface geology of the Tualatin basin has been described by Newton (1969). Van Atta (1985) discussed the stratigraphic relationship between the Scappoose Formation and the Columbia River basalt. Structural contour maps illustrating the top of the Columbia River basalt in the Tualatin Valley and surrounding areas have been prepared by Benson and Donovan (1974) and Schlicker and Deacon (1967).

The existence of several faults in and around the Tualatin Mountains has been proposed by various authors. Johnson and others (1977) and Beeson and others (1976) noted offset Columbia River basalt flows and gravity anomalies along the Portland Hills fault on the eastern edge of the Tualatin Mountains. Basillie and Benson (1971) and Beeson and others (1976) also cited topographic evidence for the Portland Hills fault. Gravity studies by Perttu (1980) and Jones (1977) could be used as evidence for the fault. Earthquake epicenters related to postulated faults in the Portland area were noted by Couch and Lowell

(1971) and Schlicker and others (1964). Historic earthquake epicenter locations near the Tualatin Mountains are shown in Figure 7. Schmela (1971) and Anderson (1978) studied the extension of the Portland Hills fault trend into the Clackamas River drainage. The trend of the Portland Hills fault to the northwest was examined by Haas (1983).

Figure 7. Historic earthquake epicenter locations near the Tualatin Valley. (From Johnson, 1987).

GEOLOGIC SETTING

STRATIGRAPHY

A stratigraphic column of the formations in the study area is shown in Figure 8. The following description is based primarily on the work of Schlicker and Deacon (1967), Trimble (1963), and Newton (1969).

The Scappoose Formation, late Oligocene to early Miocene in age, is the oldest unit exposed in the study area. The formation, shallow marine in origin, is composed of fossiliferous, tuffaceous, arkosic sandstone, siltstone, and mudstone with local conglomeratic lenses of granule and peasized gravel (Trimble, 1963). The loosely compacted sediments are highly susceptible to alteration and weathering.

Exposures of the Scappoose Formation within the Tualatin Valley are very limited, occurring mainly along the western margin of the valley. Many of these outcrops are parts of landslide complexes, and therefore are not in place (Trimble, 1963). Several exposures of the Scappoose Formation that are presumed to be in place have been mapped in the St. Helens Quadrangle, 15 - 20 kilometers northwest of the study area.

The sedimentary unit in the Bonny Slope area (T1N, R1W, Sec. 26 and 27) that was mapped as Sandy River mudstone by Trimble (1963), and Troutdale Formation by Schlicker and Deacon (1967), has more recently been interpreted as the Scappoose Formation (Thoms, pers. com., 1987). Marine fossils were collected in a housing excavation although no

Figure 8. Formations in the study area. (From Trimble, 1963; Schlicker and Deacon, 1967; and Newton, 1969).

outcroppings of the Scappoose Formation have been found in this area. This exposed "window" of the Scappoose Formation, surrounded by Columbia River basalt, may be the result of faulting or a paleotopographic high during the deposition of the Columbia River basalt. Van Atta (1985) notes that the thickness of both the Scappoose Formation and the Columbia River basalt varies widely indicating that both were deposited over a paleotopography with a relief up to 245 meters.

The Miocene Columbia River basalt unconformably overlies the Scappoose Formation. This unconformity is an eroded surface of high relief (Trimble, 1963). The Columbia River basalt forms the bedrock of the Tualatin Mountains and underlies the entire Tualatin Valley at depths ranging from a few meters to a maximum of about 500 meters (Schlicker and Deacon, 1967; Hammond, 1974; Trimble, 1963). Columbia River basalt in the Tualatin Valley is included in the Grande Ronde Formation (Beeson, pers. com., 1987).

Exposures of the basalt are limited to the margins of the Tualatin Valley with the exception of outcrops around Bull and Cooper Mountains. The formation is composed of a series of lava flows that commonly range in thickness from 10 to 20 meters and are vesicular to scoriaceous in their flow margins. The unweathered surfaces are brownish gray to dark blue-gray, dense, and finely crystalline. The flows commonly show joint systems that range in character from columnar to platy. The basalt exposures are mostly light gray to reddish brown, crumbly, and highly altered to clay minerals due to partial or complete weathering of the rock (Schlicker and Deacon, 1967).

The Helvetia Formation, early Pliocene in age, rests unconform-

ably upon the Columbia River basalt. The poorly indurated sedimentary deposits generally consist of weathered, reddish brown and light brown pebbly sand, silt, and clay. The formation occurs around almost the entire periphery of the Tualatin Valley and is always found directly above the weathered surface of the Columbia River basalt, extending up the valley slopes to elevations ranging from 50 to 300 meters (Schlicker and Deacon, 1967).

The middle Miocene to Pliocene fluvial deposits of the Troutdale Formation unconformably overlies the Columbia River basalt and makes up most of the sedimentary fill in the Tualatin Valley. The formation consists of poorly indurated gray to brown silt and clay, mottled, yellow to reddish brown silty sand, and occasional pebble conglomerate beds. Data from water wells indicate that the Troutdale reaches its maximum thickness of about 500 meters in the center of the Tualatin Valley near Hillsboro and tapers to a thin edge where it pinches out on the slopes of the surrounding hills (Schlicker and Deacon, 1967).

The Boring Lavas, late Pliocene to early Pleistocene in age, occurs as rounded hills which are found throughout the greater Portland - Vancouver area (Allen, 1975). The hills represent volcanic vents that erupted primarily high-alumina basaltic lava flows (Tolan and Beeson, 1984). The light gray to nearly black basalt is characterized by blocky or columnar jointing (Schlicker and Deacon, 1967). Spheroidal weathering is common, and in some locations the basalt has been weathered to a red clayey soil to depths of 5 meters or more (Trimble, 1963). The Boring Lava cones along the southwestern edge of the Tualatin Mountains are almost totally covered by a veneer of upland

loessal silt which ranges in thickness from less than one to more than ten meters (Schlicker and Deacon, 1967).

Quaternary sedimentary deposits cover at least fifty percent of the Tualatin Valley. Schlicker and Deacon (1967) have divided these deposits into two formations, Upland silt and Willamette silt. The Upland silt occurs at elevations above 75 meters and is characterized by massive yellow-brown sandy silt and clayey silt with occasional well rounded basalt pebbles. The loessal deposits mantle the ridges, spurs, and flatter areas of the Tualatin Mountains and range in thickness from one to fifteen meters (Schlicker and Deacon, 1967). The Willamette silt occurs in the lower elevations of the valley and is characterized by bedded silt and fine sand with occasional layers of clay, lenses of pebbly sand, and scattered granite and quartzite cobbles. The deposits are about 15 meters thick near Hillsboro and gradually thin toward the margins of the valley (Schlicker and Deacon, 1967).

STRUCTURE AND TECTONICS

The Tualatin Valley is a fairly well defined elliptical basin centered at Hillsboro, with a major axis trending roughly N65°W (Hammond and others, 1974). The basin is filled with fluvial and lacustrine Troutdale sediments and Willamette silt. The valley is bordered on the northeast by the Tualatin Mountains (Portland Hills) which have been interpreted as a faulted, northwest trending asymmetrical anticline (Balsillie and Benson, 1971; Beeson and others, 1985). The Tualatin Mountains are bordered on the east by the Portland basin which

has been interpreted as a pull apart basin genetically related to the Portland Hills - Clackamas River structural zone (Beeson and others, 1985). The Portland Hills - Clackamas River structural zone is presumed to be a northwest trending wrench fault zone which includes the Tualatin Mountains (Beeson and others, 1985). Several faults and folds have been proposed in the Tualatin Valley (Hart and Newcomb, 1965; Schlicker and Deacon, 1967; Trimble, 1963; Johnson, 1976; Hammond and others, 1974; Beeson, and others, 1976), although the locations and the amount of offset are uncertain. Boring Lavas, having been erupted through the Columbia River basalt, may define zones of fracture of faulting in the Columbia River basalt (Beeson and others, 1976). The Columbia River basalt beneath the Tualatin Valley may be broken into separate blocks which have been deformed independently (Hammond and others, 1974).

The formations in the Tualatin Valley are included in the upper part of a 7500 meter sequence of volcanic and sedimentary rocks in western Oregon (Snively and Wagner, 1964). The basement rock in this sequence are the 3000-6100 meter thick (Newton, 1969) Tillamook Volcanics which are equivalent to the Siletz River Volcanics in the central Oregon Coast Range. These submarine pillow basalts and breccias are thought to be oceanic crust formed at a spreading ridge and accreted onto the continent when the subduction zone moved from east of the Coast Range to the present continental margin (Snively and others, 1980). Following the westward jump of the subduction zone, the region could be characterized as a large depositional basin. By late Eocene, areas of local uplift and volcanism divided the regional basin into

smaller shallow depositional basins. In the northeastern part of the present Coast Range, Goble Volcanics erupted into a structural downwarp (Newton, 1969) where they are interbedded with marine sedimentary rocks of the Cowlitz Formation. The Oligocene was characterized by sedimentation in the northeast part of the Coast Range and throughout the northern Willamette Valley (Snively and Wagner, 1963). Pyroclastic volcanism in the ancestral Cascade Range provided large amounts of ash to the marine deposits of the Keasey, Pittsburg Bluff, and Scappoose Formations. Broad uplift during late Oligocene (Snively and Wagner, 1963) resulted in a westward shift in marine deposition (Kulm and Fowler, 1974) and minor deformation of rocks in the northern Coast Range (Newton and Van Atta, 1976).

