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Porphyry Copper Deposits of the Andean Orogen

CONTENTS

INTRODUCTION

The regional characteristics of porphyry copper deposits in South America southward from Pantanos and Pegadorcito, Columbia, will be summarized. The age of formation of deposits spans the period from the Permian to the present. Where possible, the general characteristics and the individual structural features of the deposits are integrated into the plate tectonic model. Individual deposits cited in this chapter, located in Fig. 1, are the best known and most fully described, and form the Andean copper belt (Peterson, 1958). Smaller porphyry copper deposits fall both east and west of the line of large, high grade deposits (e.g., Chuquicamata and Toquepala) that make up the spine of this belt. Most of those smaller deposits (e.g., Mi Vida [Koukharsky and Mirre, 1976]) are omitted from Fig. 1 and Tables 1 and 2, however. Neither the Andean orogen nor the individual deposits within it are as well described in the literature as are their counterparts in the Cordilleran orogen of North America. Therefore, generalizations relying on regional geologic mapping, geophysics, and isotopic geochemistry lack details pertinent to this type of deposit in the Cordilleran orogen.

The South American porphyry copper province has been described by Hollister (1974) to include most of the Andean orogen excepting the tin province of Bolivia. Porphyry copper deposits have not been commonly found within the tin belt, although copper-tin (e.g., San Rafael, Peru) and copper-tungsten (e.g., Llamuco, Chile) deposits are known. James (1971) shows the depth to the Moho to be appreciably greater where the tin belt exists, but disclaims any genetic significance from the coincident appearance of the tin-tungsten province and the inhibition of porphyry copper development where the sialic crust thickens. Dates on tin mineralization in this belt (Clark and Farrar, 1973) are similar to some dates for porphyry copper mineralization known elsewhere in the Andean orogen. It seems that some mechanism is needed to explain the geographic separation of porphyry copper-molybdenum and simultaneous tin-tungsten-molybdenum metallization within the same tectonic system and appearing at similar distances from the trench. The thickened crust of the tin belt is one of the few known differences.

Tables 1 and 2 list some of the most important porphyry copper deposits explored to date, but do not include Antaminas, Peru, or a number of other large skarn deposits

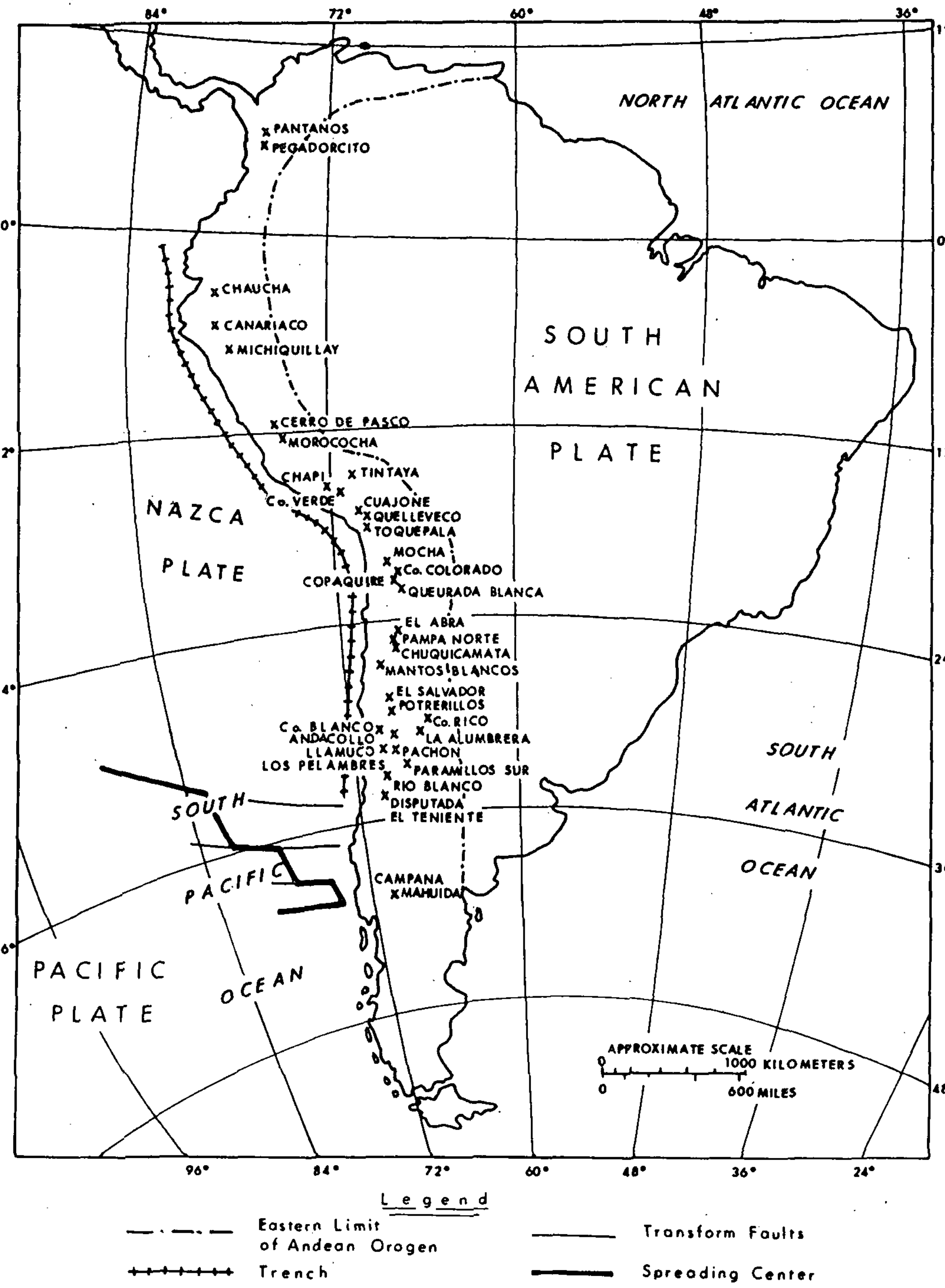

Fig. 1. Index map of South America. The major porphyry copper deposits of South America are plotted on the plate tectonic base of US Geological Survey map MF340. The approximate eastern limit of the Andean orogen is added. The richer and larger deposits tend to form a linear pattern that is subparallel to the trench.

associated with intrusions. In several of the latter, porphyry-type mineralization exists in the intrusion to some extent. Also not included are "special case" deposits such as Cerro de Pasco, where sulfide mineralization does occur in, and spatially related to, an intrusion. Suspected possible porphyry-type occurrences are omitted, as are many deposits with poorly known characteristics. Porphyry systems having two names for different parts of the same deposit are simplified (e.g., Santa Rosa is combined with Cerro Verde). Some names for newly discovered parts of previously known deposits are omitted if the older names are well known and used in the literature (e.g., Morococha). As a result of the parameters used in guiding the selection of deposits for incorporating in these tables, those listed are now among the most completely explored and adequately described mineralized intrusions in the Andean orogen.

GEOLOGIC SETTING

Regional Geology

The following summary makes mention of those aspects of the regional geology of the Andean orogen that seem to pertain particularly to the genesis of the porphyry copper deposits. For more complete descriptions of the geology, see James (1971), Ericksen (1975), or Ocola and Meyer (1973), or references cited by them. Fig. 2 gives the location of the plutonic and Precambrian metamorphic rocks and shows gravity data for the Andean copper belt. From these data, the reader may gain a reconnaissance impression of the crust.

From Campana Mahuida north at least to Chaucha, the porphyry copper province is characterized by mineralized plutons that intrude a crust which includes both old (pre-Mesozoic) and young (Mesozoic and Tertiary) rocks. The pre-Mesozoic rocks are composed largely of crystalline complexes in the vicinity of the porphyry deposits and the younger rocks are mostly arc-trench assemblages or continental volcanic and sedimentary rocks, although platform and shelf sediments are locally prominent in the post-Paleozoic environment of some deposits.

Pre-Mesozoic: The pre-Mesozoic rocks include both Precambrian and Paleozoic assemblages. Gneiss with Precambrian radiometric dates occurs in Arequipa near Cerro Verde, near Puira, northern Peru, and in various other locations fairly close to some of the larger known porphyry deposits. The reported Precambrian (Proterozoic) gneiss, schist, and plutonic rocks suggest that this part of the ancient crust was dominantly sialic in composition. Incomplete descriptions of the Precambrian imply a predominance of metasedimentray material in the nonplutonic rocks; the plutons are granodioritic. The presence of the Precambrian in the heart of the Andean porphyry copper belt suggests that many of the mineralized plutons passed through Precambrian crystalline rocks as they rose in the crust.

Paleozoic rocks, where present in the vicinity of porphyry copper deposits, are mainly nonplutonic and consist largely of metasediments with volcanic rocks only locally important. Widespread Devonian marine shelf sediments are found in Peru, Bolivia, and Chile unconformably overlying lower Paleozoic and Precambrian rocks. Carboniferous and Permian sedimentary and volcanic rocks are widely distributed within the porphyry copper province as are granodiorite plutons of the same age (Fig. 3).

Specific examples of the association of Precambrian and Paleozoic sedimentary, volcanic, and plutonic rocks are cited. Chaucha, Ecuador, lies on the boundary of a thick continental crust to the east (which probably includes Precambrian rocks) and a thick Mesozoic basic marine volcanic sequence in the upper crust to the west (Goosens and Hollister, 1973).

Michiquillay (Hollister and Sirvas, 1974) has nearby sparse outcrops of Permian, Carboniferous, and Precambrian schists erratically interspersed with younger Cretaceous marine sedimentary rocks.

The porphyry copper bearing plutons in the Quelleveco-Cuajone-Toquepala areas probably penetrated Precambrian crystalline rocks as well as Paleozoic, Mesozoic, and Tertiary rocks (James, 1971).

The region from the Copaquire deposit to Chuquicamata, Chile, also contains possible

Table 1. Stockwork-Type Porphyry Copper Deposits of South America

Deposits	K-Ar Age	Intrusive Close to Ore	Rock Intruded	Hypogene Grade, %	Primary Regional Fault	Secondary Regional Fault	Alteration Zones Present	Pyritic Halo Dimension, km	Zoned District	Remarks*
Argentina										
Campana Mahuida Neuguen	74.2	Qtz Mon Por	Cret Sed	0.8 Cu	N35E		Phy Arg Prop	3 x 2	Ag-Pb-Zn-Cu	Reserve 20 MT @ 0.8% Cu
La Alumbrera Catamarca	8.0	Qtz Mon Por	Tert Volc	0.4 Cu 0.04 Mo	N45W		Phy Arg Prop	2 x 1	None	Reserve 5 MT @ 0.5% Cu
Paramillos Sur. Mendoza	Trias (?)	Qtz Mon Por	Per Tria Sed & Vol	0.38 Cu 0.02 Mo	N-S		Potassic Phy Arg	3 x 2	Pb-Zn-Cu	Reserve 105 MT @ 0.38 Cu
Chile										
Chuquicamata, Anto	29.2	Qtz Mon Por	Granodiorite	1.2 Cu 0.04 Mo	N10E		Pot Phy Arg Prop	8 x 4 (?)	Pb-Zn-Cu-Mo	Reserve 1400 MT @ 1.2 Cu
Mocha Tarapaca	56.4	Qtz Dio Por	Tert Volc	0.6 Cu 0.03 Mo	N40W		Phy Arg Prop	4 x 3	None (?)	Reserve 107 MT @ 1.0 Cu
El Salvador Atacama	39.1	Grdr Por	Tert Volc	0.9 Cu 0.04 Mo	NA		Pot Phy Arg Prop	3 x 3	None (?)	Reserve 260 MT @ 1.34 Cu
Potrerillos Atacama	34.1	Grdr Por	Jura Sed	1.6 Cu 0.03 Mo	NA		Pot Phy Arg Prop	6 x 4	Pb-Zn-Cu	Reserve 30 MT @ 1.65 Cu
Co Colorado Tarapaca	Tert	Dac Por	Jura Sed	NA	N-S		Pot Phy Prop	4 x 2	None (?)	Reserve 100 MT @ 1.2 Cu
Copaquire Anto	22 (?)	Qtz Mon Por	Jura Sed	NA	N-S	N20W	Phy Arg Prop	4 x 2	None	High Mo section
Andacollo Coquimbo	90 (?)	Grdr	Jura Volc	0.6 Cu 0.015 Mo	N20W	N40E	Pot Phy Arg Prop	5 x 2.5	Pb-Zn-Cu-Mo	Reserve 350 MT @ 0.7 Cu
Pampa Norte Anto	29 (?)	Qtz Mon Por	Grdr	NA	N10E		Pot Phy Arg Prop	5 NSx 2 EW	None	Reserve 260 MT @ 0.7 Cu
Qbda Blanca Anto	Tert	Qtz Mon Por	Meso Volc	NA	N-S		Pot Phy Arg Prop	6 x 4	Pb-Zn-Cu	Reserve 200 MT @ 1.0 Cu
Mantos Blancos Anto	Tert?	Dac Por	And Volc	0.7 Cu Tr Mo	NA		Phy Arg Prop	3 x 1	None	Reserve 10 MT @ 1.8 Cu in 1960
Columbia										
Pegadorcito	Tert	Qtz Dio Por	Tert Volc	0.72 Cu	NA		Phy Arg Prop	5 x 5	NA	Reserve 500 MT @ 0.7 Cu (?)
Pantanos	Tert	Qtz Dio Por	Tert Volc	0.76 Cu	NA		Phy Arg Prop	5 x 5	NA	
Ecuador										
Chaucha, Azuay	9.9	Qtz Mon Por	Grdr	0.7 Cu 0.03 Mo	E-W	N10E	Phy Arg Prop	4 x 3	None	Reserve 75 MT @ 0.7% Cu

