EVALUATION
OF A THICK BASALT SEQUENCE
IN SOUTH CENTRAL WASHINGTON

J. R. Raymond
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APRIL 1968

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EVALUATION OF A THICK BASALT SEQUENCE IN SOUTH CENTRAL WASHINGTON --
GEOPHYSICAL AND HYDROLOGICAL EXPLORATION OF THE
RATTLESNAKE HILLS DEEP STRATIGRAPHIC TEST WELL

By

J. R. Raymond and D. D. Tillson

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Evaluation of a Thick Basalt Sequence in South Central Washington --
Geophysical and Hydrological Exploration of the
Rattlesnake Hills Deep Stratigraphic Test Well

By

J. R. Raymond and D. D. Tillson

INTRODUCTION

A deep stratigraphic test well -- Rattlesnake Hills Number One -- was drilled for the Standard Oil Company of California during 1957 and 1958. The 10,655-foot deep well is located in section 15, township 11N, Range 24E in Benton County, State of Washington (Figure 1). The objective of the drilling was to penetrate the thick Columbia River basalt-basalt interbed series near the Columbia Basin center and near the axis of a major anticlinal ridge (Rattlesnake Hills). Knowledge of rock types and structure underlying the basalt would determine the feasibility of further petroleum exploration, but basalt was not penetrated at the completed well depth. Since the basalt series was of secondary interest, only cursory studies and examinations of the well were made: ditch sample visual examination, standard "E" log, dipmeter log, gamma and neutron logs, and some vertical and side-hole coring.

The Rattlesnake Hills Well provides unique access to one of the world's thickest basalt sections and presented an opportunity for study of the section by use of down-hole geophysical methods. Funds were allocated in 1967 to the Pacific Northwest Laboratory by the Division of Reactor Development and Technology, United States Atomic Energy Commission for in-well investigation of this test hole. The purpose of the investigation was to measure the

XXX Tertiary Columbia River Basalt	XXX Mesozoic Intrusives Undifferentiated
ZZZ Tertiary Extrusives Undifferentiated	ZZZ Mesozoic Sediments Undifferentiated
YYY Tertiary Intrusives Undifferentiated	YYY Paleozoic-Mesozoic Metamorphics
ooo Tertiary-Quaternary Continental Sediments	vvv Pre-Cambrian
o+o Tertiary-Quaternary Marine Sediments	-○- Rattlesnake Hills Well No. 1

Figure 1

geological and hydrological characteristics of the basalt section that are pertinent to radioactive waste storage considerations. A secondary benefit was the opportunity to determine some of the physical properties of the lower basalt sequence that is not exposed for visual examination or penetrated to this depth at any other location.

Three separate operations were involved in the Rattlesnake Hills test well evaluation work: well re-entry, cleanout and fluid conditioning; geophysical logging; and drill-stem testing for hydrologic information.

Ditch samples from the original drilling and copies of the original drilling logs, litho-logs, core description, electrical logs and other information were obtained from the Standard Oil Company of California. A portion of the vertical core taken in the well at 8100 feet was obtained from the State of Washington Division of Mines and Geology.

SUMMARY AND CONCLUSIONS

The Rattlesnake Hills 10,655-foot deep stratigraphic test well located in south-central Washington state was re-entered, cleaned-out, and drilling fluid conditioned for in-hole geophysical examination and drill-stem testing. Ten different wire-line logging tools and seven drill-stem tests were used in this investigation. In addition, palynology, spectrochemical, X-ray diffraction and mineralogy studies were made on drilling and side-hole core samples. The objectives of the work were to evaluate the practicability of deep, subsurface disposal of radioactive wastes and to determine the physical properties of a portion of the Columbia River Basalt sequence that is not exposed for examination at other locations.

The geophysical logs show that the stratigraphic sequence from 600 to 10,655 feet below ground surface at the well site is made up of nearly 100 basalt flows and interflow zones. A weathered complex zone exists from about

5000 to 7000 feet where flows and interflow zones generally cannot be clearly differentiated. The top of this thick weathered zone is hypothesized as the bottom of the Columbia River Basalt series.

Analysis of the variance of spectrochemical data from the original drilling samples, and subsequently from side-hole cores as verification, offers strong evidence for the existence of six zones of chemical homogeneity. It is proposed that these zones represent a combination of regional changes in the source of the basalt flows plus gross regional changes in the conditions under which the flows were extruded, cooled, and subsequently weathered.

Fossil pollen assemblages recovered from coal cuttings between 2100 and 4800 feet offer additional evidence to support the regional time-stratigraphic correlations proposed on the basis of the chemical variations. All the pollen evidence suggests a late Oligocene to early Miocene age (about 30 million years) which is generally considered as the beginning of the Columbia River Basalt series.

The paleoecology of the Rattlesnake Hills area suggested by the pollen assemblages is a coal swamp area of generally subtropical to temperate climate with ferns, bald cypress, and gum trees predominating. Higher ground to the west was inhabited by a hardwood/conifer forest very similar to the Cumberland Plateau of today.

Side-hole core examination shows that the interflow zones are, for the most part, highly altered and weathered basalts. It was expected that the interflow zones would be made up of tuffs or tuffaceous sediments, but such material is present in very small amounts and comprises only a minor portion of the section. Thus, the interflow zones generally reflect periods of weathering between succeeding basalt flows. The basalts are characterized by high electrical resistivity, high density, low sonic transit time and low

porosity. Conversely, the interflow zones exhibit low electrical resistivity, low density, high sonic transit time and high porosity. There are also many transitional zones that show intermediate characteristics. Most of the flows show some degree of jointing and fracturing. Thin section examination of the vertical core taken at 8084 feet shows that some of the lower flows are andesites rather than basalts.

Water quality studies and drill-stem tests show that there is a high degree of formation water isolation between major sections penetrated by the well. The drill-stem tests also indicate that formation water pressure decreases with depth.

There are many zones penetrated by the well where clarified liquid wastes might be stored by injection-well techniques. There are some zones, specifically in the weathered complex between 5000 and 7000 feet, where large volumes of unclarified waste might be stored. Because of the favorable hydrology (aquifer isolation and decreased potential with depth), it is extremely unlikely that contamination of near-surface sanitary water supplies would occur with reasonable injection pressure control. Also, the lower depth formation waters would make poor potable or irrigation water supplies because of the low potential, generally low performance aquifers and extreme water hardness. Additional, similar and equally-extensive confirmatory investigations are recommended in the event that this or an adjacent site is given further consideration for waste storage.

Waste disposal by cavern or tunnel methods might be possible in some of the relatively unfractured basalt flows. Typical upper and mid-depth zones potentially suitable for such disposal occur at 1520, 2140, 2720 and 3200 feet below ground surface at the well site. Problems of tunnel and shaft excavation and construction were not evaluated in this study.

DISCUSSION

GEOLOGY

The Rattlesnake Hills Well No. 1 is located on the southwest flank of the Pasco Basin in South Central Washington. The Pasco Basin is a present and long-standing structural low near the center of the much larger Columbia Basin geologic and physiographic province (Figure 2). The Columbia Basin province encompasses nearly all of southeastern Washington, parts of northeastern Oregon and western Idaho with an areal extent of about 200,000 square miles. The Columbia Basin province may be characterized as essentially a downsagging basin filled by at least three varieties of tholeiitic basalt⁽¹⁸⁾. The basalts have been downwarped to a maximum of 200 feet below sea level in the Pasco Basin and covered by subsequent fluvial, lacustrine, eolian, glacial outwash and scabland deposits. The upper surface of the basalt stands from 2000 to 5000 feet above sea level on all parts of its periphery. At the end of the period of extrusion the basalts in the Columbia Basin must have had the form of a great planoconvex lens with its upper surface nearly flat, and its bottom surface curved. The thickness of this lens can only be conjectured for nowhere except along the uplifted margins of the basin has erosion bitten deeply enough to expose the floor upon which the first basalt was poured. All available evidence indicates that the basalt thickens rapidly towards the center of the plateau⁽¹⁷⁾. The Rattlesnake Hills Well bottoms in basalt at a depth of 10,655 feet and is the only well to make a significant penetration below the 3000 to 4000 feet of basalt exposed on the surface.

The source area for the basalts of the Columbia Basin is generally considered to be northeastern and north central Oregon^(13,18). Sourceward

tilting of the later Yakima flows was recognized by Russell⁽¹²⁾ as a distinctive habit of deformation in the Columbia Plateau. He suggested that the basining was in some way genetically related to transfer of an estimated 50,000 to 60,000 cubic miles of basalt from great depth to the surface where the flows spread out radially towards the margins of the lava fields. Russell's idea is very generalized, because of the reconnaissance nature of his work, and only begins to explain the cause of basining. Waters⁽¹⁸⁾ offers strong evidence for the existence of several varieties of basalt, each thought to represent a primary magma developed in the mantle and not a product of the differentiation of a single parent magma. Evidence presented in this report indicates that there may be five or six varieties of basalt that are chemically homogeneous, with the upper three analogous to the types described by Waters.

The surface structure is characterized by east-west and northwest-southeast trending folds in the central and western parts of the Columbia plateau while the other parts are essentially undeformed⁽¹⁸⁾. The Pasco Basin appears to be the terminus between the anticlinal ridges and synclinal valleys of the Cascade Range and the gentle west and southwest dipping lava flows⁽²⁾.

Figure 3 is a generalized cross section of the Columbia Plateau centered upon the Pasco Basin and the Rattlesnake Well. The gross regional time-stratigraphic relationship to the surrounding geologic provinces is inferred primarily on the basis of evidence from the Rattlesnake Well and should only be considered as a working hypothesis.

Additional comment or a complete bibliography on all the studies concerned with the geologic development of the Columbia Plateau is beyond

GEOLOGIC CROSS SECTIONS OF COLUMBIA RIVER BASALT PLATEAU

Figure 3

the scope of this report. For the reader interested in further details of the regional geology, selected reference should be made to the early work by Russell^(11,12) and Smith⁽¹⁴⁾, and to the later works by Baldwin⁽¹⁾, Grolier⁽⁵⁾, Mackin^(8,9), Newcomb⁽¹⁰⁾, Schmincke⁽¹³⁾ and Waters⁽¹⁵⁻¹⁸⁾. A detailed report on the geology and hydrology of the Hanford Project and surrounding area by R. E. Brown, Battelle-Northwest, is in preparation. This report, which will soon be published, should provide a framework for understanding the regional geology of the Columbia Basin Province previously unavailable from any single source.

WELL HISTORY

Original Work

The Rattlesnake Hills No. 1 Well was drilled for the Standard Oil Company of California by the Miracle and Wooster Drilling Company of Vernal, Utah. The well was spudded in on July 7, 1957 and temporarily terminated at 8418 feet on January 7, 1958. The well was re-opened on February 20, 1958 and completed at 10,655 feet on April 6, 1958. Drilling fluid was air, aerated water and aerated mud to 4847 feet, and mud from 4847 feet to total depth. Both hardrock roller-cone and tungsten carbide button-set bits were used for the drilling. The hole is cased with 18-1/2 inch casing to 22 feet and 13-3/8 inch casing to 603 feet. The well was drilled 9-7/8 inch diameter open hole from 603 feet to 8418 feet, and 9 inch open hole to 10,655 feet. An attempt was made to core from 10,652 to 10,655 feet (8-1/2 inch diameter) but no recovery was obtained. Vertical coring was also attempted from 8084 to 8100 feet with 5-1/2 feet recovery realized. The hole is extremely straight with a maximum deflection of 2° 45', noted at about 3800 feet, and

an average deflection of about $1^{\circ} 30'$. Apparently no serious problems were encountered during the drilling other than several lost-circulation zones and the very hard nature of the basalt which resulted in an average drilling rate of slightly more than 2 feet per hour (including trip time). Average bit life was about 120 feet. Standard electrical, gamma ray-neutron and continuous dipmeter logs were made by Schlumberger Well Surveying Corporation. Schlumberger also took 23 side-wall cores. The well was abandoned and cement-plugged from 540 to 690 feet on April 6, 1958. Copies of the geophysical logs and some ditch sample and side-hole core descriptive information are on file with the State of Washington Division of Mines and Geology. Also, copies of the logs and other information may be obtained from Olympia Reprographics, Olympia, Washington.

Well Re-entry

Well cleanout and fluid conditioning was performed for Battelle-Northwest by the Taylor Drilling Company, Chehalis, Washington. Re-entry was started on May 29, 1967. A National model 50 drilling rig with 3-1/2 inch drill pipe and an 8-3/4 inch roller-cone bit was used to clean out the hole. Only one drill collar was used to maintain drill string weight as low as possible. Only minor problems occurred during the cleanout work. The cement plug was penetrated at about 690 feet on May 30, 1967. A portion of the plug apparently broke off and bridged repeatedly down to 1060 feet. Old gel and lost-circulation material was circulated out below 690 feet. Numerous small bridges occurred from 1060 to 3094 feet where old cuttings and mud were encountered. Circulation was lost as each bridge was penetrated but was easily regained by pumping in drilling fluid without addition of lost-circulation material. Below 3094 feet, old cuttings and gel were continuously circulated

out of the hole. Lost-circulation material (Nut Plug and Fiberseal) was required to regain drilling fluid circulation at 4038, 5164 and 5787 feet. Tight hole was encountered at 8418 feet where the original bit size was reduced from 9-7/8 to 9 inches. Cleanout was terminated at 9157 feet on May 3, 1967 due to excessive bit drag. The well was logged and side-hole cored by Schlumberger Well Surveying Corporation, and seven drill-stem tests were made by Cook Testers. The well was abandoned and cement-plugged from 500 to 658 feet on May 13, 1967.

GEOPHYSICAL LOGGING

The objective of the geophysical work was to obtain definitive information on the characteristics of the thick basalt - basalt interbed series. The logging program was selected to provide information on the following parameters; basalt flow and interbed thickness, formation resistivities, spontaneous potential, formation density, formation porosity and permeability, mud invasion and mud cake thickness, hole size variations, nature of the pore fluid (saline or fresh water), side-hole core samples, bore-hole temperature at depth and formation seismic characteristics. Ten different wire-line logging tools were utilized to investigate the well. The methods for performing these various geophysical tests and the types of information obtained from data interpretation techniques are discussed in considerable detail in Appendix A.

Log Evaluations and Results

In some cases several geophysical parameters were measured in a single operation; thus to a degree, cross checks were obtained. However, the accuracy or reliability was not equal in all cases. The borehole compensated

sonic (BCS), microlog, compensated formation density (CFD), and sidewall neutron porosity (SNP) logs include borehole caliper measurements; however, the caliper trace on the microlog is not reliable. Spontaneous potential (SP) curves are recorded on the BCS and dual induction-laterolog-8 (DIL) logs, but the SP curve on the BCS log was taken from the sonde and cartridge body and is not accurate.

The logs start at about 600 feet below ground surface (actually below the kelly bushing on the drill rig floor). All of the log functions except the SP curve show clearly the basalt flows and interflow zones. The basalt is defined by high resistivity, high density, low porosity and low sonic transit time. Conversely, the interflow zones are characterized by low resistivity, low density, high porosity and high sonic transit time. There are often transitional or gradational sections where log functions are intermediate.

The simple caliper log shows a great deal about the formations by relating borehole size variation to physical characteristics. Dense, unfractured basalt drills nearly to bit-gauge, whereas the softer weathered and altered interflow zones are indicated by a larger hole diameter or by mud cake buildup (reduced hole size) where permeability exists. The borehole is generally irregular or rough (rugose) in fractured basalt zones. The variable density seismogram shows the best graphical picture of the formation sequence. In dense basalt the transit time is short, the various wave arrivals are regular and little wave interference or attenuation is noted. In the interflow zones the transit time is long and wave interference and attenuation occur. Many of the boundaries are exceedingly sharp and well-

defined on the variable density log. Fractured zones in basalt flows are indicated on the variable density log by wave interference, attenuation and "eye and eyebrow"-like wave appearances.