The northwest trending Portland Hills - Clackamas River structural zone was active by at least early mid Miocene (Beeson and others, 1976). Movement along the structural zone produced a topographic barrier that affected the distribution of several Columbia River basalt flows. The thinning and termination of units across this zone indicate that tectonic activity was continuous throughout this time interval (Beeson and others, 1985). The right-lateral movement along the structural zone may be related to extension of the basin and range province (Beeson and others, 1976). The structural zone may also be related to north - south compression caused by the possible subduction of the Farallon plate although the location of the subduction zone is not known (Dehlinger, 1969; Dehlinger and Couch, 1969; Crosson, 1972).

METHODS OF INVESTIGATION

INTRODUCTION

Seismic refraction lines were run along roads to investigate the near surface (0 to 50 meters deep) geologic structure. Cross sections illustrating the depth and dip of refracting layers can be modeled from the field data which is plotted a time versus distance graphs. The cross sections and graphs are presented with discussion of individual refraction lines in the results and discussion section.

Locations were chosen for the purpose of detecting Columbia River basalt. The contact of high-velocity basalt underlying low-velocity sediment should be a good refracting horizon. Therefore, lines were set up where Columbia River basalt is thought to occur at or near the surface. Displacement along the surface of the basalt should be detectable through the methods used in this study.

PROCEDURES

Field Techniques

Field work was completed between the months of June and August, 1986. A seismic refraction thumper, on loan from Oregon State University School of Oceanography was used as the energy source. The thumper consists of an electric winch which is used to lift a 300 or 500 pound weight. The weight was dropped a distance of about 3.2 meters onto a steel plate on the ground. A twelve channel refraction seismograph was

used to collect the seismic records.

The seismic lines were run along the edges of roads near locations where Trimble (1963) mapped the contact between the Columbia River basalt and overlying sedimentary fill (See Figure 2). Other factors influencing the choice of line locations were accessibility, straightness of the road, and amount of traffic. Because of the large amount of seismic "noise" caused by a passing vehicle, heavily traveled roads had to be avoided. Refraction lines were also run near intersections of roads in order to collect data in perpendicular directions to get the true dip of discontinuities.

The apparent dip of a refracting layer can be determined if the seismic profile is reversed (Telford and others, 1976). To "reverse" a profile, the energy source was dropped at both ends of the line. Thus, two sets of data, recorded in opposite directions, were collected for each line. The refraction data is presented in Appendix A.

Most of the lines were set up with a maximum shot to receiver spacing of 90 meters. The geophones were spaced a distance of 10 meters apart. The first receiver was spaced 5 meters from the shot in order to record the direct arrival velocity by at least two geophones. Whenever possible, two 90 meter lines were run end to end and an extended shot was dropped at the far end of one line to make an effective 180 meter line. The greater shot to receiver distance allows for the detection of deeper layers (Mota, 1954). A typical double line layout is shown in Figure 9.

Figure 9. Typical refraction line layout.

For example, data was collected for line A with a 300 pound weight dropped at S_1 and S_2 . Data was then collected on line A with a 500 pound weight dropped at S_3 . The larger weight was needed for the extended shot because the seismic signal was attenuated at greater distances. The geophones were then spread out over line B with a 300 pound weight dropped at S_2 and S_3 and a 500 pound weight dropped at S_1 . This produced a 180 meter seismic line with double coverage.

Data Reduction

The signal from each geophone was recorded as a trace of light on photographic paper. An example of a field record is shown in Figure 10. The first seismic wave to be detected after the shot was marked directly on the paper for each trace. The mark on each trace is taken to be the first break for the corresponding geophone. The mark on the time break geophone trace is the time that the weight hit the ground. The first arrival time for each geophone is the time elapsed between the mark on the time break trace and the mark on the geophone trace. The distance between the horizontal lines on the field record represents .01 seconds. The first arrival time for each geophone is then plotted against distance from the shot. Reversed profiles were plotted

Figure 10. Example of a seismic field record.

on the same graph. Figure 12 shows an example.

The inverse of the slope of a line fit to points on a time versus distance graph represents an apparent velocity. A FORTRAN program was used to fit a line to the points on a time-distance graph by the least squares method. C. B. Reynolds wrote the program which is listed in Appendix B. The program calculates an apparent velocity for a segment of a profile that the operator has chosen to represent a refracting surface. Corresponding segments from reversed profiles are then used to calculate "true velocities", depths, and dips of refracting layers. Standard formulas for determining these values are given in Ewing and others (1939), Nettleton (1940), Mota (1954), Dobrin (1960), and Heiland (1968). The formulas used are shown in Appendix A. Using the formulas given in Mota (1954), a FORTRAN program, entitled "Layers", was written to calculate actual velocities, dips, and depths for a two-layer and three-layer model. The program listing is given in Appendix B.

Equipment Used

SIE recording amplifier, model RA-44, 12 channels.

SIE recording oscillograph, model R-4.

Mark Products 7.5 Hz geophones.

Thumper trailer with 300 pound and 500 pound weights,

loaned by Oregon State University, School of Oceanography.

GEOPHYSICAL MODELING

SEISMIC REFRACTION

Several principles make the use of seismic refraction possible. The first of these is that sound waves travel through earth materials with a definite velocity and along a definite path. The velocity depends strongly upon the nature of the materials, particularly upon the degree of consolidation. Fermat's principle states that the sound waves will follow the path which requires the least amount of time from source to receiver (Dix, 1941). Since travel time equals distance divided by velocity, a longer path which includes a high velocity segment may require less time than the direct path.

The theory making seismic refraction possible can be illustrated by a horizontal, two-layer model. Figure 11 shows four of the many seismic ray paths that are produced at the time of impact. Ray D is a direct wave that travels at velocity V_1 . Ray C will be reflected at the discontinuity and return to the surface. Ray C also travels its entire path at velocity V_1 . Rays A and B are both refracted at the discontinuity according to Snell's Law. This states that a seismic ray will travel in a straight line through any material which has a constant velocity, but that it will be bent when it passes through a discontinuity (Telford and others, 1976). Rays such as ray A are bent at the discontinuity but will not return to the surface. Energy arriving at the discontinuity at the critical angle (I_c), such as ray B, will

Figure 11. Diagram showing paths of seismic waves leaving source at time of impact. (Modified from Laster, 1967).

travel along the discontinuity at velocity V_2 . This creates a disturbance in the upper medium producing waves which travel back toward the surface at the critical angle. The sine of the critical angle equals the ratio of the velocities of the materials on each side of the discontinuity ($\sin I_c = V_1 / V_2$). Since ray path B contains a high velocity segment ($V_2 > V_1$), it will be the first arrival at geophones spaced far enough from the source. The travel time from source to receiver gives information on the velocity and general structure of the materials beneath the surface (See formulas in Appendix A).

Several assumptions are made during the interpretation of seismic refraction data. 1) The velocity of each successively deeper geologic

layer is greater than the layer above it. 2) Each layer is isotropic and has a constant velocity within its boundaries. 3) Each layer is sufficiently thick to be detected by refraction. 4) The boundary between two layers can be approximated by a plane (Dix, 1939a; Dix, 1939b; Musgrave, 1967).

The first assumption is necessary because energy travelling from a faster to a slower layer will be refracted toward the normal in the slower layer. Thus a low velocity layer beneath a high velocity layer will not be a first arrival on the time-distance plot, and the next high velocity layer will appear deeper than it really is. In this study the deeper, more compacted sediments are less porous and will have a higher velocity than the shallower ones, and near-surface sediments will have a lower velocity than the underlying basalt.

Constant velocity within each layer is often not an accurate assumption. Compacted sediments with a linear increase in depth will show on the time-distance plot as a curved line (Rockwell, 1967). Usually the average velocity within the interval being investigated is used and provides an adequate approximation of the actual conditions. Velocity may also vary laterally within a layer but will usually be averaged out over the length of the refraction line (Dobrin, 1960; Redpath, 1973). Other factors influencing the velocity within a layer include the presence of water which will increase the velocity and joints or fractures which will decrease the velocity (Dobrin, 1960).

Many, if not most, interfaces between geologic layers are non-planar. Surface irregularities in the interfaces will affect the transmission of seismic energy. Usually the first arrival times will

be scattered about a line which can be taken as the average velocity on the time-distance plot. High frequency energy (short wavelength) is absorbed faster than low frequency energy and is scattered more by irregularities as distance from the source increases. This may result in less distinct arrivals at greater distances from the source (Redpath, 1973). A gap of no arrivals on the seismic record may indicate the presence of a large irregularity in the refracting horizon (Dix, 1952).

Most errors in seismic refraction interpretation result from three general causes: 1) incorrect reading of the data, 2) incorrect assumptions, 3) incorrect geologic interpretation (Northwood, 1967). Incorrect picking of first breaks leads to errors in depth and dip calculations, and is especially likely when velocity contrasts between two successive layers are not very great or there is a large amount of background noise. Incorrect assumptions can be minimized by using all available data on the local geology and checking interpretations against bore hole data.