Table 1. Stockwork-Type Porphyry Copper Deposits of South America—Continued

Deposits	K-Ar Age	Intrusive Close to Ore	Rock Intruded	Hypogene Grade, %	Primary Regional Fault	Secondary Regional Fault	Alteration Zones Present	Pyritic Halo Dimension, km	Zoned District	Remarks*
Peru										
Michiquillay	20.6	Qtz Mon Por	Cret Qtz	0.6 Cu 0.02 Mo	N45W	N50E	Phy Arg Prop	2 x 2	None	Reserve 575 MT @ 0.72 Cu
Tintaya (Quechua)	Tert	Qtz Mon Por	Tert Volc	NA	N50W	NA	Pot Phy Arg Prop		Pb-Zn-Cu	Reserve 100 MT @ 0.6 Cu
Quelleveco	Lower Tert	Qtz Mon Por	Cret Volc	0.6 Cu 0.03 Mo	E-W	NA	Phy Arg Prop	3 x 1.5	Pb-Zn-Cu	Reserve 200 MT @ 0.95% Cu
Canariaco, Piura	Tert	Qtz Mon Por	Cret Sed	NA	N-S	NA	Pot Phy Arg Prop	3.5 x 2	None (?)	Reserve 200 MT @ 0.5 Cu
Morococha (Toro Mocho)	7.0	Qtz Mon Por	Perm Cret	0.7 Cu 0.02 Mo	N25W	E-W	Phy Arg Prop	5 x 3	Ag-Pb-Zn Cu-Mo	Reserve 200 MT @ 0.76 Cu
Cuajone	Tert	Qtz Mon Por	Cret Volc	0.7 Cu 0.03 Mo	N60W	E-W	Pot Phy Arg Prop	5 x 4	Pb-Zn-Cu	Reserve 1300 MT @ 1.0 Cu

Jura—Jurassic
Cret—Cretaceous
Tert—Tertiary
Trias—Triassic
Qtz—Quartz

Mon—Monzonite
Por—Porphyry
Volc—Volcanic
Sed—Sediments
Dio—Diorite

Dac—Dacite
Phy—Phyllic
Pot—Potassic
Arg—Argillic
Prop—Propylitic

MT—Million Tons
NA—Not Available

*Tons (US short) × 0.91 = metric ton

Table 2. Tourmaline Breccia Pipe Deposits of South America

Deposits	K-Ar Age	Intrusion Close to Ore	Rock Intruded	Hypogene Grade, %	Primary Regional Fault	Alteration Zones Present	Pyritic Halo Dimension, km	Zoned District	Remarks*
Argentina									
Pachon, San Juan	Tert	Qtz Mon Por	Tert Volc	0.65 Cu 0.015 Mo	None	Phy Arg Prop	8 x 6	None(?)	Reserve 550 MT @ 0.65 Cu
Chile									
Los Pelambres, Coquimbo	9.96	Grdr Por	Grdr sed & Volc	0.7 Cu 0.03 Mo	None	Pot Phy Arg Prop	6.5 x 2.5	PbZnCu	Reserve 428 MT @ 0.78 Cu
Rio Blanco (Andina) Santiago	4.59	Qtz Mon Por	Tert Volc	1.34 Cu 0.03 Mo	N15W	Phy Arg Prop	5EW x 11NS		Reserve 3000 MT @ 1.24 Cu tourmaline-rich ore
Disputada Santiago	same?	Dacite	Grdr Volc	1.7 Cu	None	Phy Arg Prop	same		Reserve 50 MT 1.7 Cu
El Teniente (Braden) O'Higgins	4.32	Dacite	Tert volc	1.7 Cu 0.05 Mo	None	Pot Phy Arg Prop	3.5 x 4.0	Sb-Ag-Pb Zn-Cu	Reserve 4000 MT @ 1.05 Cu
El Abra, Anto	33.2	Qtz Mon Por	Paleo Sed	0.9 Cu 0.03 Mo	N10E	Phy Arg Prop	3.5 x 3	None(?)	Reserve 1500 MT @ 1.09 Cu
Peru									
Toquepala	58.7	Dacite	Cret volc	0.7 Cu 0.04 Mo	None	Phy Arg Prop	3 x 3	None	Reserve 400 MT @ 0.99 Cu in 1956
Chapi	Tert	Dacite	Grdr	1.0 Cu 0.03 Mo	None	Pot Phy Prop	1.5 x 1.5	None	Reserve 5 MT @ 2.0 Cu
Cerro Verde	58.8	Qtz Mon Por	Grdr	NA	None	Pot Phy Arg Prop	3 x 3	Ag-Pb-Zn-Cu	Reserve 1200 MT @ 0.67 Cu (include Sta. Rosa)

NA—Not Available
Grdr—Granodiorite
Tert—Tertiary

Qtz—Quartz
Mon—Monzonite
Por—Porphyry

Sed—Sediments
Paleo—Paleozoic
Volc—Volcanic

Pot—Potassic
Phy—Phyllic
Arg—Argillic
Prop—Propylitic

*Tons (US short) × 0.91 = metric ton

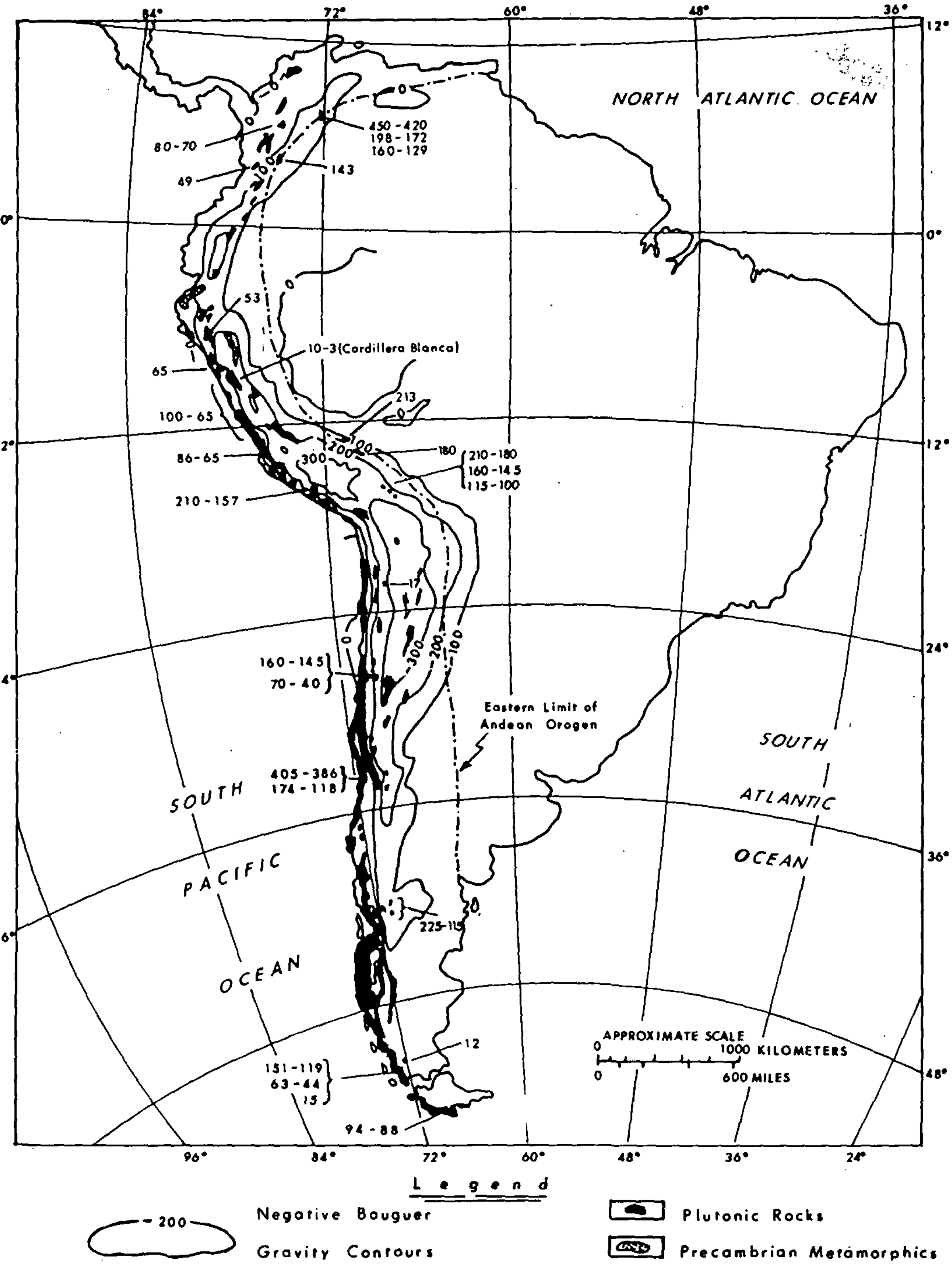

Fig. 2. Crustal elements of the Andean orogen. The Bouguer gravity anomaly map of the Andes is superimposed on the map, showing distribution of Precambrian metamorphics and the distribution of plutonic rocks. Radiometric ages are shown for the batholiths *(modified after Ericksen, 1975).*

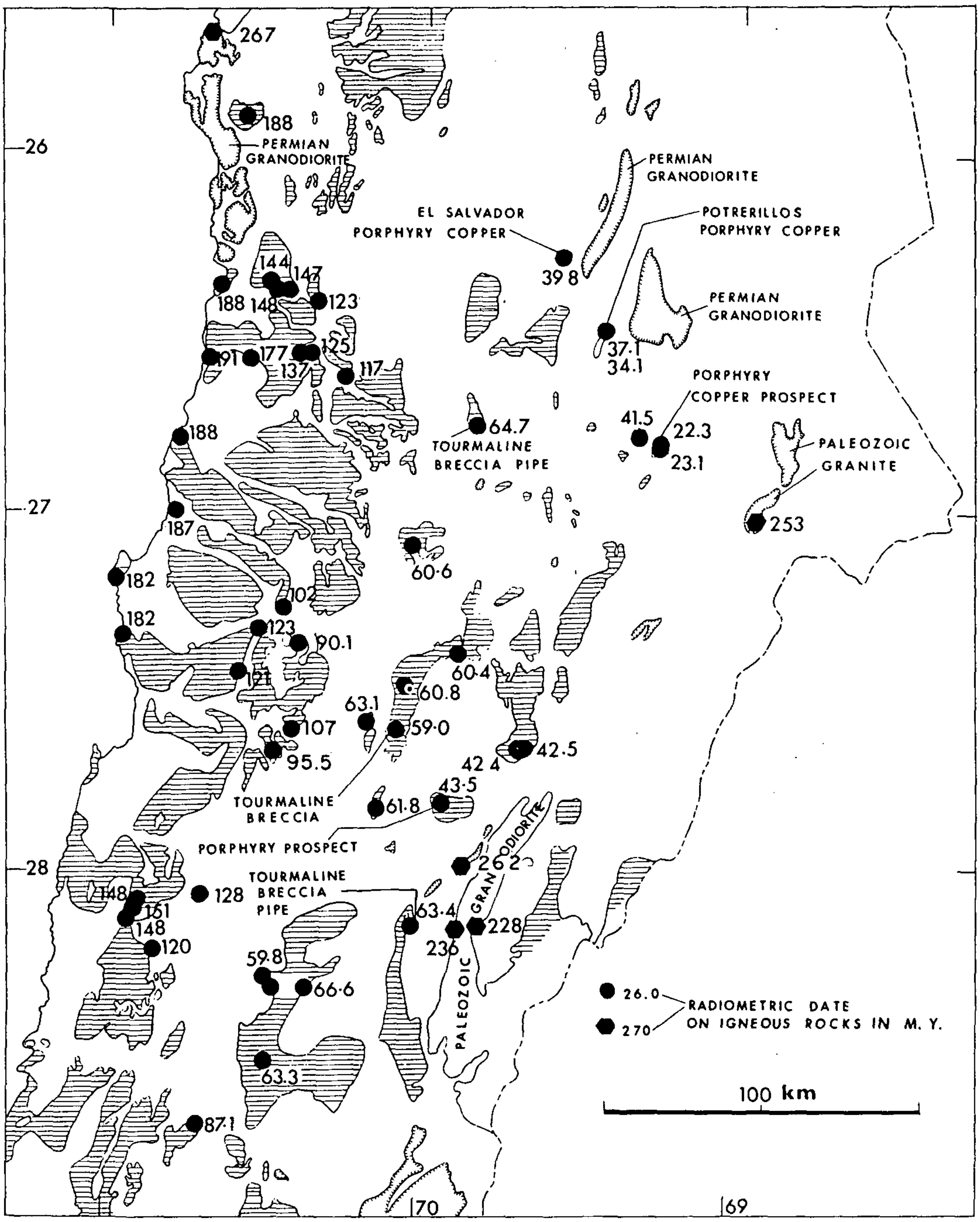

Fig. 3. Radiometric ages near El Salvador and Potrerillos, Chile. Radiometric ages of igneous rocks near El Salvador and Potrerillos deposits are typical of much of the porphyry copper province. Paleozoic or Precambrian igneous and metamorphic rocks underlie the deposits *(after Zentilli, 1974).*

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Precambrian as well as Paleozoic crystalline rocks (Hollister and Bernstein, 1975). Here the Mesozoic sequence is less volcanic than in the El Salvador-Potrerillos area, although Mesozoic as well as Permian batholithic plutonism was widespread. Fig. 3 (after Zentilli, 1974) shows the known Paleozoic radiometric ages from plutons near the El Salvador and Potrerillos deposits. The general relationships depicted in Fig. 3 are typical of the porphyry province in much of the Andes; that is, an association of radiometrically dated Mesozoic arc-trench-batholithic complexes penetrating or overlying a pre-Mesozoic plutonic and metamorphic suite. Paleozoic batholiths, therefore, had in turn invaded an older sialic crust. Plutons with porphyry copper deposits penetrated older crust, including the Paleozoic batholiths, in many parts of the orogen.