The dual induction laterolog-8 (DIL) log shows that basalt resistivity is in the range of thousands of ohms per meter per square meter (ohm-meters) where the formation is dense and relatively unfractured. This high resistivity is well beyond the quantitative range of the DIL tool. Formation electrical conductance is caused by the conductivity of contained interstitial fluid; therefore, dense unfractured basalt has, for practical purposes, infinite resistance. Resistivity of the interflow zones varies from about 5 ohm-meters to 60 ohm-meters with the average being about 10 to 20 ohm-meters. The microlog shows the interflow zones clearly by sharp decreases in resistivity and return to a relatively smooth log trace. The indicated resistivity averages about 3 to 10 ohm-meters in this case. Separation of the micro-normal from the micro-inverse curve indicates mud cake buildup which in turn reflects permeable zones. The microlog traces are very erratic and meaningless in the high resistivity sections.

The borehole compensated sonic log (BCS) shows sonic wave interval transit times of about 51 microseconds per foot (μ sec/ft) in the hard unfractured basalt sections. The observed 51 μ sec/ft transit time (19,600 ft/sec velocity) is in good agreement with the 18,000 to 20,000 ft/sec surface and near-surface basalt velocities measured on the Hanford Project by seismic refraction surveys. Formation porosity may be estimated

from the sonic log data by the Wyllie time-averaging relationship:

$$\phi = \frac{T_f - T_m}{T_l - T_m} \quad (1)$$

Where: ϕ is formation porosity
 T_f is the observed sonic transit time in the formation
 T_m is the matrix transit time and
 T_l is the sonic transit time for the interstitial liquid in the formation.

The compensated formation density log (CFD) shows that the solid basalt density is about 2.8 to 2.85 grams per cubic centimeter (g/cc); this agrees well with measured densities of near-surface basalts. Observed interflow density varies greatly with some zones indicating less than 1.8 g/cc bulk density. Porosity may also be estimated from the density log from the relationship:

$$\phi = \frac{D_g - D_b}{D_g - D_f} \quad (2)$$

Where: D_g is the grain density
 D_b is the measured bulk density, and
 D_f is the interstitial fluid density.

The sidewall neutron porosity log (SNP) shows the porosity of dense basalt to be about three to six percent. The basalt may contain from one to two percent intercrystalline water which the neutron tool would "see" as porosity. The matrix parameter was set as "limestone" on the SNP surface control panel. This is probably a fair matrix approximation but apparently a porosity error of a few percent is introduced. The indicated interflow zone neutron-derived porosity varies widely with some zones showing greater than fifty percent porosity. Many of the high porosity zones greatly affect the neutron tool because of the mud cake buildup; thus, indicated neutron-derived porosity may be erroneously high.

Data plots were made of sonic interval transit time versus neutron porosity ($\Delta T/\phi_N$); bulk density versus neutron porosity (ρ_B/ϕ_N); and bulk density versus sonic interval transit time ($\rho_B/\Delta T$). The objective of these data plots was to check the agreement of the three formation-porosity tools. Data were taken from many different zones in the well but values from very poor hole-condition zones were not used. Figure 4 shows the $\rho_B/\Delta T$ graph with g/cc bulk density plotted against $\mu\text{sec}/\text{ft}$ transit time. Data points for fair-to-good borehole zones, for mud cake zones and for caved zones are indicated. Considerable scatter is evident and the deviation is not uniquely related to hole condition. The graph indicates that 2.82 g/cc bulk density and 51 $\mu\text{sec}/\text{ft}$ transit time are good values for unfractured and nonweathered basalt. Using these values for grain density and matrix travel time, sonic derived porosity, ϕ_S , and density derived porosity, ϕ_D , are scaled at the top and right edges of the graph. The plotted ϕ_S/ϕ_D line agrees quite well with the data points thus verifying extrapolation of sonic and density-derived porosities.

Figure 5 shows the $\Delta T/\phi_N$ plot for the Rattlesnake Hills Well. The scale at the right edge of the graph shows sonic-derived porosity using a matrix transit time of 51 $\mu\text{sec}/\text{ft}$ for dense basalt. The dashed line is calculated porosity using the zero neutron porosity value for dense basalt as taken directly from the uncorrected SNP log, and the solid line represents the "best fit" curve through the data points. The top scale on the graph is ϕ_N corrected for the obvious four percent SNP log zero displacement. The theoretical curve falls well below the data plot, thus a correction is required for neutron-derived porosity values. For example, at 20% ϕ_S , ϕ_N is

Figure 4

Data Plot - Density vs Sonic Transit Time

Figure 5

Data Plot - Sonic Transit Time vs Neutron Porosity

26.6% (30.6% on the lower direct "log read" scale). Point scatter does not appear to be related to borehole condition but rather to the use of an incorrect matrix selection (limestone) on the SNP surface control panel. The panel selection is limited to three rock-type matrices on the SNP equipment, sandstone, limestone or dolomite, which are the formation rocks generally encountered in oil well logging.

Figure 6, a graph of the ρ_B/ϕ_N data, looks very much like Figure 5, as it should if the sonic and density log derived porosities are consistent. At 20% ϕ_D , the indicated ϕ_N is 26.4% (30.4% on the lower direct scale) which is almost exactly the deviation noted on the sonic transit time - neutron porosity plot. Additional examination of neutron, sonic and density-derived porosities was made to attempt correlation of porosity scatter with depth; however, no consistent relationship was evident. Errors as great as $\pm 10\%$ of the porosity are common in using the data from only one porosity log. For quantitative use, porosity values from at least two logs should be in good agreement.

The temperature log was run last to minimize the effect of mud circulation; however, it is doubtful that equilibrium conditions existed when the temperature log was made. Temperature gradients, presented in Table I, were determined at 200 foot intervals. The gradient generally increased with depth in the well. The numerous abrupt changes in gradient could not be correlated with changes noted in other geophysical logs. The temperature log was used in this study to measure approximate mud and formation temperatures to permit resistivity corrections. Personnel from the Theoretical Geophysics Branch, U.S.G.S., Menlo Park, California, also obtained temperature data; their evaluation may be available in the near future.

Figure 6

Data Plot - Density vs Neutron Porosity

TABLE ITemperature Gradient - Rattlesnake Hills Test Well

<u>Depth</u> (feet)	<u>Temperature Gradient</u> (°F/100 feet)
600- 800	0.8
800-1000	0.8
1000-1200	1.1
1200-1400	1.2
1400-1600	1.4
1600-1800	1.5
1800-2000	1.3
2000-2200	1.3
2200-2400	1.6
2400-2600	1.6
2600-2800	1.6
2800-3000	1.6
3000-3200	1.6
3200-3400	1.9
3400-3600	1.9
3600-3800	1.9
3800-4000	1.9
4000-4200	1.5
4200-4400	1.7
4400-4600	1.8
4600-4800	1.7
4800-5000	1.6
5000-5200	1.7
5200-5400	1.8
5400-5600	1.8
5600-5800	1.8
5800-6000	1.2
6000-6200	1.9
6200-6400	1.6
6400-6600	1.9
6600-6800	2.0
6800-7000	1.6
7000-7200	1.6
7200-7400	1.8
7400-7600	1.9
7600-7800	1.9
7800-8000	1.5
8000-8200	1.8
8200-8400	1.5
8400-8600	2.5
8600-8800	1.9
8800-9000	2.1
9000-9200	3.5
9200-9400	1.2

Log examination shows 92 identifiable basalt flows and 89 interflow zones. A highly altered and weathered complex zone exists from 4950 to 6800 feet in the well, within which flows and interflow zones generally could not be differentiated. Appendix B, a catalog of the total well section, lists basalt and interflow zone location, thickness and characteristics. The basalt flows average about 68 feet in thickness and the interflow zones average about 22 feet in thickness. Table II shows the number and average thickness of basalt flows and interflow zones per thousand feet of depth increments. Both the basalt flows and interflow zones are thicker immediately below the 5000 to 7000 foot complex. It is hypothesized that the Columbia River basalt series terminates at the top of the complex zone at a depth of about 5000 feet in the Rattlesnake Hills Well. The deep flows, at least in part (from the vertical core thin-section analyses), are andesites rather than basalts.

TABLE II

Depth, Number and Average Thickness of Basalt Flows
And Interflow Zones Rattlesnake Hills Test Well

<u>Zone</u> (feet)	<u>Number of</u> <u>Basalt Flows</u>	<u>Average Thickness</u> (feet)	<u>Number of</u> <u>Interflow Zones</u>	<u>Average</u> <u>Thickness</u> (feet)
1000-2000	14	55.3	15	13.7
2000-3000	11	72.9	10	20
3000-4000	10	75	10	21.8
4000-5000	15	45.7	15	19.7
Complex weathered and altered zone from 5000 to 7000 feet.				
7000-8000	7	101.6	7	30.3
8000-9000	7	86.7	7	37.2
9000-10000	11	52.9	11	25.6

Ten, 300-foot log sections from the Rattlesnake Hills Well were selected for additional discussion. These sections, chosen as being fairly representative of the entire stratigraphic sequence, show the major changes encountered in the well. Figure 7 shows the sequence from 700 to 1000 feet. At 700 feet the DIL shows that the formation is a relatively low resistivity basalt flow (1st flow). The erratic nature of the DIL traces suggests extensive fracturing or shattering, and the variable density sonic log (not shown on Figure 7) supports this observation. An interflow zone is noted from about 716 to 728 feet (1st interflow zone) by decreases in the resistivity curves to about 20 ohm-meters. The resistivity then increases gradually in a basalt flow from 728 to 868 feet (2nd flow). The resistivity in most of this flow is well beyond the range of the DIL log. Note that the deep induction curve returns on-scale to about 600+ ohm-meters at 818 feet; this may denote interconnected vertical fractures. A 38-foot thick interflow zone is encountered from 868 to 906 feet (2nd interflow). The lowest resistivity in this zone is about 8.5 ohm-meters for the medium induction log, 10 ohm-meters for the deep induction log and 20 ohm-meters for the laterolog. Another fractured and broken basalt flow occurs from 906 to 1000 feet (3rd flow), with a possible interflow zone at about 950 feet. The SP log is rather featureless and adds nothing to interpretation of the section. The caliper log shows that the hole diameter is about one inch larger than bit diameter in the 1st basalt flow at 700 feet. Mud cake buildup is evident in the 1st interflow zone by a decrease in hole size to one inch less than bit diameter. Caving is evident in the top 25 feet of the 2nd flow. Some mud cake is evident in the middle part of the 2nd flow and considerable mud cake is present in the 2nd interflow zone. The 3rd basalt flow shows

Figure 7

Geophysical Logs - 700-1000 Feet

both caved and mudcake zones. The SNP and CFD logs strongly support the DIL and caliper logs. Uncorrected neutron porosity is 10% in the 1st basalt flow at 710 feet, 55% in the 1st interflow zone, from 5 to 10% in the 2nd flow, 55% in the 2nd interflow zone and averages about 7% in the 3rd flow. The neutron porosity increase noted at 800 feet appears as an anomaly and may be due to mudcake effects. Likewise, the neutron porosity increase noted from 934 to 956 feet is at least partially due to mudcake buildup. The CFD log shows the basalt density to be about 2.8 g/cc at 705 feet, and the lowest density in the 1st interflow zone to be 1.75 g/cc ($\phi_D = 59\%$). The top part of the 2nd basalt flow has an average density of 2.78 g/cc, and the lower part averages 2.85 g/cc. The lowest density in the 2nd interflow zone is 1.8 g/cc ($\phi_D = 56\%$), and the average density in the 3rd flow is 2.8 g/cc. The density log also shows a low density (high porosity) zone from about 934 to 956 feet that is at least partially due to mudcake effect. The density correction curve (not shown in Figure 7), which is off-scale in portions of the three low density zones, indicates borehole conditions that are beyond the correction range of the CFD equipment. The BCS log shows an interval sonic transit time of about 60 μ sec/ft at 700 feet. The "horn" that occurs on the log trace at 711 feet is an anomalous effect that is often observed in sonic logs at formation interfaces. The 1st interflow zone exhibits a ΔT of about 113 μ sec/ft ($\phi_S = 59\%$). The gradational zone from about 730 to 760 feet is also apparent on the sonic log. The ΔT in the upper half of the 2nd flow (760 to 800 feet) is 55 μ sec/ft and 52 μ sec/ft from 800 to 865 feet. Two cycle skips are noted at 750 and 765 feet. Cycle skipping occurs to such an extent in the 2nd interflow zone that the sonic data cannot be used for porosity determination. Interval

transit time at the top and bottom on the 3rd flow is $55 \mu \text{ sec/ft}$. Increases in Δ_T noted at 936 feet and 954 feet correspond to a porosity of about 10 percent and occur where the nuclear logs show the porosity increases to be greater than 50 percent. The variable density sonic log shows extensive vertical and horizontal fracturing. The BCS log does not "see" the vertical fractures and the nuclear logs are effected by mud cake. The true porosity falls somewhere between 10 and 50 percent. The log data confirm that the porous area in the middle of the 3rd basalt flow is due to extreme fracturing and is not an interflow zone. Vertical fracturing is also indicated where the laterolog trace falls below the deep induction log curve at high resistivities. Several examples of this are evident in the 3rd basalt flow.

Sidewall coring was attempted at 840 and 920 feet with no recovery achieved. These negative results confirm the presence of relatively unaltered basalt. If the status of most of the interflow zones is accepted as in-place weathering of the basalt (the gradational characteristics noted at the top of many of the flows support this observation), then the thickness of the interflow zones is related to the length of time that occurred between flows. That is, the thicker the interflow zone, the longer was the time interval between flows. Changes in environment during weathering could, of course, modify the rate of change, and absolute time periods cannot be determined for any one zone without considerable age-dating work.

Estimation of formation water quality can be made from the geophysical logs. The formation resistivity factor, F , is the ratio of the electrical resistivity, R_o , of a porous medium saturated with water to the resistivity, R_w , of the water in the pores: $F = \frac{R_o}{R_w}$. The formation resistivity factor

can also be related to formation porosity: $F = \frac{1}{\phi^m}$, where ϕ is effective porosity and the exponent m is a constant related to formation cementation or induration. Empirical studies show that $F = \frac{0.62}{\phi^{2.15}}$ for unconsolidated to semi-consolidated sands and sandstones with intergranular porosity, and $F = \frac{1}{\phi^2}$ for consolidated formations with vugular or fracture porosity. The formation resistivity factor can be independently determined by $F = \frac{R_{xo}}{R_{mf}}$, where R_{xo} is the resistivity of the flushed zone close to the well-wall where 100% invasion of mud filtrate can be assumed, and R_{mf} is the resistivity of the mud filtrate. The various resistivities and porosities can be determined from the geophysical logs (R_{mf} from mud analysis). The formation water resistivity in the 1st interflow zone shown in Figure 7 can be calculated from: $\phi = 50\%$, $F = 4$, $R_o = 17$, formation temperature is about 90°F ; $F = \frac{R_o}{R_w}$, $R_w = \frac{17}{4} = 4.25$ ohm-meters. Correcting to 25°C , $R_w = 4.9$ ohm-meters. Formation water resistivity in the 2nd interflow zone is: $R_w = 10/4 = 2.5$ ohm-meters or 2.9 ohm-meters at 25°C . Formation water resistivity in the fractured portion of the 3rd basalt flow is calculated from: $\phi = 10\%$, $F = 100$, $R_o = 200$. $R_w = 200/100 = 2$ ohm-meters or 2.6 ohm-meters at 25°C . There are, however, a number of problems involved in the accurate assessment of water quality in the Rattlesnake Hills Test Well. The first problem involves determination of the true R_o in a well that was abandoned for more than ten years with mud remaining in the well. This situation could lead to deep invasion of mud filtrate into the permeable zones. The invasion could be deep enough to effect even the deep induction log so that the indicated formation resistivity reflects the conductivity of the mud filtrate rather than the conductivity of the formation water. To minimize this error, the

original electrical log was checked against the recently run induction logs. Where wide variations and deep invasion were noted, no attempt was made to calculate formation water resistivity. Another problem involves evaluating formation water resistivity in basalt zones where formation resistivity is generally above 100 ohm-meters and the resistivity is not accurately reflected by the induction logs. These zones must be by-passed as far as determination of water quality is concerned. The third problem is encountered where less than 100% water saturation occurs in porous media. Calculation of R_w in this case is much more complicated. Gas was observed in some zones in the upper part of the well during drilling; thus there cannot be 100% water saturation. The gas is located, apparently, in the fractured sections of some basalt flows. As mentioned before, the resistivity of these zones, even when water saturated, is beyond the range of the induction logs and R_w cannot be determined. Therefore, the presence of gas in some of the fractured basalts does not effect the overall evaluation of water quality in the well. All other zones are assumed to be water saturated.

The fourth problem deals with conversion of R_w values to water quality in terms of total dissolved solids for non-marine formation waters. Most of the geophysical logging techniques are oriented toward petroleum exploration and exploitation where marine formation waters are mainly NaCl solutions of moderate to high concentration. Consequently, the available conversion charts and formulae relate R_w to NaCl concentration. Accurate relation of R_w to concentration can be made for other solutions if analyses are available that define the composition of the dissolved solids. In many non-marine formation waters the main anion is bicarbonate, HCO_3^- . If the accompanying

cation is Na^+ , the activity of the solution is usually close to that of a NaCl solution having the same Na^+ concentration. However, the resistivities of NaCl and NaHCO_3 solutions with the same Na^+ concentrations are different. The HCO_3^- ion contributes only 27% as much conductivity as an equal amount of Cl^- ion. A log-calculated R_w value of 3 ohm-meters would be comparable to a total dissolved solids concentration of 1700 parts per million (ppm) as NaCl and about 2400 ppm as NaHCO_3 based on empirical logging studies of water wells. Table III shows an average analysis for near-surface well waters (200 to 400 feet below ground surface) adjacent to the Rattlesnake Hills test site. Also shown are the multipliers required to convert ion concentration to equivalent NaCl concentration for R_w determination. Total equivalent NaCl is about 131 ppm which corresponds to an R_w of 36 ohm-meters at 25°C. The water samples obtained at depth in the Rattlesnake Hills Well during the drill-stem tests were so contaminated with drilling mud and mud filtrate that meaningful water analyses could not be made, but it was assumed that the major anion in formation water at these locations was HCO_3^- . The total dissolved solids in the water in the interflow zone from 716 to 728 feet is about 1500 ppm (R_w is 4.9 ohm-meters). Total dissolved solids at 868 to 906 feet is about 2400 ppm (R_w is 2.9 ohm-meters). Thus the formation water hardness in the Rattlesnake Hills Well increases considerably with depth. This suggests isolation of the lower zones from the near-surface waters.

Most of the interflow zones tended to build up mud cake from 600 to 1700 feet which denotes some degree of permeability; however, invasion appeared slight and the permeability is probably low.

TABLE III

Chemical Analysis of Near-Surface Well Water
In the Vicinity of the Rattlesnake Hills Test Site

<u>Ion</u>	<u>Concentration</u> (ppm)	<u>Multiplier</u>	<u>Equivalent NaCl</u> (ppm)
Na ⁺	30	1	30
K ⁺	10	1	10
Ca ⁺⁺	17	0.95	16
Mg ⁺⁺	10	2	20
Cl ⁻	5	1	5
SO ₄ ⁼	1.6	0.5	0.8
HCO ₃ ⁻	181	0.27	49
Total:	254.6		130.8

Figure 8 shows the geophysical logs from 1900 to 2200 feet. This section starts in a high resistivity, moderately-fractured basalt flow (1st flow). A 24-foot thick interflow zone occurs from 1970 to 1994 feet (1st interflow), and a 2nd basalt flow is noted from 1994 to 2190 feet. Fracturing occurs in this flow from about 2090 to 2100 feet. There is a considerable reduction in resistivity in the bottom half of the flow even though no increase in porosity or fracturing is indicated on the other logs (in fact a decrease in porosity is suggested). A 2nd interflow zone, at 2190 feet, shows caving and the absence of mud cake which indicate very low permeability and virtually no invasion. This is confirmed by a lack of separation in the DIL and microlog curves. The basalt zones drill nearly to bit gauge. Formation water resistivity in the 1st interflow zone was calculated to be 3.6 to 4.7 ohm-meters at 25°C by several different evaluation methods. Calculated R_w is 0.5 ohm-meters at 2130 feet in the low resistivity basalt

Figure 8

Geophysical Logs - 1900 to 2200 Feet

zone. The original long lateral log resistivity of 500 ohm-meters and an F of 1000 were used for this calculation. The R_w value could be in error by a factor of two or more, but a definite decrease is indicated in R_w which explains the formation resistivity decrease without an increase in fracturing or porosity. Formation water resistivity in the 2nd interflow zone is 2.3 ohm-meters at 25°C. Water resistivity in a fractured, low R , basalt flow from 2200 to 2234 feet immediately below the zone shown in Figure 8 shows an R_w of 3 ohm-meters. Considerable amounts of coal were observed in the drill cuttings from the section shown in Figure 8. The coal occurred in the interflow zones, but no geophysical log changes were noted that could be attributed to its presence.

Figure 9 shows the logs from 3000 to 3300 feet. In the intervening section, between 2200 and 3000 feet, caving and lack of mud cake characterize the interflow zones. A very large cave occurs in the interflow zone at 3005 to 3020 feet where the hole diameter is greater than 15 inches. A low R , fractured basalt flow occurs from 3020 to 3070 feet; and a second thick basalt flow occurs from 3085 to 3240 feet. The top half (approximate) of this latter flow is extensively fractured but the bottom half is relatively massive and free from fracturing and jointing. Mud cake buildup indicating some permeability is observed in part of the fractured zone from 3104 to 3118 feet, and the nuclear logs partially indicate the mud cake. A third interflow zone at 3240 feet grades into a fractured basalt at about 3260 feet. Invasion is suspected in this zone because of the mud cake and the separation of the laterolog from the induction log traces. A reliable R_w value can be obtained for the 2nd interflow zone that exhibits little or no invasion.

Figure 9

Geophysical Logs - 3000 to 3300 Feet

The porosity correlations are not precise, but assuming a porosity of 35% ($F = 8$) and $R_o = 25$ ohm-meters, R_w is 4.9 ohm-meters at 25°C. Methane gas was noted in varying amounts from 2850 to 4700 feet when the well was drilled. The gas, evidently derived from carbonaceous material in the interflow zones, occurs in the basalt fractures and is prevented from moving by the relatively impermeable interflow zones and massive parts of the basalt flows. The gas was not detected by geophysical logging because of the generally high resistivity found even in the fractured basalt.

Figure 10 shows log sections from 3800 to 4100 feet. At 3800 feet the formation grades into a basalt flow. The formation between 3840 and 3854 feet may be an interflow zone but it is more likely highly fractured basalt; extensive caving is noted. An interflow zone occurs from 3891 to about 3910 feet, and a basalt flow exists from 3910 to 4135 feet. The DIL log generally shows a lower resistivity in the basalt flows below 3980 feet than is observed in the upper sections, but the other log functions show little or no change in characteristics. The most likely explanation is that the formation water resistivity has decreased. This observation is confirmed by a calculated R_w of about one ohm-meter at 3975 feet and an R_w of about 0.2 ohm-meters at 4065 feet. R_w in the interflow zone at 3894 feet is also quite low, 1.6 ohm-meters. The reduced water resistivity actually begins at about 3513 feet where an R_w of 1.85 ohm-meters was observed.

Figure 11 shows the geophysical logs from 4900 to 5200 feet. In the intervening section, between 4100 and 4900 feet, caving is still evident in the interflow zones and the basalt flows drill to bit gauge. Little mud cake buildup was noted but some permeable zones exist. Of particular

Figure 10

Geophysical Logs - 3800 to 4100 Feet

Figure 11

Geophysical Logs - 4900 to 5200 Feet

interest is the SP trace which begins to pick up character in some of the interflow zones. The reason for the SP change will be discussed later in the evaluation of a lower section. The formation is a relatively low resistivity, fractured basalt flow at 4900 feet. An abrupt change occurs in all log traces at about 4940 feet -- formation resistivity decreases, neutron porosity increases, borehole rugosity increases, formation density decreases and sonic transit time decreases. The variable density sonic log shows extensive fracturing and shattering. This anomalous zone extends to nearly 7000 feet; and, with few exceptions, differentiation cannot be made between basalt flows and interflow zones. Formation water resistivity appears low, about 0.5 ohm-meters at 5000 feet, but accurate measurement is difficult because of the erratic traces on most of the logs in this section.

Figure 12 shows the log section between 6000 and 6300 feet. Mud cake buildup begins at about 6065 feet, and the microlog indicates permeability in the mud cake zones. Mud loss problems that were first encountered in this section during drilling confirm the increase in permeability (or decrease in formation fluid pressure) noted in the logs. The formation is probably highly fractured and shattered basalt at 6000 feet, and an interflow zone is indicated from about 6188 to 6208 feet. Delineation of other flows and interflow zones cannot be made with confidence since the mud cake affects the nuclear logs. Formation porosity calculated from the CFD and SNP logs may be erroneously high and porosity calculated from the BCS log may be anomalously low because of vertical fracturing. The poor agreement between formation resistivity measured by the original electric logs and resistivity determined by the induction logs is probably due to considerable mud filtrate invasion. Formation water resistivity is estimated at 1.6 ohm-meters at 6190 feet.

Figure 12

Geophysical Logs - 6000 to 6300 Feet

Figure 13 shows the log section from 6700 to 7000 feet. Little change in log characteristics was noted in the intervening section between 6300 and 6700 feet. Extreme measures were required during drilling to maintain drilling fluid circulation from 6315 to 6500 feet. More than 2500 barrels of drilling fluid and lost circulation material were lost in this zone before partial circulation was regained. Mud loss also continued in the section shown in Figure 13 as noted by the mud cake zones and the microlog. All log traces (except SP) return to approximately pre-4940-foot conditions at about 6950 feet, and the anomalous weathered complex zone is considered to terminate at this point. Actually, the CFD and BCS logs show near normal traces at 6800 feet. Considerable change is noted in the SP curve, particularly around 6750 and 6880 feet. The large SP deflections are difficult to explain by electrochemical reaction: $E_c = -K \log R_{mf}/R_w$, where E_c is the potential created by chemical reactions, K is a constant related to formation temperature, R_{mf} is mud filtrate resistivity and R_w is formation water resistivity. Formation water resistivity is calculated as 1.25 ohm-meters (at 185°F formation temperature) at 6740 feet; whereas the observed SP of about -110 mv would require an R_w of about 0.075 ohm-meters. The SP differential can also be generated by an electrokinetic reaction (streaming potential) where the mud filtrate flowing across a mud cake layer and into the formation generates a voltage. The streaming potential is described by:

$$E_s = 0.039 (R_{mc})(T_{mc})(fl) \cdot \Delta P$$

where: E_s is the streaming potential, R_{mc} is the resistivity of the mud cake, T_{mc} is mud cake thickness, fl is mud filtrate loss and ΔP is the hydrostatic pressure difference between the formation fluid and the mud column in the borehole. The observed SP of -110 mv

Figure 13

Geophysical Logs - 6700 to 7000 Feet

would require a Δ P of 730 psi. This pressure differential can be considered an order of magnitude value because of the uncertainty in field determination of R_{mc} , T_{mc} and fl . As indicated by the drill-stem tests, pressure differentials of this magnitude exist in the lower zones of the well and may explain the large SP deflections. The resistivity-log calculated R_w of 1.25 (185°F) at 6740 feet is quite close to the mud filtrate resistivity of 1.5 (185°F). This may indicate deep invasion and reflect an erroneous measurement of formation resistivity (R_o). The original electric log indicated an R_o of about 35 ohm-meters at 6740 feet whereas the recent log shows an R_o of 20 ohm-meters. If R_o is 35 ohm-meters then R_w is about 2 ohm-meters (185°F) which is an even greater difference than the above between R_w calculated from resistivity and R_w calculated from SP (assuming electrochemical reaction). This further reinforces the observation that the large SP deflections are electrokinetically generated.

Figure 14 shows the geophysical logs for the section between 7300 and 7600 feet. The section starts in the lower third of a 260-foot thick basalt flow that exhibits low to moderate fracturing. A 32-foot thick interflow zone occurs from 7383 to 7415 feet, and a highly fractured basalt flow is evident from about 7415 to 7565 feet where another interflow zone occurs. Frequent cycle skipping noted in the sonic log trace may indicate the prevalence of horizontal fractures in the basalt formations below 7000 feet. Formation water resistivity is calculated at 2.2 ohm-meters (25°C) at 7390 feet and 1.5 ohm-meters at 7270 feet (R_o taken from the original long lateral log).

Figure 15 shows the logs from 8300 to 8600 feet. An interflow zone occurs from 8308 to 8340 feet and a moderately fractured basalt flow exists from 8340 to 8486 feet. Another interflow zone is present from 8486 to about 8540 feet, and the fractured top of a basalt flow starts at about 8540 feet. The

Figure 14

Geophysical Logs - 7300 to 7600 Feet

Figure 15

Geophysical Logs - 8300 to 8600 Feet

CFD log is completely erroneous from about 8410 to 8480 feet due to temporary loss of sonde contact with the borehole wall. This is indicated in the caliper curve (not shown in Figure 15) recorded with the CFD log. The caliper log in Figure 15 (recorded with the SNP log) clearly shows the bit diameter reduction from 9-7/8 inches to 9 inches at 8415 feet (listed in the drilling logs at 8418 feet). Mud cake is noted at 8310 feet, but below this level caving and rugose hole occur rather than mud cake buildup. Formation water R_w is 3.4 ohm-meters at 8315 feet, 2.05 ohm-meters at 8342 feet and 1.4 ohm-meters at 8500 feet (all values corrected to 25°C). Although listed as basalts, the flows in the lower part of the well may be andesites as noted in the description of the vertical core taken at 8084 to 8100 feet.

Figure 16 shows the logs from 8600 to 8900 feet. The slightly to moderately fractured basalt or andesite flow continues to 8780 feet where a 20-foot thick interflow zone occurs. Another moderately fractured flow is observed from 8800 to 8872 feet, and a second interflow zone occurs from 8872 to 8892 feet. The SNP and CFD logs both appear erroneous from about 8650 to 8750 feet and from 8810 to 8870 feet. The extreme hole rugosity may have prevented close contact of the logging sondes with the borehole wall; good sidewall contact is particularly important with the nuclear tools. Formation water resistivity is 1.75 ohm-meters (25°C) at 8794 feet and 1.3 ohm-meters at 8880 feet.

WATER QUALITY

Formation water resistivity (R_w) calculations were made at many locations in the Rattlesnake Hills well. Figure 17 is a graph of the results with R_w plotted against depth in the well. All values are corrected to 25°C. The horizontal dashed line shows the mud filtrate resistivity (R_{mf}) of 3.9 ohm-meters (also corrected to 25°C). Water resistivities that plot close to the R_{mf}

Figure 16

Geophysical Logs - 8600 to 8900 Feet

Figure 17

Formation Water Resistivity versus Well Depth

value may be suspected because very deep invasion of the formation by mud filtrate will cause measurement of R_{mf} and not R_w . The vertical dashed lines show where gross changes occur in water resistivity. These changes generally correlate with observed changes in geophysical log response and spectrochemical analysis. The water resistivity values were calculated from the relationship: $R_w = R_o / F$ and $F = 1/\phi^2$. The data points on the graph represented by a circle are from interflow zones; the points represented by crosses are from basalt or transitional zones. The indicated R_w in the basalts is generally lower than the water resistivity in the interflow zones. This may be real or it may reflect a matrix change effect since the factor ϕ^2 was used for R_w calculations in both the basalt and interflow zones. In any case, the relatively low water resistivity values show that the formation waters at depth in the Rattlesnake Hills Well are extremely hard and contain an average of several thousand parts per million total dissolved solids (as $NaHCO_3$). This also suggests that water movement is low. The sharp changes in R_w indicate that there is isolation between many zones in the well which in turn denote little probability of vertical exchange and movement of the formation water. The drill-stem tests also support this conclusion.

DRILL-STEM TESTS

Seven drill-stem tests were made at various levels in the Rattlesnake Hills well during the course of the in-hole geophysical studies. The objectives of these tests were; determination of formation fluid hydrostatic pressures, measurement of formation permeability and sampling of formation fluid. Test procedures and equipment are described in Appendix A.

Test Results

Drill-stem tests were made by the Cook Testing Co., Long Beach, California. A recently developed Lynes straddle-type, inflatable packer, drill-stem tester was used in the well. The success of the tests was due primarily to the use of this tool, and it is doubtful if any of the other conventional drill-stem tools would have performed satisfactorily under the conditions encountered in the Rattlesnake Hills Well. The Lynes packers seal against four feet of the well bore and conform to rough hole irregularities; whereas conventional packers seal against only a few inches of the hole and often fail to seal properly in a rough hole. The rugose nature of much of the well bore in the test well was evident from the caliper log of the hole, and some of the test zones were highly fractured.

Seven zones in the well were drill-stem tested. A 76-foot interval was used between packing elements for the tests. All of the tests were mechanically satisfactory with no occurrence of fluid bypass of the packing elements. Both basalt interflow zones and fractured portions of basalt flows were tested. Table IV shows the results of the tests. Column 1 lists the test number, column 2 shows the depth of the isolated interval in feet below ground surface (ft. bgs), column 3 indicates the estimated effective test zone thickness as obtained from the geophysical logs, column 4 shows the calculated permeability in millidarcies (Md) for water corrected to 60^oF, column 5 shows depth of the pressure recorder element in ft. bgs, column 6 shows the extrapolated formation fluid pressure in pounds per square inch gauge (psig), column 7 indicates the depth to the potentiometric surface in feet below ground surface (the depth to water if the zone was isolated from the rest of the well and open to the atmosphere), column 8 shows the elevation of the potentiometric surface in feet above

TABLE IV
Drill-Stem Test Data and Results

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>
Test Number	Isolated Test Interval (Ft. below ground surface)	Effective Test Zone (Ft.)	Permeability (Md)	Recorder Depth (Ft. below ground surface)	Formation Fluid Pressure (psig)	Potential Surface (Ft. below ground surface)	Potential Surface Elevation (Ft. above mean sea level)
1.	8275 - 8351	40	0.03	8279	308	7571	-4691
2.	5921 - 5997	76	19.5	5925	1696	2025	+855
3.	4832 - 4908	76	0.2	4836	1285	1881	+999
4.	4119 - 4195	50	0.2	4123	955	1923	+957
5.	3213 - 3289	20	8.0	3217	737	1520	+1360
6.	2614 - 2690	30	0.1	2618	735	926	+1954
7.	1929 - 2005	30	18	1933	384	1051	+1829

mean sea level (ft. msl) with the surface elevation at the well site taken as 2880 ft. msl.

The first drill-stem test straddled a thirty-two foot thick interflow zone centered at 8314 ft. bgs. The tool was opened for flow for 15 minutes, closed for initial shut-in for 1.5 hours, re-opened for one hour and closed for final shut-in for two hours. Indicated formation fluid hydrostatic pressure was low, -4691 ft. msl. (7571 ft. bgs). Calculated permeability is very low (0.03 Md). The plot of pressure build-up data for this test is not particularly good and the pressure and permeability values should be considered order of magnitude estimates. Run number two tested the top of a thick, highly-fractured basalt flow. The test interval was from 5921 to 5997 ft. bgs. The tool was opened for one hour and shut-in for three hours and twenty minutes. The pressure buildup data plot is good, and calculated formation permeability is 19.5 Md which is the highest permeability encountered during these tests. However, this permeability value is still only 1/100 to 1/1000 of the Ringold formation permeabilities measured on the Hanford Project. The potentiometric surface elevation is +855 ft. msl (2025 ft. bgs). Interval number three tested the top of a moderately fractured basalt flow from 4832 to 4908 ft. bgs. The tool was open for one hour and shut in for two hours. The pressure buildup data plot is excellent. Calculated permeability is low (0.2 Md). Formation fluid potentiometric surface elevation is +999 ft. msl (1881 ft. bgs). Some gas flow from the drill pipe was noted during the open period. Test number four straddled an interflow zone from 4119 to 4195 ft. bgs. The zone had an effective interval of about 50 feet with the center depth at 4139 ft. bgs. The tool was open for one hour and shut-in for three hours. The pressure buildup data plot is excellent. Calculated permeability is low (0.2 Md). Formation fluid potentiometric surface elevation is +957 ft. msl (1923 ft. bgs). Test number

five straddled an interflow zone from 3213 to 3289 ft. bgs. The tool was open for one hour thirty minutes and shut-in for three hours. The zone has an effective interval of about 20 feet with the center depth at 3239 ft. bgs. The pressure buildup data plot is good. Calculated permeability is 8 Md. Formation fluid pressure was 737 psig and the potentiometric surface elevation is + 1360 ft. msl (1520 ft. bgs). Moderate gas flow was observed during the open period. Test number six straddled an interflow zone from 2614 to 2690 ft. bgs. Effective test zone thickness was about 30 feet and the center depth was 2629 ft. bgs. The tool was open for one hour and shut-in for two hours. The pressure buildup data plot is fair. Calculated permeability is low (0.1 Md). Formation fluid potentiometric surface elevation is +1954 ft. msl (926 ft. bgs). Test number seven straddled an interflow zone from 1929 to 2005 ft. bgs. The effective test interval is about 30 feet thick and center depth is 1964 ft. bgs. The tool was open for one hour and shut-in for two hours. The pressure buildup data plot is poor and the calculated permeability of 18 Md can be used only as an order of magnitude estimate. Also the potentiometric surface elevation of +1829 ft. msl (1051 ft. bgs) is only an approximation. A nearby well at the Anderson ranch (drilled to 436 ft. bgs) shows a water potentiometric surface of 2680 ft. msl (200 ft. bgs).

Formation permeabilities in the test zones are generally low. Several locations where lost circulation problems were encountered during drilling could not be drill-stem tested due to hole rugosity and/or excessive length of section. These zones may possess permeabilities that are factors of hundreds greater than the drill-stem test sections. The elevation of the potentiometric surfaces generally decrease with depth, with the deepest test zone exhibiting a potentiometric elevation of -4691 ft. msl and the shallowest test zone showing a potentiometric elevation of +1829 ft. msl. The tests, of course, indicate that a high degree of communication does not exist between the different zones.

Formation Fluid Samples

Attempts were made to take water samples from the test zones by use of a drill-pipe cup swab. However, the swab did not perform satisfactorily due to internal roughness of the drill pipe, and samples could not be obtained by this method. Fluid samples were obtained from tests 2, 3, 5 and 7 by pulling the drill-stem tester and recovering the fluid that was forced up the drill pipe during the open-tool flow period. All of the fluid samples were contaminated by drilling mud and mud filtrate. This contamination prevented meaningful chemical analysis and the only observation that could be made was that there is no evidence of saline or highly brackish water. The geophysical logs must be relied upon to furnish information on water quality. As was noted in the drill-stem test discussions, natural gas was detected in two zones and the water sample taken from test number two contained dissolved gas. The gas was analyzed as methane and is not petroleum gas.

SIDE-WALL CORES

Sixty three side-hole coring attempts were made in the Rattlesnake Hills Well. No recovery was obtained for nine coring shots and several other cores were mostly mud cake. Varying degrees of recovery were achieved in the majority of attempts. Core-loss generally occurred in dense basalt zones where the core bullet could not penetrate the hard rock. Appendix C contains megascopic and mineralogic descriptions of the side-wall cores, and photomicrographs of selected thin sections from the cores.

It was expected that the zones between identifiable basalt flows would consist of sedimentary deposits containing considerable amounts of volcanic tuff and ash. However, the cores show that the interbasalt zones are generally highly altered basalt that has apparently weathered in place. Some tuffaceous zones are evident but they are definitely a very minor part of the section.

The sections between basalt flows are therefore designated as interflow zones rather than interbeds.

A vertical core was taken from 8084 to 8100 feet (an interflow or transitional zone is interpreted from the geophysical logs) when the well was drilled, and a 5-1/2 foot core was recovered. A portion of this core was obtained from the State of Washington Department of Natural Resources, Division of Mines and Geology. Thin sections of the core were prepared and an analysis of the sections was made by Dr. W. A. G. Bennett, Washington State Division of Mines and Geology. Dr. Bennett reports: (19)

"Three thin sections of the core taken from the hole have been studied and show a basic augite andesite. In two of the slides a quarter to a third of the area consists of vein material that borders, as well as projects into, the andesite. This vein material consists of quartz, showing doubly terminated prisms, as well as hexagonal cross sections of prisms, enclosed by a zeolite mineral that in places shows a conspicuous cleavage. Under the microscope the rock shows both veinlets of alteration minerals and, to a less extent, scattered alteration minerals. The principal alteration mineral is a bright-green chlorite (?) that has low birefringence, low 2V, and is both positive and negative. That the alteration solutions carried soda is indicated, in one instance along a larger veinlet, by albite-oligoclase (An 10 or 12) with near parallelism of extinction.

Other mineralogical details include the existence of zeolites both positive and negative, as well as uniaxial and biaxial. The assignment of mineralogical names to such minerals is hardly possible in a thin section. Much magnetite or ilmenite is present and this seems altered to reddish brown masses resembling iddingsite. A prismatic mineral present in places along the larger veinlets appears to be anthophyllite, having parallel extinction and is optically positive.

The alteration effects seem to indicate contact metamorphism by solutions released from a plutonic intrusion into andesite that was itself covered by basalt".

The core also differs megascopically from typical Columbia River basalt - the color is lighter and definite porosity is observed. The speculation may be made

that the rock is equivalent to the Fifes Peak andesite that outcrops some 70 miles west of the Rattlesnake Hills Well site.

Conflicting evidence appears to be offered by data from the sidewall cores against contact metamorphism from plutonic intrusions at depth. Amygdules, secondary mineralization and weathering deposits, when available in sufficient quantities were analysed by x-ray diffraction. The minerals identified suggest downward percolation and/or lateral circulation of aqueous solutions of surface origin as the alteration mechanism rather than igneous exudations of deep-seated origin. The most common secondary mineral found in the side-wall cores as identified by x-ray is α -quartz. It is often found as perfect quartzoids (double six-sided pyramids), from 2-5 mm in length, with no noticeable inclusions. The zeolites, laumontite, clinoptilolite, and heulandite commonly occur in all the side-wall cores and ditch samples.

Laumontite ($\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 4\text{H}_2\text{O}$) is most prevalent in the samples below 8000 feet. Between 4000 and 8000 feet, heulandite ($(\text{CaNa}_2)\text{Al}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$) predominates with occasional occurrences of clinoptilolite (variety of heulandite richer in silica). From the surface to 4000 feet, clinoptilolite occurs most exclusively. This succession of zeolites with depth and their relative abundance add weight to the surface origin of aqueous solutions as the alteration mechanism, or to possibly other late-stage hydrothermal alteration. A review of zeolite parageneses by Coombs et. al.⁽²⁰⁾ indicates that there is an apparent general correlation between the silica content of zeolites and the availability of free silica. Thus, in veins and joints in quartz-bearing rocks the typical zeolites are stilbite, heulandite and laumontite with the other zeolites being quantitatively insignificant. Since the surface flows and the flows in the Rattlesnake Hills well are neither primary quartz bearing or silica rich, this theory would

indicate an external source for the solutions causing alteration. It would also indicate that whatever the source of the alteration solutions, it was relatively constant for a period of time after each basalt flow was extruded or after the entire basalt sequence was implaced. The many additional ramifications of zeolites and their occurrence is beyond the scope of this report, but such have received considerable study by others. (21)

The occurrence of chlorite as a secondary mineral or in association with the zeolites is almost always reported in the Columbia Plateau basalts. Very little chlorite could actually be identified from the side-wall cores or ditch samples. What would appear to be chlorite megascopically was found to be montmorillonite-chlorite or the hydromica "illite" on the basis of x-ray diffraction. Montmorillonite (includes all clay minerals identified as expanding layer silicates) often was found to occur in globular to boytroidal layers after quartz or zeolites in the vesicle linings. The hydromica "illite" was found in several cases as a primary layer in vesicle linings. One sample from 5885 feet was almost completely altered to illite along numerous small veins or fractures. Free calcite, quite common in most of the ditch samples, was found as amygdule fillings greater than 5 mm in a side-wall core sample at 4145 feet.

The minerals described above, in general, are stable at or form at low temperatures and pressures. Collectively they are described as "saussurization", the alteration of calcic plagioclase in mafic rocks. (22) One notable exception to saussurization is the presence of well-formed pyrite crystals associated with the zeolites as amygdules in the side-wall sample from 1810 feet, and poorly-formed crystals included with the illite in the sample from 5885 feet. Pyrite was also readily found in the ditch samples over the entire depth of the well.

A discussion of the geothermal implications of pyrite formation and zeolite association would easily fill a volume several times this report. A very general consensus, however, is that pyrite forms from neutral or alkaline solutions and at relatively high temperatures, i.e., greater than 450°C. Because pyrite is the most common of the sulphides and is very widespread, very little significance should be attached to its limited occurrence in the Rattlesnake Hills section.

Specific mineral names in Appendix C, when given, are based on X-ray diffraction results. Specific mineral names when followed by a qualification, such as (?), were described megascopically as similar to those minerals identified by X-ray diffraction analysis.

Pieces of each side-wall core were imbedded in resin and thin sections prepared. The thin sections were examined primarily for unusual or systematic variations in the plagioclase feldspar which might occur. All of the primary feldspar in the matrix or in phenocrysts falls within the range $Ab_{60}An_{40}$ (Andesine) to $Ab_{40}An_{60}$ (Labradorite) which is quite common for the surface basalt flows of the Columbia Basin. No systematic variations apparently exist in the plagioclase type either within zones similar to those identified for chemical variations or in the well as a whole. Secondary plagioclase feldspar occurring along joints or veinlets was in the $Ab_{90}An_{10}$ (Albite) to Ab_{80} (Oligoclase) range which is consistent with the concept of sausserization⁽²²⁾. The thin sections were also used to aid in the resolution of any question that might arise as to petrologic identification of the interflow zones as extrusive flows or pyroclastics.

Detailed petrographic analysis of each side-wall core thin section was considered neither feasible nor particularly desirable at this time. Marked changes are very likely in such properties as grain size, crystallinity and mineralogy not only between flows but also within a single flow from near its

source to its distal margins (9,23). When additional data become available from other deep wells or should new evidence develop, the thin sections may be re-evaluated in more detail.

CHEMICAL VARIATIONS

Statistical analysis of spectrochemical data on the original ditch samples indicated five possible vertical intervals of chemical homogeneity. The same type of analysis applied to spectrochemical data from the side-wall core samples agrees with four of the vertical intervals, and identifies a fifth interval not previously detected from the ditch samples. The six zones identified provide a reasonable basis for stratigraphic correlations with the major Cenozoic intervals established from the surrounding region. A discussion of the analytical procedure, data reliability, statistics, results and basis for conclusions is presented.

Spectrochemical Analysis of Ditch Samples

During the original drilling of the Rattlesnake Hills well, ditch samples of the cuttings taken at approximately 100-foot intervals were analyzed for major metal oxides using a direct-reading spectrograph (Quantometer). The analyses were done by Chevron Research Corporation, La Habra, California, an affiliate of Standard Oil Company of California. Percentages were calculated for relative abundance of SiO_2 , Al_2O_3 , TiO_2 , MgO , CaO , Na_2O and K_2O in 104 samples as compared to a standard basalt sample. Since the eight metals do not all occur as the corresponding oxide in the minerals constituting basalt, the total percentages for any sample could sum to more or less than 100 percent. This is dependent on the presence in varying degrees of other components, such as water, or the change in oxides such as FeO and Fe_2O_3 . Therefore, the absolute values of the calculated oxide percentage for any given sample cannot be directly

correlated with the abundance shown by chemical analyses of surface basalts. The primary utility of these data is to identify, if possible, the vertical extent and relative composition of zones or levels of chemically homogeneous basalt flows. For the purpose of this type of analysis, the absolute values of the oxides or elements are of less importance. Also, there is no need to convert the data from percent oxide to percent metal because these forms differ only by a constant multiplier which will not affect the ratio of any two components.

Several approaches to the analysis of these data were tried before it was decided that the most definitive results relative to the primary goal would best be obtained by an analysis of ratios of one oxide to another. Using this technique, substantial evidence is found to indicate the existence of five zones of chemical homogeneous basalts.

Analysis of Oxide Ratios from Ditch Samples

A total of 28 possible pairs or ratios can be formed from the eight metal oxides for any given sample. Ratios which fall between zero and one were generally chosen for study. A plot of each of the ratios versus well depth is shown in Figures 4, 5 and 6 (Appendix D). Visual inspection of these plots shows not only that most of the ratios have one or more apparent shifts in the mean ratio but that many ratios have apparent shifts at similar depths. The application of statistical methods was necessary to determine if these apparent shifts reflect true changes in the mean ratio and hence true changes in chemical composition.

If attention is restricted to those shifts in which the mean ratio maintains a relatively constant value for about a thousand feet before and after any given shift, then the criterion should be valid from both a geological and statistical standpoint. Since the main interest is to identify "zones" of relatively

homogeneous composition, it was felt that apparent shifts between intervals shorter than one thousand feet would be as likely to be caused by sampling error as by actual composition change.

A visual inspection of ratio versus well depth plots indicates that ratios (satisfying the above interval criterion) shift in the immediate proximity of one or more of the following positions: 1600, 2600, 7700, 8400, and 9500 feet. Table V shows the identification number of these apparent shifts along with the definition of the corresponding pre-shift and post-shift intervals over which the mean ratio maintains relative constant values.

Table V
Oxide-Ratio Shift Locations -- Ditch Samples

<u>Shift No.</u>	<u>Pre-Shift Interval</u> (feet)	<u>Post-Shift Interval</u> (feet)
1	500-600	1700-2600
2	1700-2600	2700-3900
3a	6900-7700	8100-8900
3b	6900-8400	8500-9500
4	8500-9500	9600-10,700

The analysis is complicated by the fact that all the data are missing from the 7800, 7900 and 8000 foot depths. In addition, the data at 2900, 3400 and 3500 feet are generally unreliable and it was deemed appropriate, therefore, to omit them from any calculations. In Table V, the shifts 3a and 3b are so numbered because some ratios appear to shift between 7700 and 8100 feet (data are missing from 7800 to 8000), while other ratios shift around 8400 feet. These two shifts are less than the interval established as meaningful for a shift criterion and could easily be accounted for by one and the same shift changing more gradually between 7700 to 8400 feet.

In an effort to weigh the statistical evidence for or against the reality of an apparent shift in the ratios, the following procedure was carried out. For an apparent shift of the mean between any two given ratios, the difference between the estimated mean ratio over the pre-shift and post-shift intervals was compared to the variability of the ratios within the two intervals. If the difference between any two given mean ratios was larger than what was expected to occur on the basis of interval variability alone, it was concluded that there existed a statistically significant difference between the two interval mean ratios and hence sufficient evidence to indicate a real shift in the mean ratios.

Table VI summarizes the results of the statistical tests described above. A significant shift in the mean of a given ratio from one interval to the next (defined for present purpose as the difference between means significant at the 0.001 level or less) is indicated by an entry in Table VI such as 0.584-0.422. In this case, 0.584 is the mean ratio in the pre-shift interval and 0.422 is the mean ratio in the post-shift interval. Several of the ratios had mean ratio shifts at the 0.001 level to provide unambiguous evidence that real shifts occur in the mean ratios and, therefore, are representative of real changes in gross chemical composition. The reliability of the depth of these shifts required further investigation, especially those changes below 4000 feet, because of the nature of the samples.

Table VI

100-Foot Ditch Samples
Interval Means for Significant Shifts

<u>Ratio</u>	<u>Shift 1</u>	<u>Shift 2</u>	<u>Shift 3a</u>	<u>Shift 3b</u>	<u>Shift 4</u>
K/Na	.584-.422	.422-.529	.628-.434		
K/Ca		.142-.239		.267-.170	
Na/Ca		.335-.452			
K/Si		.023-.032			
K/Al		.086-.121	.164-.105		
K/Fe		.090-.132			
Na/Fe	.174-.213	.213-.249			
Ca/Si		.162-.134			
Ca/Al		.609-.510			
Ca/Fe		.638-.555		.551-.641	.641-.576
K/Ti		.547-.704			
K/Mg	.301-.223	.223-.384	.471-.288		
Ti/Na	1.28 -.782		.770-.643		.643-.781
Na/Mg		.525-.725		.738-.588	.588-.678
Ti/Ca	.376-.260	.260-.335		.336-.256	.256-.327
Ti/Mg	.661-.409	.409-.548	.575-.416		.416-.529
Ti/Si	.064-.042		.045-.039		.039-.045
Ti/Al	.232-.158		.201-.155		
Ti/Fe	.222-.166		.189-.166		.166-.188
Mg/Si		.104-.084		.081-.097	.097-.085
Mg/Al		.389-.318		.346-.390	.390-.332
Mg/Fe	.335-.406	.406-.343	.329-.402		.402-.357
Fe/Si	.292-.255				

Correlation Analysis

A correlation analysis was carried out on the oxide percent data for all 104 ditch samples by calculating the correlation coefficient for each of the 28 possible pairs of oxides. The purpose of this analysis was primarily to check on which oxides may correlate in addition to those indicated by visual examination of the ratio plots. The correlation coefficients are presented in Table VII. An asterisk (*) denotes that the corresponding coefficient

is statistically significant (different from zero) at the 0.001 level.

Table VII

Oxide Correlation Coefficients
100' Ditch Samples

	<u>SiO₂</u>	<u>Al₂O₃</u>	<u>TiO₂</u>	<u>Fe₂O₃</u>	<u>MgO</u>	<u>CaO</u>	<u>Na₂O</u>	<u>K₂O</u>
SiO ₂	1	.65*	.13	.16	.11	.11	.41*	.33*
Al ₂ O ₃	.65*	1	.32*	.18	.28	.25	.00	.17
TiO ₂	.18	.32*	1	.67*	.02	.29	.07	.30
Fe ₂ O ₃	.16	.18	.67*	1	.50*	.68*	.15	-.15
MgO	.11	.28	.02	.50*	1	.77*	-.04	-.39*
CaO	.11	.25	.29	.68*	.77*	1	-.07	-.38*
Na ₂ O	.41*	.00	.07	.15	-.04	-.07	1	.46*
K ₂ O	.33*	.17	.30	-.15	-.39*	-.38*	.46*	1

Two observations are necessary concerning these correlation coefficients.

First, the linear correlation analysis performed assumes that two variables being correlated maintain the same mean value for all points of the sample. In view of the ratio analysis described previously, this assumption obviously does not hold because shifts in the ratio means have been demonstrated. This may account for an apparent lack of correlation in those pairs which do not have a significant coefficient in Table VII. Second, in spite of the first observation, several pairs show a very high correlation, indicating that there is at least a linear relation between the variables of the pair. This can best be illustrated by the plot of the oxide data (Figure 3-D) which shows that certain variables have corresponding peaks and troughs.

Most previous work regarding chemical variability in basalts has been limited to determination of the ratio of various oxides with SiO_2 . (5,13,17,24) These silica variation diagrams provided a useful tool in differentiating gross basalt types. However, the evidence presented in Tables VI and VII indicates that not all of the major metal oxides correlate well with SiO_2 , and those that do show good correlation do not necessarily exhibit the highest degree of linear relationship.

Spectrochemical Analysis, Side-Wall Cores.

Of the sixty-three side-hole coring attempts made upon re-entry into the Rattlesnake Hills well, recovery was adequate in forty-one samples to provide diagnostic material for spectrochemical analysis. The method used for analysis was tailored as closely as possible to the methods the Standard Oil Company of California used with the ditch samples. The analyses of the side-wall cores can thus be compared directly with the results from the 100-foot ditch samples. Since most of the side-wall cores were basalt, rather than tuff or other sedimentary interbed material, it was established that the chemical variability is due primarily to gross changes in basalt types and not a function of some other variable.

Analysis of Oxide Ratios, Side-Wall Cores

Due to limitations in the spectrochemical method used on the side-wall cores, it was not possible to analyze for Na; therefore, only twenty-one possible pairs or ratios could be formed for any given sample. Plots of the nine most significant ratios are presented in 2-D. These were chosen because they exhibited the greatest variability in mean ratios.

Evaluation of oxide ratios versus well depth for side-wall cores indicates that apparent shifts occur in the proximity of one or more of the following positions: 1700, 2700, 4300, 7700 and 8600 feet. Table VIII shows the identification number of the apparent shifts along with the definitions of the corresponding pre-shift and post-shift interval.

Table VIII

Oxide-Ratio Shift Locations -- Side-Wall Cores

<u>Shift No.</u>	<u>Pre-Shift Interval</u> (feet)	<u>Post-Shift Interval</u> (feet)
1a	1020-1680	1725-2640
1b	1020-2640	2850-4246
2	2850-4246	4372-7403
3	4372-7403	7827-8510
4	7827-8510	8810-9285

The criteria used to establish shift levels in the side-wall core data were not restricted in the same way as were those for ditch sample data. Any major change in the mean of the ratios for the side-wall cores was deemed significant if preceeded by at least three sample points. This was because the errors that might be attributed to sampling were minimal. The evaluation showed that all pre-shift and post-shift intervals generally cover a range of about one thousand feet. In Table VIII, the shifts 1a and 1b are so numbered because a change in the ratio mean appears to occur around 1700 feet but data for the sample at 1680 feet are unreliable and the pre-shift interval, therefore, consists of only two points. Since no side-wall core recovery was made between 7403 and 7827 feet, shift 3 is designated at 7700 feet on the basis of the data from the ditch samples.

In order to weigh the statistical evidence for or against the reality of any apparent shift in the mean ratios from the side-wall core data, the same procedure was followed as was previously applied to ditch sample data. The difference between the pre-shift ratio mean and post-shift ratio mean was compared to the variance within each interval. In each case, if the difference was larger than expected to occur on the basis of within-interval variability alone, it was concluded that the shift was statistically significant and probably represents real changes in the mean ratios.

Table IX summarizes the results of the statistical tests for nine of the twenty-one possible ratios. Only the significant mean shifts in a given ratio are entered in the table. A significant mean shift is defined as the difference between means at the 0.001 level or less. All of the ratios had significant mean shifts at larger levels (such as 0.01 or 0.05) but these were not included.

Table IX

Side-Wall Core Samples

Interval Means for Significant Shifts

<u>Ratio</u>	<u>Shift 1a</u>	<u>Shift 1b</u>	<u>Shift 2</u>	<u>Shift 3</u>	<u>Shift 4</u>
Ti/Ca	.425-.269	.269-.307	.307-.383	.383-.323	
Ti/Mg	.594-.418	.418-.469	.469-.572	.572-.307	.387-.454
Ti/Si	.071-.041			.044-.034	
Ti/Al	.294-.185		.195-.201		
Ti/Fe	.232-.178	.189-.175	.175-.186		
K/Ca		.149-.203	.203-.326	.326-.334	.334-.214
Ca/Fe	.547-.700	.670-.573	.573-.455		
K/Mg		.228-.307	.307-.479	.479-.382	
Mg/Fe	.395-.462	.449-.381		.337-.407	.407-.342

Plots of the metal oxide percent versus depth for the side-wall cores and ditch sample are presented in Figures 2-D, and 4-D through 6-D respectively. Table X presents information on zones of homogeneity as determined from the ditch sample data, side-wall core data and geophysical logs. Information from the geophysical logs refers to gross changes in response that were noted. For example, the resistivity log shows high values from 0 to 1600 feet, medium values from 1600 to 2600 feet, high values from 2600 to 4000 feet, very low values from 4000 to 7100 feet and high values from 7800 to 9300 feet.

Statistical analysis of spectrochemical data from side-wall cores and ditch samples at 100-foot intervals from the Rattlesnake Hills well offers substantial evidence for the existence of six zones of chemical homogeneity.

Table X
Zones of Homogeneous Response

<u>Zones From</u> <u>Ditch Sample</u> <u>Data</u> <u>(feet)</u>	<u>Zones From</u> <u>Side-Wall Core</u> <u>Data</u> <u>(feet)</u>	<u>Zones From</u> <u>Geophysical Log</u> <u>Data</u> <u>(feet)</u>
0-1650	0-1600	0-1600
1650-2650	1600-2700	1600-2600
	2700-4300	2600-4000
6900-7700	4300-7700	4000-7100
6900-8450	7700-8600	7800-9300
8450-9500	8600	

The levels where the gross chemical and physical character changes occur are in the proximity of 1600, 2600, 4200, 7700, 8500 and 9500 feet. It is proposed that these zones represent either regional changes in the source of the basalt flows; gross regional changes in the conditions under which the flows were

extruded, cooled and subsequently weathered; or as is most likely, a combination of both. Further study will be required to prove the probable time-stratigraphic relation of these zones with other gross geologic intervals thought to exist in the region.

PALEOECOLOGY AND GEOCHRONOLOGY

Palynology

Original examination of the cuttings recovered during drilling of the Rattlesnake Hills Well revealed a higher than normal percentage of coal and carbonaceous shale than had been previously reported from wells drilled in the area. The occurrence of coal was confined generally between 2,000 and 5,000 feet in depth which is well below the level normally reached by wells drilled in the vicinity for water or gas. Since coal is an ideal depository for fossil pollen and spores from the plants existing in the geologic past, a study of the palynology was considered as the most promising source for information on the paleoecology and geochronology.

The basic principles behind the use of palynology in any stratigraphic studies are two assumptions: that plants evolve, and that floras migrate in time and space under the influence of environmental change. The evolution of plants affects not only the extreme gross form but also the microscopic reproductive units of plants, the spores and pollen. Spores are produced by the "lower" land and aquatic plants such as fungi, algae, bryophytes and ferns. Pollen, an elaboration of spores produced by the "higher" plants (i.e., the flowering plants and conifers), is the male part of these plants. Plants produce enormous quantities of spores and pollen which are widely

dispersed by wind, water, insects, birds and occasionally mammals. Only a minute percentage ever fulfills nature's purpose of reproduction; while many of the remainder, because of an incredible toughness and resistance to destruction, are transported to favorable sedimentary environments where they are incorporated into accumulating sediments⁽²⁷⁾.

It was planned to take sufficient side-wall cores in the coal seams upon re-entry into the well so that a fairly complete stratigraphic sequence would be available. However, the coal seams were either discrete interbeds within weathered volcanic sequences or separate interbeds that could not be positively differentiated by geophysical methods from the weathered volcanic sequences. As a result, only one side-wall core out of the forty-three recovered had any trace of organic sediments. Consequently, samples were selected from the original well cuttings at those depths where the recovery was greater than 60% coal, or composited from intervals where the recovery was greater than 20% coal. Table XI lists the depth and lithology of the 10 samples selected for pollen analysis.

Table XI

Cutting Samples from the Rattlesnake Hills Well Examined
For Spores and Pollen

<u>Sample Designation</u>	<u>Lithology</u>	<u>Depth (feet)</u>
R-1	20% Coal	2100-2300
R-2	75% Coal	2400-2420
R-3	40% Coal	3000-3100
R-4	70% Coal	3140-3160
182b	50% Coal	3340-3440
R-5	80% Coal	3500-3540
R-6a	40% Coal	4600-4700
R-6b	40% Shale	4660-4700
R-7a	40% Coal	4780-4800
R-7b	40% Shale	4780-4800

The extraction of plant microfossils from rock and the preparation for examination is known as maceration. The basic procedure is standard although minor variations were introduced to suit the specific samples. The samples were washed in distilled water, centrifuged, and dried to remove any possible surface contamination present. They were then crushed to a maximum particle size of about 3 mm and placed in dilute HCl to remove carbonate. Following this treatment the samples were washed in distilled water and placed in dilute HF to remove silicate minerals. The residue, usually plant microfossils coated with carbonaceous material, was removed by oxidation with HNO_3 and KClO_3 . The remaining spores and pollen were chemically stained (usually with safranin) and mounted on glass slides for microscopic examination.

The identification and classification of pollen and spores is known as taxonomy. The system which is normally used is the so called "natural classification," in which pollen grains are assigned to existing natural plant groups. This procedure is generally possible only with Late Cretaceous and Tertiary pollen, because during this period most of the extant plant genera made their first appearance. Throughout the Tertiary the floras of the world were taking on an evermore modern aspect with most of the modern genera appearing before the end of the Pliocene. By comparison with the literature and modern reference material, many Tertiary pollen and spores can be assigned to modern genera. Form generic names are used for pollen which cannot be assigned to modern extant genera. This report is restricted to generic names only since in any discussion of ecology the artificial specific name has little value.

Thirty-eight taxa (genera and form genera) of fern spores, gymnosperm pollen, angiosperm pollen, and algae were identified in the samples from the Rattlesnake Hills Well. Several genera included more than one species but were not subdivided except for the form genera.

Table XII is a list of the genera with their common names (where known) and the climatic or environmental distribution of the modern genera where applicable.

Table XIII is an occurrence list of the palynomorph taxa with depth. No attempt was made to analyze statistically the frequency of occurrence because of the composite nature of the samples. A general quantitative count was made which, with the data in Table XII and XIII, provides the basis for age and paleoecology interpretations.

Table XII

List of Palynomorph Genera with Common Names of Parent Plants
And Climatic or Environmental Distribution of Modern Plant Genera

<u>Genus*</u>	<u>Common Name**</u>	<u>Climate or Environmental Distribution</u>
(Fern Spores)		
<u>Osmunda</u>	Fern	Temperate to tropical swamps, shaded moist woodlands, mainly northern hemisphere.
<u>Lycopodium</u>	Club moss	Temperate to tropical, most are mesophytic, cosmopolitan, widespread.
<u>Azolla</u>	Water fern	Subtropical, swamps and lakes.

Table XII continued

<u>Genus*</u>	<u>Common Name**</u>	<u>Climate or Environmental Distribution</u>
<u>Laevigatosporites</u>		Widespread; spores common in swamp sediments.
<u>Polypodiidites</u>	Fern	Widespread; spores common in swamp sediments.
Deltoidospora		Widespread; spore common in swamp sediments.
(Gymnosperm Pollen)		
<u>Taxodium</u>	Bald cypress	Warm temperate to subtropical, swamps and floodplains of southeastern United States and Mexico.
<u>Pinus</u>	Pine	Variable, swamps to rocky highlands, predominantly dry sites, northern hemisphere.
<u>Cedrus</u>	Cedar	
<u>Abies</u> ?	Fir	
<u>Picea</u> ?	Spruce	Boreal to temperate generally high altitude, moist soils, mainly northern hemisphere.
<u>Tsuga</u>	Hemlock	Temperate.
<u>Larix</u> or <u>Pseudotsuga</u>	Larch or Douglas Fir	Boreal to temperate.
<u>Podocarpus</u> ?	Conifer	Warm temperate, moist woodlands and mountains of the southern hemisphere, Caribbean, and South America.

Table XII continued

<u>Genus</u> *	<u>Common Name</u> **	<u>Climate or Environmental Distribution</u>
(Angiosperm Pollen)		
<u>Gramineae</u> , undiff.	Grass	Widespread.
<u>Carya</u>	Hickory	Cool temperate to subtropical, variable habitat, southeast Asia, eastern North America.
<u>Fagus</u>	Beech	Temperate, often forms homogeneous forests, northern hemisphere.
<u>Quercus</u>	Oak	Temperate, to subtropical, wide range of habitat, northern hemisphere, mountains of tropics.
<u>Ulmus</u> or <u>Planera</u>	Elm	Boreal and temperate to warm temperate, lowlands, river valleys, northern hemisphere.
<u>Liquidamber</u>	Gum	Warm temperate to subtropical component oak-hickory forest, northern hemisphere.
<u>Ilex</u>	Holly	Warm temperate to subtropical bogs, moist depressions, cosmopolitan.
<u>Nyssa</u>	Tupello or black gum	Temperate to warm-temperate swamps and floodplains southeastern United States and Mexico.

Table XII continued

<u>Genus</u>	<u>Common Name</u>	<u>Climate or Environmental Distribution</u>
<u>Alnus</u>	Alder	Variable, swamps, wet woods, stream margins, cosmopolitan.
<u>Engethardtia</u> ?		Temperate or subtropical.
<u>Peterocarya</u>	Angiosperm tree	Temperate, northern hemisphere of the Old World.
<u>Acer</u>	Maple	Widespread.
<u>Salix</u>	Willow	Widespread.
<u>Castanea</u>	Chestnut	Widespread.
<u>Jussiaea</u>		Warm temperate to tropical wet conditions.
Rugaepollis		
Plicapollis		
Tilliaepollenites		
Ovoidities or Schizosporis		
Tetradopollenites		
(Algae)		
Sigmopollis		Swamps.
Botrydcooccus		Fresh water lakes and swamps.
Veryachium		Marine, only one specimen found may be contaminant.

Occurrences of Palynomorph Taxa in Rattlesnake Hills Well
(K. R. Newman - December, 1967)

Taxa	Depth	2000'	R-1 2100-2300'	R-2 2400-2420'	2500'	R-3 3000-3100'	R-4 3140-3160'	182b 3340-3440'	R-5 3500-3540'	4000'	R-6a	R-6b 4660-4700'	R-7a	R-7b 4780-4800'
Spores	Osmunda spp.	X	X	X		X	X	X	X		X		X	X
Lycopodium spp.												X		X
Azolla sp.														X
Laevigatosporites spp.		X	X	X		X	X	X	X		X	X	X	X
Polypodioidites spp.									X			X	X	X
Deltoidospora sp.														X
Gym. Pollen	Taxodium sp.	X	X	X		X	X	X	X		X	X	X	X
Pinus spp.			X			X	X		X			X	X	X
Cedrus spp.			?			X	X	X	X			X		X
Abies ? spp.			?						?					
Picea ? spp.			?											?
Tsuga sp.						X			X			X		X
Larix or Pseudotsuga			X			X	X	X	X					
Podocarpus spp.						?								
Angiosperm Pollen	Gramineae		X				X	X	X			X		X
Carya sp.		X	X	X		X	X	X	X		X	X	X	X
Fagus sp.								X	X					X
Quercus spp.		X	X			X	X	X	X		X	X	X	X
Ulmus or Planera spp.		X	X	X		X	X	X	X		X	X	X	X
Liquidamber		X	X	X		X	X	X	X		X	X	X	X
Ilex				?				X				X		
Nyssa		X	X	X		X	X	X	X		X	X	X	X
Alnus			X			X	X	X	X		X	X	X	X
Engethardtia ? ap.			X					X	X					
Peterocarya spp.			X			X		X	X			X	X	X
Acer ?				X			X	X	X					
Salix sp.									X			X		
Castanea ? sp.												X		
Jussiaea sp.			X					X	X			X		X
Rugapollis spp.								X	?			X		
Plicapollis sp.								X			X	X	X	X
Tilliaepollenites sp.								X	X					
Ovoidites 1			X			X		X	X					
Ovoidites 2								X			X	X	X	X
Tetrad			X	X		X		X	X		X		X	X
Algae	Sigmopollis sp.		X	X		X		X			X	X	X	
Botrydoccus sp.								X						
CF Veryachium sp. (Contaminant?)								X						

Paleoecological and Geochronological Interpretations

Plants are ideally the most sensitive of the terrestrial ecologic indicators since they are rooted to one spot and must tolerate the environment in which they grow. Analysis of fossil floras should provide data on climatic conditions at the time of growth. There are several problems, however, that must be considered. In all paleontology, a generally accepted truism is, "the present is the key to the past." In paleoecological interpretations, it would be assumed that any organism, whether plant or animal, reacted to a given environment in much the same way as their modern counterpart. For example, a cypress or gum tree would have had the same ecological requirements in Oligocene as it does today. The problem with this assumption is that we are not really familiar with the ecological requirements and range of tolerances of most present day genera and species of plants. However, if a total range of variables within a **genus** is taken, and as many genera as possible utilized, a reasonable qualitative estimate of climatic conditions at the site of deposition can be made for the time a particular flora existed.

A second problem is whether a given sample is truly representative of the flora at the time of deposition. Differences in the number of pollen and spores produced can be highly variable; differences in the preservation or resistance to attack and the methods of pollen dispersal will all be reflected in the relative quantities of taxa that can be obtained from a given sample.

These problems and others lead to complications in interpretation that must always be borne in mind when arriving at conclusions concerning the ecology. Without the benefit of a significant number of samples taken both

laterally and vertically, any conclusions regarding paleoecology must be regarded as tentative and qualitative.

As seen in Table XII, the bulk of the genera indicate a temperate to warm-temperate climatic range, with a few also suggesting subtropical to tropical climates. The assemblages throughout the sampled interval are fairly uniform in aspect and the differences in climates indicated might be ascribed to differences in elevations occupied by the plants, to differences between modern and mid-Tertiary plants, or to the presence of relict plants remaining from earlier tropical climates.

The dominant genera on a quantitative basis from the samples are Laevigatosporites, Osmunda (fern), Ulmus/Planera (elm), Nyssa (Tupello), Liquidamber (gum), Quercus (oak), Carya (hickory), Taxodium (bald cypress), and the conifers. Taken together these genera indicate a temperate to warm-temperate to possibly subtropical climate. The requirements for most are humid conditions with no seasonal droughts. In the case of Taxodium (bald cypress) there must be more than 40 inches of rainfall per year and winter temperatures generally averaging not less than 32°F.

The various conifer pollen types are fairly common in the samples, but it is probable that the parent plants existed on higher ground away from the coal swamps. There is no evidence of arid-type plant pollen in any of the samples which suggested that the mountains or hills of the time were relatively low, causing no rain shadow or extremely well-drained slopes.

In Chaney's⁽²³⁾ "Ancient Forests of Oregon," a very similar assemblage is described for the Bridge Creek flora, John Day Basin, Oregon. Oak, beech, birch, hickory, chestnut, sweet gum and katsura are the common trees.

Along with the dawn redwood, these trees are all recorded from the Eocene deposits of Alaska and are members of the Arcto-Tertiary flora that migrated southward into Northeastern Asia at the same time that it came down into Washington and Oregon. Oak trees are largely restricted to the more humid western part of Washington and Oregon today. Sweet gum, beech, and hickory no longer live in Western North America, but are common to the hardwood deciduous forest of the Cumberland Plateau of Tennessee. All of the trees are represented by living genera that survive in valleys of Central China. Two notable exceptions are Metasequoia (dawn redwood), and Cercidiphyllum (katsura) both common to the Bridge Creek flora but not identified in the Rattlesnake samples. The reason for this may be that the environmental requirements for Metasequoia and Cercidiphyllum require slightly higher rainfall and more uniform temperatures than the other genera described from the Rattlesnake samples.

Another assemblage which contains many of the less predominant genera found in the Rattlesnake samples is described by Hopkins⁽²⁹⁾ from the Eocene-Middle Oligocene, Coos Bay area, Oregon. Bald cypress, willow, alder, holly, and cattail which are characteristic of a low moist and poorly drained coastal area comprise the bulk of the flora. On a slightly higher upland stood a hardwood forest similar to that currently present in parts of Eastern United States and Central China. Typical trees were elm, sweet gum, oak, basswood, chestnut, and bayberry. Other trees present in more upland habitats included beech, pine, spruce, hickory and hazelnut. Several of the more tropical genera such as Typha (cattail) and Glyptostrobus (contonwater pine) and trees from the family Magnoliaceae (*Magnolia*) and

Bombacaceae (tropical trees) present in the Coos Bay flora suggest an earlier and more tropical environment than that represented by the Rattlesnake samples.

In summary, the ecologic picture suggested by the Rattlesnake samples is a coal swamp area inhabited by ferns, bald cypress, tupello, gum, with perhaps willow, alder, holly and cattail nearby. The higher ground and hills to the west were inhabited by a hardwood forest and mixed hardwood/conifer forest similar to the Cumberland Plateau of today. Interpretations of the paleoecology indicates a flora of temperate to semi-tropical nature, possibly transitional from Eocene-early Oligocene tropical/subtropical floras to the more temperate floras of the Miocene and Pliocene^(30,39).

All of the evidence to date, both floral and faunal as well as geologic, indicates that the Tertiary (70 million years) generally was a period of cooling with occasional temporary reversals. World-wide the climate was becoming colder. The interval of time (7 million years) between the Eocene and middle Oligocene is considered as too short and the cooling insufficient to make major changes in the local floral picture. The tropical environment of the Eocene was still in evidence during early Oligocene^(29,32). By the time the Miocene began (25 million years) fossil pollen and spores along with other floral and faunal evidence indicates major climatic changes had occurred⁽²⁸⁾.

The age of the coal sequence in the Rattlesnake Hills Well must be younger than Early Oligocene since that age is believed to have had the last tropical/subtropical climate in the region⁽³²⁾. The Rattlesnake coals are also younger than the nearest surface coals at Roslyn, Washington which contain a pollen assemblage derived almost entirely from tropical plants⁽³³⁾.

If middle Oligocene (33 million years) is considered as the oldest probable age, the upper limit will depend on the vertical stratigraphic range of the various taxa. Unfortunately, in this part of the geologic column, there is very little published about pollen and spore range zones. The significance of any range zone bases or tops indicated by Table XIII would be very questionable.

Some evidence does exist, however, for an upper range zone by the fact that all the samples contain Liquidamber pollen. Smiley⁽³⁴⁾ reported that Liquidamber is not known, as a megafossil from any deposits younger than middle Miocene. Grolier⁽⁵⁾ reported that two samples from the Vantage Sandstone Member of the Yakima Basalt contained 0.5% Liquidamber. A Potassium-Argon age date by Evenden⁽⁴¹⁾ on the Ginkgo Flow that immediately overlies the Vantage Sandstone was found to be 13.4 million years. This age would generally be considered closer to the upper Miocene.

Another line of evidence is also furnished by the fact that none of the Rattlesnake Hills Well samples yielded any Compositae pollen at all. Newman⁽³⁵⁾ reports that no Compositae pollen has been reported from any pre-Miocene rocks in North America, while all Miocene or younger samples reported do contain Compositae pollen. This negative evidence would suggest an Oligocene age. (Note: Compositae is a system comprised of several of the most highly developed families in the plant kingdom which are characterized by having the small florals or florets borne in dense involucrate heads resembling single flowers. Examples are the daisy, aster, and dandelion).

In summary, based on the sparse stratigraphic range data available at present, the age of the coal intervals samples in the Rattlesnake Hills Well is within the range of middle Oligocene to middle Miocene and could

easily be considered middle Oligocene to late Oligocene. As other palynomorph sequences are determined in older time equivalent and younger rocks within the region, it will be possible to make more precise age and environmental determinations.

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APPENDIX AGEOPHYSICAL LOGGING TECHNIQUES AND
DATA INTERPRETATION METHODSDUAL INDUCTION - LATEROLOG-8 (DIL)

The DIL survey provides simultaneous logarithmic recording of three formation resistivity measurements. A spontaneous potential (SP) curve is also recorded. The DIL serves to measure the undisturbed true formation resistivity, evaluate the mud filtrate invaded zone resistivity and determine stratigraphic breaks. Conventional electrical logging tools employ electrodes from which direct current is transmitted into the formation through conductive well-bore fluid (usually drilling muds); whereas the induction logging tools induce an alternating current into the formation by means of insulated coils. The induction tool consists of a transmitter coil and a receiver coil wound coaxially on an insulating mandrel. An alternating current of constant magnitude and frequency is fed to the transmitter coil, and the alternating magnetic field generated by this current induces eddy currents in the formation surrounding the well bore. These currents, in turn, induce emf's in the receiver coil. The intensity of the current induced in the formation and in the receiver coil is proportional to formation conductivity. Auxiliary coils are incorporated in the logging sonde to focus the current and minimize the influence of the mud column and the effects of adjacent formations.

The DIL records a medium penetration curve and a deep penetration curve. The medium induction tool has an effective investigative diameter of 60 inches (receives 50 percent of its signal from within a 60-inch cylinder),

and the deep induction tool has an effective investigative diameter of about 130 inches. With the deep induction log, there is almost no signal contribution from a 3-foot diameter cylinder near the well bore. Vertical resolution for both induction tools is about 40 inches. The induction devices have the following advantages over the conventional resistivity tools:

- Bore hole fluid, hole size and condition have little or no effect on the induction log.
- The induction tools have a large depth of investigation without distortion.
- The induction log gives good stratigraphic definition where bed thickness is not less than 4 feet.
- The induction log is very accurate in formations where resistivity is less than 50 ohms/meter/square meter (ohm-meter).

The main limitation of the induction log is the low sensitivity at high formation resistivities. The log cannot be relied on above a few hundred ohm-meters.

The Laterolog-8 curve recorded with the DIL is a conductive, point-electrode focused, shallow investigative electric log. The objective of the LL8 log is accurate, shallow-zone resistivity measurement under most borehole, mud and invasion conditions. The effective diameter of investigations is about 30 inches and vertical resolution is about 3 feet. Because of the focused nature of the current, adjacent formation effect is negligible. High mud resistivity and large hole size can effect the indicated resistivity because mud resistivity, formation resistivity and invaded zone resistivity are measured in series.

MICROLOG

The Microlog is a non-focused resistivity log recorded with three electrodes mounted a short distance from each other on an insulated pad. The pad is pressed against the wall of the bore hole. The electrode system is shielded from bore-hole mud and measures the resistivity of a small area of material located directly under the pad. The electrodes are mounted one inch apart on the pad and a micro-normal and a micro-inverse curve are recorded. The radius of investigation for the micro-inverse curve is about one inch. Where mud cake builds up on a porous and permeable formation (due to filtration), the micro-inverse curve responds mostly to the low resistivity of the mud cake. The radius of investigation for the micro-normal curve is about four inches; therefore, it samples the formation even beyond relatively thick mud cakes and responds at least partially to the formation characteristics. The microlog is primarily used to delineate and evaluate porous and permeable beds. A caliper curve showing hole diameter variations is also recorded with the microlog.

COMPENSATED FORMATION DENSITY LOG (CFD)

The standard formation density logging tool consists of a radioactive gamma ray emitting source (usually Co^{60} or Cs^{137}) and a gamma ray detector mounted some distance apart on a well-wall skid. The source is collimated to direct most of the radiation into the well wall beneath the skid and the detector is shielded from direct radiation from the source. The emitted gamma rays interact with the material around the well bore and the photons are scattered back to the detector. The intensity of the back-scattered radiation depends upon the electron density of the material penetrated, and the detector signal is an exponential function of the density of the

medium -- the higher the formation density, the smaller the detector signal. The purpose of the density log is to determine the bulk density of the formation. Then, if the grain density is constant, formation porosity can be derived. The radius of investigation of the density tool is very small. Most of the recorded signal is derived from interactions occurring within about six inches of the well bore. It is obvious that build up of mud cake or rugose hole conditions that prevent close contact of the tool pad against the formation will cause large errors in density measurement. Schlumberger's Compensated Formation Density equipment (CFD) incorporates a second close-spaced detector that responds only to material very close to the bore hole, the objective being to correct for bore hole conditions. The two detector signals are fed into an analog computer in the surface panel and the computer derives a value of uncompensated formation density from the sense detector, computes a density correction using the signal from both the sense and auxiliary detectors, and adds to or subtracts from the uncompensated value to obtain corrected density. No prior knowledge of formation density, mud cake density or hole diameter variations is needed. The formation density and the correction signal are recorded on the log. When the correction signal curve deflects off-scale, the interpreter knows that bore hole conditions were encountered that were beyond the range of the compensating signal. The CFD equipment also records a formation porosity curve. Formation porosity is automatically computed from surface panel selection of one of several set grain-density values. In addition a caliper curve of bore-hole size variation is recorded.

SIDEWALL NEUTRON POROSITY LOG (SNP)

The SNP logging tool consists of a side-wall skid containing a spaced fast neutron radiation source (Pu-Be or Am-Be) and a epithermal neutron detector. The fast neutrons penetrate through the formation adjacent to the well bore and collide with nuclei in the formation. The neutrons are slowed down to thermal energy levels (moderated) and eventually captured. In the absence of efficient moderating materials near the well bore, the neutrons travel a relatively long distance before thermalization, and few thermal neutrons are scattered back to the detector. However, many thermal neutrons are scattered back to the detector if a moderating agent occurs in the formation. Light element nuclei (such as hydrogen, helium or carbon) are efficient in moderating neutrons to thermal energies. Hydrogen in water and petroleum hydrocarbons are the major moderators present in subsurface earth formations. Actually the SNP detector measures eipthermal rather than thermal neutron intensity. This serves to cancel out the absorption effects of varying water salinity and strong thermal neutron absorbers that may occur in minor amounts in the subsurface formations. Thus the SNP log serves to define total formation porosity in saturated zones. The radius of investigation is small, on the order of a foot from the well bore in the higher porosity zones. Mud cake on the bore hole wall is a disturbing influence on the SNP log since the cake keeps the logging skid away from the formation and introduces a high porosity and low density material between the tool and the formation.

BOREHOLE COMPENSATED SONIC LOG (BCS)

Sonic logging involves the recording of the time required for a sound wave to transverse a finite length of formation. These travel times are continuously recorded versus depth as the sonde is moved up the bore hole. The standard sonic logging sonde consists of a sound transmitter (magnetostrictive oscillator) and two sound receivers mounted on a sound insulating mandrel. The first receiver is mounted three feet below the transmitter and the second receiver is located two feet below the first receiver. Sound pulses generated by the transmitter travel in all directions from the source, across the mud, into the formation, down the formation and thence to the receivers. The first energy arrival at the receivers is from refracted waves that have traveled through the formation. Several waves traveling through either the mud or the sonde body arrive at the receivers at much later times. The first energy arrival at the first receiver opens a timing gate and the energy arrival at the second receiver closes the gate. The sound travel path to the second receiver differs from the path to the first receiver by the length separating the receivers. Thus the time gate signal is a measure of the reciprocal velocity of sound in the formation between the receivers. The transmitter is pulsed at the rate of 15 to 20 pulses per second with a transmitted sound wave frequency of about 20 kHz. The BCS equipment incorporates an additional transmitter and receivers whose signals serve to compensate for variations in bore-hole size and attitude of sonde in the hole. The rate of sound propagation through the rock depends on the elastic properties of the rock matrix and contained fluids. Given a specific matrix and fluid, the sound velocity can be correlated with matrix porosity. Thus

the sonic log is used primarily for porosity determination. The sonic log also gives important information on the seismic characteristics of formations. A caliper log is recorded along with the sonic log. The sonic log is relatively unaffected by mud cake and variations in bore hole size. The radius of investigation of the sonic tool is small - about one foot beyond the mud cake in soft formations and about four feet in hard formations. A phenomenon described as "cycle skipping" may be noted on sonic logs by the occurrence of sharp, high transit time deflections on the recorded curve. Cycle skipping is caused by sonic energy attenuation by the formation to such an extent that first arrival energy opens the time gate but does not trip the second receiver and close the time gate. The gate is then closed by higher energy later sound wave arrivals. Thus an erroneously long transit time is recorded. Horizontal fractures and gas-containing formations are primary causes of cycle skipping. Indeed, cycle skipping is diagnostic of horizontal fractures in hard formations. Vertical fractures are not detected by the sonic log and when porosity is mostly due to vertical fractures, the sonic derived porosity will be anomalously low.

SONIC AMPLITUDE - VARIABLE DENSITY LOG

Data for the sonic amplitude - variable density log are taken on the same run and simultaneously with the BCS data. A single receiver transit time is also recorded on the same log. The sonic amplitude log is a record of the three-foot receiver output for an early compressional wave. The sonic amplitude log is helpful in defining fractured zones although other factors such as sonde standoff can effect the relative amplitude of the receiver output.

The variable density log is a "picture" of the total three-foot receiver signal. The receiver signal is fed to a cathode ray tube and the light patterns photographed with a camera. The band-like characteristic of the film recording is obtained by sweeping a beam across the cathode ray tube and modulating the beam with the receiver signal. The modulation is such that positive receiver signals show up as dark bands, and the negative signals show up as light bands with the shading proportional to signal intensity. Thus a continuous variable-density microseismogram is produced that shows arrival, intensity, distortion and interferences of the various seismic waves. Qualitatively, the variable density log can be used to assess seismic characteristics of the formation and show fractured zones. Other factors such as sonde position in the bore hole can cause anomalous distortions and attenuations of the waves that are unrelated to formation characteristics. Research is being carried out to quantitatively evaluate the large amount of information displayed on the variable density log.

CALIPER LOG

The caliper log shows variations in bore hole diameter. Several of the tools run in the Rattlesnake Hills Well incorporated a caliper log. This log is the simplest yet one of the most important tools used in formation evaluation. The caliper log records the distance between the wall pads of the various probes and the spring-loaded or hydraulically-actuated back-up pad that presses against the opposite side of the bore hole wall. Changes in almost any formation characteristics such as hardness, density or degree of fracturing will cause variations in the size of the hole drilled by a given bit size. Also, permeable zones cause mud-cake buildup on the bore

hole wall which show up as anomalous diameter reductions on the caliper log. The log is invaluable in defining stratigraphic breaks, fractured and permeable zones.

SPONTANEOUS POTENTIAL (SP)

The SP log, recorded simultaneously with the electrical log, is a record of naturally occurring potential differences between a surface electrode and an electrode in the well. The source of these potentials may be electrochemical or electrokinetic in nature. The electrochemical emf is caused by electrolyte concentration differences between the drilling mud in the bore hole and the formation water in porous media penetrated by the well. Electrokinetic potentials are generated by mud filtrate passing through the mud cake and the formation in permeable zones. The SP log serves to detect permeable beds, locate their boundaries and determine formation water resistivity. The SP log has limited value in wells drilled with fresh muds and penetrating fresh water formations. The recorded curve is generally rather featureless due to the small electrolyte concentration difference between the mud and the formation water.

TEMPERATURE LOG

The temperature logging sonde consists of one or more thermistors or resistance thermometers connected as one leg of a Wheatstone bridge. Temperature is recorded by the degree of unbalance of the bridge. The temperature measured is actually that of the mud column in the well. If the mud has remained undisturbed for a long period of time and no vertical flow of fluid occurs in the well, the recorded temperature will be close to

the formation temperature. The formation temperature is determined by the geothermal gradient. Thus, under equilibrium conditions, the temperature log can measure the geothermal gradient or variations from the normal gradient. Also, information on thermal conductivity of the formation may be derived. The temperature log is used to correct mud and formation fluid electrical resistivity to a standard temperature. Equilibrium conditions seldom exist in the bore hole due to disturbance caused by drilling, mud circulation and logging; therefore, the temperature log usually gives only an approximation of true subsurface temperature conditions.

SIDE-WALL CORING

Side-wall formation samples are taken "in-hole" by firing hollow cylindrical steel-core bullets into the bore hole wall. The core bullets are fired sequentially one at a time by electrically ignited powder charges. The bullets are loaded in a side-wall coring gun that can contain up to 30 bullets. The bullets containing the core samples are pulled from the formation after firing by means of retrieving cables attached to the guns. The cores are nominally one inch diameter by two inches long. The side-wall samples are used to confirm and clarify the geophysical log interpretations and provide a physical sample of the formations.

DRILL STEM TEST EQUIPMENT AND PROCEDURES

Drill-stem tests, and other similar packer and straddle-packer tests, are widely used in the petroleum industry for reservoir evaluation and for predicting well performance. The tests involve isolating a section of the well and making pressure and fluid flow measurements in the isolated section.

Isolation of a well section is achieved by straddling a zone of interest with packers or bridge plug-packer combinations. Well packers and bridge plugs incorporate expandable rubber elements that press against the well bore to make a water-tight seal. A typical drill-stem test tool consists of an upper packer element and a lower packer element separated by spacing rods. The spacing between the packing elements can vary (by selection of spacing rods) from a few feet to several hundred feet depending on the well bore conditions and the objectives of the tests. The isolated or packed-off zone can be shut-in to make formation pressure tests or opened to the atmosphere to make fluid flow tests and obtain fluid samples. Test ports exist in the section between the packing elements to permit access to the sealed-off well section. A multiple shut-in valve can selectively open or close the ports. The test tools incorporate one or more sensitive time-pressure recorders to monitor hydrostatic pressures, flow pressures and shut-in pressures.

In operation, the tool is lowered in the well on drill pipe to the desired test depth; the pressure recorder indicates initial hydrostatic pressure (IHP). This pressure is caused by the column of drilling fluid above the recorder element. The packers are then expanded against the well bore by drill pipe manipulation or by pressuring the packing elements with fluid or gas. The isolated well section is then opened to the atmosphere (the multiple shut-in valve is opened by drill pipe manipulation) and the pressure recorder indicates initial flow pressure (IFP). After a given time interval, the test ports are closed and the recorder indicates the final flow pressure (FFP) before closure and initial shut-in pressure (ISIP) after closure. The recorder monitors pressure build-up during the shut-in time

interval. The packers are then released by drill pipe manipulation (recorders indicate final shut-in pressure, FSIP, just before packer releases) and the test tool is retrieved or moved to the next test zone in the well.

Estimation of formation fluid hydrostatic pressure, formation permeability, transmissibility and well bore damage can be derived from the recorded flow and pressure data. Average rate of fluid flow from the formation test section is determined from the final flow pressure, and original formation fluid hydrostatic pressure is determined from an extrapolation of the shut-in pressure curve. Formation transmissibility and permeability are estimated from a semi-logarithmic time--shut-in pressure curve and knowledge of fluid flow rate (van Everdingen method). The technique is analogous to the semi-log method for well-pumping test analysis, and the same assumptions are made in equation derivation for both methods with corresponding limitations and inaccuracies inherent in the results.

APPENDIX BRATTLESNAKE WELL -- SECTION CHARACTERISTICS

<u>Basalt Flows</u>	<u>Thickness</u> (feet)	<u>Remarks</u>	<u>Interflow Zones</u>	<u>Thickness</u> (feet)	<u>Remarks</u>
603 - 650+	47	Fractured	650 664	14	
664 - 716	52	Low resistivity, (R)	716 728	12	Gradational
728 - 868	140	High R	868 - 906	38	
906 - 1014	108	Frac. & broken prob. interflow zone 950'	1014 - 1028	14	Gradational
1028 - 1086	58		1087 - 1096	10	
1096 - 1116	20		1116 - 1128	12	
1128 - 1172	44	Gradational	1172 - 1181	9	
1181 - 1202	21	Gradational	1202 - 1209	7	Gradational
1209 - 1257	48		1257 - 1277	20	Gradational
1277 - 1320	43		1320 - 1340	20	
1340 - 1366	26		1366 - 1376	10	
1376 - 1400	24		1400 - 1406	6	
1406 - 1420	14		1420 - 1436	16	
1436 - 1586	150		1586 - 1600	14	Gradational
1600 1665	65		1665 1690	25	
1690 - 1705	15		1705 - 1710	5	
1710 - 1802	92	Gradational, Poss. inter. 1718 & 1740	1802 - 1815	13	
1815 - 1970	155	Gradational	1970 - 1994	24	
1994 - 2190	196	R decrease at 2100	2190 - 2202	12	

Appendix B continued

<u>Basalt Flows</u>	<u>Thickness</u> (feet)	<u>Remarks</u>	<u>Interflow Zones</u>	<u>Thickness</u> (feet)	<u>Remarks</u>
2202 - 2272	70	Gradational	2272 - 2306	34	
2306 - 2400	94		2400 - 2423	23	
2423 - 2465	33		2465 - 2475	10	
2475 - 2489	14		2489 - 2498	9	
2498 - 2522	24		2522 - 2539	17	
2539 - 2628	89		2628 - 2660	32	Gradational
2660 - 2841	181		2841 - 2862	21	
2862 - 2882	20	Low R Basalt	2882 - 2893	11	
2893 - 2934	41	" " "	2934 - 2955	21	Gradational
2955 - 3005	50	Low R Basalt	3005 - 3020	15	Gradational
3020 - 3070	50	" " "	3070 - 3085	15	
3085 - 3240	155	Gradational High R Basalt	3240 - 3260	20	Gradational
3260 - 3390	130		3390 - 3403	14	
3403 - 3417	13		3417 - 3430	13	
3430 - 3461	31		3461 - 3471	10	
3471 - 3486	15		3486 - 3502 ?	16 ?	
3502? - 3508?	6 ?		3508 - 3540+	32 ?	Gradational
3540 - 3736	196	High R Basalt	3736 - 3800	64	Gradational
3800 - 3891	91		3891 - 3910	19	"
3910 - 4135	225	Low R Basalt	4135 - 4180	45	"
4180 - 4213	33		4213 - 4235	22	

Appendix B continued

<u>Basalt Flows</u>	<u>Thickness</u> (feet)	<u>Remarks</u>	<u>Interflow Zones</u>	<u>Thickness</u> (feet)	<u>Remarks</u>
4235 - 4241	6		4241 - 4244	8	
4249 - 4253	4		4253 - 4263	10	
4263 - 4268	5		4268 - 4278	10	
4278 - 4285	7		4285 - 4291	6	
4291 - 4297	6		4297 - 4320	23	Gradational
4320 - 4365	45		4365 - 4385	20	Gradational
4385 - 4449	65		4449 - 4465	16	
4465 - 4484	19		4484 - 4505	21	
4505 - 4523	18		4523 - 4538	15	
4538 - 4568	30		4568 - 4620 ?	42 ?	May be two flows and inter.
4620 - 4634	14		4634 - 4646	12	
4646 - 4760	114	Low R Flow	4760 - 4780	20	Gradational
4780 - 4825	45		4825 - 4850	25	Gradational
4950 - 6800 feet - Complex zone, highly altered & weathered. Individual flows cannot be distinguished except for:					
5433 - 5503	70				
5702 - 5866	164		58866 - 5908	42	
Log functions back to approximate pre-4950' conditions at about 6800 feet.					
6800 - 6861	61	Low R flow	6861 - 6884 ?	23 ?	Gradational
6884 - 7085	201	Low R flow	7085 - 7121	36	Gradational
7121 - 7383	262	Low R flow	7383 - 7415	32	Gradational
7415 - 7565	150	Fractured flow	7565 - 7600+	35	Gradational

Appendix B continued

<u>Basalt Flows</u>	<u>Thickness (feet)</u>	<u>Remarks</u>	<u>Interflow Zones</u>	<u>Thickness (feet)</u>	<u>Remarks</u>
7600 - 7816	216	Fractured Low R flow	7816 - 7834	18	
7834 - 7860	26		7860 - 7910	50	
7910 - 7928	18		7928 - 7950	22	
7950 - 7967	17		7967 - 7986	19	
7986 - 8008	22		8008 - 8033	25	
8033 - 8050	16		8050 - 8220		Altered & weathered zone. No definite breaks.
8220 - 8308	88	Medium R flow	8308 - 8340	32	Gradational
8340 - 8486	146		8486 - 8540	54	Gradational
8540 - 8780	240		8780 - 8800	20	
8800 - 8872	72		8872 - 8892	20	
8892 - 8913	21		8913 - 8985	72	
8985 - 9000	23		9008 - 9165		Complex weathered zone. Two or more flows and interflow zones.
9165 - 9280	115		9280 - 9300	20	
9300 - 9480	180		9480 - 9520	40	
9520 - 9537	17		9537 - 9560	23	
9560 - 9578	18		9578 - 9600	22	
9600 - 9632	32		9632 - 9648	16	
9648 - 9660	12		9660 - 9704	44	
9704 - 9712	8		9712 - 9723	11	
9723 - 9735	12		9735 - 9770	35	
9770 - 9840	70		9840 - 9868	28	
9868 - 9910	42		9910 - 9927	17	

Appendix B continued

<u>Basalt Flows</u>	<u>Thickness (feet)</u>	<u>Remarks</u>	<u>Interflow Zones</u>	<u>Thickness (feet)</u>	<u>Remarks</u>
9927 - 10003	76		10003 - 10028	25	
10028 - 10060	32		10060 - 10083	23	
10083 - 10192	109		10192 - 10258	Possibly two or more flows and interflow zones.	
10258 - 10384	Possibly two or more flows and interflow zones		10384 - 10402	18	
10402 - 10411 ?	9 ?		10411 - 10422 ?	11 ?	
10422 - 10445	23		10445 - 10470	25	
10470 - 10480 ?	10 ?		10480 - 10495 ?	15 ?	
10495 - 10506 ?	11 ?		10506 - 10558	52	
10558 - 10590	32		10590 - 10600	10	
10600 -					

APPENDIX CRATTLESNAKE HILLS WELL SIDE-WALL CORE DESCRIPTIONS

<u>Depth</u> (feet)	<u>Recovery</u>	<u>Description</u>
840	No Recovery	
885	1" broken sample in mud.	80% of sample is dark brown to black basalt, aphanitic. Microporphyritic with a general felty texture in thin section. Calcite and illite(?) common as secondary filling along partings. 5% of sample is light brown to tan tuffaceous material with random grains of magnetite and some free calcite. 1% of sample consists of tachylite or sideromelane shards.
920	No Recovery	
1020	Mud w/cuttings	95% of cuttings consist of rust-brown colored, weathered(?) basalt, aphanitic to phaneritic. Vesiculates, 0.5 - 1.0 mm diameter common, filled with calcite and yellow-green montmorillonite-chlorite. 5% of cuttings are unweathered dark aphanitic basalt chips with a few minor tuff fragments.
1425	1-1/2" core	70% of sample is brown to black scoriaceous basalt, very dense with no secondary filling in vesicles. Basalt glass common. 30% of sample is lost circulation material with some salt and pepper tuff fragments and minor free montmorillonite-chlorite.
1500	Mud w/cuttings	Very poor recovery. Few basalt chips, black, phaneritic with abundant white veinlets (zeolite(?)). One phenocryst of plagioclase about 5 mm long.
1680	2" core	Solid mud cake.
1725	Mud w/cuttings	90% of sample is dense, black, vesicular basalt. Numerous veinlets filled with plagioclase and zeolite(?). Vesicles up to 2 mm diameter common, filled with soot-brown globular layer of montmorillonite. Several phenocrysts of plagioclase up to 2 mm in length.

Appendix C continued

<u>Depth</u> (feet)	<u>Recovery</u>	<u>Description</u>
1810	Mud w/cuttings	90% of sample is black, aphanitic basalt. Some surfaces appear to be weathered to grey-brown. Amygdules common, filled completely with zeolite (clinoptilolite) and pyrite. Veins of pyrite radiating into matrix. Several perfect pyritohedrons to 1 mm. Several vesicles filled with acicular layer of montmorillonite covered by cobalt-blue globular layer of montmorillonite.
1982	1-1/2" core	Mostly basalt cuttings embedded in old mud cake. 95% of cuttings are dense, brown to grey basalt, very glassy with abundant vesicles to 2 mm in diameter. Practically no secondary filling.
2195	1-1/2" core	95% of sample aphanitic grey-brown to black basalt. Vesicles common up to 3 mm in diameter filled with layered chalcedony.
2282	2" core	95% of sample dense grey-black basalt. Weathered to grey or tan-grey on fracture surfaces. Several large plagioclase phenocrysts to 5 mm in length, $Ab_{40}An_{60}$ (Labradorite).
2415	1-1/2" core	45% of sample dense grey weathered basalt, diktytaxitic with openings to 1 mm diameter. 55% of sample white to light-brown tuff with abundant basalt glass shards (tachylite). Very soft and friable.
2530	1-1/4" core	95% of sample is grey to grey-brown basalt, dense diktytaxitic with no phenocrysts. Rim of some of the vesicles appears to be weathered or iron-stained. Vesicles lined with chalcedony.
2640	1-1/2" core	90% of sample is very dense grey-black basalt. Diktytaxitic (abundant vesicle openings 0.5 - 1 mm diameter) voids lined with chalcedony and occasionally filled with a-quartz or zeolites (clinoptilolite(?)). 5% of sample is small chips of hard very dense red-brown scoriaceous material. A few shards of basalt glass (tachylite) present in free state.

Appendix C continued

<u>Depth</u> (feet)	<u>Recovery</u>	<u>Description</u>
2850	1/2" core	95% of sample is very dense grey to brown basalt with zeolites (heulandite) very common filling diktytaxitic openings. When voids not filled, commonly coated with a layer of soot-brown montmorillonite followed by a globular layer of cobalt-blue montmorillonite.
2950	No Recovery	
3012	1" core	60% of sample is grey to brown very dense basalt. Small less than 0.5 mm basalt glass inclusions common. 20% tuffaceous material with montmorillonite-chlorite amygdules. Free quartz crystals covered with illite. 10% carbonaceous shale.
3075	1-1/4" core	95% of sample is dense grey basalt. Vesicular with openings up to 5 mm common. Vesicles lined with zeolites(?). Some free quartz grains present.
3245	Mud w/cuttings	95% of sample is brown to grey basalt, very dense with vesicles greater than 5 mm filled with zeolite (clinoptilolite) or chalcedony.
3395	No Recovery	
3470	1/2" core	95% of sample is black, very dense, basalt. Microporphryitic and diktytaxitic with a red-brown iron stain around the vesicles common. Vesicles lined with zeolite or chalcedony.
3512	1" core	95% of sample is grey-brown to red-brown basalt, very dense with minor diktytaxitic openings. Zeolite(?) encrustations on some of the openings and along minor veinlets.
3750	1" core	95% of sample is very dense grey-brown basalts with vesicular openings greater than 5 mm. Openings filled with cobalt-blue to black boytroydal montmorillonite. Free zeolite grains coated with chalcedony. Some free basalt (tachylite(?)) glass.

Appendix C continued

<u>Depth</u> (feet)	<u>Recovery</u>	<u>Description</u>
3845	Mud w/cuttings	90% of sample is aphanitic black basalt. Small veinlets (less than 0.25 mm) common, lined with z-quartz.
3895	Mud w/cuttings	95% of sample is grey to brown-grey, very dense basalt. Diktytaxitic with zeolite (clinoptilolite) filling of amygdules common. Some cavities filled with layer of black boytroidal montmorillonite followed by a layer of chalcedony.
4145	Mud/cuttings	95% of sample is very dense black to grey-black basalt. Porphyritic in part with phenocryst of plagioclase (Ab ₅₀ An ₅₀ - Labradorite) greater than 5 mm in length. Some voids filled completely with calcite. Minor small quartz veinlets.
4246	1" core	95% of sample is red-brown weathered basalt, very dense. Vesicles up to 5 mm filled with a-quartz. Illite in small veins and vugs interlayered with black goytroidal montmorillonite.
4372	1" core	95% of sample is red-brown to blue-grey weathered andesite. Microporphyritic with plagioclase (Ab ₆₀ An ₄₀ - Andesine) porphrys to 1 mm. Matrix has a felty texture with microlites of feldspar too small to measure. Abundant fractures and voids filled with a-quartz, zeolites, and montmorillonite-chlorite.
4573	No Recovery	
4767	Mud w/cuttings	95% of sample is tan to grey-brown basalt, highly weathered and altered. Pseudomorphs of montmorillonite-chlorite filling numerous vesicles. Some minor zeolites present.
4835	No Recovery	
5244	1-1/4" core	95% of sample is red-brown weathered basalt. Abundant montmorillonite-chlorite filling angular voids. Microlites of plagioclase in matrix (Ab ₆₀ An ₄₀ - Andesine).

Appendix C continued

<u>Depth</u> (feet)	<u>Recovery</u>	<u>Description</u>
5885	1/2" core	95% of sample is highly altered basalt or tuff. Megascopic appearance of serpentine. Microscopically shows complete filling and alteration along numerous veins. Mostly illite with some vugs of montmorillonite-chlorite. Minor pyrite in very poor crystals disseminated in illite.
6250	1" core	90% of sample is brown-grey andesite. Flow layering (trachitic) texture with irregular vesicules. Montmorillonite layering with zeolites in center of vesicules common. Some minor veins filled with montmorillonite.
6592	No Recovery	
6755	1" core	90% of sample very dense red-brown basalt(?). Appears highly weathered or altered along numerous small fractures. Fractures filled mostly with montmorillonite-chlorite with occasional zeolite(?) inclusion.
6880	No Recovery	
7095	1" core	95% of sample is grey tuff, very friable. Some voids filled with black globular montmorillonite. Some inclusions of a-quartz.
7310	Mud w/cuttings	75% of sample of yellow-brown to white tuff, aphanitic to phaneritic with abundant small grains of magnetite. Too soft and friable to make thin section.
7403	1" core	90% of sample is grey to black dense basalt. Felty texture with minor veins of zeolite and montmorillonite-chlorite.
7620	Mud w/cuttings	75% of sample is brown to grey basalt. Aphanitic with trachitic texture. Microlites of plagioclase (Ab ₅₀ An ₅₀).
7690	No Recovery	
7827	1" core	95% of sample is grey tuff or ash. Slightly layered. Abundant zeolites (heulandite) inclusions.

Appendix C continued

<u>Depth</u> (feet)	<u>Recovery</u>	<u>Description</u>
7934	1/2" core	90% of sample is grey andesite, glassy, with a trachitic texture. Very clear chalcedony in small veins parallel to flow layering. Zeolites common but not well formed. Microporphryritic of plagioclase are $Ab_{55}An_{45}$ - Andesine.
8172	1/2" core	95% of sample is grey to red-brown altered tuff or socriaceous basalt. Amygduloidal with numerous fillings of zeolite (heulandite). In some cases, voids layered with montmorillonite-chlorite before the zeolite.
8315	1/2" core	40% of sample is very dense blue-black basalt. 40% of sample is grey tuff with zeolite (laumontite) and pyrite along partings. 10% of sample is free calcite in crystals to 5 mm.
8460	No Recovery	
8510	1/2" core	90% of sample is very dense blue-grey basalt. Montmorillonite-chlorite and some zeolites common in small veins and as fillings in vesicles.
8720	No Recovery	
8810	Mud w/cuttings	90% of sample is dense black basalt. Zeolites (laumontite) common along partings. Free well-formed crystals of α -quartz.
8840	Mud w/cuttings	95% of sample is dense black basalt. Felty texture with intercrystalline glass similar to 8810'. Less zeolitization and only two α -quartz crystals.
8869	No Recovery	
8974	1" core	95% of sample is grey to black tuff with very dense basalt fragments. Abundant zeolites (laumontite) along partings with some rings of montmorillonite-chlorite.
9025	1/2" core	90% of sample is dense grey to black basalt. Felty texture with microporphrys of labradorite, $Ab_{30}An_{70}$. Minor occurrences of zeolites along veins.

Appendix C continued

<u>Depth</u> (feet)	<u>Recovery</u>	<u>Description</u>
9105	1" core	75% of sample is dense grey basalt. Veinlets radiating throughout sample are larger than seen before and completely filled with zeolite (heulandite). Microlites of plagioclase average $Ab_{35}An_{65}$ - Labradorite. Abundant magnetite in matrix.
9218	No Recovery	
9285	Mud w/cuttings	90% of sample is grey to brown dense andesite. Appears to be weathered or oxidized in part. Microlites of plagioclase average $Ab_{55}An_{45}$ - andesine. Magnetite common in matrix.

885

1020

1425

1680

Figure 1-C

1725

1810

1982

2195

Figure 2-C

2282

2415

2530

2640

Figure 3-C

2850

3012

3075

3245

Figure 4-C

3470

3512

3750

3845

Figure 5-C

3895

4145

4246-A

4246-B

Figure 6-C

4372

4767

5244

5885

Figure 7-C

6250

6755-A

6755-B

7095

Figure 8-C

7403

7620

7827

7924

Figure 9-C

8172

8315

8510

8810

Figure 10-C

8840

8974-A

8974-B

9025

Figure 11-C

9105-A

9105-B

9285

SCALE

Figure 12-C

APPENDIX D

SPECTROCHEMICAL ANALYSES AND METALLIC OXIDE RATIOS
FOR SIDE-WALL CORES AND DITCH SAMPLES

FIGURE I-D

METALLIC OXIDE RATIOS FOR SIDE-WALL CORE SAMPLE

FIGURE 2-D

SPECTROCHEMICAL ANALYSIS 100' DITCH SAMPLES

FIGURE 3-D

FIGURE 4-D

METALLIC OXIDE RATIOS FOR 100' INTERVAL DITCH SAMPLES

FIGURE 5-D

METALLIC OXIDE RATIOS FOR 100' INTERVAL DITCH SAMPLES

FIGURE 6-D

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