The depths to the refracting horizons shown on the cross sections are not exact, and at best are close approximations. The depth values cover a range, resulting from different velocity readings in opposite directions for each layer and variations in velocity along the line. The values shown on the cross sections are within the calculated range and represent a simple geologic interpretation that is consistent with the data. Similarly, locations of faults and vertical offsets are shown within their possible range (For example, see Figure 12).

The remainder of this chapter is used for discussion and presen-

tation of the data for each refraction line. The lines are presented in order from southeast to northwest through the study area. The time versus distance plot and schematic cross section is included with the discussion for each line.

RESULTS AND DISCUSSION

Thompson Road Line

The Thompson Road line is 90 meters long. This location (Shown in Figure 3), was chosen for the purpose of determining the depth and dip of the upper surface of the Columbia River basalt. Columbia River basalt has been mapped at this location (Trimble, 1963; Schlicker and Deacon, 1967; and Newcomb, 1967), although outcrops could not be found in the field. The surface along this line consists of a clayey soil with widely scattered basalt cobbles and boulders. The length of the line was limited to 90 meters because NW Thompson Road has no straight segments longer than about 100 meters in this vicinity.

Two velocity layers were observed in the time-distance curve (Figure 12). The surface layer has an average velocity of about 700 m/s. The second layer has a velocity of 1475 m/s. The surface of the first refracting layer has been modeled to include a fault. The fault is shown schematically on the cross section as a vertical displacement. The time-distance curve indicates that the southeast side of the fault has moved up relative to the northwest side. The throw of the fault was calculated to be about 6 meters.

The surface of the second layer dips between 0 and 5 degrees to the northwest. The depth to the first refracting layer below the

THOMPSON ROAD LINE

Figure 12. Thompson Road refraction line, time-distance plot and generalized cross section.

northwest shot point is between 8 and 11 meters. The depth to the first refracting layer below the southeast shot point is between 6 and 9 meters below the surface.

Bonny Slope Line

The Bonny Slope line (See Figure 3), 350 meters long, is made up of two segments which have a bend between them of about 45 degrees. Segment one, 170 meters long, was run in an east-west direction. Segment two, 180 meters long, was run at approximately N45°W. Both segments share a common shot point at the curve in NW Laidlaw Road. The location of the Bonny Slope line was chosen to investigate the nature of the contact between the Columbia River basalt and the sedimentary unit that Trimble (1963) has mapped as Sandy River mudstone and Schlicker and Deacon (1967) have called Troutdale Formation. The Bonny Slope line crosses this mapped contact near the middle of the line (See Figure 3).

The time-distance plot and generalized cross section of the Bonny Slope line are illustrated in Figure 13. This line differs from the others in the study in that the seismic signal was rapidly attenuated or possibly refracted downward in the central part of the line. The first breaks for the geophones 140 - 170 meters from the northwest shot point could not be picked off the seismic record. The time-distance plot was difficult to model because high velocities (greater than 2000 m/s) were only recorded in the central part of the line.

The time-distance curve for the Bonny Slope line indicates the presence of at least three velocity layers that may be discontinuous. The surface layer has a velocity ranging between 500 and 800 m/s.

Lower velocities for this layer were recorded on the west end of the line.

The second layer has a velocity ranging between 900 and 1750 m/s. This layer has been split into two units on the cross section, the upper unit shown as being discontinuous. The lower velocity (1300 - 1400 m/s) upper unit of the second layer is better defined on the southeastern half of the line and may be a separate unit above the 1754 m/s layer. The 925 m/s layer is included on the northwest end of the line in response to the apparent velocity of 742 recorded on the 0 - 80 meter segment of the line. The 1733 - 1754 m/s layer is shown to be continuous throughout the line. A velocity in this range was recorded from each shot point.

A forth velocity layer is indicated on the cross section with a velocity of around 6500 m/s. This high velocity layer was detected only in the central part of the line on the extended shots from each end of the line. The apparent velocity of 5623 m/s was also recorded on the 170 - 260 meter segment from the 260 meter shot point. This layer was not encountered on profiles shot from the central shot point (170 meters).

Depths to the first refracting layer were calculated to be between 4 and 13 meters. This layer apparently dips away from the central part of the line between 5 and 10 degrees.

The upper part of the second layer is between 5 and 7 meters thick on the southeastern half of the line. This layer dips between 0 and 5 degrees to the southeast. The thickness of this layer is estimated to be between 0 and 15 meters at the northwest end of the line.

The lower part of the second layer is shown to be between 13 and 25 meters thick, although these values are at best close approximations.

The depth to the high velocity layer in the central part of the line is shown to be between 25 and 40 meters on the cross section. The absence of this unit on either end of the line may indicate that this layer dips away from the central part of the line up to 15 degrees. This layer could also be discontinuous or possibly faulted.

Several of the first arrivals are scattered about a line when plotted on a time versus distance graph. This may indicate the presence of an undulatory refracting surface.

Laidlaw Road Line

A 90 meter line was run along NW Laidlaw Road (See Figure 4). This location was chosen for the purpose of locating the upper surface of the Columbia River basalt sloping into the valley. Equipment problems, traffic noise, and limited space along NW Laidlaw Road resulted in discontinuing this line past 90 meters.

Three velocity layers were interpreted from the time-distance plot (Figure 14). The surface layer was recorded to have a velocity of 573 m/s. Apparent velocities of 1552 and 1735 m/s were recorded for the first refracting layer which has an actual velocity of 1638 m/s. Several of the phones recorded first breaks that did not fit on a straight line indicating an undulating upper surface on the second layer. A third velocity layer is indicated on the time-distance plot with an apparent velocity of 4800 m/s. This layer was recorded by the last three phones (80 - 90 meters) on the shot at the west end of the line.

LAIDLAW ROAD LINE

Figure 14. Laidlaw Road refraction line, time-distance plot and generalized cross section.

The surface of the second layer has an apparent dip of about 5 degrees westward which is roughly parallel to the topography. The upper surface of this layer occurs at a depth of about 6 meters below the west shot point and 7 meters below the east shot point. The third layer was recorded on the east end of the line and is estimated to occur approximately 19 - 25 meters below the surface.

Bronson Creek Line

The Bronson Creek line, 360 meters, was run under ideal conditions along NW 124th Street (See Figure 4). There was minimal noise and the quality of the seismic signal was good. This line was run roughly perpendicular to the slope of the hill which extends down to Bronson Creek between two Boring Lava cones. The line is run across an area that has been mapped as Columbia River basalt (Trimble, 1963), Troutdale Formation (Newton, 1967), and across the contact between the two formations (Schlicker and Deacon, 1967). The lines were run to determine the local thickness of the sediment or "weathered" layer overlying the Columbia River Basalt.

The time-distance plot (Figure 15) is relatively complicated and indicates the presence of at least three velocity layers. The first breaks for most of the phones could be fit directly on straight lines on the time-distance plot which may indicate that the refracting horizons are relatively smooth.

Surface velocities ranged between 500 and 960 m/s. Higher surface velocities were recorded from the 0 and 360 meter shot points (See Figure 15). Velocities between 500 and 600 m/s were recorded for each of the other shot points on the line.

BRONSON CREEK LINE

Figure 15. Bronson Creek refraction line, time-distance plot and generalized cross section.

Apparent velocities of the second layer ranged between 1300 and 3500 m/s, averaging around 1500 m/s. The lack of symmetry between the reversed profiles on the time-distance plot (See Figure 15) may indicate that the second layer is broken up into separate blocks. Calculated true velocities for the second layer ranged between 1400 and 3000 m/s. The higher velocities were recorded in the central part of the line, which is opposite of what was recorded for the surface layer. The wide range of velocities may indicate that the second layer has several different velocity zones which may be related to degree of consolidation of the rock.

The time-distance plot indicates the presence of a third layer which was detected on each end of the line. An apparent velocity of 10,000+ m/s was recorded in each direction by distant geophones from the central shot point. A velocity of 8750 m/s was also recorded by the last four geophones (340 - 360 meters) on the 270 meter shot. The high apparent velocities may indicate that the third layer is steeply dipping or possibly faulted.

A simplified interpretation of the time-distance plot is presented in the cross section in Figure 15. Depths to the first refracting layer range from 6 - 12 meters at the end shot points to 19 - 27 meters in the central part of the line. The surface of this refracting layer is nearly horizontal but becomes deeper in the central part of the line because of the surface topography. The depth to the second refracting layer is estimated to be between 25 and 60 meters.

Springville Lane Line 1

Springville Lane line one, 180 meters, was run in an east-west

direction perpendicular to Springville Lane line two. The shot point at the east end of line one is at the same location as the central shot point on line two. Trimble (1963) mapped the contact between Columbia River basalt and Boring Lava near this location (See Figure 4). This area was mapped as Upland silt by Schlicker and Deacon (1967). The lines were run for the purpose of determining the local thickness of surface sediment and the dip of the basalt.

The records were of good quality and interpretation of the time-distance plot (Figure 16) was relatively straight forward with the exception of the profile that was shot from the west end of the line. The seismic energy was highly attenuated on the eastern end of the line and there was difficulty picking first breaks past 130 meters (from the west end of the line).

Three layers are interpreted from the time-distance plot. The surface velocity was recorded to be 417 m/s on three of the four profiles. Apparent velocities for the second layer range from 1105 to 1522 m/s, averaging around 1350 m/s. The first breaks were scattered about a line on the time-distance plot indicating an undulating upper surface on the second layer. The profile shot from the west end is broken up into apparent velocities of 1105, 2325, and 2551 m/s on the time-distance plot (See Figure 16). These segments do not correlate with the corresponding velocity segments from the other shot points and may represent either the second or third velocity layer. The value of 1105 m/s was used for the depth and dip calculations for the second layer because of its similarity to the velocities from the other shot points. The apparent velocities of 2326 and 2551 m/s were interpreted

Figure 16. Springville Lane refraction line 1, time-distance plot and generalized cross section.

to represent a third layer. A third velocity layer is also indicated by the apparent velocity of 3333 m/s on eastern end of the time-distance plot (See Figure 16).

The "true" velocities and depths to the refracting layers are shown on the generalized cross section. The second layer has a true velocity ranging from 1200 to 1500 m/s and occurs at a depth of 2 to 3 meters below the surface. This layer is nearly horizontal, having a dip between 0 and 3 degrees to the east. The third layer is estimated to have a velocity between 2400 and 3400 m/s and occur at a depth of 18 to 30 meters below the surface. The offset velocity segments representing the third layer on the time-distance plot may indicate that this layer is broken into blocks with varying amounts of dip. The absence of the third layer on the west facing profiles is interpreted to indicate that the third layer dips westward.

Springville Lane Line 2

Springville Lane line two (See Figure 4), 180 meters long, was the "best behaved" of all the lines run in this study. The records were of good quality, the first breaks were generally easy to pick, and the time-distance curve had a relatively straight forward interpretation. Springville Lane has very little traffic and the line was run on a clear, calm day which resulted in collection of data with very little background noise. Furthermore, the seismic energy was transmitted with very little attenuation. The time-distance curve (Figure 17) can be interpreted as a nearly horizontal three-layer model.

The surface velocity was recorded to be between 400 and 700 m/s which is in agreement with the surface layer velocity recorded for

SPRINGVILLE LANE LINE 2

Figure 17. Springville Lane refraction line 2, time-distance plot and generalized cross section.

Springville Lane line one. The direct wave may have encountered higher velocity material near the 0 and 180 meter (from the north end of the line) shot points resulting in faster surface velocities. Apparent velocities for the second layer ranged from 1478 to 1540 m/s for profiles shot in the southern direction and 1621 to 1671 m/s for profiles shot in the northern direction. Apparent velocities of 3667 and 3714 m/s were recorded for the third layer. Nearly all of the first breaks plotted directly on straight lines indicating relatively smooth refracting horizons.

A schematic cross section for Springville Lane line two is presented in Figure 17. The surface layer was calculated to have a thickness ranging from 1 to 3 meters. The first refracting horizon dips southward less than 1 degree and has an actual velocity of approximately 1575 m/s. The third layer occurs at a depth of 48 to 50 meters and dips southward a fraction of a degree. This layer has a calculated true velocity of 3685 m/s.

Germantown Road Line

A 90 meter refraction line was run along the southern edge of NW Germantown Road about 15 meters east of the intersection with NW Kaiser Road (See Figure 5). This location was chosen for the purpose of attempting a correlation with the data collected along NW Kaiser Road south of the intersection. There was good transmission of the seismic energy and good records were obtained in the field. This line encountered a high velocity layer very near the surface. Interpretation of the time-distance plot (Figure 18) indicates the presence of three velocity layers with refracting surfaces roughly parallel to the sur-

GERMANTOWN ROAD LINE

Figure 18. Germantown Road refraction line, time-distance plot and generalized cross section.

face topography.

The surface layer along this line is relatively thin which caused some difficulty recording an accurate surface velocity. The first refracting horizon was recorded as the first break by the second geophone which was spaced 10 meters from the shot point. Therefore, the surface velocity was only recorded by the closest geophone to the shot point and was assigned a value of 456 m/s. This value was based on the first arrivals recorded at each end of the line and is in agreement with surface velocities recorded on other lines.

A true velocity of 2025 m/s was calculated for the second layer. This layer is represented by apparent velocities of 1767 and 2373 m/s. A third layer is indicated on the time-distance curve by the apparent velocities segments of 2624 and 3888 m/s. This layer has a true velocity of 3131 m/s.

The true velocities and depth to velocity layers are shown on the schematic cross section in Figure 18. The second layer occurs at a depth of 2 meters below the southwest shot and 3.5 meters below the northeast shot. The upper surface of this layer dips northeastward approximately 5 degrees. The third layer dips about 7 degrees eastward and occurs at a depth of 13 to 17 meters below the surface.

Kaiser Road Line

Kaiser Road Line, 180 meters long, was run in a southern direction from the intersection of NW Germantown and NW Kaiser Road, nearly perpendicular to Germantown Road Line (See Figure 5). The purpose of this location was to record the seismic velocity of Columbia River basalt which crops out on the northern half of the line. Similar to

Germantown Road Line, there was low attenuation of the seismic energy, the first breaks were clearly visible, and the records were good compared with most of the other lines. The time-distance plot (Figure 19) is interpreted to represent two velocity layers, the upper (weathered) velocity being recorded by only the first two phones at the southern end of the profile. The second layer, which has a relatively high velocity, occurs at the surface on the northern end of the line.

The surface velocity was recorded to be 556 m/s. This value is in agreement with surface velocities measured on other lines, although it was recorded by only one shot point on this line.

Apparent velocities recorded for the second layer ranged from 2167 to 3366 m/s with an average value of about 2600 m/s. The higher velocities were recorded on the northern end of the line. True velocities were calculated to be between 2600 and 3100 m/s. The field data plots as a series of segments having relatively the same slope on the time-distance curve, thus indicating that the upper surface of the second layer may be broken up into separate blocks. The amount of offset between blocks is a few meters or less and therefore not shown on the schematic cross section.

The generalized cross section for Kaiser Road line is presented in Figure 19. The dip of the interface between the two layers varies between 0 and 3 degrees to the south. The second layer occurs at a depth of 6 meters at the south end and at the surface on the north end of the line.

Rock Creek Line

Rock Creek line, 145 meters in length, was run along the northern

KAISER ROAD LINE

Figure 19. Kaiser Road refraction line, time-distance plot and generalized cross section.

edge of NW Germantown Road (See Figure 5). This location was chosen for the purpose of attempting to locate the subsurface contact between the Columbia River basalt and the alluvium occurring near Rock Creek. The velocity difference between stream alluvium (400 - 2000 m/s) and underlying basalt (2500 - 4500 m/s) indicate that this surface should be detectable by seismic refraction (Telford and others, 1976). Heavy traffic noise along NW Germantown Road and problems with the operation of the electric winch resulted in the collection of records that were of relatively poor quality. Furthermore, the total travel time for the westward profile had to be reduced 0.030 seconds to make the total travel times equal for each shot. In theory, the total travel times (from source to most distant geophone) must be equal for reversed profiles.

Three velocity segments can be interpreted from the time-distance plot (Figure 20). An accurate surface velocity was not obtained because of the large geophone spacing used on this line (10 - 15 meters). The surface layer is estimated to have a velocity of 556 m/s. This value is based on the first breaks recorded by the geophones nearest to the shot points and surface velocities recorded on other lines.

Apparent velocities of 1167 and 1484 m/s were recorded for second velocity layer. The calculated true velocity for this layer is 1304 m/s. The third layer has a velocity of 4205 m/s. This value was calculated from apparent velocities of 4394 and 4105 m/s.

The second layer is nearly parallel to the surface topography and occurs at a depth of 2.5 to 4.5 meters below the surface (See Figure 20). The third layer occurs at a depth of 13 meters below the west

ROCK CREEK LINE

Figure 20. Rock Creek refraction line, time-distance plot and generalized cross section.

shot point and 17 meters below the east shot point. This implies that the third layer is horizontal.

Cornelius Pass Line

Cornelius Pass Line (See Figure 6) was the first line run in this study. The purpose of this line was to record the depth to Columbia River basalt which has been mapped at this location (Trimble, 1963; Schlicker and Deacon, 1967). This line was started near the intersection with NW Kaiser Road with the intention of continuing it southward into the valley along Cornelius Pass Road. Cornelius Pass Road is one of the main thoroughfares in the area which caused a problem with background noise. First breaks could not be distinguished on the record past 90 meters. Although field work at this location was discontinued after the first day, two 90 meter segments were completed on either side of NW Kaiser Road.

The time-distance plot (Figure 21) for the segment north of NW Kaiser Road is interpreted to represent three velocity layers that nearly parallel the surface topography. The surface layer has an average velocity of 432 m/s. This layer is estimated to vary in thickness from 2 to 4.5 meters. The surface layer is apparently thicker at the northern end of the line.

The second layer is represented by apparent velocities of 1076 and 1562 m/s on the time-distance curve (See Figure 21). This layer has a true velocity of 1271 m/s and dips about 4 degrees to the south. The third layer has a velocity of 2911 m/s. The apparent velocities recorded for this layer range from 2121 to 4669 m/s. The second refracting surface occurs at a depth of 15 meters below the south shot

Figure 21. Cornelius Pass refraction line, time-distance plot and generalized cross section.

and 18 meters below the north shot. This surface has an apparent dip of 3 degrees to the south.

The data recorded for the 90 meter segment run south of NW Kaiser Road has a similar appearance to the previous segment run on Cornelius Pass Road although higher velocities are indicated on the time-distance plot (See Figure 21). This segment can be modeled as three velocity layers which dip to the south.

The surface layer has a velocity of 556 m/s. This layer has a thickness of 3 meters below the north shot and 3.5 meters below the south shot point. These values are in agreement with those calculated for the first segment of this line.

A true velocity of 1355 m/s was calculated for the second layer, which is similar to the corresponding layer in the first segment. Apparent velocities of 1333 and 1377 m/s were recorded for this layer. The second layer has an apparent dip of about 5 degrees to the south. The upper surface of this layer roughly parallels the surface topography.

The velocity and depth to the third layer deviates from the values calculated for the first segment. Apparent velocities recorded for this layer ranged from 3558 to 6500 m/s. A true velocity of 4586 m/s was calculated for the third layer. The third layer occurs at a depth of 22 meters below the north shot and 30 meters below the south shot point (See Figure 21). The top of the third layer has an apparent dip of 10 degrees to the south.

SUMMARY AND CONCLUSIONS

The generalized cross sections that have been presented thus far illustrate velocity layers in the subsurface. The velocities and depths to the layers are calculated values that represent possible models of the data that was collected on each line. The following cross sections are geologic interpretations of the velocity - layer models. The interpretations are based primarily on the refraction data along with previous mapping in the area and observations in the field. The cross sections in this chapter represent possible geologic models of the calculated geophysical models.

Figure 22 contains cross sections of the four refraction lines in the northwest half of the study area (See Figures 5 and 6) along with Laidlaw Road refraction line (See Figure 4). These cross sections are grouped together because of their similar appearance and interpretation.

All five cross sections contain three layers with the exception of Kaiser Road line, which has only two. The surface layer in each cross section ranges in velocity from 432 to 577 m/s. This relatively low velocity is indicative of very poorly consolidated material such as soil or alluvium (Dobrin, 1960). This layer ranges in thickness from 0 to 7 meters and occurs as a fairly uniform surface layer which appears to mantle the topography. This layer is interpreted as alluvium on Rock Creek refraction line and loessal deposits of Willamette and Upland silt on the other lines.

Figure 22. Comparison and interpretation of Cornelius Pass, Rock Creek, Germantown Road, Kaiser Road, and Laidlaw Road refraction lines.

The second layer, which is absent from Kaiser Road line, can be interpreted as highly weathered basalt or sedimentary rock. This layer ranges in velocity from 1272 to 2025 m/s and averages about 15 meters thick. The velocities of clay (915 - 1830 m/s), sandstone (1830 - 2440 m/s), and fractured basalt (2745 - 4270 m/s), (Redpath, 1973) are within the range of the velocity for the second layer. Trimble (1963) notes that the basalt in the Tualatin Mountains readily alters to clay minerals and the alteration (weathering) may be as deep as 52 meters (Allen, 1948). The velocity of fractured basalt would be lowered depending on the degree of weathering. The velocity of the second layer is also within the range that would be expected for the sand, silt, and clay of the Troutdale Formation.

The third layer (2911 - 4586 m/s) is interpreted as Columbia River basalt. Fresh vesicular basalt crops out in the ditch along along NW Kaiser Road at the north end of the line. This unit was interpreted to be high-Mg Grande Ronde Basalt (Beeson, pers. com., 1987). All five lines were run at locations where Trimble (1963) has mapped Columbia River basalt (See Figures 4 - 6), although the only outcrops of fresh basalt were found along NW Kaiser Road. The basalt occurs at depths ranging from 0 to 31 meters, averaging around 17 meters below the surface. It should be noted that the upper surface of the basalt roughly parallels the surface topography on each cross section. This may indicate that the basalt controls the topography and the second velocity layer is weathered basalt, which would be expected to overlie fresh rock. It is uncertain as to why the weathered layer is absent from the Kaiser Road line.

Figure 23 illustrates the geologic interpretation of Springville Lane lines 1 and 2 (See Figure 4). These lines are located along the margin of an area that has been mapped as Boring Lava by Trimble (1963) and Schlicker and Deacon (1967). The area immediately to the west topographically resembles a Boring Lava cone (See Figure 2), although no outcrops of Boring Lava were found in the field. Consistent data was collected from each line and both were modeled as three velocity layers.

The surface layer is interpreted as Upland silt. The velocity (400 - 700 m/s) is similar to the surface velocities recorded on other lines and Upland silt was expected to occur here. The silt mantles the topography and ranges in thickness from 2 to 4 meters.

The velocity of the second layer (1200 - 1575 m/s) is indicative of weathered basalt or a sedimentary unit. This layer is shown to range in thickness from 16 to 48 meters and is interpreted as Boring Lava. Trimble (1963) notes that Boring Lava may be weathered 25 feet (7.6 m) or more. The relatively low velocity of the basalt may be due to an average velocity of highly weathered and fractured basalt. The spheroidal weathering of Boring Lava (Trimble, 1963) may result in the seismic signal traveling with several high- and low-velocity segments which would result in an average velocity lower than what would be expected for fresh basalt. A low velocity (weathered) zone on top of the third layer may have lowered the average velocity further, thus causing the second layer to appear thicker than it actually is.

The third velocity layer (2450 - 3685 m/s) is shown as Columbia River basalt on the cross sections. This velocity is within the range

of what was recorded for Columbia River basalt on other lines. This layer may actually be Boring Lava. The seismic velocity of unweathered Boring Lava could be the same as the seismic velocity of Columbia River basalt.

The difference between the upper surface of the third layer in each cross section in Figure 24 can be explained by the two time-distance plots. Springville Lane line 2 has three distinct velocity segments in both directions of the reversed profile (See Figure 17). This can be modeled as three nearly-horizontal velocity layers. The reversed profiles on Springville Lane line 1 (See Figure 16) do not appear to match and have been modeled as a series of broken blocks. This is interpreted to indicate that Springville Lane line 1 was run perpendicular to the local subsurface structure while Springville Lane line 2 was run parallel to the local structure and therefore did not detect any structural discontinuities.

Figure 24 illustrates the geologic interpretation of the three remaining refraction lines. Bronson Creek refraction line was run across an area that has been mapped as Columbia River basalt (Trimble, 1963) and Troutdale Formation (Hart and Newcomb, 1965) (See Figure 4). The surface layer velocity (500 - 900 m/s) (See Figure 15) is indicative of poorly consolidated sediment. The surface layer is interpreted as Troutdale Formation mantled by Upland silt. The two formations may not be distinguishable through seismic refraction and are therefore grouped together here. The lower surface velocities (500 m/s) recorded in the central part of the line could indicate that the loessal deposits are thicker on the crest of the ridge. The higher surface

Figure 24. Comparison and interpretation of Thompson Road, Bonny Slope, and Bronson Creek refraction lines.

velocities (900 m/s) recorded from the end shot points may be the result of more Troutdale "influence".

The second layer shown in the Bronson Creek cross section (1400 - 3000 m/s) could be interpreted as weathered basalt or compacted sediment. Because of the line location and the depth of the unit, fractured or weathered basalt is more likely than sediment, although the Troutdale may grade into Columbia River basalt through a weathered basalt zone.

A faulted or very steeply dipping third layer is indicated by the very high apparent velocities on the time-distance plot (See Figure 15). This layer, which is interpreted as Columbia River basalt, may be broken into blocks.

Thompson Road and Bonny Slope refraction lines were run for the purpose of examining the sedimentary unit that Trimble (1963) has mapped as Sandy River mudstone, Schlicker and Deacon (1967) have mapped as Troutdale Formation, and Thoms (pers. com., 1987) has interpreted as Scappoose Formation. The town of Bonny Slope (See Figure 3) is located on an exposed "window" of sediment that is presumably stratigraphically below the Columbia River basalt. The data collected on the Bonny Slope line indicate that the sedimentary unit is not underlain by high velocity material (Columbia River basalt). Thus it is concluded that this sedimentary unit is part of the Scappoose Formation.

The surface velocity (500 - 800 m/s) layer on Thompson Road and Bonny Slope lines is interpreted as Upland silt. This layer varies in thickness from 3 to 12 meters and is found throughout both lines. The second layer on Thompson Road line was modeled as being faulted with

about 8 meters of offset. Based on its velocity, location, and the presence of basalt cobbles in the soil along Thompson Road, this layer is interpreted as weathered basalt. A third layer was not detected on Thompson Road line.

The data collected on the Bonny Slope refraction line indicate that this was the only line in the study that crossed a large, shallow (0 - 50 m) velocity discontinuity. The time-distance plot (See Figure 13) indicates several discontinuous velocity layers. The velocity layers were interpreted as separate geologic units (See Figure 24), although the different velocities may be related to degree of compaction or the presence of water, not necessarily changes in lithology.

The main point to note on the Bonny Slope refraction line is that the Columbia River basalt is absent from the southeast half of the line. A high velocity (>3000 m/s) layer was encountered on the northwest half of the line, although the data indicate that this unit is discontinuous or possibly steeply dipping (apparent velocities of 7500 and 7667 m/s). In the central part of the line, attenuation of the seismic energy indicated disrupted, rather than smooth refracting horizons. Based on these observations, the Bonny Slope line was modeled to include a fault. This may be an erosional contact between the Columbia River basalt and the Scappoose Formation rather than a fault plane as is shown in the cross section (Figure 24). Dispersion of the seismic signal would also be expected along a steeply dipping erosional surface. The geologic models produced could not prove or disprove the presence of a major fault in the study area, although the data col-

lected on the Bonny Slope line supports the hypothesis that the Scappoose Formation is exposed at the town of Bonny Slope.

The following general conclusions can be made from this study:

- 1) Upland silt mantles most of the study area at fairly uniform thicknesses ranging from 2 to 10 meters.
- 2) Columbia River basalt roughly parallels the surface topography at depths of 0 to 30 meters averaging around 15 meters below the surface.
- 3) The basalt is usually overlain by a 5 to 15 meter thick layer interpreted to be a weathered zone. This layer is usually of uniform thickness and parallels the basalt.
- 4) Offset refacting horizons indicate that the Columbia River basalt is broken up into blocks in several places.

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APPENDIX A

Appendix A presents the refraction data that was taken directly off the field records for each line. The data is presented in the order that it was discussed in the text. This data was used for the purpose of constructing the time-distance plots.

The data is presented using the following format: 1) The values under the line column indicate, in meters, the location of the geophone array on the line. Zero meters is taken to be on the left hand side of the line on the time-distance plots. 2) The values under the shotpoint column indicate, in meters, the location where the weight was dropped. The shot points are shown in Figures 3 - 6. 3) The values under the numbered columns (1 - 12) indicate, in seconds, the first arrival times recorded by the 12 geophones. 4) The column on the right indicates the relative quality of each field record based on a scale from A-F. The record quality was determined based on the amount of background noise and the ability to pick first arrivals.

The geophone spacing was five meters between the first two geophones on each end of the line and ten meters between the other geophones which resulted in 90 meters lines. Exceptions to this were the 0 - 80 line on the Bonny Slope line and the 145 meter Rock Creek line. Because of limited space on the Bonny Slope line, the first array was set up with five meter spacing between the first three phones on each end of the line and ten meters between the other phones. Because of limited time completing the Rock Creek line, a single 145 meter line

was set up using a ten meter spacing between the three phones at each end of the line and fifteen meters between the other phones.

Thompson Road Line

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.011	.030	.037	.047	.047	.050	.058	.069	.075	.079	.080	A
	90	.076	.074	.069	.066	.061	.046	.035	.030	.025	.011	.007	0	A
		Northwest										Southeast		

Bonny Slope Line

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-80	0	0	.014	.025	.036	.053	.070	.079	.087	.089	.099	.101	.105	C
	80	.117	.116	.110	.098	.081	.070	.057	.035	.023	.012	.014	0	B
	170	.118	.117	.113	.107	.103	.100	.090	.085	.084	.076	.076	.073	D
80-170	80	0	.009	.016	.034	.044	.057	.072	.076	.083	.090	.092	.093	C
	170	.073	.066	.061	.059	.052	.048	.041	.034	.025	.017	.014	0	B
	0	.105	.106	.107	.108	.108	.111	.112	-	-	-	-	-	F
170-260	170	0	.010	.017	.025	.033	.042	.047	.053	.059	.062	.066	.067	A
	260	.061	.059	.059	.058	.052	.043	.040	.034	.025	.014	.008	0	B
	350	.120	.118	.120	.116	.116	.111	.104	.099	.094	.083	.075	.077	C
260-350	260	0	.008	.012	.027	.037	.046	.050	.060	.062	.064	.070	.071	A
	350	.077	.076	.073	.073	.070	.064	.057	.050	.039	.018	.008	0	A
	170	.067	.070	.071	.083	.091	.097	.103	.109	.110	.115	.121	.122	B
		Northwest										Southeast		

Laidlaw Road Line

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.006	.025	.029	.035	.039	.042	.051	.062	.069	.070	.071	C
	90	.072	.070	-	.065	.056	.046	.040	.038	.032	.014	.006	0	C
		West										East		

Bronson Creek Line

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.004	.011	.022	.033	.042	.051	.061	.075	.081	.085	.089	A
	90	.090	-	-	.086	.082	.076	.062	.047	.033	.021	.009	0	A
	180	.126	.126	.127	.127	.126	.126	.127	.126	.123	.119	.124	.118	C
90-180	90	0	.007	.020	.036	.051	.070	.088	.100	.105	.111	.113	.115	A
	180	.118	.116	.114	.111	.103	.095	.078	.060	.042	.026	.011	0	A
	0	.089	.092	.095	.101	.104	.109	.111	.113	.120	.121	.130	.133	B
180-270	180	0	.008	.020	.044	.058	.076	.086	.093	.097	.100	.104	.105	A
	270	.105	.100	.097	.090	.084	.077	.071	.059	.042	.021	.010	0	B
	360	.142	.133	.141	.129	.121	.116	.103	.097	.091	.081	.078	.075	D
270-360	270	0	.009	.021	.037	.041	.046	.053	.060	.068	.070	.068	.069	A
	360	.076	.066	.062	.056	.048	.042	.037	.030	.020	.009	.003	0	A
	180	.105	.104	.105	.109	.110	.117	.125	.131	.139	.141	.142	.141	D
		North										South		

Springville Lane Line 1

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.007	.020	.032	.039	.049	.053	.057	.062	.084	.086	.086	A
	90	.086	.076	.075	.062	.059	.052	.046	.037	.030	.019	.007	0	B
	180	-	.145	.133	.127	.118	.113	.108	.097	.089	.084	.080	.077	C
90-180	90	0	.008	.020	.031	.037	.045	.050	.056	.065	.070	.072	.073	B
	180	.077	.070	.067	.057	.054	.049	.039	.036	.029	.019	.007	0	A
	0	.086	.093	.097	.099	.114	-	.116	.130	-	-	-	-	F
West												East		

Springville Lane Line 2

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.004	.014	.018	.026	.033	.039	.047	.053	.060	.063	.066	A
	90	.062	.059	.056	.052	.044	.040	.033	.027	.020	.014	.006	0	A
	180	.115	.111	.109	.107	.104	.097	.092	.085	.082	.075	.073	.068	C
90-180	90	0	.008	.019	.025	.031	.037	.043	-	.053	.064	.067	.068	A
	180	.068	.063	.061	.054	.048	.040	.033	.029	.026	.010	.004	0	A
	0	.066	.068	.072	.080	.085	.093	.097	-	.110	.115	.116	.117	B
North												South		

Germantown Road Line

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.010	.013	.019	.024	.030	.034	.038	.042	.047	.045	.049	A
	90	.045	.046	.044	.042	.037	.034	.030	.025	.021	.017	.012	0	A
Southwest												Northeast		

Kaiser Road Line

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.008	.017	.025	.030	.033	.037	.040	.041	.042	.043	.046	B
	90	.042	.040	.038	.036	.030	.024	.020	.017	.010	.007	.003	0	A
	180	.071	.064	.063	.062	.057	.053	.044	.040	.036	.035	.033	.032	B
90-180	90	0	.002	.004	.006	.010	.011	.015	.018	.022	.025	.026	.024	A
	180	.032	-	.024	.020	.021	.016	.013	.011	.007	.004	.002	0	B
	0	.046	.047	.049	.048	.050	.054	.058	.067	.068	.072	.072	.075	C
South												North		

Rock Creek Line

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-145	0	0	.019	.027	.036	.040	.044	.048	.050	.054	.057	.060	.063	D
	145	.092	.085	.078	.078	.073	.066	.060	.050	.039	.028	.016	0	C
West												East		

Cornelius Pass Line 1

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.009	.015	.024	.033	.042	.048	.052	.059	.062	.061	-	A
	90	.061	.059	.058	.058	.053	.052	.045	.038	.033	.024	.012	0	A
		South						North						

Cornelius Pass Line 2

<u>Line</u>	<u>Shotpoint</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>Record Quality</u>
0-90	0	0	.014	.018	.029	.035	.041	.049	.057	.060	.060	.061	.061	B
	90	.060	.058	.057	.055	.051	.045	.034	.032	.022	.015	.009	0	A
		South						North						

A. Critical angle, dip, depth and thickness of layers

$$\theta \text{ (critical angle)} = \frac{1}{2} \left[\sin^{-1} \frac{v_0}{v_d} + \sin^{-1} \frac{v_0}{v_u} \right]$$

$$\sin \theta = \frac{v_0}{v_1}$$

$$\phi \text{ (dip)} = \frac{1}{2} \left[\sin^{-1} \frac{v_0}{v_d} - \sin^{-1} \frac{v_0}{v_u} \right]$$

$$v_u > v_d$$

$$Z_d = \frac{t_{1d} v_0}{2 \cos \theta} \quad Z_u = \frac{t_{1u} v_0}{2 \cos \theta}$$

$$D_d = \frac{Z_d}{\cos \phi} \quad D_u = \frac{Z_u}{\cos \phi}$$

Multiple dipping layer formulas in Ewing, Woollard and Vine, 1938, and Mota, 1954.

$$v_0 < v_1 < v_2$$

$$Z_0 = \frac{t_1}{2} \frac{v_1 v_0}{\sqrt{v_1^2 - v_0^2}}$$

or

$$Z_0 = \frac{1}{2} \sqrt{\frac{v_1 - v_0}{v_1 + v_0}} X_c$$

$$Z_1 = \frac{1}{2} \left(t_2 - 2Z_0 \frac{\sqrt{v_2^2 - v_0^2}}{v_2 v_0} \right) \left(\frac{v_2 v_1}{\sqrt{v_2^2 - v_1^2}} \right)$$

B. Fault throw:

$$z_t = \frac{\Delta t v_0}{\cos \theta} = \Delta t \left(\frac{v_0 v_1}{\sqrt{v_1^2 - v_0^2}} \right)$$

APPENDIX B

```
C      PROGRAM THAT FITS A LINE TO A SET OF POINTS REPRESENTING
C      SEISMIC REFRACTION FIELD DATA.
C      THE SET OF POINTS ARE PICKED BY THE OPERATOR WHILE THE
C      PROGRAM IS RUNNING.
C      THE LINE IS CALCULATED BY THE LEAST SQUARES METHOD.
C      THE PROGRAM CALCULATES VELOCITY, ZERO INTERCEPT, AND
C      QUALITY OF FIT EACH LINE CALCULATED.
C      PROGRAM HAS BEEN MODIFIED AND TRANSLATED TO FORTRAN FROM
C      BASIC BY DAVE NAZY, PSU GEOLOGY DEPARTMENT.
C      THE PROGRAM WAS WRITTEN BY C. B. REYNOLDS AND WAS TAKEN
C      FROM "MICROCOMPUTER APPLICATIONS IN GEOLOGY", P. 47-57.
C
      DIMENSION A(100,2),B(100,2),C(100,2),D(100,2),DATA(100,2)
      DIMENSION XT(100,2)
      CHARACTER*4 LINE(10)
      CHARACTER*15 FILENAME
C
C      READ NAME OF SEISMIC LINE
C
      89 WRITE (*,80)
      80 FORMAT (/, ' TYPE THE NAME OF THE SEISMIC LINE' ,/)
      READ (*,90) LINE
      90 FORMAT (10A4)
      WRITE (*,100)
      100 FORMAT (/, ' TYPE DATA FILE NAME eg. B:SEIS.DAT ' ,/)
      READ (*,110) FILENAME
      110 FORMAT (A)
      OPEN (5,FILE=FILENAME)
      OPEN (6,FILE='LPT1')
C
C      READ NUMBER OF SHOT POINTS
C
      WRITE (*,200)
      200 FORMAT (/, ' HOW MANY SHOT POINTS ARE THERE ON THIS LINE? ' ,/)
      READ (*,*) NSP
      DO 10 I=1,NSP
C
C      READ DATA FILE
C
      CALL READM(DATA,N,M,100,2)
      DO 20 J=1,N
      DO 20 K=1,M
      IF (I.EQ.1) A(J,K)=DATA(J,K)
      IF (I.EQ.2) B(J,K)=DATA(J,K)
      IF (I.EQ.3) C(J,K)=DATA(J,K)
```

```

      IF (I.EQ.4) D(J,K)=DATA(J,K)
20  CONTINUE
10  CONTINUE

```

C

C READ WHICH SHOT POINT TO USE

C

```

299 WRITE (*,300)
300 FORMAT (/, ' WHICH SHOT POINT DO YOU WANT TO WORK WITH? ',//)
      WRITE (*,310)
310 FORMAT (/,10X, ' 1 - SHOT PT A ',10X, ' 2 - SHOT PT B ',//,10X, ' 3
      1- SHOT PT C ',10X, ' 4 - SHOT PT D ',//)
      READ (*,*) N1
      DO 30 J=1,N
      DO 30 K=1,M
      IF (N1.EQ.1) XT(J,K)=A(J,K)
      IF (N1.EQ.2) XT(J,K)=B(J,K)
      IF (N1.EQ.3) XT(J,K)=C(J,K)
      IF (N1.EQ.4) XT(J,K)=D(J,K)
30  CONTINUE

```

C

C READ WHICH POINTS TO USE

C

```

399 WRITE (*,400)
400 FORMAT (/, ' TYPE THE NUMBER OF THE FIRST PHONE YOU WANT FIT ON
      1 THE LINE ',/)
      READ (*,*) N2
      WRITE (*,420)
420 FORMAT (/, ' TYPE THE NUMBER OF THE LAST PHONE YOU WANT FIT ON THE
      1LINE ',/)
      READ (*,*) N3

```

C

C CALCULATE VELOCITY, ZERO INTERCEPT TIME, AND QUALITY OF FIT

C

```

      N4=(N3-N2)+1.
      XD=0.0
      TD=0.0
      XTD=0.0
      XQD=0.0
      TQD=0.0
      DO 40 I=N2,N3
          XD=XD+XT(I,1)
          TD=TD+XT(I,2)
          XTD=XTD+XT(I,1)*XT(I,2)
          XQD=XQD+XT(I,1)**2
          TQD=TQD+XT(I,2)**2
40  CONTINUE
      XM1=(XTD-(XD*TD)/N4)/(XQD-(XD**2)/N4)
      INT=1000.*(TD-XM1*XD)/N4+0.5
      ZINT=INT/1000.
      VEL=1/XM1
      IRSQ=1000.*XM1*(XD*TD/N4-XTD)/(TQD-(TD**2)/N4)-0.5
      RSQ=(IRSQ/1000.)*(-1.0)
C PRINT RESULTS

```

```

        WRITE (6,450) LINE
450  FORMAT (10A4)
        IF (N1.NE.1) GO TO 461
            WRITE (6,460)
460  FORMAT (//,' VELOCITY CALCULATED FROM SHOT POINT A')
461  IF (N1.NE.2) GO TO 471
            WRITE (6,470)
470  FORMAT (//,' VELOCITY CALCULATED FROM SHOT POINT B')
471  IF (N1.NE.3) GO TO 481
            WRITE (6,480)
480  FORMAT (//,' VELOCITY CALCULATED FROM SHOT POINT C')
481  IF (N1.NE.4) GO TO 491
            WRITE (6,490)
490  FORMAT (//,' VELOCITY CALCULATED FROM SHOT POINT D')
491  WRITE (6,500) VEL
500  FORMAT (/, ' VELOCITY OF LINE FIT TO DATA IS ',F8.2,' M/SEC')
        WRITE (6,510) ZINT
510  FORMAT (/, ' THE ZERO INTERCEPT OF THE LINE IS ',F6.4,' SECONDS')
        WRITE (6,520) N2,N3
520  FORMAT (/, ' THE LINE WAS FIT TO GEOPHONES ',I2,'-',I2)
        WRITE (6,530) RSQ
530  FORMAT (/, ' THE QUALITY OF LINE FIT IS ',F5.2)
        WRITE (6,540)
540  FORMAT ('*****',////////)
C
C  READ TO CONTINUE OR EXIT PROGRAM
C
        WRITE (*,600)
600  FORMAT (//,' DO YOU WANT TO CALCULATE ANY MORE VELOCITIES ?',//)
        WRITE (*,610)
610  FORMAT (/,10X,' 1 - YES, SAME LINE, SAME SHOT POINT',/,10X,' 2 -
1YES, SAME LINE, DIFFERENT SHOT POINT',/,10X,' 3 - YES, DIFFERENT
2LINE',/,10X,' 4 - NO, EXIT PROGRAM')
        READ (*,*) M4
        IF (M4.EQ.1) GO TO 399
        IF (M4.EQ.2) GO TO 299
        IF (M4.EQ.3) GO TO 89
        STOP
        END
C
        SUBROUTINE READM(E,N,M,N1,M1)
        DIMENSION E(N1,M1)
C  READ SIZE OF MATRIX
        READ (5,1000) N,M
C  READ MATRIX ONE ROW AT A TIME
        DO 1001 I=1,N
            READ (5,1002) (E(I,J),J=1,M)
1001  CONTINUE
        RETURN
1000  FORMAT (2I2)
1002  FORMAT (2F7.3)
        END

```

```

C
C   PROGRAM CALCULATES DIPS AND DEPTHS OF UP TO THREE REFRACTING
C   LAYERS.  THE OPERATOR INPUTS THE APPARENT VELOCITY AND THE
C   ZERO INTERCEPT OF EACH REFRACTING LAYER WHILE THE PROGRAM IS
C   RUNNING.
C
C   THE PROGRAM UTILIZES THE FORMULAS PRESENTED IN THE PAPER
C   BY LINDONOR MOTA ENTITLED "DETERMINATION OF DIPS AND DEPTHS
C   OF GEOLOGIC LAYERS BY THE SEISMIC REFRACTION METHOD",
C   GEOPHYSICS, V. 19, NO. 2, P. 242-254.
C
C   THE PROGRAM WAS WRITTEN IN FORTRAN TO RUN ON AN IBM
C   COMPATIBLE PC BY DAVE NAZY, PSU GEOLOGY DEPARTMENT.
C
C   CHARACTER*4 LINE(10)
C   OPEN (6,FILE='LPT1')
C   DEG=360./6.2831854
C
C   READ NAME OF SEISMIC LINE
C
C   14 WRITE (*,100)
C   100 FORMAT (/,' TYPE NAME OF SEISMIC LINE',/)
C   READ (*,110) LINE
C   110 FORMAT (10A4)
C
C   INPUT REQUIRED DATA
C
C   13 WRITE (*,200)
C   200 FORMAT (/,' TYPE THE VELOCITY OF THE SURFACE LAYER ',/)
C   READ (*,*) V0
C
C   WRITE (*,300)
C   300 FORMAT (/,' TYPE THE APPARENT VELOCITY OF THE SECOND LAYER FROM
C   1THE LEFT SHOT ',/)
C   READ (*,*) VA1
C
C   WRITE (*,400)
C   400 FORMAT (/,' TYPE THE APPARENT VELOCITY OF THE SECOND LAYER FROM
C   1THE RIGHT SHOT ',/)
C   READ (*,*) VB1
C
C   WRITE (*,500)
C   500 FORMAT (/,' TYPE THE FIRST ZERO INTERCEPT TIME FROM THE LEFT SHOT
C   1',/)
C   READ (*,*) TA1
C
C   WRITE (*,600)
C   600 FORMAT (/,' TYPE THE FIRST ZERO INTERCEPT TIME FROM THE RIGHT
C   1SHOT ',/)
C   READ (*,*) TB1

```

```

C      IF (VA1.GT.VB1) THEN
          IDIP1=1
        ELSE
          IDIP1=2
        ENDIF

C      WRITE (*,610)
610    FORMAT (/, ' ARE THERE THREE LAYERS IN YOUR MODEL ? ',/)
        WRITE (*,620)
620    FORMAT (/, ' TYPE 1 FOR YES, 2 FOR NO ',/)
        READ (*,*) I

C      IF (I.EQ.2) GO TO 10

C      WRITE (*,700)
700    FORMAT (/, ' TYPE THE APPARENT VELOCITY OF THE THIRD LAYER FROM
1THE LEFT SHOT ',/)
        READ (*,*) VA2

C      WRITE (*,800)
800    FORMAT (/, ' TYPE THE APPARENT VELOCITY OF THE THIRD LAYER FROM
1THE RIGHT SHOT ',/)
        READ (*,*) VB2

C      WRITE (*,900)
900    FORMAT (/, ' TYPE THE SECOND ZERO INTERCEPT TIME FROM THE LEFT
1SHOT ',/)
        READ (*,*) TA2

C      WRITE (*,1000)
1000   FORMAT (/, ' TYPE THE SECOND ZERO INTERCEPT TIME FROM THE RIGHT
1SHOT ',/)
        READ (*,*) TB2

C      IF (VA2.GT.VB2) THEN
          IDIP2=1
        ELSE
          IDIP2=2
        ENDIF

C      TWO LAYER CASE
C
C      10 RCA1=0.5*(ASIN(V0/VA1)+ASIN(V0/VB1))
          RDIP1=0.5*(ASIN(V0/VB1)-ASIN(V0/VA1))
          CA1=RCA1*DEG
          DIP1=RDIP1*DEG
          IF (DIP1.GT.0) GO TO 8
          DIP1=(-1.0)*DIP1
        8  V1=V0/SIN(RCA1)
          ZA1=(V0*TA1)/(2*COS(RCA1))

```



```

      ZB1=(V0*TB1)/(2*COS(RCA1))
      HA1=ZA1/COS(RDIP1)
      HB1=ZB1/COS(RDIP1)
C
      IF(I.EQ.2) GO TO 11
C
C   THREE LAYER CASE
C
      BETA2=ASIN(V0/VA2)+RDIP1
      ALPHA2=ASIN(V0/VB2)-RDIP1
      GAMMA2=ASIN((V1/V0)*SIN(ALPHA2))
      DELTA2=ASIN((V1/V0)*SIN(BETA2))
      RCA2=(GAMMA2+DELTA2)/2.0
      RDIP2=((GAMMA2-DELTA2)/2.0)+RDIP1
      CA2=RCA2*DEG
      DIP2=RDIP2*DEG
      IF(DIP2.GT.0) GO TO 9
      DIP2=(-1.0)*DIP2
9   V2=V1/SIN(RCA2)
      ZA2=(V1*(TA2-(ZA1/V0)*((COS(ALPHA2+BETA2)+1.0)/COS(ALPHA2))))/
      1(2.0*COS(RCA2))
      ZB2=(V1*(TB2-(ZB1/V0)*((COS(ALPHA2+BETA2)+1.0)/COS(BETA2))))/
      1(2.0*COS(RCA2))
      HA2=(1.0/COS(RDIP2))*((ZA1*COS(ALPHA2-RDIP2+RDIP1)/COS(ALPHA2))
      1+ZA2)
      HB2=(1.0/COS(RDIP2))*((ZB1*COS(BETA2+RDIP2-RDIP1)/COS(BETA2))
      1+ZB2)
C
C   PRINT RESULTS
C
      11 WRITE (6,1100) LINE
      1100 FORMAT (10A4)
C
      WRITE (6,1200) V0
      1200 FORMAT (//,' V0 = ',F7.2,' M/SEC')
C
      WRITE (6,1300) V1, VA1, VB1
      1300 FORMAT (//,' V1 = ',F7.2,' M/SEC',5X,' VA1 = ',F7.2,' M/SEC',5X,
      1' VB1 = ',F7.2,' M/SEC')
C
      WRITE (6,1310) TA1, TB1
      1310 FORMAT (//,' LEFT ZERO INTERCEPT = ',F7.4,' SECONDS',10X,' RIGHT
      1ZERO INTERCEPT = ',F7.4,' SECONDS')
      IF (IDIP1.EQ.1) THEN
        WRITE (6,1400) DIP1
      1400   FORMAT (//,' V0/V1 DIPS ',F5.2,' DEGREES TO THE LEFT')
      ELSE
        WRITE (6,1410) DIP1
      1410   FORMAT (//,' V0/V1 DIPS ',F5.2,' DEGREES TO THE RIGHT')
      ENDIF
      WRITE (6,1500) ZA1
      1500 FORMAT (//,' THICKNESS OF TOP LAYER BELOW LEFT SHOT = ',F5.2,'

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```

1METERS')
WRITE (6,1600) ZB1
1600 FORMAT (/,' THICKNESS OF TOP LAYER BELOW RIGHT SHOT = ',F5.2,'
1METERS')
WRITE (6,1700) HA1
1700 FORMAT (/,' DEPTH TO V1 BELOW THE LEFT SHOT = ',F5.2,' METERS')
WRITE (6,1800) HB1
1800 FORMAT (/,' DEPTH TO V1 BELOW THE RIGHT SHOT = ',F5.2,' METERS')
WRITE (6,1900) CA1
1900 FORMAT (/,' CRITICAL ANGLE (V0/V1) = ',F5.2,' DEGREES',/)
C
  IF (I.EQ.2) GO TO 12
C
  WRITE (6,1910) V2, VA2, VB2
1910 FORMAT (/,' V2 = ',F7.2,' M/SEC',5X,' VA2 = ',F7.2,' M/SEC',5X,'
1VB2 = ',F7.2,' M/SEC')
  WRITE (6,1920) TA2, TB2
1920 FORMAT (/,' 2nd LEFT INTERCEPT = ',F7.4,' SECONDS',10X,' 2nd
1 RIGHT INTERCEPT = ',F7.4,' SECONDS')
  IF (IDIP2.EQ.1) THEN
    WRITE (6,2000) DIP2
2000  FORMAT (/,' V1/V2 DIPS ',F5.2,' DEGREES TO THE LEFT')
  ELSE
    WRITE (6,2010) DIP2
2010  FORMAT (/,' V1/V2 DIPS ',F5.2,' DEGREES TO THE RIGHT')
  ENDIF
  WRITE (6,2100) ZA2
2100 FORMAT (/,' THICKNESS OF 2ND LAYER BELOW LEFT SHOT = ',F5.2,'
1METERS')
  WRITE (6,2200) ZB2
2200 FORMAT (/,' THICKNESS OF 2ND LAYER BELOW RIGHT SHOT = ',F5.2,'
1METERS')
  WRITE (6,2300) HA2
2300 FORMAT (/,' DEPTH TO V2 BELOW THE LEFT SHOT = ',F5.2,' METERS')
  WRITE (6,2400) HB2
2400 FORMAT (/,' DEPTH TO V2 BELOW THE RIGHT SHOT = ',F5.2,' METERS')
  WRITE (6,2500) CA2
2500 FORMAT (/,' CRITICAL ANGLE (V1/V2) = ',F5.2,' DEGREES',/)
C
  12 WRITE (6,2600)
2600 FORMAT ('*****')
  WRITE (*,2700)
2700 FORMAT (////,' DO YOU WANT TO CALCULATE ANY MORE VELOCITIES AND
1DIPS? ',/)
  WRITE (*,2800)
2800 FORMAT (/,' 1 - YES, USING THE SAME LINE ',//,10X,' 2 - YES,
1USING A DIFFERENT LINE ',//,10X,' 3 - NO, EXIT PROGRAM ',/)
  READ (*,*) J
  IF (J.EQ.1) GO TO 13
  IF (J.EQ.2) GO TO 14
  STOP
END

```