It can be inferred by extrapolation of data through most of the Andean porphyry copper province that the mineralized plutons penetrated silicic crust that probably included Precambrian crystalline rocks and Paleozoic sediments, metasediments and plutons. Basic volcanic and ultrabasic rocks are rare in the pre-Mesozoic rocks. The general relationships of the older and younger rocks in the Arequipa area are shown in cross section in Fig. 4, modified from James (1971) and Ocola and Meyer (1973). This section, typical of most of the Andes where porphyry copper deposits are known, illustrates the older crust overlain by Mesozoic and Cenozoic rocks which may include arc-trench assemblages near porphyry deposits.

Where Precambrian rocks may be absent (Fig. 5), the continental crust intruded by the porphyry copper plutons may reasonably

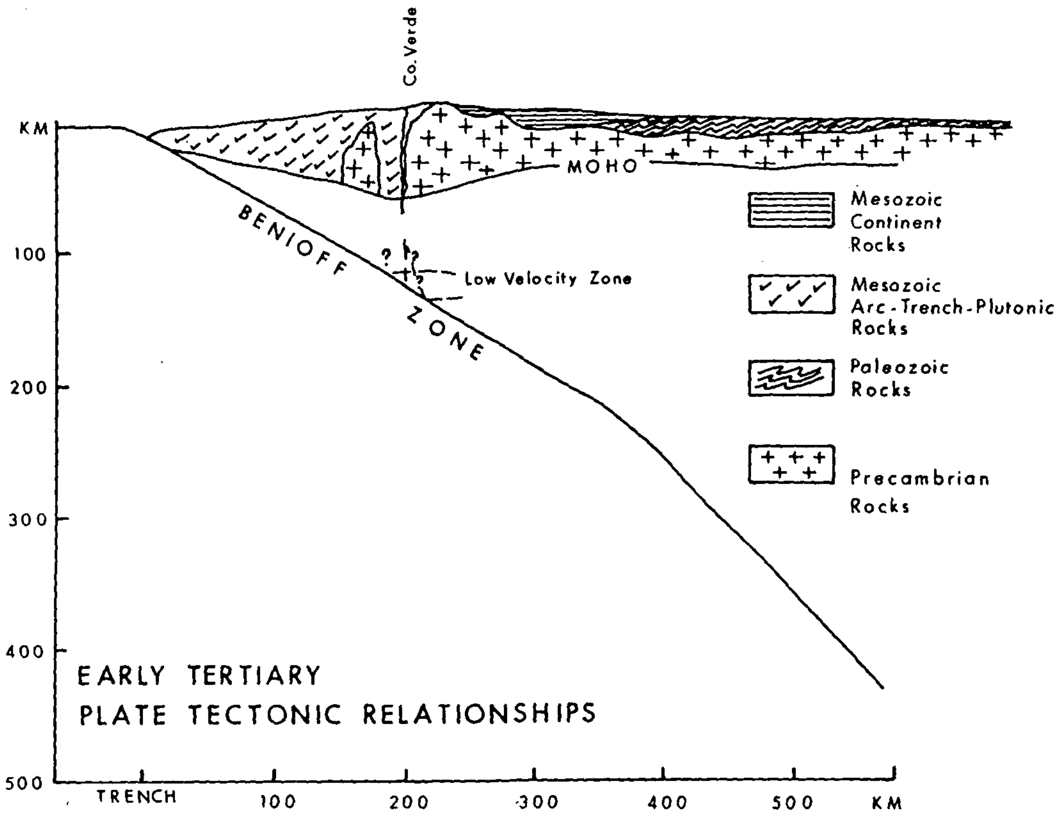

Fig. 4. Section through Arequipa, Peru. The Cerro Verde tourmaline breccia pipe and associated mineralization lie in the plane of the section through Arequipa, Peru. This section shows the hypothetical plate tectonic relations that existed in the Eocene at the time of mineralization *(modified after James, 1971)*.

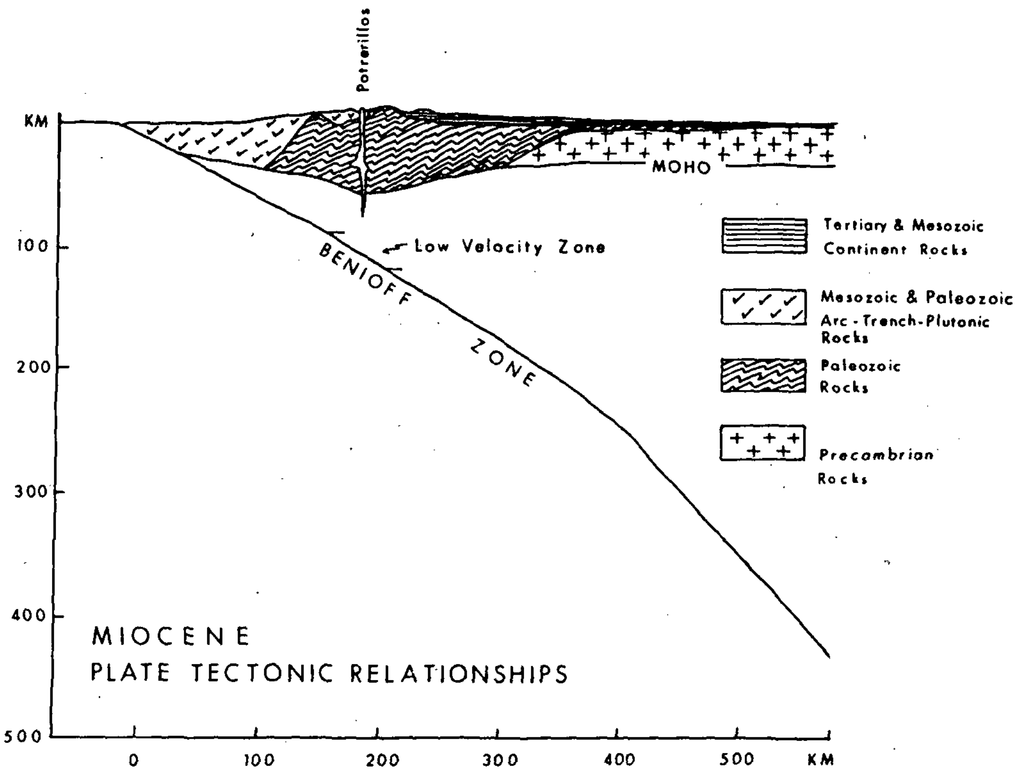

Fig. 5. Section through Potrerillos, Chile. Potrerillos is shown in this diagramatic cross section of the plate tectonic relationships as they existed in the Miocene at the time of mineralization.

be expected to include a thick section of metamorphosed Paleozoic rocks which, in effect, provide an analogous crustal environment to those areas where a Precambrian assemblage is present. In the porphyry copper province, the bulk of the crustal rocks consist of a pre-Mesozoic sialic assemblage that is believed to have an important influence on the nature and composition of the younger intrusions. The setting of the porphyries is therefore rather more cratonic than oceanic in character, if not strictly definable as cratonic.

Mesozoic and Tertiary: Mesozoic and Tertiary rocks are typically dominated by numerous, successive, arc-trench sequences near the coast and by continental volcanics and sediments in the interior. Both are intruded by plutonic rocks whose ages are penecontemporaneous with the arc-trench assemblages which Dickinson (1970), Hamilton (1969), and others have called subduction-related. These are almost entirely quartz dioritic to granodioritic near the coast and in the areas where porphyry copper deposits are known. In places volcanic members of the arc-trench sequence are abnormally rich in copper and other metals (Goossens, 1973), and some volcanogenic massive sulfide deposits are known from the Mesozoic marine volcanic sequence of the Andes. This is in contrast to the pre-Mesozoic, where such deposits only rarely have been discovered.

Fig. 5 shows the general relationship of most of the Mesozoic arc-trench-batholithic rocks with porphyry prospects and deposits near El Salvador. The tourmaline breccia pipes and other important porphyry copper prospects have dates less than 70 m.y. (million years) in this area. The occurrence of the Permian and Mesozoic arc-trench-plutonic rocks to the west of the porphyry deposits is typical of other parts of the copper belt. Generally the pre-porphyry copper igneous assemblages consisting of arc-trench and associated plutonic rocks of Mesozoic age are close to and west of porphyry deposits in the Andes. Important exceptions to this simplification (Fig. 2) include deposits that lie entirely within the arc-trench rocks (as at Braden) or entirely west of and outside of the influence of the arc-trench-batholithic suite (as at Andacollo).

Although some members of the Mesozoic rock suites may contain an abnormal copper content, the setting of the deposits generally suggests that the copper content of the individual porphyry copper deposit is independent of the type of Mesozoic or pre-Mesozoic host rock. In any case, that part of the crust with the most anomalous copper content, the Mesozoic marine volcanic rocks, are only minimally involved in the Andean copper belt deposits.

The Tertiary section of both pre- and post-mineral age is largely andesitic, though Guest (1969) and others record local large volumes of dacite and rhyolite. Volcanic rocks coeval with mineralized plutons have been noted in some deposits (e.g., Pelambres [Sillitoe, 1973]), and in many of these examples, rhyolite and dacite are prominent. On the other hand, some mineralized plutons are not associated with observed coeval or comagmatic volcanic rocks (e.g., Copaquire [Hollister and Bernstein, 1975]).

In terms of genesis, the basic crustal setting for most Andean orogen porphyry copper deposits (Fig. 2) appears to have been similar to that of the Lowell and Guilbert (1970) model deposit of the southern Cordilleran orogen. A cratonic environment, which consists of a thick pre-Mesozoic crust (commonly including crystalline rocks of Proterozoic age), is associated with successive Mesozoic arc-trench-plutonic sequences that lie to the west of most of the deposits. No obvious source for the copper is visible or inferrable in the exposed or near surface portion of the crust.

Plate Tectonics: In this discussion, plates, transform, transverse, Benioff zone, and transcurrent faults as well as subduction zone are used in the sense of Herron's (1972) and Wollard's (1973) descriptive papers on the Pacific (including the Nazca) plate. The South American plate appears to be overriding the Nazca plate, which has, itself, spread from the East Pacific rise. Subduction begins with the trench and extends under the Andean orogen. Clague and Jarrard (1973) present evidence that the Pacific plate also had a generally northerly component of movement during the time when most Andean porphyry copper deposits formed. Therefore it would appear that both the suggested northerly trend of the Pacific plate and the easterly compressive force associated with subduction could have been operative during formation of most porphyry copper deposits.

For much of the porphyry copper province in the Andes, fold axes in Mesozoic and early Tertiary volcanic and sedimentary rocks parallel the coast and the present trench. It is assumed that paleo-trenches either coincided with or paralleled the present trench. A poorly defined belt of Mesozoic thrusting paralleling the trench has been found from west central Argentina to central Bolivia. Such structural features as folding and thrusting are omitted from Fig. 2 because they cannot be illustrated on a map with such a small scale.

The fold axes and thrust belt may have developed as a consequence of tectonic transport westward of the South American plate and from subduction at the Nazca-South American plate boundary. Most batholiths are also aligned parallel to the trench. If these quartz diorite-granodiorite batholiths are viewed as subduction-derived, then the Upper Paleozoic batholiths may imply that subduction preceded Mesozoic separation of South America from Africa, and that compression associated with subduction was initiated in the Upper Paleozoic. Should the dates on batholiths be correlated with rapid subduction, then indirectly radiometric dating of these rocks may be used to establish those periods when compression on an axis normal to the coast and trench were most actively present. In general, ages of batholiths tend to fall within periods of folding. Few porphyry copper deposits formed during

Geology of the Deposits

On the basis of their internal structure, South American porphyry copper deposits can be separated (after Ruiz, 1965, and Hollister, 1974) into either a tourmaline breccia type or a stockwork type. Tourmaline breccia type deposits are summarized in Table 2. They may have no obvious association with regional structure, or with fault or fold structures related to failure in a moving plate, but potassium-argon dating does support the contention that these deposits formed simultaneously with movement of an oceanic plate down a Benioff zone.

The stockwork-type deposits summarized in Table 1 contain intersecting veins and veinlets and may more frequently be associated with major regional faults. The stockworks may be genetically related to displacement on major strike-slip faults or some other structural elements evolved in the margin of a moving plate.

The following sections present some characteristics and modes of occurrence of the two structural types of deposit.

Petrography: The petrography of intrusions closely related to ore in time and space, in either structural type of deposit and regardless of age or location, seems remarkably constant. Similar types of alteration are ubiquitous in the mineralized intrusives, and these tend to mask any primary petrographic differences. Despite this, megascopic examination provides little reason to suspect that substantial compositional differences exist between dacite at Toquepala, quartz monzonite porphyry at Michiquillay, quartz monzonite porphyry at Campana Mahuida, or dacite at El Teniente. These represent a considerable range of ages (from 4.3 to 58.7 m.y.), as well as variable distances from the leading edge of the continental plate. Minor compositional variations from the dominant quartz monzonite porphyry do exist; for example, the granodiorite at El Salvador and the quartz diorite at Mocha. Variants display a random distribution within the plate; that is, they occur at erratic distances from the trench.

Limited data on the petrography of the intrusions listed in Tables 1 and 2 do not permit construction of plots of various parameters on individual deposits, as in Figs. 36a, b and 42 (pp. 103, 104, 130) for the Cordilleran orogen. However, the petrography of Andean porphyry copper deposits may be generally described in terms of relevance to their genesis. All intrusions associated with the major porphyry copper deposits appear to be consistent with the model developed by Lowell and Guilbert (1970).

Interpretation of chemical data from Haynes (1972) and Palacio and Oyarzun (1975) tends to support the analysis based on reconnaissance petrographic identifications, at least in the area from El Salvador to the east. Fig. 6, modified from Haynes (1972), appears to show a nearly constant potash index for sulfide-associated, intermediate, porphyritic intrusions irrespective of distance inland from the trench for the area studied.

Lacy (1957, p. 3) gives one explanation for the lack of strong variance, suggesting that the rocks are a common end product of differentiation. The greatest difficulty with this concept, however, is the absence, in some deposits, of the products of differentiation other than the mineralized intrusion. In the extreme case, e.g., Michiquillay (Hollister and Sirvas, 1974), the only igneous rock exposed is the intrusion that hosts mineralization. At the surface near Michiquillay (Fig. 9), only the mineralized intrusion or other small intrusions of nearly the same composition are found near the ore deposit. Volcanic rocks at a distance from Michiquillay appear to have their own source vents.

If similarity of the crustal section cut by these various Andean mineralized plutons had influenced their composition, then the small range in chemical composition apparently present for the intramineral intrusion may reflect the similarity of the crustal setting that hosts the deposit. This hypothesis is a speculation not amenable to proof.

Dickinson (1970) presents evidence that most melts in continental-type orogen are derived from the upper side of the Benioff zone. Gilluly (1971) gives an even more convincing theoretical explanation for ande-

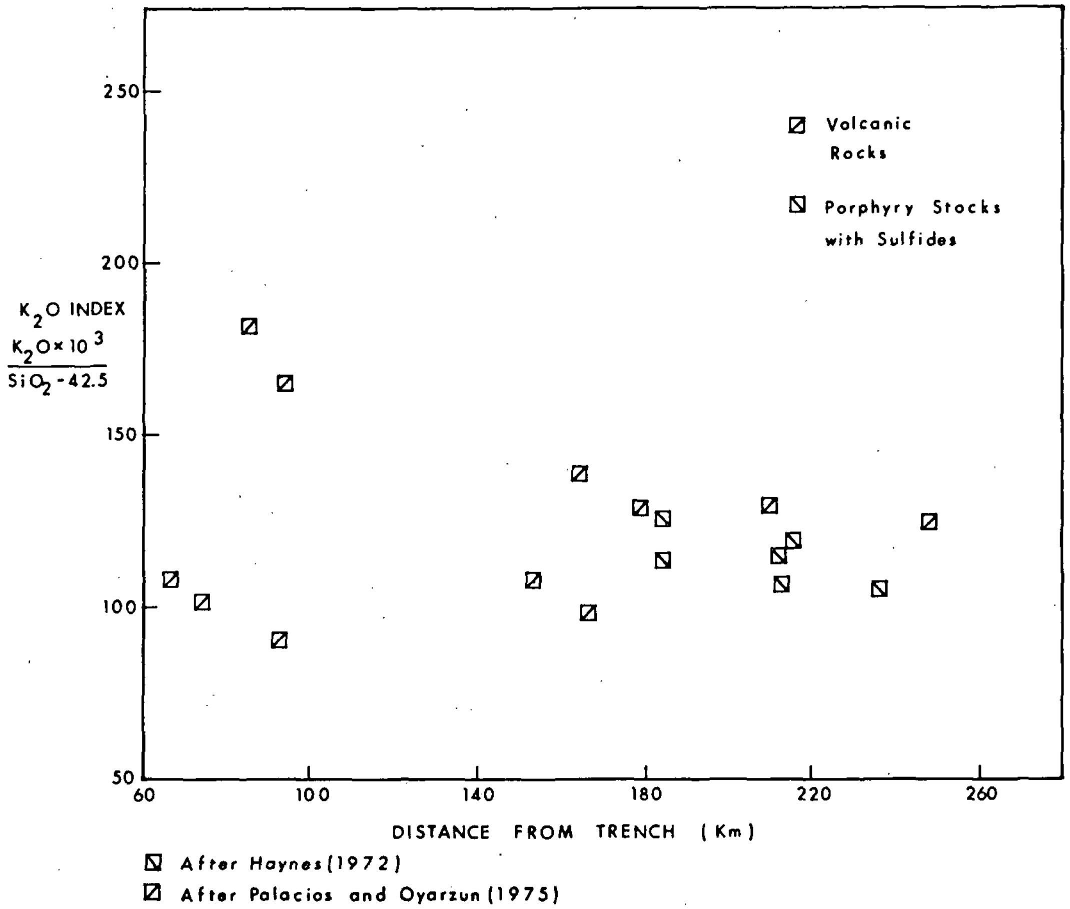

Fig. 6. Potash index of igneous rocks, Atacama Region, Chile. Mineralized plutonic rocks appear to have potash index trends similar to those of extrusives for that segment of the orogen where porphyry copper deposits occur *(modified after Haynes, 1972).*

site and granodiorite formation from the subduction zone. Fig. 6 illustrates data compatible with evidence used by each for calc-alkalic magmas. Generally, as distance is gained from the trench, the potash content of those igneous rocks derived from the subduction zone tends to increase. Apparently intrusions close to ore in age and space in Andean porphyry copper deposits may make an important exception, because the potash content of these specific intrusions has not been shown to have any systematic variation away from the plate's leading edge. A comparable analysis could be made in the Cordilleran orogen for intrusions close to ore in time and space from Yerington generally east through Battle Mountain, the Robinson district, and Bingham. Here again, these mineralized intrusions do not appear to heed the rule that subduction-derived magmas generally have a significant increase in potassium and alkalies eastward from the plate edge.

James (1971), Clark (1970), Haynes (1972), and Farrar (1970) each make a case for a general eastward migration of igneous activity with time in the Andean orogen. Age dating on porphyry copper deposits alone, to the contrary, shows an almost complete time independence in their occurrence geographically within the plate. Paramillos Sur, on geologic bias, has been listed as the oldest of any deposits shown on Tables 1 and 2 (Ljungren, 1970) and it lies in the eastern foothills. El Teniente (Clark, 1972)

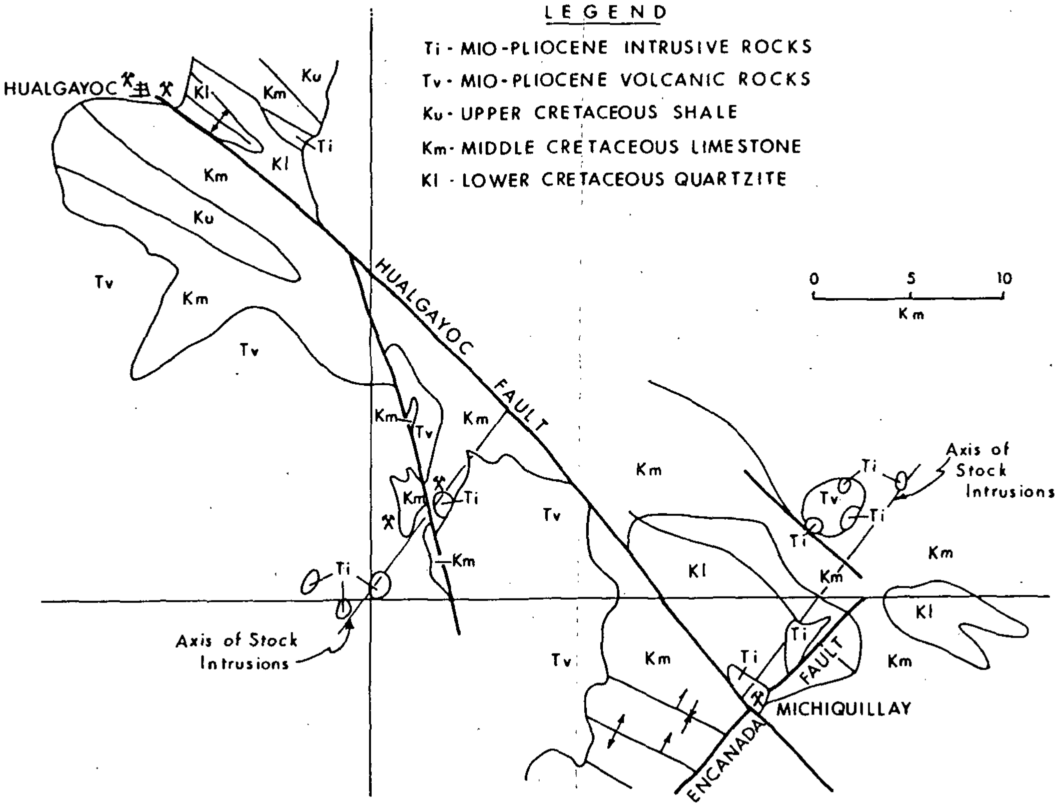

Fig. 7. Michiquillay regional geology. Michiquillay occurs on the intersection of the Encañada and Hualgayoc faults. It is conceivable that the northeast-trending line of stocks may have formed at the approximate time of development of Michiquillay, since the axes of the two lines of stocks are subparallel and stocks on either side of the Hualgayoc fault are petrographically similar. If this is the case, right lateral movement may have occurred on the Hualgayoc fault after the stocks were intruded. Recent movement has also occurred on Encañada fault, however, since it is visible on both sides of the Hualgayoc fault (*modified after Benavides, 1956*).

appears to be the youngest, and it lies west of the divide. The pre-Karoo Haib porphyry copper deposit in South-West Africa probably formed prior to the separation of South America from Africa, and it lies even further east than Paramillos Sur. If potassium-argon (K-Ar) dating is to be believed, the erratic distribution of porphyry copper deposits in time and space in the Andean orogen needs some fuller explanation than is now offered by Sillitoe's (1972) plate tectonic model.

Herron (1972), Le Pichon and Hayes (1971), and others have shown that both paleomagnetic evidence and an assumed 2.0 cm/yr spreading rate calculated for the Atlantic coincide to date the initial separation of South America from Africa at about 140 m.y. Separation appears to have been completed over the next 35 m.y. Some magmatic activity and metallization within and near the copper belt preceded this event, because 180 to 199 m.y. intrusions are found in Bolivia (Lohmann, 1970, and Clark and Farrar, 1973). Tin mineralization has been associated with a few of these magmas. Clark (1972) has demonstrated the existence in Chile of Permian (228 to 261 m.y.) and lower Mesozoic (177 to 191 m.y.) granodioritic batholithic intrusions, and other data (Fig. 3, modified from Zentilli, 1974) corroborates this conclusion. Triassic continental volcanics are known within the Andean orogen. Epizonal magmatism (and also porphyry copper-type deposits) therefore may logically date from the Permian if porphyry copper formation may be related in any way with magmatic events of the type dated. Comments by Sillitoe (1972) and others on the copper content and depth of erosion, on the other hand, suggest that the younger deposits (Tertiary) are more likely to be economically significant. It is clear that the separation of South America from Africa is inconsequential in the history of porphyry copper evolution in the Andean orogen, although the most intensely metallized known deposits date from well after that event.

Alteration: Alteration phenomena in each Andean porphyry copper center appear to fall within the zones compiled by Lowell and Guilbert (1970) and others for alteration of quartz monzonitic to quartz dioritic composition in intrusion. All major porphyries listed in Tables 1 and 2 have a phyllic zone, surrounded by an argillic zone, and an outer propylitic zone. The younger, less intensely eroded deposits may not, however, have an exposed central potassic core zone found in some of the older deposits. In some younger deposits extensive biotization (as in Braden) may represent potassic alteration, but orthoclase may not be well developed in these areas. Each of the deposits contains the typical pyrite halo, as described by Rose (1970), around the copper-bearing center. This is common to all deposits, regardless of the presence or absence of other alteration mineral assemblages.

The phyllic zone generally appears to be coincident with the areas of greatest fracturing, and along with the potassic zone is usually the locus of copper mineralization where metal zoning exists. In some deposits (e.g., Chuquicamata and Michiquillay) copper occurs most prominently in the phyllic zone, while in others (e.g., San Salvador, Gustafson and Hunt, 1975) copper is well developed in a potassic zone. The alteration zones are much the same as at Butte (Sales and Meyer, 1948).

In the phyllic zone, the quartz, sericite, pyrophyllite (if present), other silicates, and pyrite are systematically or zonally developed from fracture surfaces into the host rock. The suites of alteration minerals change outwardly, on a large scale, from the potassic core through the phyllic, argillic, to the propylitic zones; but mineral zoning away from fractures within any one zone may display the entire range of alteration minerals. Where the host rock of the deposit is cut by many closely spaced intersecting veins and veinlets, individually developed, zonally arranged mineral assemblages overlap; and the cumulative or aggregate effect provides the mineralogy found in one or the other of the respective alteration zones. Therefore, quartz, sericite, and the clay minerals are not distributed in a random pattern in the phyllic zone. Rather they are zonally developed about individual fractures and the alteration designation is determined by the pervasive dominance of key minerals.

In the breccia pipe model, repeated shattering and rotation of fragments in the conduit during the passage of hydrothermal fluids may permit uniform alteration of the entire pipe, which is enveloped by halos of lower grade alteration.

In most Andean deposits, regardless of structural type, alteration mineralogy has been inadequately described in the literature. Where tourmaline occurs as an alteration product, it may appear as an added silicate mineral in any of the zones but most commonly is found as a replacement for original ferromagnesian silicates. Pyrophyllite and other minerals megascopically indistinguishable from sericite may occur in the phyllic zone (as at El Salvador and Chuquicamata), but these are easily confused with sericite and are only rarely reported.

Structure: The localization of South American porphyry deposits appears to be a function in some manner of internal failure within the continental plate. Wollard (1973) and others have inferred extensional conditions above the subduction zone at the margin of the continental plate. All porphyry copper deposits apparently formed in an environment of tensional stress, as most copper and molybdenum sulfides occur as fracture filling rather than wall rock replacement or dissemination.

In breccia pipes, the rotated fragments are cemented with gangue and metallic sulfide minerals. Stockworks are composed of many, repeatedly opened veins and veinlets filled with virtually the same sulfide mineral suite and in much the same paragenetic sequence as found in the breccia. In the breccia pipes the release of pressure that led to the original piercement helped generate the extensional conditions that produced the internal structures of the pipe. For the stockwork model, some peculiarity of the tectonic environment led to local extensional conditions. The causative factors may be unique for each stockwork deposit. Fracture patterns of individual deposits may betray the genesis of the stress-strain relationships that led to fracture development.

Hollister (1974) cites evidence that many stockwork deposits are associated with strike-slip faults. Specific stockwork porphyry copper deposits can be related genetically to regional structural features. Incomplete coverage by large-scale published geologic maps prohibits assessment of tectonic relationships for all stockwork deposits; however, where regional structures are known, a genetic relationship between major faults and stockwork deposits is frequently demonstrable. Because few tourmaline breccia deposits are close to or appear to be directly influenced by major faults, no such relationship may be claimed for them.

To avoid confusion in interpretation of the two structural models, it should be noted that weak tourmaline alteration and small breccia pipes may occur erratically in the stockwork deposits. However, the stockwork deposit rarely has dominant circular fracture or veinlet patterns, although it may have an identifiable weakly developed circular pattern about a specific stock. On the other hand, breccia pipes tend to have strong circular and radiating fracture (veinlet) patterns around a central pipe. Either type of fracture pattern may form a well developed stockwork of veinlets. The diagnostic fracture pattern of breccia pipes is circular, whereas the characteristic pattern of stockworks is formed by sets of conjugate veinlets, or by intersecting but offsetting sets of parallel veinlets. Plates 2 and 3 (pp. 22A, 22B) are photographs of stockworks.

Examples of Stockwork Types: Where plate failure appears to be a major transverse or transcurrent fault or other strike-slip structural element developed in the plate, stockworks may have formed directly in subsidiary fractures conjugate to regional faults. Because transcurrent and transverse faults are the most important and persistent ruptures developed as a consequence of plate movement, association of some porphyry copper deposits with those faults might be expected. Fractures conjugate to major faults may have provided openings for hydrothermal fluids, but the major regional faults remain barren.

Chuquicamata is perhaps the best example of this type. The West Fissure, which strikes N10E, appears to have acted within the parameters Herron (1972) used for regional transcurrent faults. Perry (1952) states that "the West Fissure was an early, pre-porphyry structure along which profound, primary crustal adjustment occurred. The evidence is strong for believing that it controlled emplacement of the porphyry, quartz and sulfides, ending its activity in final relief of stresses after the close of the mineralizing epoch." Accompanying this fault and appearing on its projection for 150 km, Ridge (1972) finds "a long narrow belt of stocks . . . that extends from Caracoles to El Abra in the north." At the time of porphyry mineralization (29 m.y.) Clague and Jarrard (1973) imply a northerly component of movement of the Pacific plate (interval 20-42 m.y.). Their hypothesis suggests that the Nazca plate moved north relative to South America; and the movement on the West Fissure, which parallels the plate boundary, is on the west side of north (Fig. 8).

Perry (1952) further states, "The intensely mineralized belt constituting the ore body contains veins and innumerable criss-cross vein structures with intense mineralization and alteration of intervening porphyry." Perry (1973) points out that the numerous large veins that accompany the veinlets within the ore deposit are incompatible with a strict definition of stockwork. The term stock-

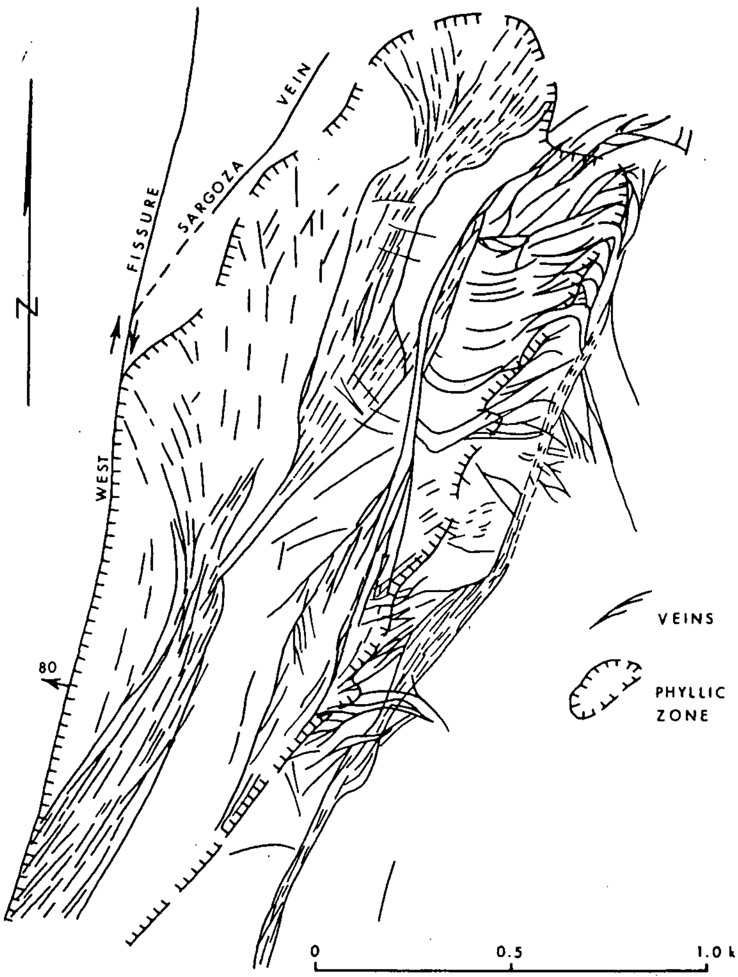

Fig. 8. Structure at Chuquicamata, Chile. The Chuquicamata deposit is a vein and stockwork filling of ore and gangue minerals on the east side of a regional fault. The fractures are those that should be expected as right lateral displacement occurred along the West Fissure. The conjugate set developed are typical of this type of stockwork deposit (*modified after Lopez, 1942*).

work used to describe Chuquicamata mineralization is, however, broadly accepted.

Lopez (1942) indicated that mineralized fractures are a conjugate set genetically related to the West Fissure, and that they formed when the west block of that fault moved north relative to east. Fig. 8 modified from Lopez (1942) shows the relationship of phyllic alteration zone to mineralized fractures. Repeated opening of stockwork fractures controlled hydrothermal activity, including alteration and sulfide deposition.

Where transcurrent faults intersect major strike-slip faults, simultaneous movement on each fault may permit a stockwork to develop at the intersection. In such stockwork deposits the fracture systems commonly appear in and near intrusions emplaced and controlled by intersections. Michiquillay lies at the intersection of the N45W striking Hualgayoc fault, and a N50E strike-slip crossing structure (Fig. 3). The Hualgayoc fault has had largely horizontal movement, but doming related to intrusion gives the impression of local vertical movement. Both strike-slip trends as well as conjugate frac-

Plate 1. Tourmaline breccia at Toquepala. Irregular breccia fragments are cemented with a black tourmaline-rich matrix. Quartz and sulfides occur with the tourmaline.

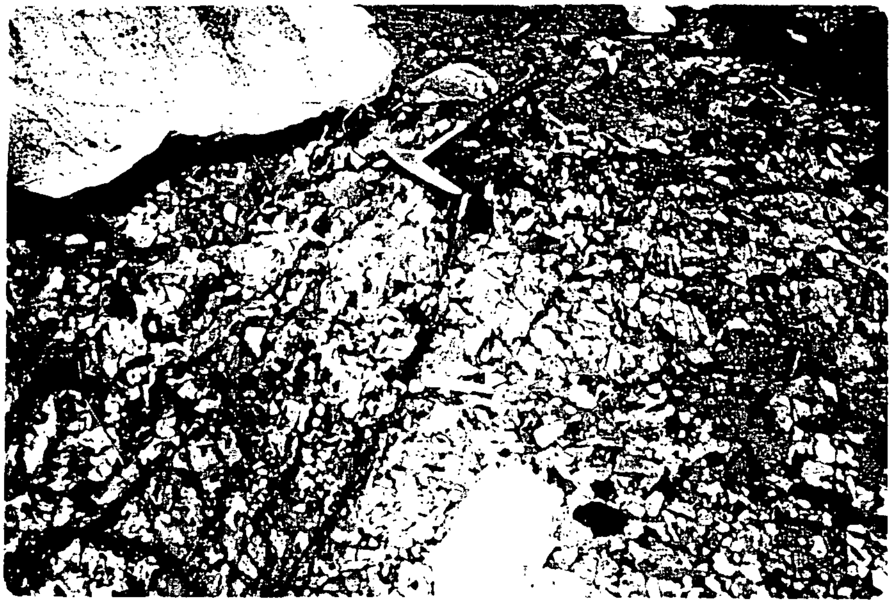

Plate 2. Stockwork outcrop. Veins and veinlets of quartz-limonite occur which cut sericitized andesitic volcanics in this leached capping over ore. At depth the vein structures contain hypogene chalcopyrite and pyrite with quartz.

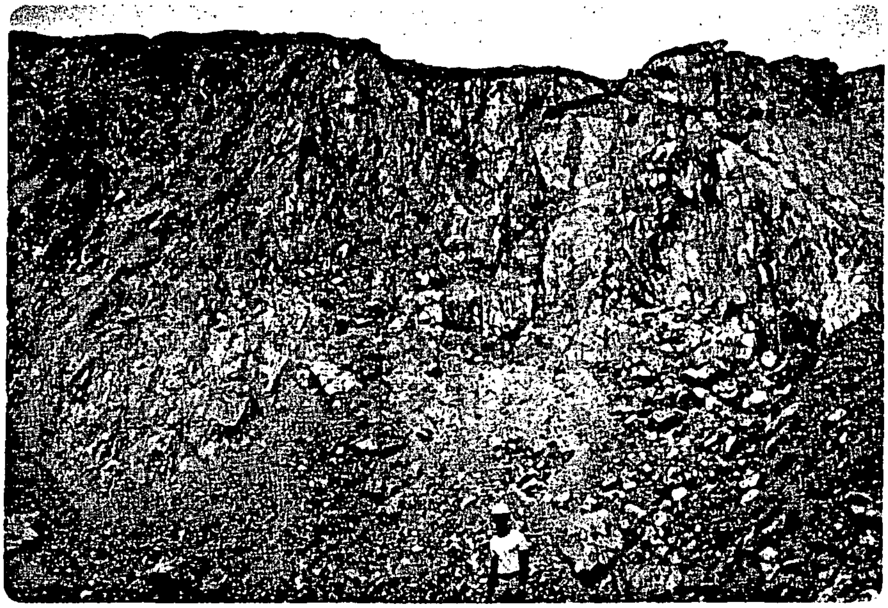

Plate 3. Stockwork outcrop. Near surface mine bench at Esperanza mine showing vein and veinlet structures emphasized by iron oxide content. This leached capping is over supergene and hypogene ore.

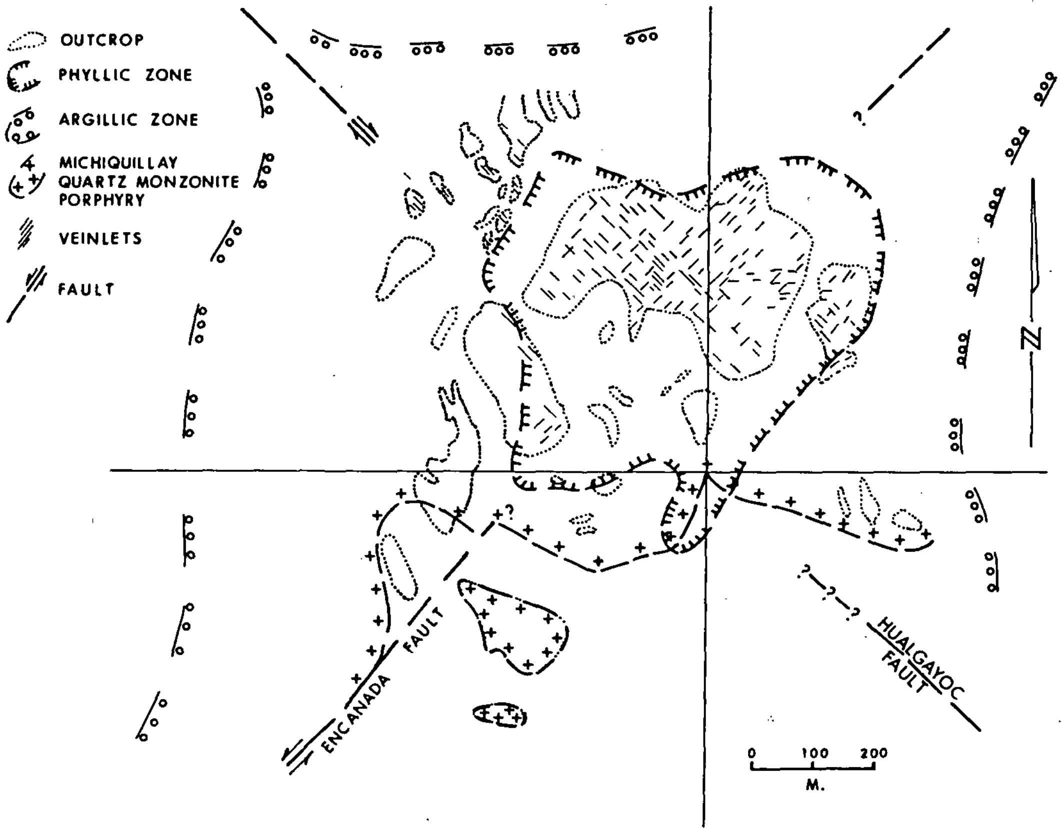

Fig. 9. Surface geologic map, Michiquillay. Intersection of the Hualgayoc and Encañada faults is the center of alteration and mineralization for the Michiquillay deposit. The stockwork developed is largely derived by repeated simultaneous displacements along both faults.

tures are developed in the stockwork. As can be seen in Fig. 9, the resulting network of veins and veinlets is fully as striking a feature as the Chuquicamata stockwork, but the differences in orientation of the veins and veinlets is clear. Fig. 9 shows the relationship between stockwork and hypogene alteration zones at Michiquillay. The stockwork was produced by simultaneous movement of both faults, and the area of intersection is clearly the center of hydrothermal activity. In this instance, one component of the stockwork is itself part of the transcurrent fault.

Where major transverse faults cut the leading edge of the continental plate, porphyry copper deposits may develop in situations somewhat analogous to those examples cited previously. The Chaucha deposit appears related to such a major structure identified with plate motions. Goossens (1972) points out that the deposit is on the Chaucha fault, a strike-slip structure that Goossens and Hollister (1973) define as a transverse fault having more than 8 km of post-Cretaceous horizontal displacement. The Chaucha porphyry copper occurs at the intersection of the Chaucha fault and the northerly trending Cordillera fault. Stockworks in this deposit have dominant trends N10E and E-W (Fig. 10), reflecting regional faults; and the center of intrusive activity, hydrothermal alteration, and mineralization is the intersection of the two faults. In this deposit, faulting, intrusion, and mineralization are demonstrated to be a continuous sequence of events.

Where veinlets and veins form through stress release in response to intrusion of a circular stock, the veinlets may describe a

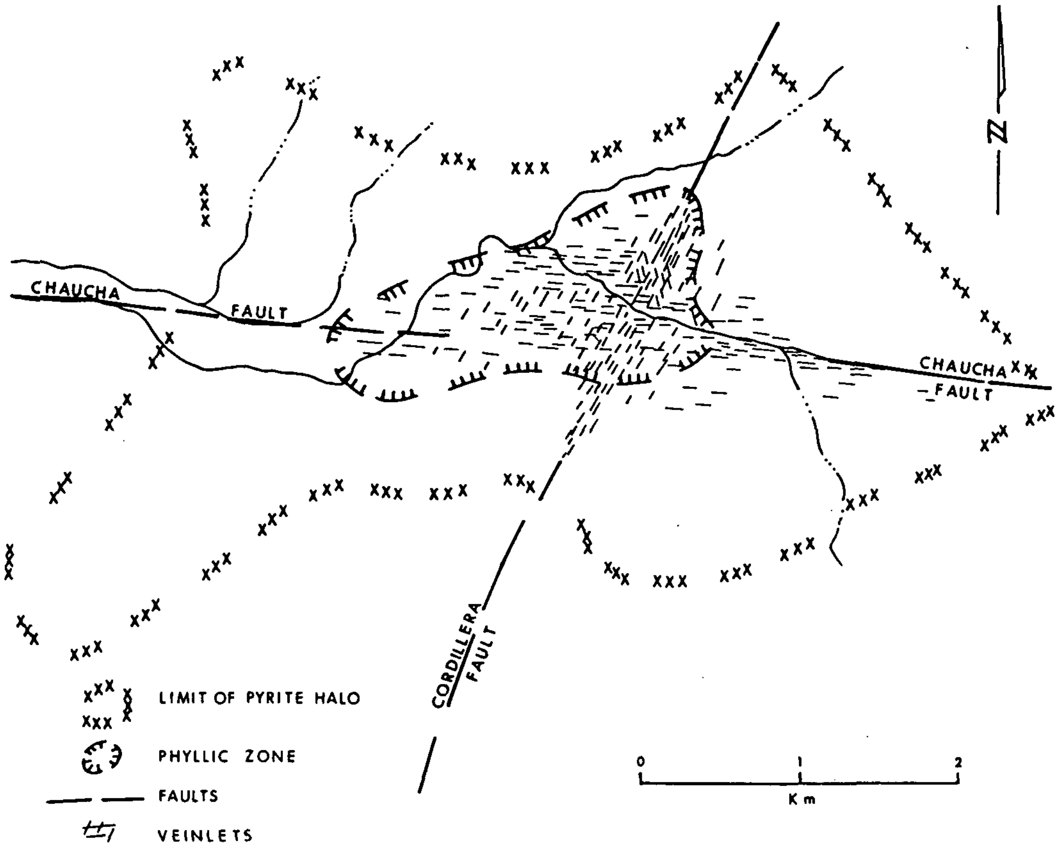

Fig. 10. Surface geologic map, Chaucha. Intersection of the Chaucha and Cordillera faults is the center of alteration and mineralization for Chaucha. The stockwork is largely composed of closely spaced mineralized segments of each fault that have developed during simultaneous displacements along both *(modified from Ljungren, 1970).*

circular pattern. The circular pattern may be superimposed on, or be visible through, the normal stockwork trend developed during formation of the deposit. Campana Mahuida, Argentina (Fig. 11), exemplifies circular fractures occupied by veinlets of quartz and sulfide that cut Cretaceous sandstone. They are related to a stock that does not outcrop. The first hole drilled in the United Nations program at Campana Mahuida penetrated the center of the circular pattern and intersected an altered and mineralized intrusion. Veinlets trending N35E are superimposed on the circular set, and some dikes of altered igneous rock follow this alignment. Intrusion of the stock, formation of the circular and northeast sets, and alteration and mineralization have been demonstrated to be part of one continuous process (Ljungren, 1970).

Although strike-slip movement seems most common on large regional faults with a demonstrable genetic tie to stockwork porphyries, high-angle deep-penetrating dip-slip normal and reverse faults also occur in the continental plate and may also be significant in porphyry copper development. Morococha (the Toro Mocho porphyry copper) may be an example of a deposit that developed in conjunction with major faults having prominent dip-slip movement. Terrones (1958) infers that the N25W-trending regional faults present there (displaying dip-slip movement) appear to have influenced early, premineral, epizonal magmatism. Eyzaguirre, et al.

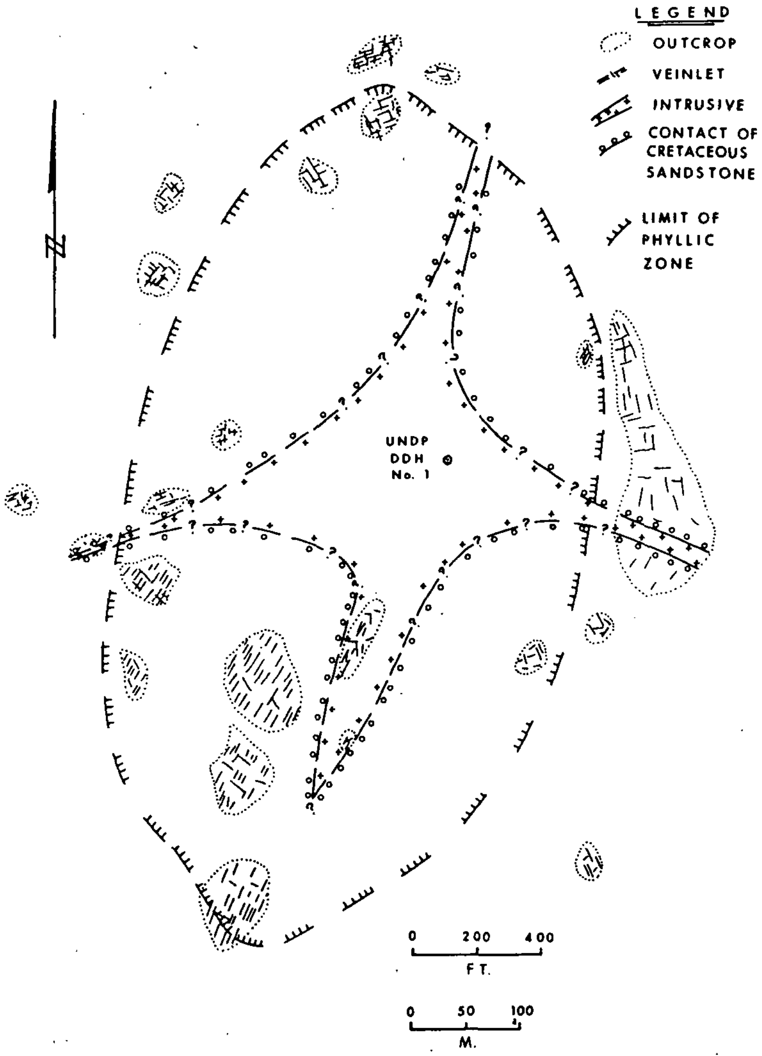

Fig. 11. Structure in outcrop at Campana Mahuida, Argentina. Interpretation of structure and alteration are shown for Campana Mahuida deposit, based on outcrop studies. A circular set of fractures appears to be annular to a nonoutcropping plug. Dikes radiating from the quartz monzonite plug may be seen in outcrop. The plug is the central heat source for mineralization in the district (*modified from Ljungren, 1970*).

(1975), show that the sequence of plutonic and hydrothermal activity may have spanned only 1.1 m.y. However, the porphyry copper deposit in Morococha was explored after comprehensive descriptions of the district were published, and a link between mineralization and the faults has not been demonstrated. Dominantly east-west fracturing is present in what is now known to be the porphyry copper center (Haapala, 1949), although these faults could be subsidiary fractures. The Haapala (1949) discussion of breccia at Morococha illustrates the occurrence of breccia pipes in a stockwork deposit. Cerro de Pasco Corp. maps (Fig. 12) do not clearly show the N25W structures referred to by Terrones (1958).

Examples of Breccia Pipe Type: In contrast to the stockwork deposits, Ruiz (1965), Sillitoe and Sawkins (1971), and Hollister

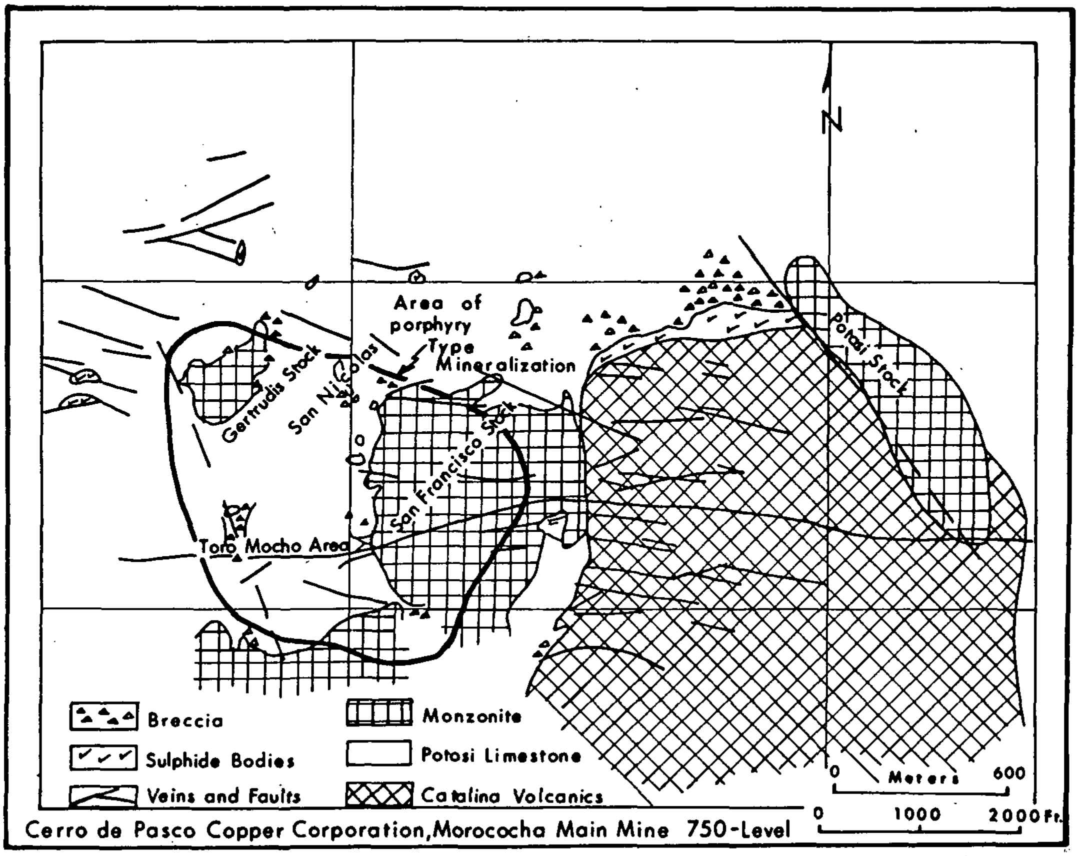

Fig. 12. Morococha, Peru, including Toro Mocho area. An outline geologic map of Morococha shows that the area which may include porphyry-type mineralization includes both quartz monzonite and intruded limestone. Skarn development is widespread in limestone near igneous contacts (*modified after Haapala, 1949*).

(1974) imply a separate model for tourmaline breccia pipes. This discussion generally follows the Sillitoe and Sawkins (1971) classification without change, but expands it to include porphyry copper deposits in the Andean orogen they did not mention. On a regional basis, the outstanding feature of tourmaline breccias is an apparent lack of dependency on or involvement with a regional fault. This applies to Toquepala (Richard and Courtright, 1958) and to El Teniente (Howell and Molloy, 1960). Similarly, no genetic dependence on regional structure can be discerned from published detailed maps of Disputada, Los Pelambres, or Cerro Verde.

Plate 1 (p. 22A) is a photograph of tourmaline breccia from Toquepala.

The controlling structure for nearly all subsidiary features of the breccia pipe type is the pipe itself or the intrusion that may have preceded it. In South America the common association of tourmaline with breccia pipes and the tendency for pipes to occur near the leading edge of the moving continental plate are characteristic. Tremendous volumes of boron needed to fill the pipes have no easily discernable source in the subduction zone. The generally circular or elliptical form of the pipes, their circular and radiating fracture patterns, their steep or vertical tubular shape, and their random distribution may best be explained by strong vertical movement of material that punctured the crust at will.

Diagnostic structural features of the large breccia pipe model usually include the following:

1) A pipe composed of angular fragments cemented with tourmaline and other minerals.

2) Common occurrence of circular and radial mineralized fractures around the tourmaline breccia pipe.

3) A pebble breccia (e.g., Braden pipe) cutting both 1 and 2.

Apparently the fracturing was initiated by an intrusion, or by boron-rich hydrothermal fluids, or both, but evolution of structures now visible in and around some pipes required repeated movements within the conduit. These movements may have been of both collapse and injection type, and they led to fracturing of the walls, as well as to repeated brecciation in the pipe. Involvement of magma with the earliest fractures can be demonstrated in a number of deposits. Dacite at Toquepala has a close time-space relationship to mineralization and occupies an annular ring. Howell and Molloy (1960) describe a similar dacite cone sheet at El Teniente, which they state is "closely associated in age with ore." Paragenetically, copper is penecontemporaneous with tourmaline in the majority of these deposits, although metals other than copper may accompany the tourmaline. Additionally, some pipes are barren of sulfides.

The general setting of Toquepala (Fig. 13) and detail of a portion of the pipe (Fig. 14) illustrate a typical breccia pipe deposit. Veinlets encircle the tourmaline breccia or, more rarely, are radial to it. In detail the breccia irregularly cuts the peripheral stockwork of veinlets. Although some veinlets cut the breccia pipe, the repeated veining suggests a more complicated relationship between the two. Ore grade mineralization lies in both the breccia and the circumferential stockwork of veinlets in the adjacent wall rock. In the Toquepala ore body, the stockwork of veinlets around the breccia is not as dense as that at Chuquicamata, although some ore at both Cerro Verde and El Teniente extends into the stockwork zone. In Toquepala, however, as with most breccia pipe types, the best grade occurs in the breccia, with the hypogene grade weakening away from it. Intensity of fracturing and quantities of hypogene copper and molybdenum sulfide mineralization fade as distance is gained from the pipe. Dacite fills a few of these circular peripheral fractures, but it in turn is the host for ore minerals occurring in circular veinlets. Minor amounts of ore minerals may be found disseminated in the dacite as well. The phyllic alteration zone occupies the pipe and the adjacent walls where fracture density is greatest.

Fig. 14 demonstrates a feature found locally in some large pipes. In some large

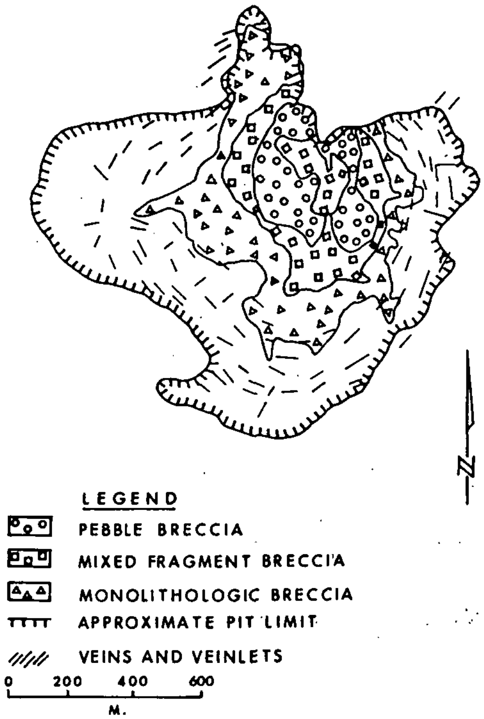

Fig. 13. Structural outline of Toquepala, Peru. Toquepala tourmaline breccia (ore breccia) is ringed by an annular mineralized fracture pattern. Annular fractures may have formed partly in response to intrusion of a pre- or early mineral dacite plug, but strong mineralization within these fractures indicates some formed in response to development of ore breccia. Pebble breccia is post-sulfide but has appreciable sulfide content since numerous rounded fragments of tourmaline breccia are incorporated in it. It represents the latest hydrothermal phase.

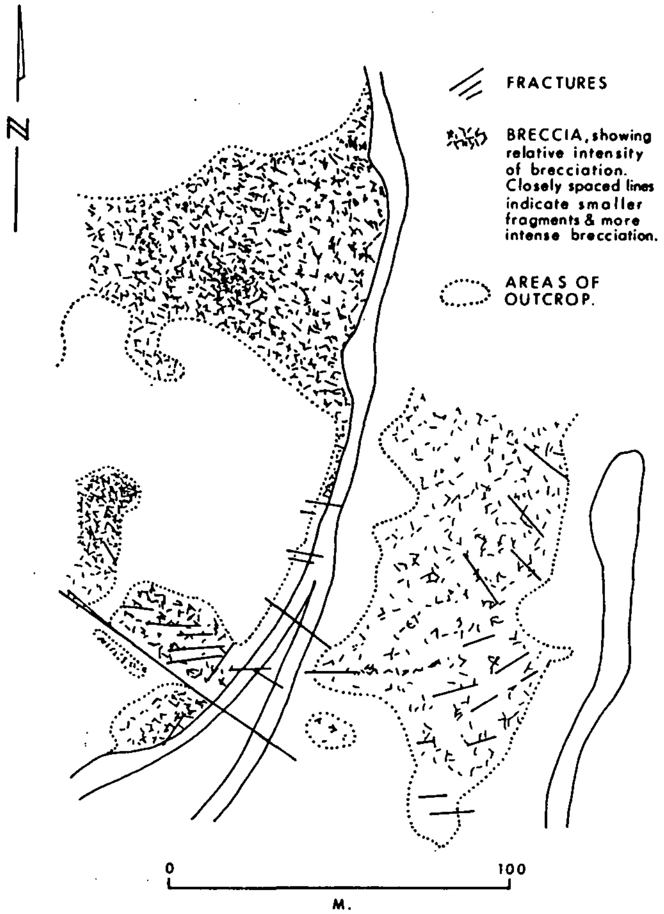

Fig. 14. Detailed surface geologic map of Toquepala. Details of breccia development in outcrop are diagramatically portrayed by intensity of "chicken" scratches. Smaller breccia fragments more closely packed together are shown by shorter, more clustered scratches. Fractures cutting breccia are intra-mineral in age and are part of the circular fracture pattern.

pipes within any small area, individual breccia fragments may tend to have about the same mass, and fines are missing. Where mixing is thorough, and the breccia consists of numerous fragments of rock (including both dacite and tourmaline breccia itself brecciated), size classification is best developed. Change in the size of fragments from one part of a mixed fragment breccia to another may be gradual, and the change from a mixed fragment breccia to wall rock nearly always occurs in a breccia zone containing fragments of wall rock only. One possible explanation of the size classification phenomena is that fines were carried upward and away by rising fluids, while coarser fragments were sorted according to mass. Fines may also have reacted with fluids to form tourmaline and other gangue silicate minerals. Variation in fragment size from place to place may be seen in Fig. 14 as nonsystematic but gradual. The change from a mixed fragment breccia to unshattered wall always involves passing through a zone of breccia containing only fragments of the rock found in the wall.

Where a number of small diameter pipes have penetrated the surface (e.g., Cabeza de Vaca, Chile), fracture patterns may be complex due to overlapping. Segerstrom

(1967) notes "90 breccia bodies which are either circular or lenticular in plan in an area 1300 by 2000 meters" in this area. Thus the example presented for Toquepala may be the simplest case for a single large pipe, with the possibility remaining that numerous closely spaced pipes may have interlocking boundary fracture zones.

Post-tourmaline breccia (e.g., pebble breccias) and igneous rock also exist in this structural model, indicating continued igneous and hydrothermal activity after the main episode of tourmalinization. Later breccia also may be devoid of any clear connection with regional structures at the surface and may be mineralized with sulfides but not with tourmaline in typical stockwork-type deposits (as at the Chuntacala ore body at Cuajone).

DISCUSSION

Unifying features of porphyry copper deposits in the Andean orogen are similar petrography, similar alteration zoning in and about ore, and nearly identical paragenesis of sulfide minerals regardless of structural type. Each structural type (stockwork or breccia pipe), however, displays individual details of ore emplacement, and the stockwork model tends to be more intimately involved with regional faults whose movements are compatible with plate tectonics. Deep regional faults may have intersected the source of magmatic-hydrothermal fluids and given rise to stockwork-type deposits during repeated movement that caused tensional openings in intersecting or conjugate sets. Lacking this escape, hydrostatic pressure in the fluids could build up to the point where a piercement structure and breccia pipe formed. Thus a common source but different mechanism of emplacement may explain many similarities of the two deposit types. Boron in breccia pipes may signify intense pneumatolitic activity in breccia pipe deposits, in contrast to stockworks in which tourmaline is rare.

Most known K-Ar dates for larger deposits in the Andean orogen are listed in Tables 1 and 2. Not shown are data for smaller porphyry deposits such as that at Cerro Rico, Argentina, with a date of 5.9 m.y. Additional dates are known for incompletely described porphyry deposits, but these tend to fall within the range of those listed and do not invalidate generalizations derived from the data given.

Misleading results from isotopic dating may have a variety of causes. It is assumed that those using the data are aware of such limitations, and qualifications applied to ages derived from the Andean orogen will not be examined.

Clark (1972) provides a 4.32 m.y. age for El Teniente, and for this deposit Ridge (1972, p. 593) speculates, "Tennantite mineralization took place in the Pliocene." The geologic evidence supports the K-Ar age. Lowell (1974) provides a date of 4.6(?) m.y. for Rio Blanco and of 10 m.y. for Los Pelambres. Goossens (1972) mentions two young-age determinations for Chaucha. The 9.9 m.y. age is preferred as the more plausible geologically. Michiquillay also has two ages recorded, but Damon's (1973) explanation for the 20.6 m.y. date is sufficient to justify its use. A. H. Clark (1976) advises that the 22 m. y. date noted in Table 1 for Copaquire disagrees with a date determined at Queens University. He has obtained a 30 m.y. date for this deposit. Dates presented in the tables generally have some geologic support and therefore are believed to be valid.

The narrow range in time for K-Ar dates on Andean porphyry copper deposits contrasts to the broader spacing of dates reported for similar deposits of the Cordilleran orogen.

A wider age spread for Andes deposits seems possible when more of them are investigated and brought into production. With present information, however, youth is apparently a general characteristic of deposits throughout the length of the Andean orogen, from Pantanos south to Campana Mahuida.

Published information on ore mineralogy exists for some Andean deposits. Copper sulfosalts (generally enargite and tennantite) are more common in Andean, as opposed to Cordilleran orogen deposits. Enargite appears to be an important constituent of some ores at Morococha and Chuquicamata and the dominant copper mineral in Cerro de Pasco and some other Andean deposits. Most published mineralogic descriptions are too incomplete, however, to permit broad generalizations for the entire Andean porphyry copper province. Chalcopyrite remains the most common hypogene copper ore mineral, and most deposits contain molybdenite and minerals of zinc, lead, and silver in some type of zonal arrangement with copper. Metallic sulfides occur preferentially as fracture fillings of tectonically formed openings.

Ore reserves data in the two tables derive from the literature, with sources listed in the bibliography. Some reserves seem substantially higher in grade than are reported for similar deposits exploited in the Cordilleran orogen. High grade ore is usually enveloped by halos of progressively lower grade material; the copper content fades as distance from the mineralizing center increases. For this reason quoted reserves do not reflect ultimate tonnage or grade potential, and mining may involve a much larger tonnage of lower grade material. Lowell (1974) cites 1400 million mt reserve at Chuquicamata with a grade of 1.2% Cu, but an additional 1300 million mt of 0.3% Cu also exist. He cites an additional 4300 million mt of 0.3% Cu around the El Teniente (Barden) reserves, which are given in Table 2 as 4000 million mt of 1.05% Cu.

Data on past mining may be similarly misleading. V. D. Perry (1973) stated that past tonnage and grade of ore treated at Chuquicamata "to 1952 as 363 million tons with a recovered grade of 1.4%." Waste moved in this operation averaged 0.4% Cu and would have been commercial for mines in much of the Cordilleran orogen; it should be included with produced ore for comparison with other mines. Unfortunately such data are missing for most Andean mines.

CONCLUSION

The nature of porphyry copper deposits of the Andean orogen permit the structural geologist to establish distinct stockwork and breccia pipe models. Presence of tourmaline preferentially in breccia pipes lends support to the distinction. In other porphyry copper provinces where tourmaline may appear more rarely, establishment of the two models is less easily recognized and less universally accepted, but may be real, nevertheless.

The erratic geographic distribution of Andean mineralized calc-alkalic intrusions through time finds no easy explanation in the plate tectonic evolution of South America. Granitic intrusions generally are oldest closest to the trench and younger to the east. Porphyry copper magmas are haphazard in time and spatial distribution, however. Variations in composition from quartz monzonite may occur in mineralized intrusions, but these display no systematic pattern as a function of distance from the trench. In particular they do not become more potassic toward the east.

Thus time, space, and compositional factors of porphyry intrusion do not conform to the general rule of being younger to the east for subduction-derived magmas. Granitic intrusions do have this tendency.

Independence from both age and compositional trends of subduction-generated magmas shown by mineralized intrusions suggests an origin distinct from the typical island arc-batholith-associated magmas.

On the other hand, most larger porphyry copper deposits lie within the Andean copper belt, which in turn coincides with the projected surface trace of 100 to 150 km depth interval cut by paleo-Benioff zones existing at the time of mineralization. The zone of partial melting (low velocity zone) under modern conditions most frequently is suggested to be somewhere within this same depth interval.

Existence of both stockwork and breccia pipe models implies that a porphyry copper system generated at depth may be guided to the surface by large regional structures. In their absence, the hydrostatic and lithostatic pressure within the system is adequate to bring it into the upper crust as a piercement, which may then develop as a breccia pipe.

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OPEN-FILE REPORT 0-80-12

GEOTHERMAL GRADIENT DRILLING, NORTH-CENTRAL CASCADES OF OREGON, 1979

by
Walter Youngquist
Consulting Geologist

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1980

DISCLAIMER

This report has not been edited for complete conformity with Oregon Department of Geology and Mineral Industries standards.

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GEOTHERMAL GRADIENT DRILLING, NORTH-CENTRAL CASCADES OF OREGON, 1979

by

Walter Youngquist

INTRODUCTION

In the summer, 1979, a geothermal gradient drilling program was initiated on the western flank of the North-central Cascade Mountains of Oregon, specifically from the vicinity of Santiam Pass on the south, to just southeast of Austin (Carey) Hot Springs on the north (Figure 1), an airline distance of approximately 45 miles. The principal purpose of this drilling program was to gain information on geothermal gradients in selected areas to depths greater than from that obtained in previous drilling.

Except for two wells to approximately 1500 feet in depth, one near Breitenbush Hot Springs, and one near Austin (Carey) Hot Springs, drilled by Sunoco Energy Development Company, the results of which are proprietary, no drilling below the depth of 500 feet had been done in this region. A secondary objective was to gain experience in drilling intermediate (2000-foot) wells in these volcanic terrains.

A five to seven well program was proposed, with a budget of $450,000. The range in number of wells to be drilled was established to account for differences in opinions as to what the costs would be of these wells, depending on drilling conditions encountered. As these were unknown in advance, the five to seven well program objective was set. Ultimately six wells were drilled; in a sense seven were drilled as two wells were attempted to be drilled at site 3. Projected depth of these wells was to 2000 feet. The deepest well drilled went to 1965 feet (well number 2--Twin Meadows).

<u>Public Information.</u> All information gained from these wells was specified to be public information, with samples to be stored in at least one publicly available site (ultimately two such sites have been established).

<u>Participants/Funding Sources.</u> This project was funded by the U. S. Department of Energy, Region X, Grant No. DE-FG-51-7ET2743 in the amount of $300,000. Southland Royalty Company of Fort Worth, Texas, Sunoco Energy Development Company of Dallas, Texas, and the Eugene Water & Electric Board of Eugene, Oregon each contributed $50,000 to the project. In addition, the Eugene Water & Electric Board made available to the project its facilities at Carmen Dam for supply logistic and storage purposes, and subsequently

Total 8,162' drilled for $55.13/ft, ave cost.

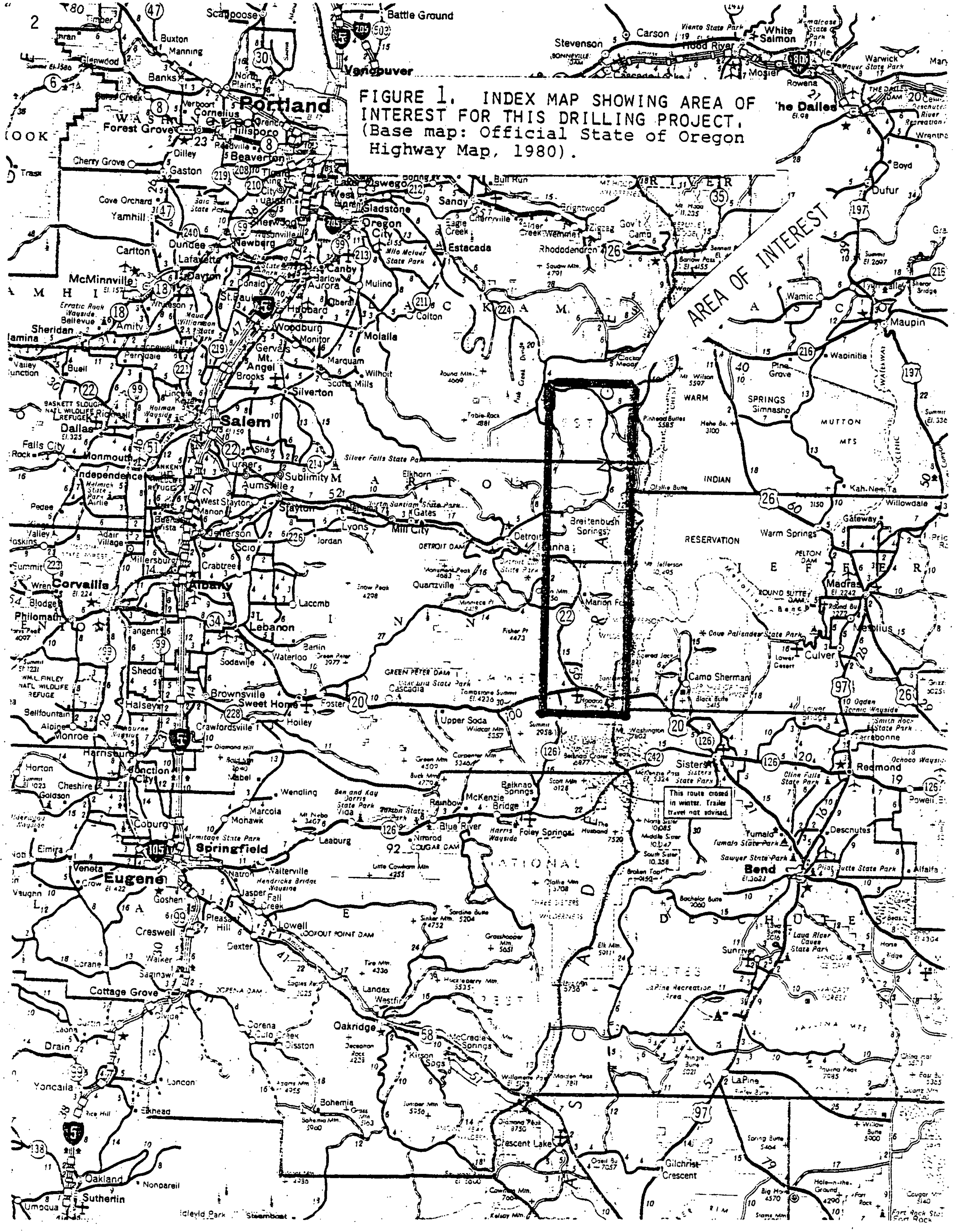


FIGURE 1. INDEX MAP SHOWING AREA OF INTEREST FOR THIS DRILLING PROJECT. (Base map: Official State of Oregon Highway Map, 1980).

also picked up a number of cost over-runs peripheral to the project, including the ultimate abandonment costs of the wells, and the restoration of the drill sites to the satisfaction of the U. S. Forest Service. All drill sites are on Forest Service land. The Eugene Water & Electric Board was the prime contractor for this project.

Drilling Contractor and Technical Manager. The drilling contractor was Southwest Drilling and Exploration Company, Inc. of Central, Utah. Technical Manager was Walter Youngquist, geothermal consultant for the Eugene Water & Electric Board.

Technical Services. Technical services in the form of temperature gradient logging, and gamma ray logging were provided under an actual cost sub-contract agreement between the Eugene Water & Electric Board and the Oregon Department of Geology and Mineral Industries. In turn, the Oregon Department of Geology and Mineral Industries contracted some of the work of gradient analysis and conductivity testing with Dr. David Blackwell, Geothermal Laboratory, Southern Methodist University, Dallas, Texas.

Additional Technical Support. Additional technical support was provided by the Branch of Field Geochemistry and Petrology of the U. S. Geological Survey, Menlo Park, California. A complete suite of well-cuttings was supplied to that organization, and they have subsequently prepared open-file reports of their findings on each of these wells, giving a lithologic log of each well together with detailed observations on such rock alteration as may exist, with interpretations of the significance of such alteration. These open-file reports have been listed at the end of this present report. Their contents, in abstracted form, have been included in this report in the discussions of the individual wells. Terry E. C. Keith, James R. Boden, and Melvin Beeson of the U. S. Geological Survey kindly supplied this information.

Reports of Drilling Operations. During the progress of this project, reports of drilling operations were submitted at two-week intervals to all participants, and were also sent to other concerned organizations including the Oregon Department of Geology and Mineral Industries, and the headquarters personnel of the Willamette and Mount Hood National Forests. Copies of the detailed driller's logs and of all temperature and gamma ray logs were also provided all participants and to the Oregon Department of Geology and Mineral Industries. Upon abandonment of these wells, complete driller's logs were supplied to the Mount Hood National Forest and Willamette National Forest personnel for the wells in their respective areas, and to the District Geothermal Office of the U. S. Geological Survey in Santa Rosa, California.

This present report is the final report on this project, and, as prescribed by contract, is being placed on open-file with the Oregon Department of Geology and Mineral Industries in Portland, Oregon.

Well-cuttings and Their Disposition. Well-cuttings were taken at regular ten-foot intervals for logging purposes. One complete set of cuttings was deposited with the Oregon Department of Geology and Mineral Industries, Portland, Oregon. Sunoco Energy Development Company did not request a separate set of cuttings. Southland Royalty Company specified that their cuttings be placed on file with the University of Utah Research Institute, Salt Lake City, Utah. A smaller set of cuttings from each well was supplied to the U. S. Geological Survey, Branch of Field Geochemistry and Petrology, Menlo Park, California, which samples are the basis for the open-file reports prepared by that organization on each of the wells, and from which information has been drawn for this report. For conductivity information, a set of samples taken at 25-foot intervals were sent to Dr. David Blackwell at the Geothermal Laboratory, Southern Methodist University, Dallas, Texas. Dr. Blackwell subsequently prepared reports on each of these wells with respect to heat flow and apparent thermal gradients. This information has been incorporated into the present study, appearing chiefly in the form of Figures 5, 6, and 7, and Table 1 at the end of this report.

REGIONAL GEOLOGY AND BASES FOR WELL LOCATIONS

Regional Geology. Geologists generally recognize two geological provinces in this portion of the Oregon Cascades--the High (younger) