GeothermEx, Inc.
SUITE 201
5221 CENTRAL AVENUE
RICHMOND, CALIFORNIA 94804

(415) 527-9876
CABLE ADDRESS: GEOTHERMEX

②

RESULTS OF
TEMPERATURE GRADIENT
AND HEAT FLOW
IN
SANTIAM PASS AREA,
OREGON

VOLUME I - TEXT

SHU-
COPY 2

for

SUN ENERGY DEVELOPMENT CO.

Dallas, Texas

by

GeothermEx, Inc.
Berkeley, California

Billie L. Cox
Murray C. Gardner
James B. Koenig

August 1981

DISCLAIMER

CONTENTS

CONTENTS (continued)

ILLUSTRATIONS

Figures

Tables

Plates

GeothermEx, Inc.
SUITE 201
5221 CENTRAL AVENUE
RICHMOND, CALIFORNIA 94804
(415) 527-9876
CABLE ADDRESS: GEOTHERMEX

CONCLUSIONS

1. There is a weakly defined thermal anomaly within the area examined by temperature-gradient holes in the Santiam Pass area. This is a relict anomaly showing differences in permeability between the High Cascades and Western Cascades areas, more than a fundamental difference in shallow crustal temperatures.

2. The anomaly as defined by the 60°F isotherms at 400 feet follows a north-south trend immediately westward of the Cascade axis in the boundary region. It is clear that all holes spudded into High Cascades rocks result in isothermal and reversal gradients. Holes spudded in Western Cascades rocks result in positive gradients.

3. Cold groundwater flow influences and masks temperature gradients in the High Cascades to a depth of at least 700 feet, especially eastward from the major north-south trending faults. Pleistocene and Holocene rocks are very permeable aquifers.

4. Shallow gradient drilling in the lowlands westward of the faults provides more interpretable information than shallow drilling in the cold-water recharge zones. Topographic and climatological effects can be filtered out of the temperature gradient results.

5. The thermal anomaly seems to have 2 centers: one in the Belknap-Foley area, and one northward in the Sand Mountain area. The anomalies may or may not be connected along a north-south trend.

6. A geothermal effect is seen in holes downslope of the Western-High Cascade boundary. Mixing with cold waters is a powerful influence on temperature gradient data.

7. The temperature-gradient program has not yet examined and defined the geothermal resources potential of the area eastward of the Western Cascades - High Cascades boundary. Holes to 1,500-2,000 feet in depth are required to penetrate the high permeability-cold groundwater regime.

8. Drilling conditions are unfavorable. There are very few accessible level drill sites. Seasonal access problems and environmental restrictions together with frequent lost circulation results in very high costs per foot drilled.

RECOMMENDATIONS

1. Explore the area eastward of the weak temperature anomaly; drill intermediate depth holes.
2. Include geochemical analyses of water from drill holes and cold springs in the program.
3. Drill no further shallow temperature-gradient holes in the western part of this prospect.
4. Use geologists during drilling to recommend early abandonment of unfavorable drill sites when necessary, revise initial locations, and supervise drilling.
5. Plan and execute a geologic survey of rocks associated with spring discharge in the Cascades in the area of the prospect.

INTRODUCTION

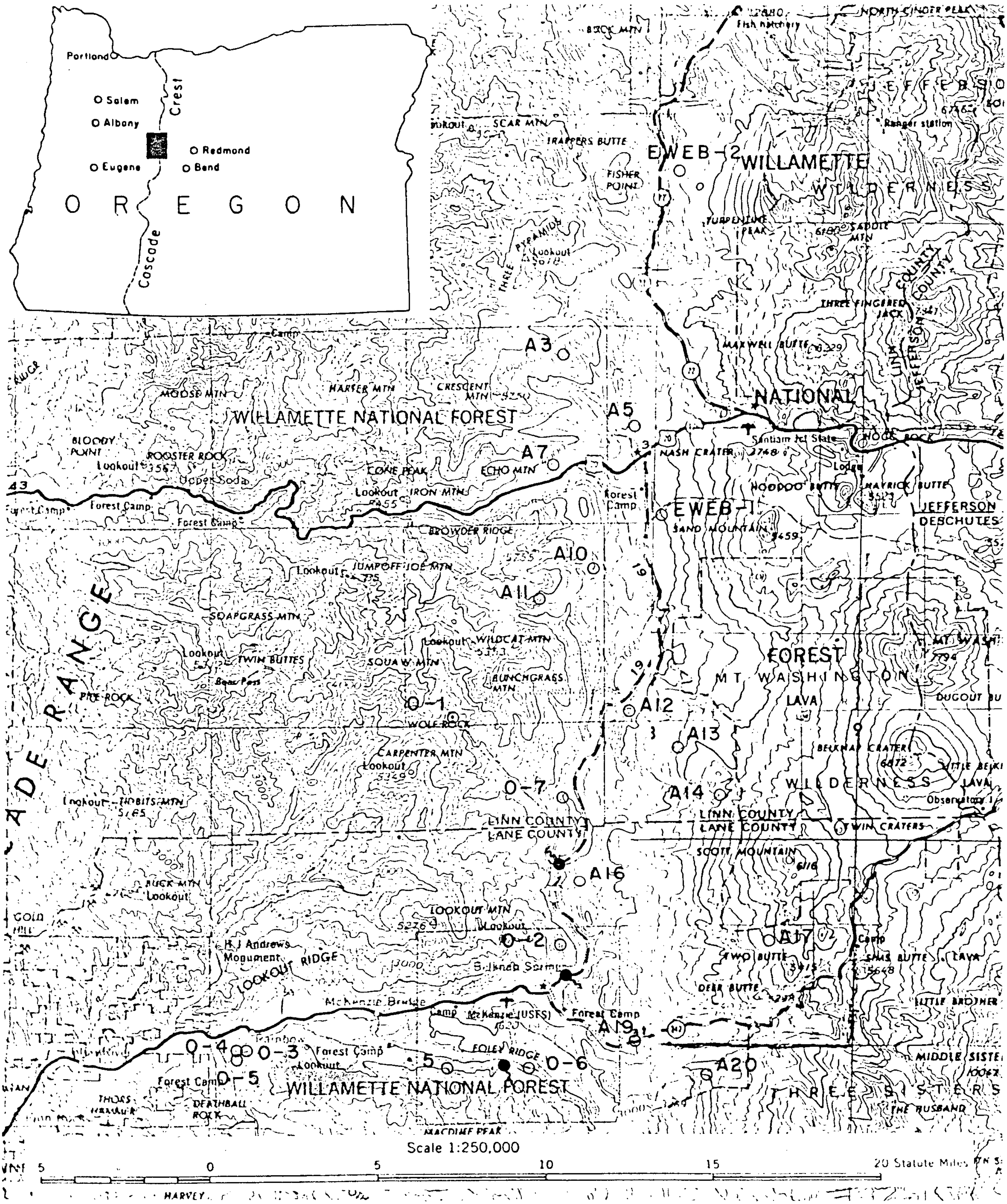
During the period between September 9, 1980 and February 6, 1981, 13 shallow (less than 500 feet depth) temperature-gradient holes were drilled for Sun Energy and Development Company (SUNEDCO) in the Santiam prospect area, Linn and Lane Counties, Oregon (figure 1). The holes ranged in depth from 135 feet to 500 feet. Two additional holes were drilled and abandoned because of lost circulation problems. Drilling histories are summarized on table 1.

The holes were distributed in T. 13, 14, 15 and 16 S., R. 6 and 7 E., in an area of approximately 200 square miles. The locations, depths and bottom-hole temperatures are shown on plate 1. Temperatures and other thermal information were available from 7 shallow holes drilled by the Oregon Department of Geology and Mineral Industries (DOGAMI) and 2 intermediate depth wells sponsored by the U.S. Department of Energy (DOE) and Eugene Water and Electric Board (EWEB) within the Santiam prospect area. These locations and temperatures are also plotted on figure 1 and plate 1.

The drilling contractor was Southwest Drilling and Exploration, Inc. (Southwest) of Central, Utah. No geologist was present during drilling operations. The drilling crew collected samples at 10-foot intervals. Rock cuttings were shipped to GeothermEx, Inc. for lithologic descriptions. The average time spent per hole was 8½ days, which is excessive for shallow holes. Shallow temperature-gradient holes are usually drilled within 2 to 5 days per hole.

The holes were completed with one-inch diameter iron pipe, plugged on bottom, cemented in place, filled with water and capped and locked. A GeothermEx geologist traveled to the prospect area and measured temperatures on several different occasions after the holes were allowed to equilibrate. Temperatures were measured with Envirolabs model DT 201 A thermistor, at depth intervals of 10 feet.

This report integrates available information on geology, geophysics and geochemistry with the data acquired from the drilling program, as well as the data published by the Oregon Department of Geology. The geology was presented in previous reports to SUNEDCO (GeothermEx, 1973, 1977 and 1980) and the geology is briefly treated in this report. Lithologic data are presented in both written logs (Appendix A) and graphic logs (Appendix B). Temperature data are presented in tables and graphs, and in Appendix B.



EXPLANATION

○ EWEB gradient holes ○ DOGAMI gradient holes

○ SUNEDCO gradient holes ●~ Hot springs

Figure 1. Location map of the Santiam prospect, Linn and Lane Counties, Oregon.

GeothermEx, Inc.

Table 1. Summary Drilling Histories of Temperature-Gradient Holes, Santiam Prospect, Oregon

A-1

Spud: 9/9/80
Complete: 9/11/80
T.D.: 80 feet
T.D. pipe: 0

Lost circulation at 35 feet. Drilled with partial returns to 65 feet and cemented. Drilled out of cement with no returns. Abandoned hole at 80 feet depth.

A-1-A

Spud: 9/11/80
Complete: 9/15/80
T.D.: 42 feet
T.D. pipe: 0

Attempted to drill at a position closer to the easement using an air hammer and foam. Drilled to 31 feet, lost circulation and cemented. Drilled out of cement and lost circulation. Abandoned the hole at 42 feet depth.

A-19

Spud: 9/16/80
Complete: 10/1/80
T.D.: 280 feet
T.D. pipe: 185 feet

Began drilling with an air hammer and foam and encountered severe problems with caving in the upper part of the hole. Drilled and reamed hole to 82 feet and set 80 feet of plastic casing. Pulled plastic casing and set 66 feet of 7-inch metal casing. Drilled with mud to 280 feet, lost circulation and stuck the rods. Drillers were not able to retrieve all the rods and had to set gradient pipe at 185 feet.

Table 1 (continued)

A-12

Spud: 10/2/80
Complete: 10/7/80
T.D.: 500 feet

Drilled to 220 feet and lost circulation. Regained partial returns and resumed drilling. At 330 feet regained complete circulation and continued drilling to total depth.

A-14

Spud: 10/8/80
Compelte: 10/18/80
T.D.: 355 feet
T.D. pipe: 350 feet

Drillers fought lost circulation from 160 feet to total depth. Fractures were encountered at 317 feet and 320 feet. The rods fell from 345 feet to 355 feet and plugged the bit in the process.

A-16

Spud: 10/19/80
Complete: 10/28/80
T.D.: 420 feet
T.D. pipe: 415 feet

Drilled a 5-1/8-inch pilot hole to 95 feet. Reamed with 5-5/8-inch and 6-1/4-inch bits to 95 feet. Drilled ahead with 6-1/4-inch bits to total depth. Returns of mud were partial from 100 feet to 230 feet. At 230 feet circulation was lost but regained. Fractures and lost circulation problems were encountered at 300, 310, 330 and 340 feet.

A-5

Spud: 10/29/80
Complete: 11/1/80
T.D.: 500 feet
T.D. pipe: 495 feet

Drilled in clay with no problems.

Table 1 (continued)

A-3

Spud: 11/2/80
Complete: 11/11/80
T.D.: 500 feet
T.D. pipe: 495 feet

Drilled predominantly in clay with no problems.

A-7

Spud: 11/13/80
Complete: 11/26/80
T.D.: 500 feet
T.D. pipe: 500 feet

Set 50 feet of 7-inch casing and drilled a 6-1/4-inch hole to total depth without problems.

A-11

Spud: 11/28/80
Complete: 12/8/80
T.D.: 470 feet
T.D. pipe: 470 feet

Set 20 feet of 7-inch casing. Drilled to 344 feet and lost circulation. Regained circulation, drilled to 470 feet and completed the hole.

A-10

Spud: 12/15/80
Complete: 12/22/80
T.D.: 480 feet
T.D. pipe: 480 feet

Drilled to 230 feet and lost circulation. Regained circulation, drilled to 240 feet, lost circulation and stuck the rods. Broke loose and drilled ahead with partial returns to 480 feet.

Table 1 (continued)

#5

Spud: 12/15/80
Complete: 1/6/81
T.D.: 500 feet
T.D. pipe: 500 feet

Drilled to 20 feet with no returns and set 7-inch casing. Drilled ahead with problems in hole caving. Encountered partial loss of circulation at 201 feet. Drilled to total depth in predominately soft material.

A-20

Spud: 1/8/81
Complete: 1/15/81
T.D.: 466 feet
T.D. pipe: 465 feet

Drilled to 55 feet fighting cave-in problems. Moved rig 15 feet over and spud-in. Encountered the same problem but persevered. Lost circulation at 62 feet and regained same. Drilled to 466 feet and lost circulation in 2-foot void. Set gradient pipe.

A-13

Spud: 1/20/81
Complete: 1/26/81
T.D.: 296 feet
T.D. pipe: 295 feet

Drilled with no returns to 20 feet and set 7-inch casing. Drilled out of casing with partial returns. Lost returns at 280 feet. Cemented with 12 sacks. Drilled out of cement and lost circulation at 295 feet. Drilled ahead 1 foot without regained circulation and completed the hole.

A-17

Spud: 1/29/81
Complete: 2/6/81
T.D.: 318 feet
T.D. pipe: 318 feet

Table 1 (continued)

Drilled to 115 feet depth and lost circulation. Regained circulation and continued drilling. Encountered lost circulation at 170, 180, 185, 190, 199, 210, 246, 290 and 318 feet. Completed the hole at 318 feet because of bad weather.

LOCATION AND PHYSIOGRAPHY

The Santiam prospect is located in Western Oregon, in T. 13, 14, 15 and 16 S., R. 6 and 7 E. Eugene is about 60 miles west; Albany and Corvallis are 80 miles WNW; Salem is 100 miles NW; and Bend is 70 miles east. Topographic map coverage is provided by the 1:250,000 scale Salem and Bend AMS sheets, and by the 1:62,500 scale McKenzie Bridge, Echo Mountain, Three Sisters, and Three Fingered Jack 15-minute quadrangle maps.

The project area is in the Middle Cascades geomorphic province, on the western slope of the Cascade Range. The range is a generally NS-trending feature comprised of Tertiary and Quaternary volcanos, several of which have been active in historic time. The holes were drilled on U.S.F.S. administered land, in the Willamette National Forest, along the west side of the Mount Washington and Three Sisters Wilderness areas. Access to the prospect area is provided by U.S. Highway 20 along the South Santiam River, and by U.S. Highway 126 along the McKenzie River. There are also paved, graveled and dirt logging roads traversing the area.

Topographic relief is spectacular in this region. The valley of the McKenzie River near Belknap Hot Springs is at an elevation of 1,620 feet, while the peaks of the Three Sisters volcanos, 12 miles to the east, rise to over 10,000 feet. The Sisters are glaciated. Snowmelt from the Sisters flows westward to tributaries of the McKenzie River and the McKenzie in turn flows into the Willamette Valley. Peaks in the northern part of the prospect provide snowmelt for the Middle and South Santiam Rivers. The climate is humid and temperate, with warm, dry summers and cold, wet winters. The mean annual temperature at McKenzie Bridge is 50°F. The average annual precipitation is 80 inches per year.

Geothermal manifestations in the Santiam prospect include hot springs at 3 locations: Belknap Hot Springs (T. 16 S., R. 6 E., section 11), Foley Hot Springs (T. 16 S., R. 6 E., section 28), and Bigelow or Deer Creek Springs (T. 15 S., R. 6 E., section 23). Other hot springs in the region include Breitenbush Hot Springs, 50 miles north of Belknap Hot Springs; Cougar Hot Springs, 8 miles SW of McKenzie Bridge; and McCredie and Kitson Hot Springs, 30 miles south of Belknap Hot Springs. All of these springs lie along the approximate boundary between the Tertiary Western Cascades volcanic rocks with the Quaternary High Cascades volcanic rocks.

GEOLOGIC FRAMEWORK

The Sun-Santiam prospect is located in the Cascades Mountains at or very near the junction of two geological subprovinces: the Western Cascades and High Cascades (plate 2). Both subprovinces are comprised almost entirely of intrusive and extrusive igneous rocks and associated volcaniclastic sediments. Together, the Western and High Cascades span nearly the entire Cenozoic Era. A 30 to 70 mile wide strip of the crust, hundreds of miles long, has been repeatedly the scene of magmatism.

Briefly, from late Eocene to late Miocene time the rocks of the Western Cascades were deposited, deformed slightly, hydrothermally altered by the effects of intrusions, and eroded. From Pliocene to Holocene time, High Cascade volcanos were built on top of the Western Cascade platform, and flows from the eruptive cones filled eroded canyons in the older rocks. The dip of Western Cascade rocks indicates a broad synclinal downwarp below the High Cascades, with modifying folds and faults. The deep crustal configuration below the Cascade Mountains is the subject of continued research and analysis (Geothermal Resources Council, 1981). There is considerable controversy and there are many unanswered questions, which geophysical data, geologic mapping and interpretive efforts are only beginning to analyze. The role of plate tectonics and the position of residual magma are contested by geologists and geophysicists.

Although no drilling has revealed early Eocene and older rocks at depth, it may be conjectured that they exist in at least discontinuous form, or perhaps as metamorphosed equivalents of their original rock types. In whichever form, they may contribute to reservoir extent and thickness.

STRATIGRAPHY

The stratigraphy in the Santiam prospect has been discussed in detail by GeothermEx reports (1973, 1977, 1980) to SUNEDCO. Sections of these reports are summarized and reproduced here. The principal stratigraphic units appear on table 2.

Pre-Tertiary (Late Jurassic to Late Cretaceous)

There are no known Pre-Tertiary rocks cropping out in the Santiam prospect area. The nearest exposures of Pre-Tertiary rocks are about 50 miles SW of Belknap Hot Springs. These are undifferentiated Late Jurassic to Late Cretaceous deep marine sediments and Late Cretaceous intrusions. All have been deformed, altered and metamorphosed. The rocks belong to or are correlative with the Galice and Rogue Formations. They include meta-graywacke, meta-argillite, slate, gneiss, greenstone, peridotite, quartz-diorite, and serpentine. Permeablility is most likely confined to fracture zones in the thickest graywackes and crystalline rocks.

Tertiary, Eocene

Eocene rocks are also unknown in the study area, but are found near Eugene, and may be encountered at great depth below the volcanic rocks of the Western Cascades Sequence. The rocks consist of shallow marine sediments, including sandstones, siltstones, and mudstones, with lesser amounts of volcanic flows, tuffs, breccias and conglomerates. The rocks belong to or are correlative with the Umpqua, Tyee, Colestin and Fisher Formations. They range in thickness to over 10,000 feet. Primary permeablility is variable and would be good in coarse sediments and breccias, but greatly lessened by compaction and alteration.

Tertiary Intrusive Rocks

Intrusive rocks of the study area consist of two physical types: hypabyssal remnants of eroded volcanic centers, including plugs and dikes; and more deeply emplaced stocks. Chemically, the dikes and volcanic necks range from rhyodacite to basalt. Texturally they cover the same aphanitic to porphyritic range as their lava counterparts. Locally, xenoliths ranging in size from a few millimeters to one meter can be found in the volcanic necks and dikes. When removed from context, these hypabyssal intrusive rocks

TABLE 2: Stratigraphic column of the Cascades province, Oregon.

Age	Name MAP SYMBOLS	Lithologic character	Thickness (feet)	Distribution of outcrops
Quaternary	Alluvium Qus	Gravel, sand, silt, and local till	0–500	Major stream valleys
Pliocene and Quaternary.	Volcanic rocks of the High Cascade Range and Boring Lava. Qcc Ql Qhc TQhc	Flows and less abundant pyroclastic rocks of basaltic andesite and olivine basalt, less abundant pyroxene andesite, and sparse dacite. Flows are typically porous textured and sparsely porphyritic, and contain phenocrysts of olivine that is partially altered to reddish iddingsite. Form constructional surfaces, modified in part by glaciation. Locally faulted but not folded.	0–>3,000	Limited mostly to crest and eastern slope of Cascade Range, but a few scattered cones and intracanyon flows farther west.
Pliocene	Troutdale Formation. not present	Conglomerate, sandstone, and micaceous siltstone; poorly indurated stream deposits. Conglomerate is massive and crossbedded in part and is composed chiefly of well-rounded pebbles of basalt and quartzite. Undeformed.	0–400 (>1,000 near Portland, Trimble, 1957).	Lower valleys of Sandy, Clackamas, and Molalla Rivers.
		Unconformity		
Middle and late Miocene.	Sardine Formation. Tmv	Flows, tuff brecica, lapilla tuff, and tuff of hypersthene andesite, less abundant basaltic andesite, augite andesite, and aphyric silicic andesite, and sparse dacite and olivine basalt. In Cascade Range in northern Oregon, composed of a lower pyroclastic unit and an upper unit of flows. Flows are typically platy and porphyritic and contain phenocrysts of calcic plagioclase and prismatic black hypersthene. Massive tuff breccia is locally abundant. Folded, faulted, and altered.	0–10,000, average about 3,000.	Western Cascade Range north of McKenzie River, and eastern edge of Western Cascade Range farther south.
Middle Miocene	Columbia River Basalt. Tmv	Flows of tholeiitic basalt and tholeiitic andesite. Flows typically are columnar and hackly jointed and are composed of very fine grained black basalt that contains abundant glass, plagioclase, augitic pyroxene, and chlorophaeite, but little or no olivine.	0–1,500	Valleys of Bull Run, Sandy, Salmon, Clackamas, and Molalla Rivers, and foothills farther south to the vicinity of Sweet Home.
		Unconformity		
Middle and late Oligocene and early Miocene.	Marine tuff and sandstone. Tov	Waterlaid tuff, volcanic-wacke arkosic-wacke, and less abundant siltstone, granule sandstone, pebbly conglomerate, and impure coquina. Shallow-water marine deposits that interfinger eastward with the Little Butte Volcanic Series.	0–600	Valleys of Butte, Abiqua, Silver, and Drift Creeks, and foothills between Lebanon and Dorena Dam.
Oligocene and early Miocene.	Little Butte Volcanic Series. Tov	Dacitic and andesitic tuff and less abundant flows and breccia of olivine basalt, basaltic andesite, and pyroxene andesite, dacitic and rhyodacitic flows and domes, and rhyodacitic tuff. Massive pumice lapilli vitric tuff is the most abundant rock type. Basaltic flows typically contain sparse phenocrysts of calcic clinopyroxene (salite) and olivine, the latter altered to green clay, as well as microphenocrysts of calcic plagioclase and pyroxene. Basal member is rhyodacitic welded tuff containing abundant crystals of feldspar, quartz, and biotite. Folded, faulted, and altered.	3,000–15,000; average 5,000–10,000.	Western Cascade Range south of the McKenzie River; foothills and eastern edge of Western Cascade Range farther north.
		Local unconformity		
Late Eocene	Colestin Formation. not present	Andesitic lapilli tuff, tuff, conglomerate, volcanic-wacke sandstone, and less abundant flows and tuff breccia of basaltic andesite and pyroxene andesite. Massive pumice lapilli vitric tuff most abundant rock type.	0–3,000; average about 1,500.	Foothills of the Cascade Range between Calapooya Creek and the South Umpqua River, and scattered localities in the Range farther south to the vicinity of Hornbrook, Calif.
Late, middle and early Eocene.	Spencer, Tyee, and Umpqua Formations. not present	Sandstone and siltstone of the Spencer Formation (not exposed within the map area) overlie micaceous sandstone and dark mudstone of the Tyee Formation, which in turn overlie sandstone, mudstone, conglomerate, and interbedded basaltic flows and tuff of the Umpqua Formation. Deep marine and shallow marine sediments.	0–>500 (>9,000 southwest of Cottage Grove, Hoover, 1959).	Foothills of the Cascade Range between Calapooya Creek and Glide, and Coast Ranges of Oregon farther north and west.

are not readily distinguishable from extrusive rocks. Because of deep weathering, heavy vegetative cover and steep topography, data do not allow the positive association of specific hypabyssal systems with specific extrusive events. Reliable age data also are unavailable for these rocks.

The intrusive stocks of the study area range chemically from diorite to monzonite. All are porphyritic, with medium to fine-grained groundmass. Feldspar phenocrysts are common in each of these intrusive bodies. Locally, phenocrysts of augite, hornblende, biotite, quartz and metallic sulfides are present. Distinct hornfels aureoles are another characteristic of these intrusives. To the west of the study area, similar stocks are associated with base metal mineralization. A single K-Ar date of the stock at Detroit Dam by Sutter (1978) yields an upper Miocene age. It is uncertain if this is typical of the entire suite of intrusions. Chemical data are not available for correlations between these intrusives and specific volcanic events.

Cascade Range, Oligocene to Present

The Western Cascades sequence has been split into two very general sets of age and compositional units (GeothermEx, 1980), lacking stratigraphic or formational assignments: Oligocene and lower Miocene volcanic sediments, lavas and andesitic tuffs; and mid-Miocene to lower Pliocene volcanic rocks, with minor volcaniclastics and volcanic sediments. The High Cascades sequence has been divided tentatively into 3 similarly broad units: strongly eroded Pliocene-lower Pleistocene lavas; less-eroded Pleistocene lavas; and the most recent lavas, which lack a developed soil horizon. In many places, the distinction between Pliocene and Pleistocene lavas has been difficult, and the geographic boundaries should be considered subject to revision.

Western Cascades Sequence

The Western Cascades are deeply eroded, and include the Little Butte Volcanic Series, the Breitenbush Tuff, some flows belonging to the Columbia River Basalt, and the Sardine Formation. They range from 5 to 40 million years old, and are up to 20,000 feet thick (Hammond, 1976). According to Hammond (1976) the Breitenbush Tuff may be a regional marker bed dividing the Western Cascades into lower and upper parts. In the previous GeothermEx report (1980), the Western Cascades sequence was split into two units and described as follows:

Oligocene-lower Miocene tuffs and other volcanic rocks. The Oligocene to lower Miocene sequence consists of andesitic ash-flow tuffs, with subordinate quantities of basalt to dacite lavas and volcanic sediments. Ash-flow tuffs comprise approximately 70% of the sequence, the tuffs being both welded and cemented. Their composition ranges from predominantly vitric to crystal-lithic and to lithic. Plagioclase and minor quartz are the most common crystals; lapilli-size pumice and volcanic rock fragments make up the lithic component. Eutaxitic texture is common in the welded tuffs. Devitrification of the ash component, and celadonite alteration are pervasive throughout the tuffs of this sequence.

Groundwater movement through this sequence varies according to rock type. The cemented and lightly welded tuffs tend to alter readily, becoming increasingly plastic, and forming gouge-filled fault zones rather than open fault planes when subjected to stress failure. These characteristics make the lightly welded tuffs rather effective barriers to groundwater movement. They should not be expected to serve as geothermal reservoirs.

Conversely, the highly welded tuffs form moderate- to low-porosity, brittle horizons within this sequence. In spite of pervasive celadonite alteration, the more highly-welded tuffs tend to fracture brittly and to maintain relatively open faults along well-defined planes. Good permeability may be expected in fractured zones and along or adjacent to fault planes. The potential for geothermal aquifers cannot be evaluated fully, because of variations in thickness, altitude and local distribution of these welded tuffs.

Lavas which occur intermittently throughout the tuff sequence tend to be fractured. Alteration of these lavas tends to take place at a slower rate than with the cemented tuffs. They would tend to form aquifers of moderate permeability and of local extent.

Middle Miocene-lower Pliocene volcanic and volcaniclastic rocks. The middle Miocene-lower Pliocene sequence consists of basaltic to andesitic lavas and scoriaceous tuffs, with local volcanic sediments, palagonite tuffs, and base-surge debris deposits. Porphyritic hornblende dacite lavas and welded tuffs occur locally in the upper portion of this sequence. Secondary zeolite is common in lava flows in the lower portions of this sequence. Hydrous iron oxides and clays are common alteration minerals throughout the sequence. Celadonite alteration is restricted to zones of major groundwater movement. Devitrification is pervasive throughout the tuffaceous units.

Groundwater movement through this volcanic sequence probably is highly variable in amount and velocity. Lava flows and palagonite tuffs tend to be aquifers of moderate capacity, with water flowing through former cooling fractures in the lavas and through stress fractures in the palagonite tuffs. Scoriaceous cemented tuffs, volcanic sediments, and base-surge debris deposits tend to devitrify rather readily, thereby forming hydrologic barriers rather than aquifers.

High Cascades Sequence

Overall, the High Cascades is characterized by flow sequences of essentially flat-lying basalt erupted from fissures and volcanos, with individual flows varying in thickness from about 20 to several hundred feet, to a total of 7,000 feet, extruded onto the eroded surface of the underlying Western Cascade rocks. The basalt is an olivine basalt variety, accompanied by olivine andesite, hypersthene andesite and minor dacite and rhyolite. Shield volcanos and stratovolcanos and cinder cones of basalt and andesite and ash of the same composition, have been built upon the flow tableland in the most recent eruptions. Flank eruptions have sent flows down canyons eroded by streams and glaciers.

The age of the extrusions making up this subprovince is Pliocene to Holocene. Eruptions have been dated as having occurred within the last few hundred years within 20 miles east of Belknap Springs (Heinrichs, 1973). In the absence of complete radiometric dating, effective means of age-estimation of rocks in the High Cascades are the degree of erosion by glaciers and the development of soil and vegetation cover on the most recent flows, as well as reference to the 6,600 year old explosive eruption of Mount Mazama (Crater Lake), which showered the area with a marker-bed of pumice and has helped to separate Pleistocene from Holocene rocks.

Earliest eruptions of the High Cascades appear to have been from a chain of N-S volcanos close to the present boundary with the Western Cascades. Taylor (1965, 1968) has described the base of the High Cascades as marked by a significant erosional and/or angular unconformity, overlain by homogeneous, coarse-grained diktytaxitic basalt flows. Above these flows are fine-grained dense basalts. Williams (1944) proposed that an eastward-facing erosion scarp 1,500 to 3,000 feet high existed along the site of a steep normal fault. Subsequent authors, such as Jan (1967), have also proposed the boundary of the two subprovinces to be the site of a fault with recurring movement, but field evidence is questionable, and Taylor doubts the existence of a major throughgoing fault.

Broad shield volcanos composed of olivine basalt and basaltic andesite were built by quiet eruptions. Limited explosive activity produced steep summit cones at former crater areas; and near the end of each volcano's history, fissure eruptions on flanks produced vesicular basalt that overlapped older flows. In the area east of Belknap Hot Springs, examples of the early phases of High Cascade eruptions are found at Mount Washington, North Sister, the Husband, Sphinx Butte, the Wife, and Broken Top.

Glacial erosion has modified the shapes of all these volcanos; they are reduced to exposed central pipes or plugs and dikes of olivine micro-norite, with hornshapes and radiating ridges separated by cirques as remnants of the former great shields. Parasitic cones of basalt and ash have been destroyed, but attitudes of remnant rocks give evidence of their former existence. All summit craters are eroded to reveal the resistant crystalline plugs. Some volcanos, like Black Crater, subsequent to erosion were again modified by recent eruptions of cinders and agglomerate.

The glaciated basalt and basaltic andesite flows and eruptive vents comprise the oldest major unit of the High Cascade subprovince. Dips are original slope of desposition, ranging from 1° to 3° in the fluidal flows to 30° where pyroclastic ejecta and upturned flows surround central plugs. No distinct break in the eruptive activity can be discerned, but sometime in the Pleistocene epoch, the kind and composition of eruptions changed in some places. In other areas Williams (1957) proposed that no significant change occurred into Holocene time.

During the Pleistocene epoch, large, steep-sided composite cones of andesite and dacite were emplaced through and on top of the older shield volcanos, as well as in depressions between them. South Sister and the western part of North Sister are sites where this occurred. Intracanyon basalts were also erupted during this time, but none have been mapped in the vicinity of the McKenzie Valley. The peak areas of South and Middle Sisters were constructed just after this time by a combination of basalt and basaltic andesite flows and cinders.

Late Pleistocene and Holocene basalt and basaltic andesites erupted from vents on the eastern flank of the High Cascades and the plateau further eastward, extending to a 10 to 30 mile wide band on the east side of the crest. However, except for the peak areas of South and Middle Sisters, younger Pleistocene to Holocene lavas do not exist closer than 18 miles from Belknap Hot Springs.

The unit which Williams (1957) has called Youngest Basaltic Flows and Related Cinder Cones, and which are unglaciated lavas, occupies an extensive and significant part of the area east and north of Belknap Hot Springs. About 40 square miles of this lava, with cinder cones at Belknap Crater, Twin Craters, and nine other nameless vents, exist within 10 miles of the hot springs. Similar features are found at Yapoah Crater and Collier Cone, 2 miles south of McKenzie Pass. Black basalt erupted about 1,000 years ago from Nash Crater, Sand Mountain, Belknap Crater and Little Belknap; these vents are part of a chain of vents aligned along a N-S fissure or fissure set. At Collier Cone and Sims Butte, near North Sister, a flow originated that extended for at least 15 miles down White Branch; other flows were erupted from near LeConte Crater south of South Sister. These flows are remarkable for their very fresh appearance. Ropy crusts, lava tubes, pressure ridges and other very youthful features are evident. The surface is generally pahoehoe. The vent of Little Belknap exhibits red coloration by fumarolic activity. Taylor reports age dates from 3,000 to 1,500 y.b.p. for most of the Belknap lavas. Some of the western Belknap flows were dated at 360± 160 years b.p. by radiocarbon dating of tree roots burned by the flows.

Two small domes composed of dacite obsidian flows, near the south slope of South Sister, may be younger than the Belknap flows. The two domes are the only acidic lavas of late Quaternary age in the region. Similar very youghful rhyolite and dacite bodies are associated with thermal areas at Lassen Peak, Medicine Lake, Newberry Caldera and possibly other places in the High Cascades.

Taylor has been accomplishing detailed mapping and sampling of the High Cascades. He would place all High Cascades volcanism within the last 1.5 million years, and place all rocks mapped as older and closer to the Western Cascade boundary into the Western Cascade subprovince. He has also identified three glacial stages from study of moraines, and has utilized carbon dates of material from the moraines and associated ash deposits to establish the latest glaciation at 2,500 y.b.p. A tongue of the latest Wisconsin ice reached just to Belknap Hot Springs.

Pliocene-lower Pleistocene volcanic rocks. The Pliocene-lower Pleistocene volcanic rocks, which are herein considered to be the early eruptives of the High Cascade volcanics, consist of aphanitic to porphyritic basalts and basaltic andesites, with associated pyroclastic rocks and lahars near apparent vent areas. Olivine and plagioclase commonly are present as phenocrysts.

Physiographically, the lavas of this sequence form erosionally resistant ridge crests in the Western Cascades, which in many places display a slight dip to the west. However, in the upper McKenzie and North Santiam Rivers the distribution of these lavas suggest slight to moderate dip to the east (plate 2).

An open system of cooling fractures, combined with very limited alteration, makes the lavas of this sequence an excellent aquifer. However, this aquifer system serves fundamentally to recharge meteoric water into the deeper groundwater system. Springs issuing from these rocks chemically are youthful and are in equilibrium with surface temperature conditions.

Pleistocene volcanic rocks. The Pleistocene volcanic rocks are predominantly lavas, ranging from porphyritic olivine and olivine-plagioclase basalts, commonly diktytaxitic, to porphyritic plagioclase andesites. Near Major composite volcanic vents, thick accumulations of pyroclastic deposits, autobrecciated lava, agglutinates and lahars are common. Included in this sequence are the extensive lavas forming the base of the High Cascade platform, and the volcanic peaks of the High Cascades.

The lavas and pyroclastic deposits of this sequence have undergone very little alteration, and are highly permeable to groundwater infiltration. In spite of precipitation that locally exceeds 60 and even 80 inches annually, surface run-off is moderate to low, with a high percentage of precipitation directly entering into the groundwater system. As such, these volcanic rocks provide excellent recharge into the deeper hydrologic system.

Holocene volcanic rocks. This unit is separated from other Quarternary volcanic rocks only to demonstrate the occurrence and distribution of the most recent volcanism within the study area. The rocks are predominantly thin flow and autobreccias of porphyritic olivine basalt and basaltic andesite, lacking developed soil surfaces. Also included are the cinder cones marking their eruptive sources. Vent distribution is generally linear, and location of the flows is controlled in turn by vent locations and topography. Physically, they commonly are highly fractured to rubbly. Like other Quaternary lavas with the study area, these are excellent aquifers.

STRUCTURE

Persistent, linear, vent patterns have been observed throughout this region in all rocks from middle Tertiary Western Cascades to the most youthful High Cascades cinder cones of Holocene age. The controlling systems of faults and/or fractures are invariably aligned N-S. None of the lineaments transects the most youthful flows, although Taylor has observed coincidental alignments of vegetation parallel to the fractures in older flows. He associates the vegetation abundance with abundant groundwater and with depressions where soil and pumice have accumulated. The lineaments or joint sets are parallel to the main trend of the Cascade Mountains. However, the sequence of eruptions appears to move with time from NW to SE and the magmas which supplied the eruptions may have been affected by a deeper-seated structural trend. Taylor suggested a NW trend, oblique to the Cascades, cutting across the High Cascades in the vicinity of the Three Sisters and continuing SE toward Newberry Caldera. Peck, et al. (1964) have proposed also that lines can be drawn to connect volcanic centers of four ages: (1) Oligocene andesite of the Little Butte Volcanic Series; (2) Oligocene to early Miocene basalt of the Little Butte Volcanic Series; (3) Miocene dacite and andesite of Little Butte Volcanic Series and Sardine Formation; (4) Pliocene and Quaternary rocks of the High Cascades. They see the center of volcanism as having migrated northward and eastward, with channelization of ascending magmas occurring along deep fracture zones (see figure 2).

Rocks of the Western Cascades generally dip to the NE. Dips on different beds, and in different parts of the area, range from a few degrees to as much as 35°. The dips most probably represent the eastern limb of the Breitenbush Anticline, which is a gentle, north-plunging, easternmost, regional fold of an en echelon series of folds in the Western Cascades. The western limb of the Breitenbush Anticline displays the steepest dips in the area; 30° to 50° westward. Some beds in the Sardine Formation exhibit gentle anticlines and synclines.

The rocks of the High Cascades are undeformed, and their slopes are variable in direction as well as in inclination. They generally represent the original slopes along which the lavas poured. Near Smith Reservoir, however, the High Cascades rocks have gentle dips to the NE, in concordance with the underlying Western Cascades.

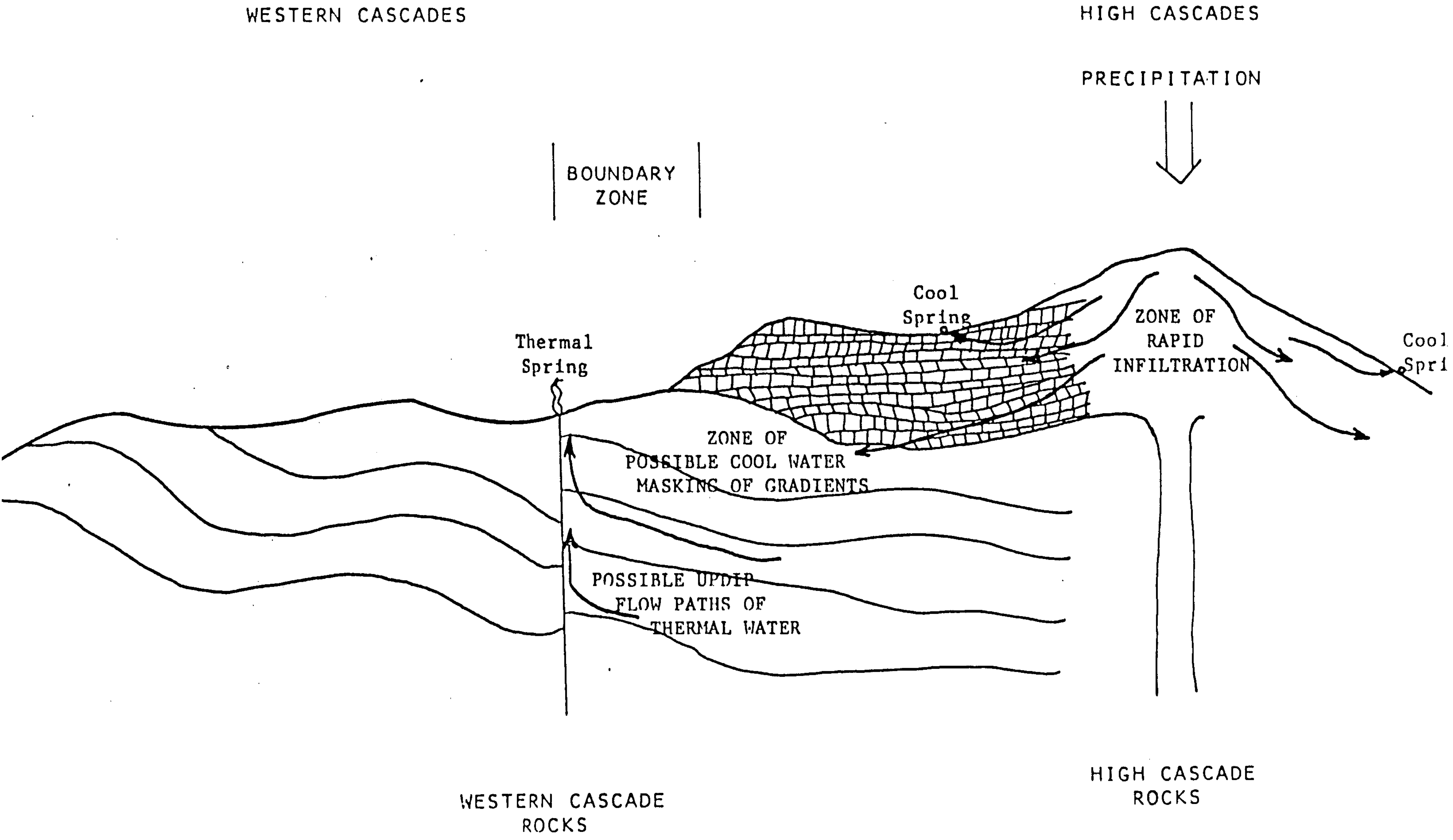


Figure 2. Diagrammatic representation of flow patterns of cool and thermal waters in the Western Cascades/High Cascades Region, Oregon.

Major folds parallel the principal Cascadian axis. Folding pre-dated extrusion of High Cascades lavas. Although slow sinking of the crust occurred in the area 100 miles to the north from about 10 million years ago to about 2 million years ago, followed by slow rising of as much as 8,000 feet, the Cascades in the Santiam-McKenzie area have recorded only tectonic downwarp, with elevation principally dependent upon accumulation of lavas rather than upon tectonic rebound. Downwarp followed by limited upwarp would result in the structure observed in the Cascades, with the Western Cascades formations dipping to the east. The area of study must have subsided, if a slice of crust was subducted below it and great volumes of eruptive material were extruded at the same time.

Much of the boundary zone between the Western and High Cascade provinces is obscured by Quaternary volcanism and by Holocene glacial and lacustrine deposits. Portions of the boundary zone, such as along the upper McKenzie River, are marked by a well-developed N-S trough. Normal faulting with downdropping to the east, such as observed in the Breitenbush and McKenzie River areas, has been viewed as evidence for a graben along the eastern portion of the study area. However, Hammond (1974), Rollins (1976) and others have found north-trending normal faults in this same boundary area with downdropping to the west. Further, the area west of Mt. Jefferson shows little evidence of faults of any significant offset. In the few places along the Western/High Cascades boundary where reliable attitudes could be taken, the Tertiary volcanic sequences appear to be dipping to the east. In the Mt. Hood area, structural subsidence has been found to be localized and rather circular, rather than forming part of a north-trending trough (Beeson et al., 1979). These data suggest structural flexures along the Western/High Cascade boundary, manifested in east-dipping monoclines. Locally the flexing appears to have been severe enough to have resulted in normal faulting. The relationship between flexing along the Western/High Cascades boundary and uplifting in the Western Cascades is unclear at this time.

Intensely eroded east-trending features are present in the McKenzie, North Santiam and Breitenbush River areas. Quaternary High Cascade lava flows in two of these zones suggest that these are Pleistocene phenomena. It is quite possible that these erosional features represent major structures that continue eastward through the High Cascades, and that possibly are still active, at least locally.

Evidence of Holocene structural weaknesses in the High Cascade province is seen in the Santiam and McKenzie River areas as alignments of very young cinder cones. The most obvious of these are associated with Scott Mountain and Sand Mountain. A possible cause for these alignments is tensional strain along the crest of the uplifted High Cascade block. However, there is no surface evidence for offset or ground rupture. The eruptive centers themselves are unglaciated, and the process of eruption should be considered as a continuing phenomenon.

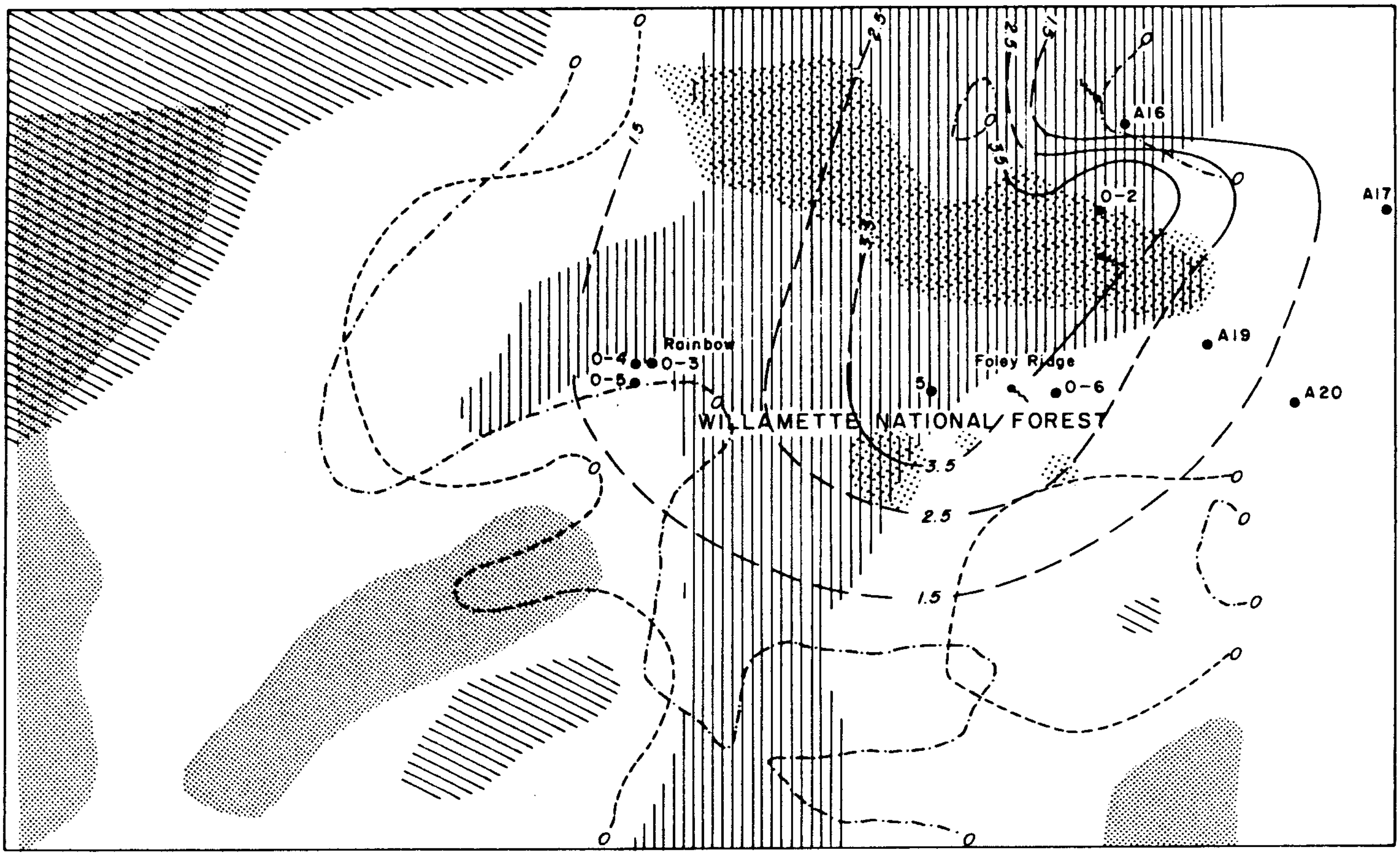
GEOPHYSICS

In addition to previous geophysical work described in the earlier GeothermEx reports (1973, 1977, 1980), the Oregon State University geophysics group has recently completed both a regional aeromagnetic survey and a regional gravity survey, which cover the south end of the Santiam Prospect. These two surveys were discussed in Brown, et al., 1980, and the following results were found.

The regional aeromagnetic survey showed a close correspondence between magnetic highs and topographic highs in the Belknap-Foley area. Younger ridge-capping volcanics belonging to the High Cascades sequence have higher proportions of magnetically susceptible lavas than the older Western Cascades lavas (Brown, et al., 1980). Thus aeromagnetic surveys may help define the High Cascades/Western Cascades boundary. An interpretation by Couch and Connard (in Brown et al., 1980) suggests a possible fault downdropped on the east side. The depth to the Curie point (600°C or 1,112°F isotherm) is estimated to be greater on the west side than on the east side of the fault.

The regional gravity survey showed a steep gravity gradient coincident with the Western Cascades/High Cascades transition zone, and also at the locations of the thermal springs. The larger anomalous area may be interpreted either as a large graben-bounding fault zone downdropped on the east side, an area of shallow silicic intrusives, or a combination of both (Brown, et al., 1980). The geophysical contour maps at 1:250,000 scale have been reproduced on figure 3. Heat flow contours obtained from the gradient hole data have been superimposed onto the aeromagnetic and gravity contours. There is a coincidence of aeromagnetic lows with gravity lows and heat flow highs in the vicinity of Belknap Hot Springs and Foley Hot Springs. The E-W trend in this area may indicate that the heat flow contours also extend westward in this region. The aeromagnetic and gravity data did not extend north of the Lane and Linn County boundary.

A summary of regional seismic studies performed by the U.S. Geological Survey was presented at the 1981 Cascades Conference (Geothermal Resources Council, 1981) by Craig Weaver. He stated that the Oregon Cascades range is nearly aseismic with the exception of Mt. Hood. He explained that plate shear is being aseismically accommodated but that the Oregon Cascades shows good geothermal potential, expecially when compared with the Washington Cascades and British Columbia.



Explanation

●A16 Location of hole, with number

0------- Gravity, 0 milligals

▥ Residual gravity low, < -6 mgal

▧ Residual gravity high, > +6 mgal

2.5 ——— Heat flow contour

Hot springs

0–·–·–·– Aeromagnetic, 0 gammas

░ Aeromagnetic low, < -150 gammas

▒ Aeromagnetic high > +150 gammas

FIGURE 3. Aeromagnetic and residual gravity with superimposed heat-flow, south Santiam Prospect, Oregon (from Brown *et al.*, 1980).

If SUNEDCO does not already possess deep resistivity data, there is some value in obtaining this type of geophysical coverage, especially for illuminating deep structure. Deep resistivity E-W profiles using dipole-dipole techniques will help construction of a geological cross section, perhaps showing the actual contact zone of the High Cascades/Western Cascades sequences through the northern and southern ends of the Santiam prospect.

HYDROLOGICAL REGIME

Surface Water

The area is drained by the McKenzie and Santiam River, both tributaries of the Willamette River. Principal tributaries of the McKenzie are Blue River, Smith River, Deer Creek, White Branch, Horse and Separation Creeks. Hackleman Creek drains part of the area of Belknap lava flows into the Santiam River. All drainage enters the Willamette about 60 miles west of Belknap Hot Springs. The average stream gradient exceeds 25 feet per mile.

The drainage area of the McKenzie River near McKenzie Bridge is about 350 square miles. Mean discharge at McKenzie Bridge annually is about 2,000 second-feet. This translates into about 1,200,000 acre-feet per year. The upper course of the McKenzie River has been dammed 7 miles north of Belknap Hot Springs as part of the EWEB power system. Smith River has been dammed for the same purpose 10 miles north of the springs.

Groundwater

Stearns (1929) described groundwater in the upper McKenzie Valley in terms of surface run-off related to precipitation and spring flow. He estimated that 50 percent of annual precipitation, or over 60,000 acre-feet, appears as spring flow in the McKenzie basin, and that 75 percent of precipitation on the lava beds east of Belknap Hot Springs reaches the water table. Cavernous aa segments of the recent flows are especially permeable and serve as conduits for flow into shallow aquifers. Many of the creeks (Deer, Smith, Boulder, Scott, etc.) are spring fed and therefore some flow is reasonable dependable throughout the year, although low-water periods occur.

Smith (1938) reasoned that there was a separation of groundwater into different regimes, in which deep circulation fed the several hot springs of the area, and shallow, cold circulation appeared in the higher strata and the valley alluvium. Whether hot springs result from ascending hot gases or convective water flow into fractures, or both, cannot be determined on the basis of existing data.

Rainfall has been observed to infiltrate rapidly into fractured eruptive rocks in the area, especially in the Pleistocene and Holocene volcanic High Cascades zone. The shallow soil cover, together with pumiceous material, assists infiltration, after which water moves in fractures and along strata boundaries downslope and discharges from many springs on the walls of stream canyons.

Spring flow is especially prodigious in the walls of the upper McKenzie River valley. The watertable slopes steeply westward, from the peaks of the High Cascades to the Belknap and Little Belknap lava plateaus, thence from the boundary of the Western Cascades to the Willamette River. The cool groundwater of the region rather consistently averages 50°F in temperature.

It may be concluded on the basis of the incomplete information that if a thermal reservoir exists northeastward of Belknap Hot Springs, great amounts of water are available for recharge. Further, the deep canyons of the Western Cascades probably do not drain much of the fluid mass from the reservoir; the hot springs of the region do not have much flow in comparison to recharge and runoff records. (Belknap, Cougar, Foley, Deer possibly total 200 gallons per minute.) A significant amount of the deep, hot circulation probably is dispersed in the cool groundwater west of the boundary of the Western Cascades and not show up because of extreme dilution.

Thermal Springs

Belknap and Deer Creek Hot Springs appear to discharge along north-trending faults; Foley Hot Springs are not associated with recognized faults. All are located along the Western Cascades/High Cascades boundary zone. The calculated geothermometry temperatures from Na-K-Ca and SiO_2, although ranging up to 226^oC, cluster around 100^oC, indicating a low temperature resource (figure 4). R.H. Mariner (1980 U.S. Geological Survey Cascades Conference, Menlo Park, Calif.) stated that sulfate geothermometry may give more accurate estimates than alkali and quartz geothermometry. He estimated a source temperature ranging from 150^oC to 200^oC for Belknap-Foley system, using sulfate geothermometry.

Belknap Hot Springs are located along the north shore of the McKenzie River, discharging approximately 75 gpm at 75^oC (167^oF) from silicified volcanic breccia. The concentration of SiO_2 is 96 mg/l. The conductive quartz temperature is 135^oC. The amorphous quartz (chalcedony) temperature is 107^oC. The alkali (Na-K-Ca) temperature is 114^oC by the 1/3 and 82^oC by the 4/3 calculation. From these figures, the U.S.G.S. has estimated a range in base reservoir temperature of 80^o to 145^oC and an average

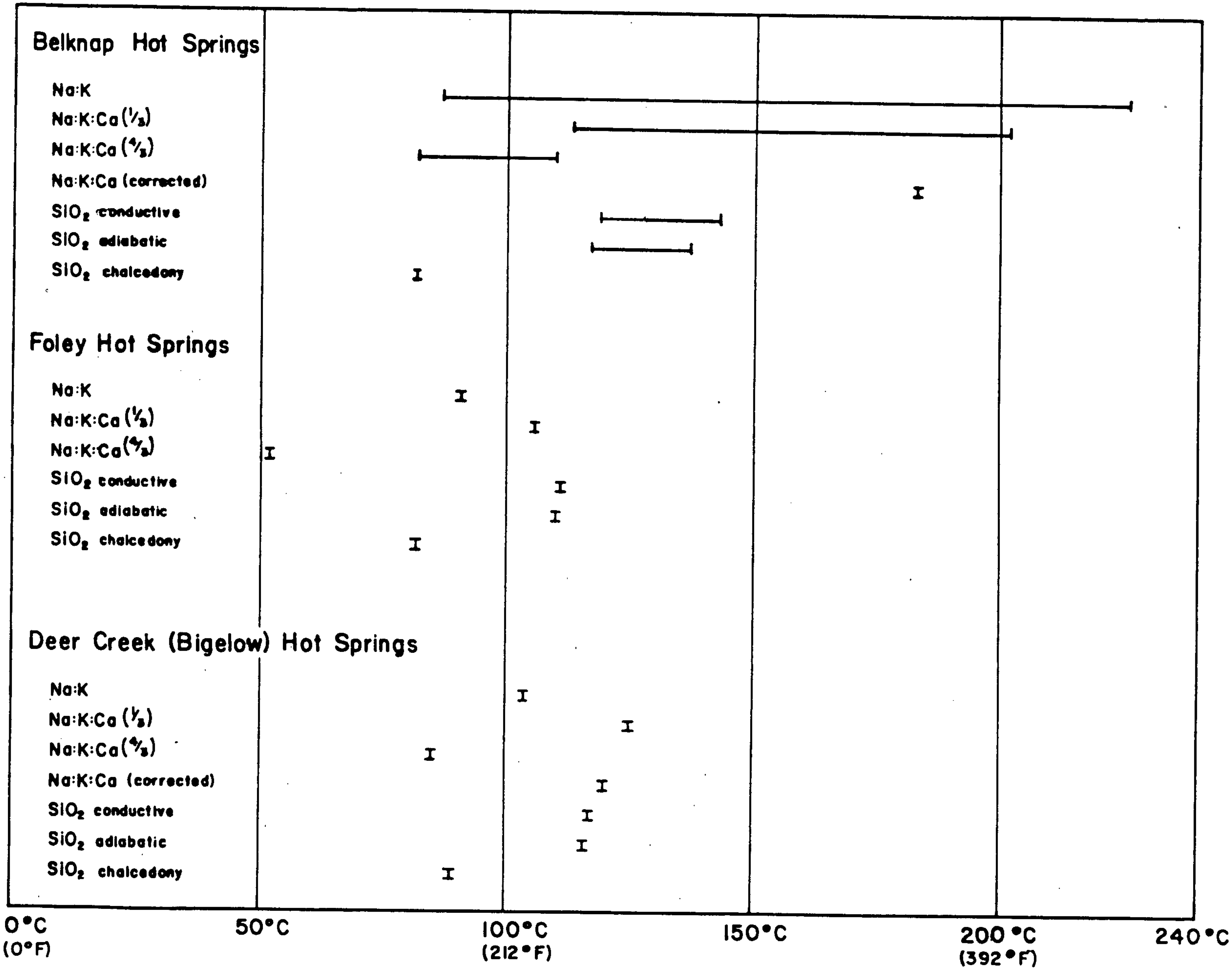


Figure 4: Geothermometry of hot spring waters, Santiam prospect, Oregon. (Data from Brown, et al., 1980)

reservoir temperature of 140°C, between 0.5 and 1.5 km depth. Water from Belknap Spring is slightly alkaline (ph=7.6) sodium-calcium chloride type (Na=690 mg/l, Ca=210 mg/l, K=15 mg/l, Cl=1,300 mg/l, SO_4=170 mg/l, and HCO_3=17 mg/l). It is not known what percentage of deep water this represents, but the spring appears to represent leakage downstream from an erosional or structural break in a deep-seated aquifer.

Dear Creek Spring flows 2 gpm at approximately 70°C (158°F) from silicified breccia in upper Western Cascades strata. The spring location may be controlled by combination of fracture zones near the province boundary and deep erosion by the McKenzie River. The SiO_2 content is 69 mg/l. Conductive quartz temperature is about 115°C and amorphous quartz temperature is about 85°C. The water is sodium chloride, with Na=540 mg/l, Ca=188 mg/l, K=16 mg/l, Cl=1,148 mg/l and SO_2=102 mg/l; HCO_3 is not reported.

Foley Hot Springs are located near the Horse Creek, 3 miles south of the McKenzie River. The flow is approximately 25 gpm at 79°C (174°F), from coarse volcanic breccia. The SiO_2 content is 60 mg/l. Conductive quartz temperature is about 111°C and amorphous quartz temperature is about 82°C. The water is sodium-calcium chloride type (Na=475 mg/l, Ca=494 mg/l, k=11 mg/l, Cl=1,304 mg/l, SO_4=550 mg/l, and HCO_3 is not known).

TEMPERATURE GRADIENTS

The thirteen holes drilled for SUNEDCO at Santiam prospect were completed after drilling to total depth by installing a one-inch iron gradient pipe with a plugged bottom, which was cemented in place near the surface, filled with water, capped and locked. Temperature measurements were made with Envirolabs Model DT-201 A digital thermometer during the following time periods by a GeothermEx geologist: November 22 and 23, 1980, January 14 and 15, 1981, February 12 and 13, 1981, and June 26 and 27, 1981. All of the holes, with the exception of A10 and A14, were abandoned on June 26 and 27, 1981, according to procedures outlined by the Sweet Home Ranger District office of the U.S.F.S. Forest Service personnel were invited to observe abandonment, but declined. Hole A10 was inaccessible due to logging operations; the gradient pipe in hole A14 could not be found, although the site was cleaned and restored by the geologist.

Temperatures were measured and recorded at 10 foot intervals as the thermistor probe was lowered into the hole. This data is presented in Appendix B. A summary of final temperature profiles appears on figure 5. Temperatures at 400-foot depth intervals have been contoured on plate 3. Thermal and lithologic data also are shown on topographic profiles on plate 4. Following this discussion is a hole-by-hole summary which relates temperatures to geology and hydrology.

The highest temperature observed in the holes drilled for SUNEDCO in the Santiam prospect was 66.2°F at 502 feet, in hole 80-5. Two other holes had maximum temperatures in the 50°-60°F range: hole A11 measured 59.7°F at 464 feet, and hole A7 measured 53.2°F at 489 feet. These holes were located on the west side of the north-trending fault and fracture zones, in the region of the Western Cascades/High Cascades contact zone. Holes A11 and A7 were located in the northern area, near Sand Mountain, while hole 5 was located just west of Foley Hot Springs. The remaining holes showed very low bottom-hole temperatures, between 36.9°F and 46.9°F were measured in the remaining holes which were located along the eastern side of the north-trending faults, in very permeable High Cascade volcanic rocks in which great amounts of cool groundwater is moving.

The holes showing the highest bottom-hole temperatures were also the holes with the highest temperature gradients. Hole A11 had the highest average temperature gradient, with 7.2°F/100 feet between 370 feet and 460 feet depths. Hole 80-5 showed 5.2°F/100 feet between 250 feet and 500 feet, while Hole A7 showed a gradient of 3.2°F/100 feet

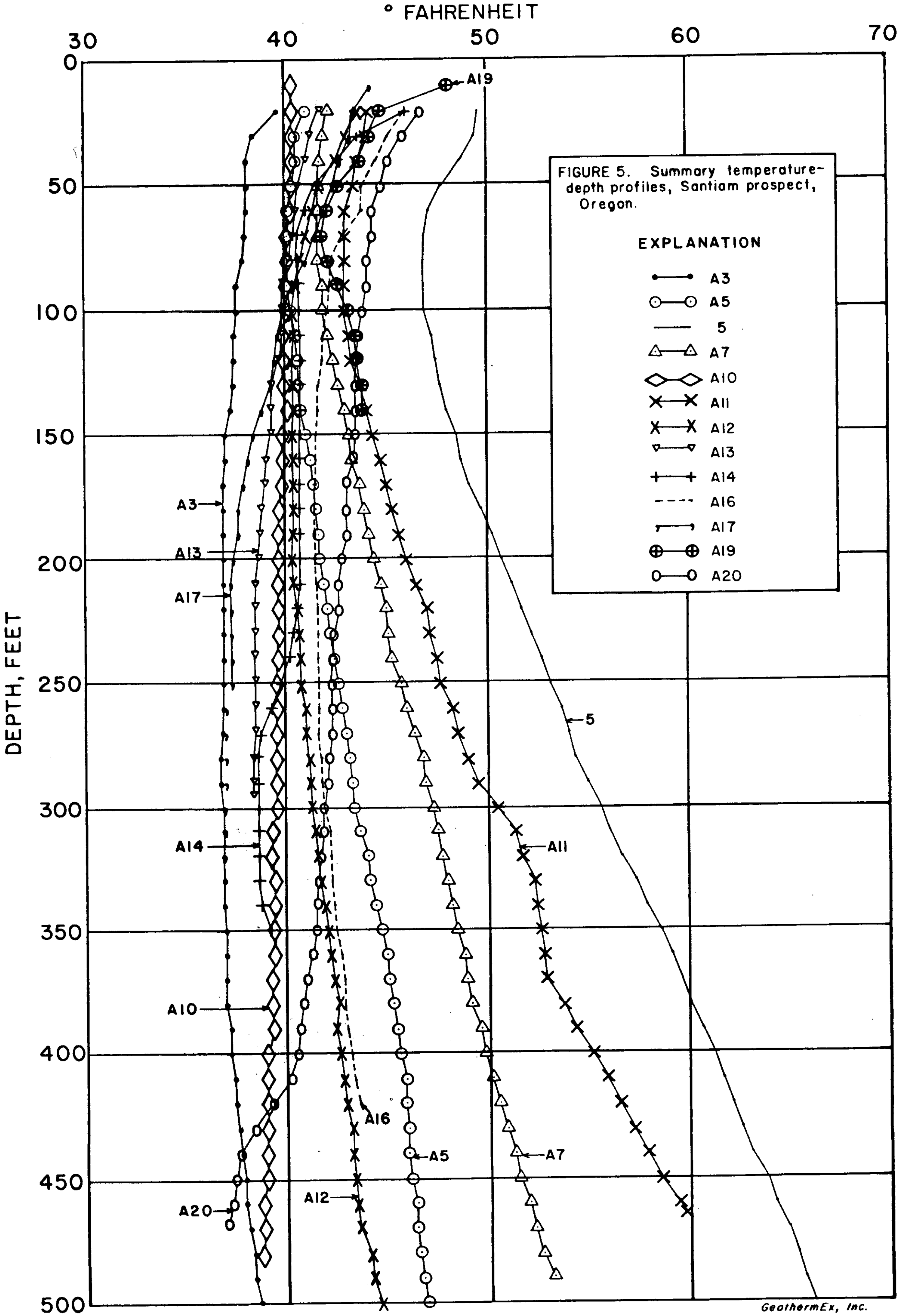


FIGURE 5. Summary temperature-depth profiles, Santiam prospect, Oregon.

GeothermEx, Inc.

between 300 feet and 460 feet. Regional average temperature gradients range between 3.3° to 3.8°F/100 feet; only two of the SUNEDCO holes were above regional average. Hole A19, had an average gradient of 3.3°F/100 feet between 70 feet and 130 feet, although the bottom-hole temperature was only 43.9°F at 135 feet depth. The remaining holes showed temperature gradients ranging from 2.0°F/100 feet to reversals. These are clearly in cold recharge zones.

Maximum temperatures in the intermediate-depth DOGAMI and EWEB holes (Appendix B) were higher than for the SUNEDCO holes. EWEB-2 reached 87.9°F at 1,935 feet, and EWEB-1 reached 77.1°F at 700 feet. Both of the intermediate-depth wells were drilled near the major north-trending faults marking the Western Cascades/High Cascades boundary. EWEB-2 was drilled on the east side of a fault and showed a reversed and isothermal gradient to 787 feet depth. The gradient then rose steeply, averaging 4.0°F/100 feet, to 87.9°F at 1,935 feet. The high gradient in this hole below an isothermal and reversed gradient has positive implications for the area along the east side of the fault. The EWEB-1 hole was drilled further south, in young unaltered basalt flows dated at approximately 3,000 years of age. This hole was on the west side of the fault and showed a constant high temperature gradient of 5.6°F/100 feet to 650 feet depth, reaching a maximum temperature of 77.1°F. The gradient then reversed, became isothermal and rose again near the bottom of the hole. Blackwell, in Youngquist (1980) stated that this gradient profile is indicative of lateral flow of warm water along an aquifer between 656 feet and 722 feet superimposed on a background of relatively low heat flow.

Most of the shallow holes drilled for DOGAMI (Appendix B) had bottom-hole temperatures above 50°F. Hole 0.6 had a bottom-hole temperature of 70.8°F at 492 feet; hole 0.1 reached 64.5°F at 505 feet; holes 0-2 through 0-5 had maximum temperatures ranging from 53.1°F to 58.7°F at 200 feet to 492 feet depths. These holes were all located in the western region. Hole 0-7 showed 45.5°F at 171 feet, and was located just north of Deer Creek Hot Springs probably in a cool recharge zone. The lowest average tmperature gradient in 'DOGAMI' holes ranged from 2.6° to 2.9°F/100 feet in holes 0-3, 0-4 and 0-5. Hole 0-6 had 3.9°F/100 feet between 100 and 492 feet, 0-1 showed 4.1°F/100 feet between 148 feet and 505 feet, and 0-2 averaged 4.8°F/100 feet between 330 feet and 492 feet.

The 50°F and 60°F isotherm contours at 400 feet depth (plate 3) describe an anomalous thermal region which trends N-S along the west side of the N-S trending faults, in the High Cascades/Western Cascades contact zone. High temperatures and gradients are clustered in 2 areas, the Sand Mountain area to the north, and the Belknap-Foley area to the south. These 2 areas may or may not be connected along the N-S trend. Too few data points exist to be conclusive. The anomaly confined by the contours is probably relict from the change between high permeability High Cascades rocks and low permeability Western Cascades rocks. The area east of the geomorphic province "join" is highly affected by cold water flow; mixing with thermal water and flow past thermal areas masks any anomaly and depresses temperature gradients below normal regional values.

Plate 5 shows the relationship of mean annual air temperature (MAAT) and bottom-hole temperature for selected gradient holes along an E-W traverse corresponding principally to the McKenzie River. Those holes upslope of the boundary between the Western and High Cascades have bottom-hole temperatures significantly below MAAT for the elevation. This more clearly than any other factor shows that these holes have been chilled by downward-circulating cold water of the High Cascades.

Holes downslope of the Western-High Cascade boundary are warmer than MAAT, as expected. Holes 5 and 0-6 are significantly warmer than might be expected, indicating a geothermal effect, whereas hole 0-4 indicates only a moderate warming with depth (moderate gradient).

Thus, the Western-High Cascades boundary serves as a hydrologic boundary, separating areas of permeable surface rocks (High Cascade) from less-permeable or impermeable surface rocks (Western Cascade). If the Western Cascade surface rocks were more permeable, there might also be temperatures below MAAT in shallow holes.

This condition does not disqualify the High Cascades as a geothermal province, nor does it greatly enhance the Western Cascades. It does mean that gradient holes in the High Cascade range must be deeper than about 1,000 feet. Two of EWEB's 1980 holes (EWEB-1 and especially EWEB-2) located near the Western-High Cascade boundary, had significant positive gradients only below 1,000 and 1,500 feet. This suggests that gradient holes in the High Cascade section should go to 1,500-2,000 feet in depth, depending upon elevation, geology and exact location. Even then, individual holes in the High Cascade might not show positive gradients; but, the geologic, temperature and hydrologic data thus obtained are essential if the prospect is to be explored further.

Hole S-80-A3

T. 13 S., R. 6 E., SW ¼, SE ¼, section 2

This was the most northerly of the holes drilled for SUNEDCO at Santiam prospect, and is located just east of Crescent Mountain, which rises to an elevation of 5,760 feet. Numerous creeks originate at the mountain and feed into Lava Lake. The wellhead elevation was 4,560 feet. Seven days were spent drilling the hole, to a depth of 500 feet.

The hole is located in Tertiary-Quaternary older High Cascades volcanics, near a contact with Quaternary undifferentiated sediments. There are no faults mapped here, but the hole is along the dip slope of an eastward-dipping monocline. It is also within the contact zone of the High Cascades/Western Cascades volcanics. The lithology of the hole consisted of gravel to 20 feet depth, comprised of tuffaceous sediments and tuffs. Below the gravels, the section alternated between basalt porphyry, clay and a sedimentary tuff to 300 feet. From 300 feet to 500 feet, the predominant lithology was clay and minor basalt prophyry, with a 10 feet thick section of tuffaceous sandstone at 400 feet.

The temperatures and temperature gradients reflect the topography and the lithology. The temperature at 20 feet was 39.7°F, which decreased to 36.7°F at 270 feet. The temperature then increased to 38.5°F between 290 feet and 500 feet depth, with an average gradient which was close to 1°F/100 feet. The cold temperatures reflect the cold groundwater movement. The increasing temperature gradient from 300 feet to 500 feet would be expected in a clay zone, where the thermal conductivity and permeability is low, effectively increasing the temperature gradient.

Hole S-80-A5

T. 13 S., R. 7 E., SW ¼, SE ¼, section 18

This hole was located approximately 2 miles SE of A3, along the west side of Lava Lake, which is fed by creeks from Crescent Mountain. The wellhead elevation was 3,540, which is more than 1,000 feet lower than hole A3. Five days were spent drilling to a total depth of 500 feet.

The site is on the upthrown west side of a major N-S trending fault, in Tertiary undifferentiated sediments. The contact with very recent lavas is less than ¼ mile to the east. The lithology included 30 feet of unconsolidated gravel and clay at the surface to 140 feet, with a 40 feet thick basalt porphyry flow from 30 feet to 70 feet. Another basalt flow was encountered between 140 feet and 160 feet. The lower part of the hole, from 160 feet to 500 feet, was in clay and sand.

Temperatures ranged from 40.1°F at 60 feet to 46.9°F at 500 feet. The average temperature gradient was nearly isothermal to 190 feet. Below 190 feet, to 500 feet, the average gradient was 2.0°F/100 feet. The last survey showed a decreasing gradient of 1.4°F/100 feet between 360 feet and 500 feet, which was probably due to convection in the gradient pipe.

Hole S-80-A7

T. 13 S., R. 6 E., NE ¼, NW ¼, section 26

S-80-A7 is located approximately 3 miles south of A3, and 3 miles SW of A5, along Toad Creek, which flows from Echo Mountain into Hackleman Creek, and then into Fish Lake. The elevation of the hole was 3,680 feet. Eleven days were spent drilling, reaching a total depth of 489 feet.

The surface geology is Quaternary older High Cascades volcanics, on an eastward dipping monocline. Several Tertiary intrusives crop out approximately 6 to 8 miles east of the site. The drilling encountered volcanic gravels from surface to 20 feet, and a basalt porphyry flow between 20 feet and 200 feet. The basalt porphyry was fractured and vesicular between 300 feet and 470 feet, with minor clay. Between 300 feet and 470 feet a slightly vesicular basalt flow, containing some opal was drilled. The section from 470 feet to 490 feet was brown clay.

Temperatures ranged from 41.7°F at 50 feet to 53.2°F at 489 feet. The average temperature gradient was 1.5°F/100 feet between 50 feet and 160 feet. This average increased to 2.9°F/100 feet between 160 feet and 460 feet. An earlier survey showed a gradient of 3.2°F/100 feet in the lower interval between 300 feet and 460 feet. The earlier survey may be more accurate because the water often convects after equilibration, producing lower gradients at the bottom of the pipe.

Hole S-80-A10

T. 14 S., R. 6 E., SE ¼, NE ¼, section 12

This hole was sited approximately 3 miles SW of hole A7, along the east side of Browder Ridge. Gate Creek and Smith River flow off the ridge, and join just south of the drill site, flowing south to the McKenzie River. The elevation of the hole was 3,360 feet. Nine days were spent drilling to a total depth of 480 feet.

The surface is mapped as a contact between Tertiary undifferentiated sediments and Quaternary older High Cascades volcanics. Cuttings were gravel and clay from surface to 240 feet. Circulation was lost between 240 feet and 260 feet. Below the lost circulation zone, a basalt flow was encountered from 260 to 320 feet. A welded breccia between 320 feet and 430 feet was partially altered to a white (kaolinite?) clay. Another basalt flow completed the section from 430 feet to 480 feet.

The temperatures ranged from 40.3°F at the surface to 38.7°F at the bottom of the hole. This reversal was most probably caused by drilling in a recharge zone near a stream junction, where the ground is clearly saturated with cold water.

Hole S-80-A11

T. 14 S., R. 6 E., SE ¼, NE ¼, section 15

This hole was located approximately 2 miles SW of hole A10, just north of Browder Creek on the south side of Browder Ridge. The wellhead elevation was 3,840 feet. Eleven days were spent completing the hole to 464 feet depth.

The location was along the contact of the Western Cascades and High Cascades volcanics. On a regional scale, there is a NW lineament which passes through this location. It begins with a NW-trending fault to the NW, runs along the Western Cascades/High Cascades contact, through an offset in the major north trending fault, and finally defines a contact between Recent volcanics and High Cascades volcanics. This is likely to be a zone of structural weakness.

The drilling encountered gravel, clay and silt from surface to 120 feet. Below the sediments, a 30 feet thick basalt flow, followed by a 100 feet thick pyroxene andesite flow, was drilled through in the 120 feet to 250 feet interval. At 250 feet, a 40 feet thick basalt flow was encountered, followed by a 10 feet thick breccia zone, partially altered to clay. From 300 feet to 340 feet, a pale green tuff containing opal was encountered, possibly correlative with the Breitenbush Tuff of Hammond (1976). Below the tuff, there was another pyroxene andesite flow from 340 feet to 370 feet, followed by a 10 feet thick red clay zone from 370 feet to 380 feet. Below the red clay was a 30 feet thick basalt flow. A green clay zone was found from 410 to 450 feet, and finally, 20 feet of dark green basalt at the bottom of the hole from 450 to 470 feet.

The temperatures showed a reversal to 100 feet, with a temperature of 43°F. The temperature then rose to 59.7°F at 464 feet. The temperature gradient averaged 3.5°F/100 feet between 120 feet and 240 feet, rising to 4.8°F/100 feet between 240 feet and 300 feet in the basalt and breccia zone, just above the tuff. The gradient dropped to 3.6°F/100 feet between 300 feet and 370 feet above the red clay zone, then rose steeply to 7.2°F/100 feet between 370 feet and 460 feet, in the basalts below the clay. The upper, red clay seems to act as a thermal cap in this high gradient zone.

<u>Hole S-80-A12</u>

T. 14 S., R. 7 E., SE ¼, SE ¼, section 31

This hole was located approximately 4 miles SE of hole A11, on the north side of Bunchgrass Ridge. Kink Creek joins the McKenzie River less than 1 mile SW of the location, and Tamolith Falls cascade to the north of the site. This is clearly an area of high groundwater saturation. The wellhead elevation was 2,880 feet. Seven days were spent drilling to a total depth of 500 feet.

The hole was drilled along the east side of a major north-trending fault, in Quaternary High Cascades volcanics, near a contact, with Tertiary-Quaternary older High Cascades volcanics. Drilling encountered olivine basalt from surface to 20 feet, with pyroxene andesite between 20 and 60 feet, and olivine basalt again from 60 feet to 210 feet. Two 10 feet thick clay zones were encountered between 210 and 220 feet, and from 340 feet to 350 feet, alternating with olivine basalt flows. A 60 feet thick clay zone was encountered at the bottom of the hole between 430 feet and 500 feet.

Temperatures ranged from 40.3°F at 210 feet to 44.6°F at 500 feet. The temperature gradient reversed from surface to 120 feet, and was isothermal from 120 feet to 300 feet, indicating cold groundwater flow. The average gradient between 300 feet and 360 feet was 1.8°F/100 feet. This decreased to 1.4°F/100 feet between 370 feet and 420 feet, and increased again to 2.0°F/100 feet between 420 feet and 500 feet. The increase in gradient was probably caused by lower thermal conductivity of clays.

Hole S-80-A13

T. 15 S., R. 7 E., SW ¼, SW ¼, section 4

Hole S-80-A13 is located approximately 1½ miles SE of A12, along the NW slope of Bunchgrass Ridge. Belknap Crater, which reaches an elevation of 6,842 feet, lies 6½ miles to the east. The wellhead elevation of this drillhole was 3,560 feet. The hole reached 295 feet depth after 8 days of drilling.

The surface is mapped as Quaternary High Cascades volcanics. There are no significant structural features. The hole is along the east side of the north-trending fault, although over 2 miles east of the surface expression of the fault. The drilling encountered gravel and silt from surface to 30 feet, and predominantly basalt throughout the rest of the hole. There was a 20 feet thick vitric tuff from 80 to 100 feet, and a vesicular basalt breccia from 110 to 130 feet. The remainder of the hole was drilled in basalt. Circulation was lost from 280 feet to the bottom of the hole at 290 feet.

The temperatures ranged from 41.9°F at 20 feet to 38.3°F at 295 feet. This reversal clearly reflects cold groundwater flow from the High Cascades.

Hole S-80-A14

T. 15 S., R. 7 E., SW ¼, NW ¼, section 15

This hole is located approximately 1½ miles SE of hole A13, near the head of Anderson Creek, just south of Bunch Grass Ridge. The wellhead elevation was 3,800 feet. The hole reached a total depth of 348 feet after 7 days of effort.

The surface is mapped as Quaternary High Cascades volcanics. There are no important structural features mapped in the immediate vicinity; there is a Quaternary cinder cone approximately 3½ miles to the east of the drill site. The hole was drilled in olivine basalt which varied from slightly to highly vesicular throughout the hole.

Temperatures ranged from 46.0°F at 10 feet to 38.7°F between 300 feet and 330 feet. The temperature gradient reversed from surface to 60 feet, became isothermal from 60 feet to 220 feet, reversed again from 220 feet to 280 feet, and was isothermal from 280 feet to 340 feet. The temperature increased slightly to 39.2°F at the bottom. This is clearly a cold groundwater recharge zone.

Hole S-80-A16

T. 15 S., R. 6 E., NE ¼, SW ¼, section 25

The location of this hole is approximately 5 miles S-SW of hole A12, along Twisty Creek, about a mile before it enters the McKenzie River. The McKenzie flows south to Belknap Springs, approximately 2½ miles south of hole A16, then west to the Willamette Valley. Deer Creek Hot Springs lie approximately 1 mile to the NW of the drill site. Hole A16 is at a wellhead elevation of 2,640 feet. Driller spent approximately 7 days on this hole to reach a total depth of 420 feet.

The surface geology is Quaternary High Cascades volcanics. There is no significant structure at this site, although it is on trend with the major north-trending faults. It is approximately ½ mile east of a contact with Quaternary-Tertiary older High Cascades volcanics. Drilling encountered sand from surface to 10 feet depth, and basalt throughout the remainder of the hole. The basalt was an olivine basalt, and was vesicular between 60 feet and 80 feet depths.

Temperatures ranged from 46.0°F at 20 feet to 43.5°F at 420 feet. There was a reversal from surface to 150 feet, followed by an isothermal zone from 150 feet to 260 feet. There was an average temperature gradient of 1.2°F/100 feet between 260 feet and 420 feet. This hole was clearly in a cold groundwater recharge zone.

Hole S-80-A17

T. 16 S., R. 7 E., NE ¼, SW ¼, section 2

This site is located approximately 5 miles SE of hole A16, and 6 miles east of Belknap Hot Springs. There are numerous lakes and springs in the area, as well as glaciers eastward from the site, indicating very saturated cold groundwater conditions. The site is near Irish Camp Lake, at a wellhead elevation of 4,480 feet. Eleven days were spent drilling to 320 feet depth.

The surface geology is Quaternary High Cascades volcanics. There is a north-trending fault approximatley 1 mile east of the location, which terminates in the Quaternary cinder cone named Two Buttes. The lithology of the hole was entirely basalt, except for 10 feet of either gravel or an interflow zone at 40 to 50 feet. Some of the basalt was vesicular.

Temperatures ranged from 44.2°F at 10 feet to 36.9°F at 320 feet, showing a reversal from surface to total depth. The observed temperature regime would be predictable in this type of terrain.

Hole S-80-A19

T. 16 S., R. 7 E., NE ¼, SE ¼, section 19

Hole A19 is located approximately 3 miles SE of Belknap Hot Springs, in the drainage basin of Lost Creek, which is fed by glaciers from the Three Sisters volcanos. The elevation of the hole was 2,080 feet. Twelve days were spent drilling, reaching a total depth of 135 feet.

The surface geology is Quaternary undifferentiated sediments, near a contact with Quaternary High Cascades volcanics. The location is approximately 2 miles east of the north-trending Cascade graben margin as mapped by Brown et al., (1980). The cuttings showed basaltic gravels from surface to 90 feet. The remainder of the hole consisted of basalt and olivine basalt, containing small amounts of olivine basalt vitrophyre.

Temperatures ranged from 48.0°F at 10 feet to 41.9°F at 70 feet. The temperature gradient profile showed a reversal from surface to 70 feet. The average temperature gradient between 70 feet and 130 feet was 3.3°F/100 feet, reaching a bottomhole temperature of 43.9°F at 134 feet depth.

Hole S-80-A20

T. 16 S., R. 7 E., SW ¼, SE ¼, section 21

This hole was sited approximately 2 miles SE of hole A19, just south of the east arm of Foley Ridge, between Rainbow Creek and Gold Creek. The wellhead elevation was 3,920 feet. The total depth of the hole was 468 feet, after 8 days of drill time.

The surface geology is mapped as Quaternary High Cascades volcanics. There is no significant structure at this location, although the north-trending faults all terminate at this latitude, and the rivers turn from a N-S trend to E-W trend at this latitude. Foley Hot Springs is approximately 5½ miles westward of A20. The lithology consisted of gravel and clay from surface to 200 feet. There was basalt between 200 feet and 340 feet, and silt between 340 feet and 370 feet. The silt was underlain by 20 feet of autobrecciated basalt breccia from 370 feet to 390 feet, an andesite flow from 390 feet to 400 feet, and another silt stratum from 400 to 420 feet. An andesite breccia was present between 420 feet and 440 feet, followed by an andesite flow from 440 feet to 460 feet.

Temperatures ranged from 46.8°F at 10 feet to 37.0°F at 468 feet. The temperature gradient showed reversals throughout the entire hole. This hole was clearly in a cold groundwater recharge zone.

Hole S-80-5

T. 16 S., R 6 E., SE ¼, NE ½, section 30

This location is approximately 1½ miles west of Foley Hot Springs, near Wilelada Creek, south of the west limb of Foley Ridge. Ten days were spent drilling to reach a total depth of 500 feet. The elevation of the hole was 2,000 feet.

The surface geology is Western Cascades volcanics, near a contact with Quaternary undifferentiated sediments and Quaternary High Cascades volcanics. The DOGAMI map shows several north and NW-trending faults just south of the site, and others a few miles to the north. The lithology of the hole consisted of gravels from surface to 170 feet. These contained some chalcedony and clasts of silicified breccia. There was a thick brown clay zone from 170 feet to 250 feet depth. The rest of the hole consisted of clay and basalt flows. The basalt was fractured and silicified in some zones, with plagioclase altered to a blue-green mineral. There was abundant pyrite in one of the basalt flow zones between 380 feet and 400 feet.

The temperatures ranged from 46.9°F at 70 feet to 66.2°F at 500 feet. The temperature gradients showed a reversal, then recovery between surface and 170 feet. The average temperature gradient between 170 feet and 250 feet was 5.0°F/100 feet. This gradient increased to 5.2°F/100 feet between 250 feet and 500 feet. The hole is within a geothermal anomaly, although its boundaries are not well defined.

HEAT FLOW

Thermal conductivity measurements were not made on samples from the Sun-Santiam prospect. However, conductivity and heat flow analyses were made on the holes drilled for DOGAMI and EWEB, and these results were used to estimate thermal conductivities for the Sun holes. The estimated heat flow values appear on table 3 and plate 3, and are contoured on figure 6. Heat flow calculations were made using the formulae:

$$Q = K_{is}\ dt/dx \text{ and } K_{is} = K_b^{1-\phi}\ K_p^{\phi}$$

where Q = heat flow in HFU (μcal/cm^2-sec), K_{is} = *in situ* thermal conductivity, dt/dx = temperature gradient in °C/km, K_b = bulk thermal conductivity, conductivity of material in pores, assumed to be water with K_p value of 1.43, and ϕ = porosity. Bulk thermal conductivity values were estimated using 3.8 TCU for basalt, 3.0 TCU for basalt gravels, and 2.5 TCU for clay. Porosity values were assigned using a range of 30% to 40% for unconsolidated sediments, and 5% to 10% for volcanic rocks.

Regional heat flow values for Oregon average 1.6 HFU, compared with a worldwide continental average of 1.5 HFU. There is a major change in heat flow across the High Cascades/Western Cascades boundary, noted by Blackwell, *et al.*, 1978 (figure 7a). On the west side of the boundary, including the Coast Range, the Willamette Valley, the Klamath Mountains. and the Western Cascades provinces, heat flow averages 1.0 ± 0.03 HFU, while in the High Cascades province, the average heat flow is 2.51 ± 0.20 HFU. For comparison, the Battle Mountain High heat flow anomaly averages 2.5 to 2.9 HFU. Blackwell *et al.* noted that Bouguer gravity lows correspond with heat flow highs, indicating that the high heat flow in the Cascades may be related to a regional crustal feature rather than to upper crustal groundwater circulation. Using this heat flow model, which includes a central magma chamber beneath the High Cascades axis, Blackwell predicted temperatures greater than 700°C at depths less than 10 KM on the east side of the High Cascades/Western Cascades boundary, while temperatures may be only 300°C at 10 Km on the west side of the boundary. At the 1981 Cascades conference (Geothermal Resources Council, 1981) Blackwell concluded that based on recent drilling, there is no large shallow subvolcanic magma chamber less than 10 Km deep beneath the Cascade Range.

Alternative models explain Cascades heat flow patterns with large-scale regional flow of groundwater, calling for hydrothermal circulation systems driven by elevation differences and water flow primarily from east to west

(Blackwell, et al., 1978). In the first of these models, water circulates to great depths (> 3 km), then flows laterally at depth, coming to shallow depths below the hot springs. In the second alternative model, water circulates to depths beneath the volcanos, comes up to shallow depths, then flows laterally, perhaps along a tuff unit. In the last alternative model, the thermal anomaly is confined to a narrow band along the physiographic boundary with possibly a high permeability zone as the controlling factor. These 4 models are illustrated in figure 7b.

The holes drilled for SUNEDCO in the Santiam prospect range up to 3.7 HFU. Only 2 of the 13 holes show values above the regional 2.5 HFU average. Hole All had a high of 3.9 HFU at the depth interval between 370 feet and 460 feet. Hole #5 shows a high heat flow value of 3.7 HFU between 250 feet and 500 feet. Heat flow values are contoured on figure 6. The DOGAMI and EWEB gradient holes show four values above 2.5 HFU. Hole 0-2 had a high of 3.7 HFU from 330 to 492 feet depths; Hole EWEB 1 showed a high of 3.5 HFU between 165 feet and 670 feet; hole 0-6 showed a high of 2.7 HFU between 100 feet and 492 feet; and hole 0-1 showed a high of 2.6 HFU between 148 feet and 505 feet.

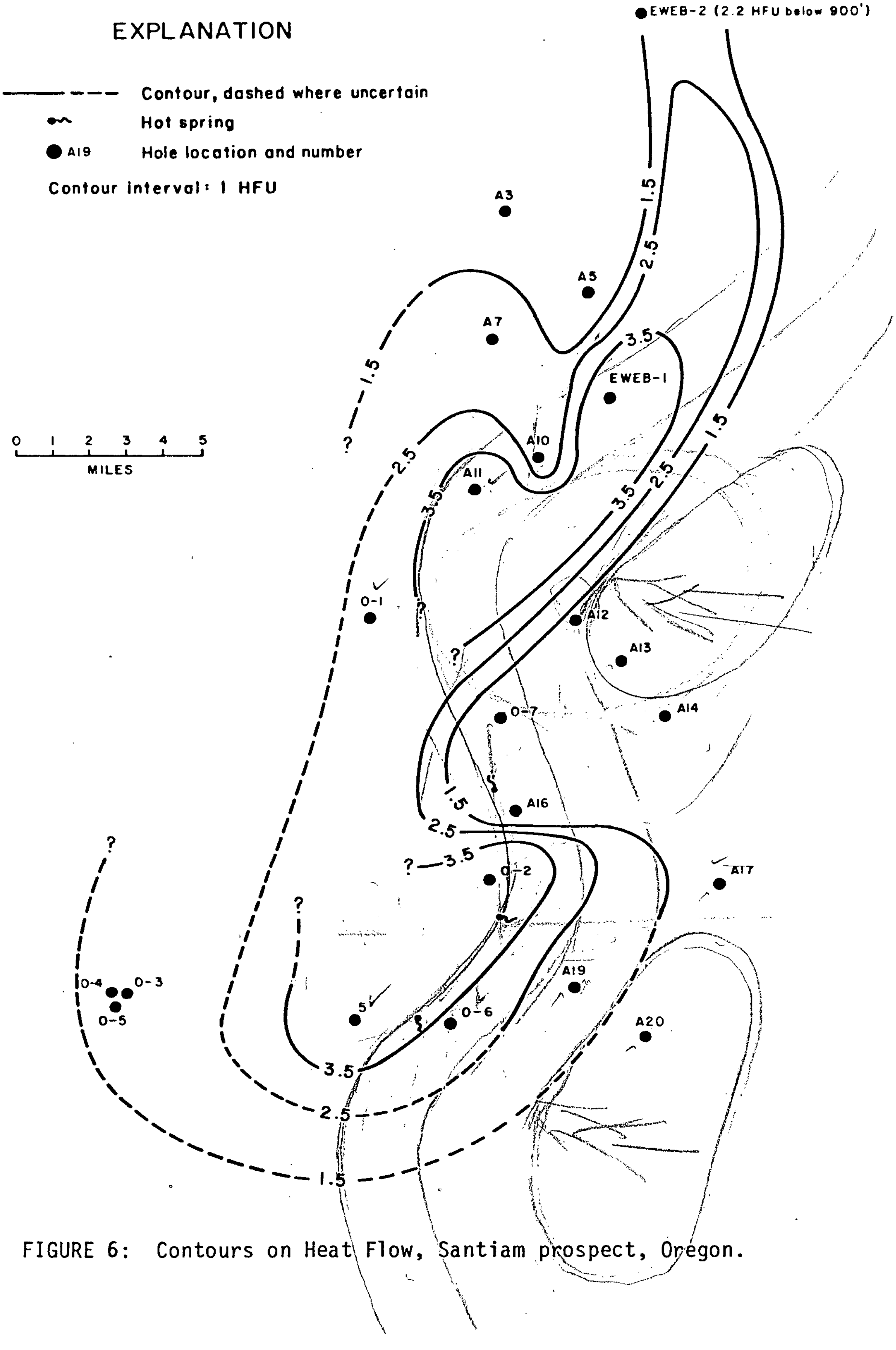
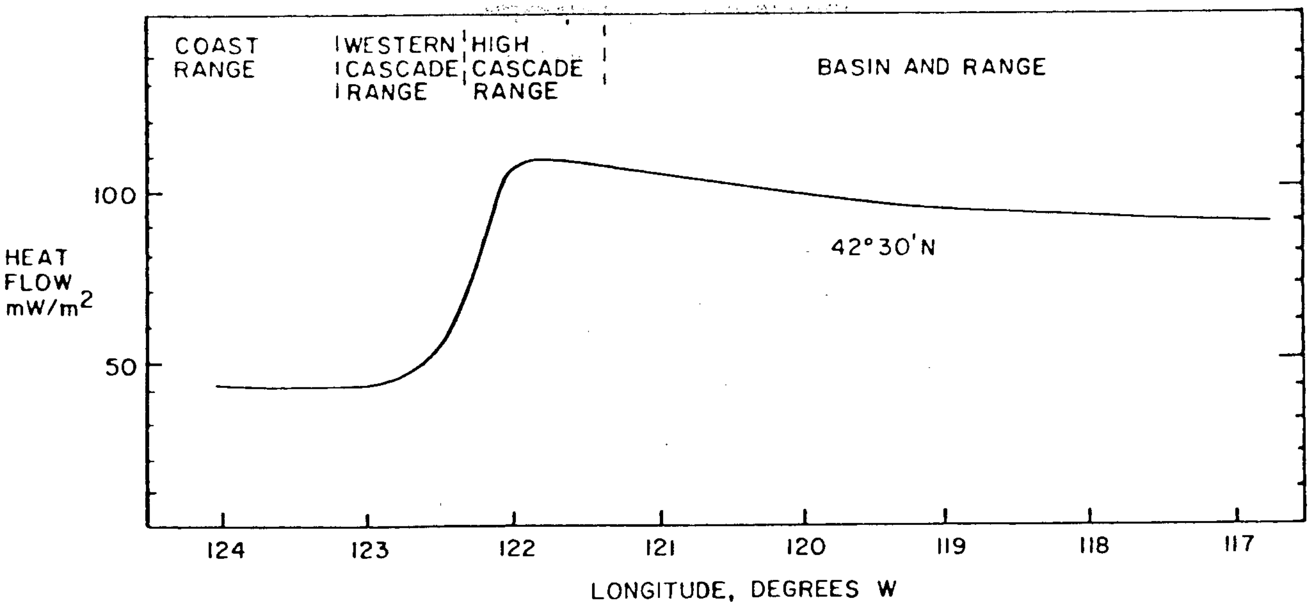
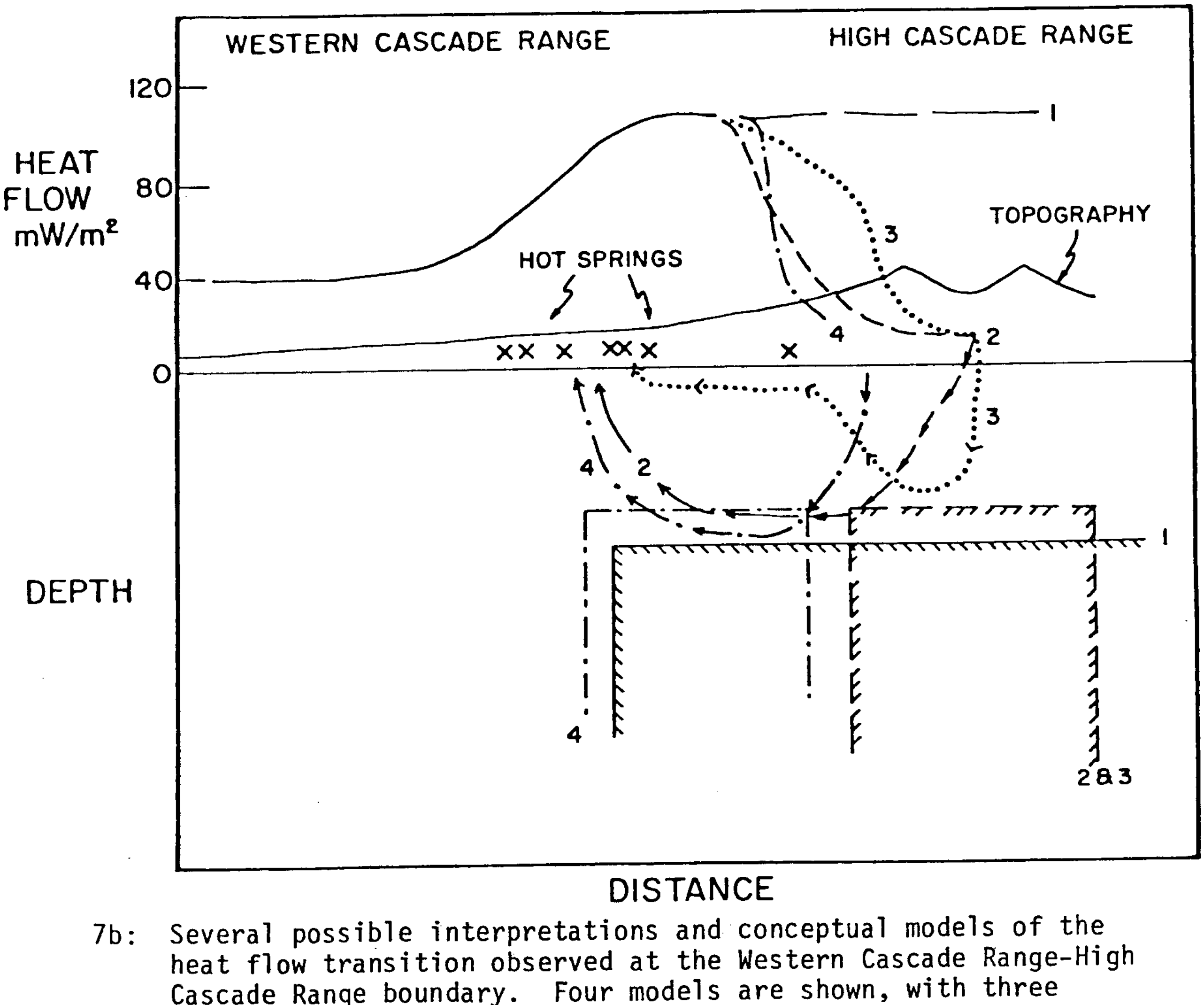


FIGURE 6: Contours on Heat Flow, Santiam prospect, Oregon.



7a: Generalized east-west heat flow profile for band of 1^{0} latitude centered at latitudes $42^{0}30'$N. (from Blackwell, et al., 1978)



7b: Several possible interpretations and conceptual models of the heat flow transition observed at the Western Cascade Range-High Cascade Range boundary. Four models are shown, with three different variations in the heat source at depth. Model 1 assumes that the observed anomaly (see Figure 7) is essentially conductive. In the other three models, the observed heat flow is interpreted in terms of regional water circulation. (from Blackwell, et al., 1978)

FIGURE 7: HEAT FLOW PROFILE AND CONCEPTUAL HEAT FLOW MODELS THROUGH THE OREGON CASCADES.

Table 3. Temperatures, temperature-gradients, and estimated heat flow of temperature-gradient holes, Santiam prospect, Oregon

Hole # elevation, feet	Depth of gradient pipe, feet	Bottom hole temperature (^{o}F)	Depth interval, feet	Temperature gradient ^{o}F/100 ft	Temperature gradient ^{o}C/km	Lithology	Estimated Heat Flow HFU
S-80-A3 (4,560)	500	38.5	290-500	1.0	18.2	85% Clay 15% Basalt Porphyry	0.5
S-80-A5 (3,440)	500	46.9	190-500	2.0	36.5	80% Clay 20% Sand (basaltic)	0.9
S-80-A7 (3,680)	489	53.2	50-160	1.5	27.3	100% Basalt	1.0
			160-460	2.9	52.9	90% Basalt 10% Clay	1.9
			300-460	3.2	58.3	95% Basalt 5% Clay	2.2
S-80-A10 (3,360)	480	38.7	GL-480	--Reversal--			
S-80-A11 (3,840)	464	59.7	120-240	3.5	63.8	100% Basalt and Andesite	2.4
			240-300	4.8	87.5	85% Basalt and Andesite 15% Breccia	3.3
			300-370	3.6	65.6	60% Tuff 40% Andesite	2.4
			370-460	7.2	131.2	55% Clay 45% Basalt	3.9
S-80-A12 (2,880)	500	44.6	300-360	1.8	32.8	85% Basalt 15% Clay	1.2
			370-420	1.4	25.5	100% Basalt	1.0
			420-500	2.0	36.5	90% Clay 10% Basalt	1.0
S-80-A13 (3,560)	295	38.3	GL-295	--Reversal--			

Table 3 (continued)

Hole # elevation, feet	Depth of gradient pipe, feet	Bottom-hole temperature (°F)	Depth interval, feet	Temperature gradient °F/100 ft	Temperature gradient °C/km	Lithology	Estimated Heat Flow HFU
S-80-A14 (3,800)	348	39.2	GL-420	--Isothermal with Reversals--			
S-80-A16 (2,640)	420	43.5	260-420	1.2	21.9	95% Basalt 5% Clay	0.8
S-80-A17 (4,480)	320	36.9	GL-320	--Reversal--			
S-80-A19 (2,080)	135	43.9	70-130	3.3	60.1	65% Basalt 35% Gravel (basaltic)	2.1
S-80-A20 (3,920)	468	37.0	GL-468	--Reversal--			
S-80-5 (2,000)	502	66.2	170-250	5.0	91.1	100% Clay	2.3
			250-500	5.2	94.8	60% Clay 40% Basalt	3.7
0-1 (3,440)	505	64.5	148-505 (150-500)	4.1	75.6		2.6
0-2 (2,320)	492	58.7	330-492	4.8	88.3		3.7
0-3 (1,520)	200	53.1	80-200	2.9	53.0		1.7
0-4 (1,440)	285	57.5	50-280	2.8	51.0		1.6
0-5 (1,240)	262	55.2	150-260	2.6	48.0		1.5
0-6 (1,760)	492	70.8	100-492	3.9	70.9		2.7
0-7 (2,363)	171	45.5					
EWEB-1 (3,120)	1,837	76.8	165-670	5.6	102.8	Andesite and Volcanics	3.5
			GL-1,820	1.3	23.9	Andesite and Volcanics	0.8

Table 3 (continued)

Hole # elevation, feet	Depth of gradient pipe, feet	Bottom - hole temperature (^oF)	Depth interval, feet	Temperature gradient ^oF/100 ft	Temperature gradient ^oC/km	Lithology	Estimated Heat Flow HFU
EWEB 2 (3,760)	1,935	87.9	980-1,970	3.8	69.4	Volcanics	2.2

REFERENCES

Beeson, M. H., Moran, M. R., Canderson, J. L. and Vogt, B. F., 1979, Stratigraphy and structure of the Columbia River Basalt Group in the Cascade Range, Oregon: unpublished manuscript.

Blackwell, D. D., 1978, Heat flow and energy loss in the western United States, in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, R. B. Smith and G. P. Eaton, editors: Geol. Soc. of Am. Memr. 152.

Blackwell, D. D., Hull, D. A., Bowen, R. G. and Steele, J. L., 1978, Heat flow of Oregon: Oregon Dept. Geol. and Min. Ind. Special Paper 4, 42 p.

Brown, D. E., McLean, G. D., Priest, G. R., Woller, N. M., and Black, G. L., 1980, Preliminary geology and geothermal resource potential of the Belknap-Foley area, Oregon: Oregon Dept. of Geol. and Min. Ind. Open File Report 0-80-2.

GeothermEx, Inc., 1973, Geothermal target #2, Belknap Hot Springs, Oregon: unpublished confidential report for Sun Oil Company.

GeothermEx, Inc., 1977, Evaluation of geothermal prospects in western Cascade Range, Central Oregon: unpublished confidential report for Sunoco Energy Development Company.

Geothermal Resources Council, 1981, Symposium on the geothermal potential of the Cascade Mountain Range: Program with Abstracts.

Hammond, P. E., 1974, Brief outline of volcanic stratigraphy and guide to geology of southern Cascade Range, Washington and northern Cascade Range, Oregon: unpublished manuscript.

Hammond, P. E., 1976, Geology of the upper Clackamas and North Santiam River area, northern Cascade Range, Oregon: unpublished manuscript.

Heinrichs, D. F., 1973, Paleomagnetic study of recent Cascade lavas, Three Sisters, Oregon: Jour. Geophys. Res., v. 78, no. 26, p. 5983-5992.

Hull, D. A., et al., 1977, Preliminary heat-flow map and evaluation of Oregon's geothermal potential: The Ore Bin, v. 39, p. 109-123.

Jan, M. Quasim, 1967, Geology of the McKenzie River Valley between the south Santiam Highway and the McKenzie Pass Highway, Oregon: Master's thesis, Univ. of Oregon.

Peck, D. L., *et al*., 1964, Geology of the central and northern parts of the western Cascade Range in Oregon: U. S. Geol. Survey Prof. Paper 449.

Peterson, N. V., and Youngquist, W., 1975, Central, Western and High Cascades geological reconnaissance and heat flow hole location recommendations: Oregon Dept. Geol. and Min. Indust., unnumbered Open-File Report.

Rollins, Anthony, 1976, Geology of the Bachelor Mountain area, Linn and Marion Counties, Oregon: Master's thesis, Oregon State Univ.

Smith, S. D., 1938, The geology and mineral resources of Lane County, Oregon: Oregon Dept. Geol. and Min. Indust. Bull. 11, 65 p.

Stearns, H. T., 1929, Geology and water resources of the upper McKenzie Valley, Oregon: U. S. Geol. Survey Water Supply Paper 597-D, p. 171-188.

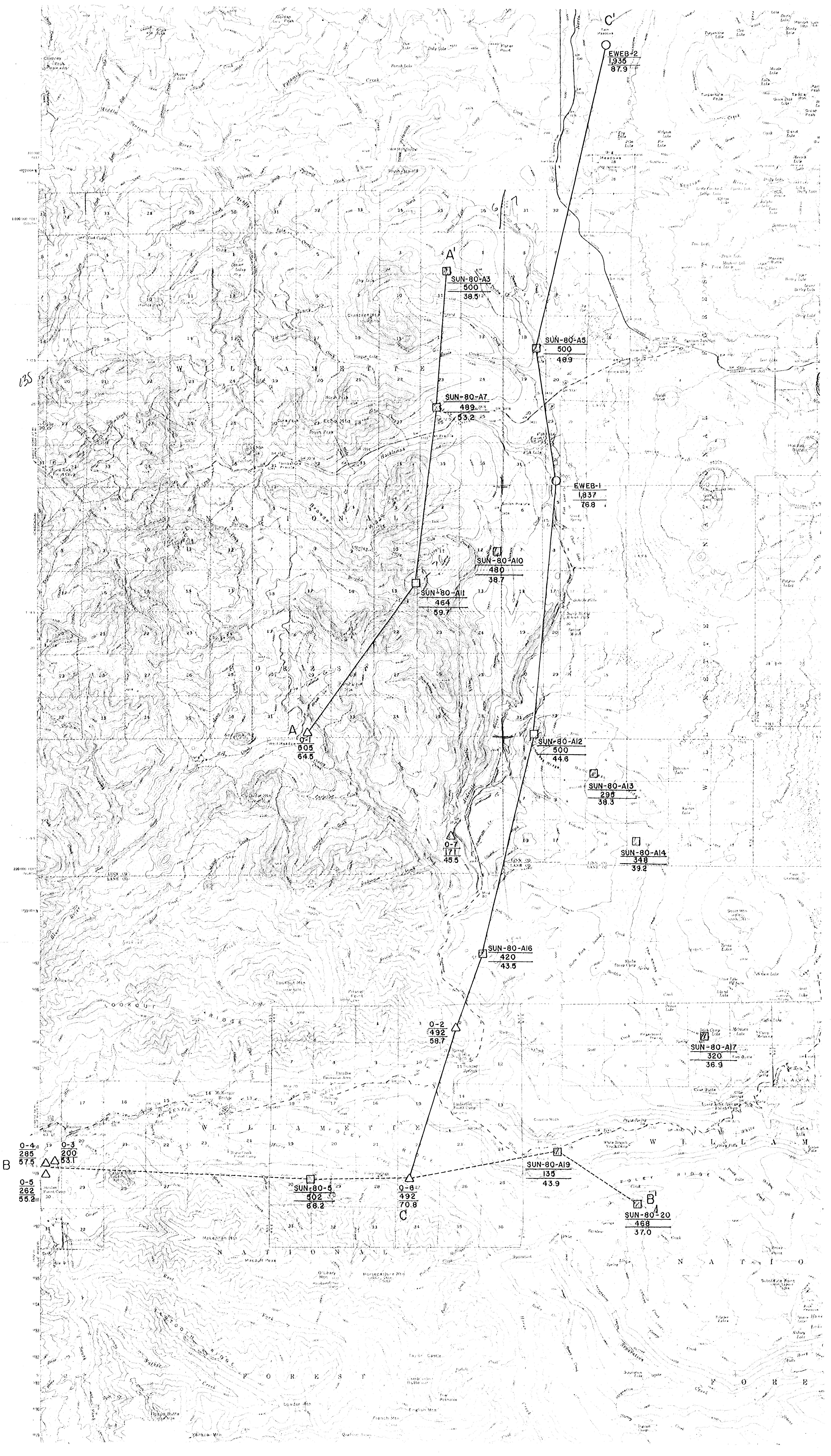
Sutter, John F., 1978, K-Ar ages of Cenozoic volcanic rocks from the Oregon Cascades west of 121°30': Isochron/West, No. 21, p. 51-21.

Taylor, E. M., 1965, Recent volcanism between Three Fingered Jack and North Sister, Oregon Cascade Range: The Ore Bin, v. 27, no. 7 p. 121-147.

Taylor, E. M., 1968, Roadside geology, Santiam and McKenzie Pass Highway, Oregon: *in* Andesite Conference Guidebook: Oregon Dept. Geol. and Min. Indust. Bull. 62, p. 3-34.

Williams, Howel, 1944, Volcanoes of the Three Sisters Region, Oregon Cascades: Calif. University, Dept. Geol. Sci. Bull., v. 27, no. 3, p. 37-83.

Youngquist, Walter, 1980, Geothermal gradient drilling, north-central Cascades of Oregon, 1979: Oregon Dept. of Geol. of Min. Indust., Open File Report 0-80-12.



SCALE 1:62500

0 1 2 3 4 MILES

3000 0 3000 6000 9000 12000 15000 18000 21000 FEET

1 .5 0 1 2 3 4 5 KILOMETERS

CONTOUR INTERVAL 80 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

GeothermEx, Inc.

Drawn W.R.H. Approved B.L.C.
Date 8/81 Project SUNEDCO

EXPLANATION

SUN-80-A10	Hole number	☐	SUNEDCO gradient holes
468	Depth, feet	△	Oregon Department of Geology gradient holes
37.0	Bottom-hole temperature, °F.	○	Eugene Water and Electric Board gradient holes
- - - - - - -	Line of cross section (Plate 4).		

②

Plate I. Locations, depths, and bottom-hole temperatures of temperature-gradient holes in the Santiam prospect, Oregon.

Explanation of Map Units

Qus	Quaternary undifferentiated sediments
Qcc	Quaternary unglaciated cinder cones
Ql	Quaternary lavas with no developed soil horizon
Qhc	Quaternary High Cascade volcanics
TQhc	Tertiary–Quaternary older High Cascade volcanics
Tmv	Miocene–lower Pliocene volcanics and volcaniclastics
Tov	Oligocene–lower Miocene tuffs and other volcanics
Ti	Tertiary intrusive stocks, dikes and plugs

Explanation of Map Symbols

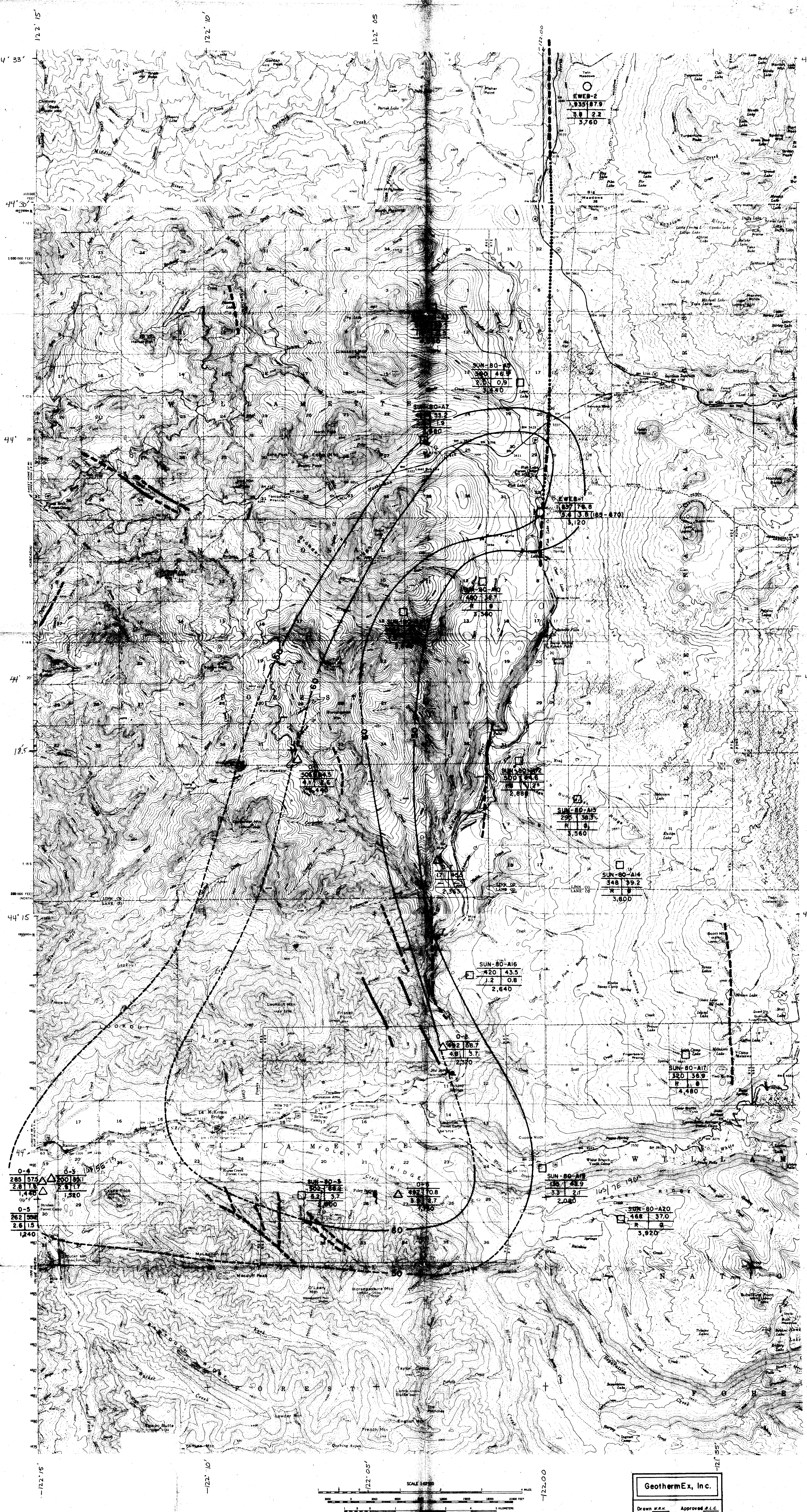
——— - - -	Contact, dashed where inferred
━━ ━ ━ •	Fault; dashed where approximately located, dotted where inferred, queried where uncertain
⊥	Strike and dip of beds
	Monocline
	Anticline
	Hot spring
6.2 ± 0.2 ○	Radiometric age-dates from Laursen and Hammond, 1978
5.06 ± 0.06 •	Radiometric age-dates from Sutter, 1978
●	Gradient hole location

GeothermEx, Inc.

Drawn B I J Approved MCG
Date 8/81 Project SANTIAM

②

PLATE 2. Geologic map of the Santiam prospect, Linn and Lane Counties, Oregon.
Scale 1: 62,500



GeothermEx, Inc.

Drawn W.R.H. Approved B.L.C.
Date 8/81 Project SUNEDCO

N

EXPLANATION

Note: Gradients and heat flow are for lowest depth interval, unless otherwise indicated.

SUN-80-A20	
468	37.0
5.2	3.7
2,000	

Hole number	
Depth, feet	Bottom-hole temp. °F
Temp. gradient °F/100'	HFU
Elevation, feet	

○ Eugene Water and Electric Board gradient holes

□ SUNEDCO gradient holes

△ Oregon Department of Geology gradient holes

——— Contour on temperature at 400' depth, °F (actual)

– – – " (inferred)

━━━ Fault (actual)

••••• " (inferred)

▬ ▬ ▬ " (approx.)

●~ Hot springs

②

Plate 3. Contours on temperature at 400 feet depth, Santiam prospect, Oregon.

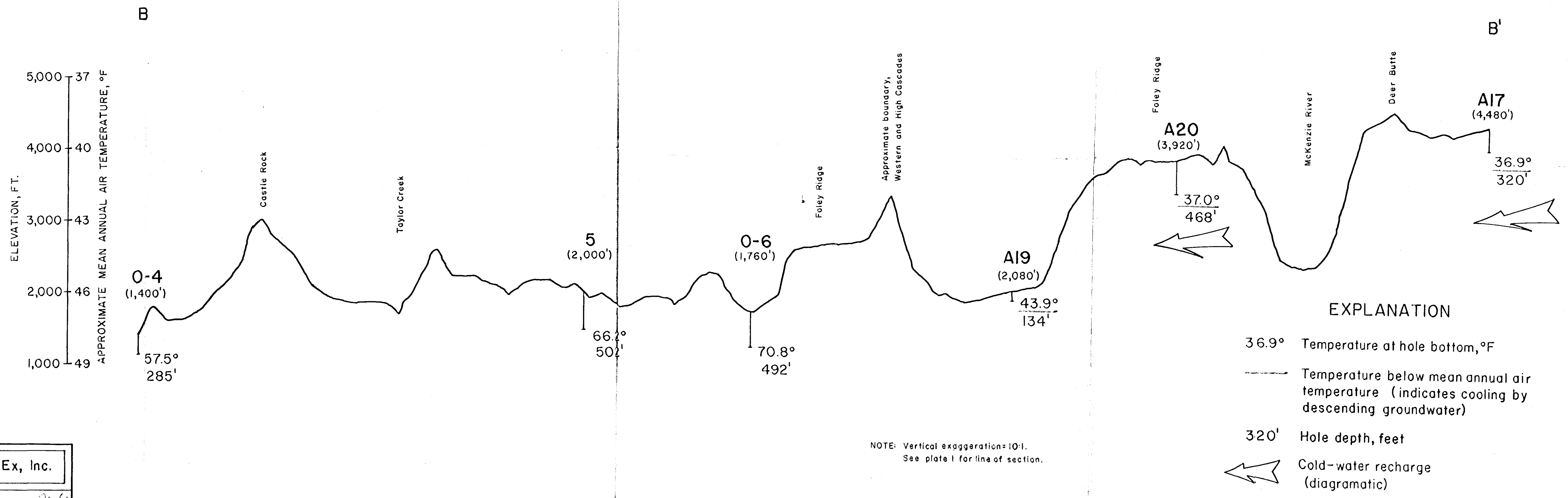
NOTE: Profile of topography is at vertical scale of 1" = 5,000'. Well data is at vertical scale of 1" = 500'. See plate 1 for lines of section.

GeothermEx, Inc.

Drawn W.R.H. Approved B.L.C.
Date 8/81 Project SUNEDCO

②

Plate 4. Thermal cross-sections through Santiam prospect, Linn and Lane Counties, Oregon.



NOTE: Vertical exaggeration=10:1.
See plate 1 for line of section.

GeothermEx, Inc.

Drawn W.R.H.　Approved
Date 8/81　Project SUNEDCO

②

Plate 5. Effect of mean annual air temperature and cool-water recharge on temperatures measured in shallow holes.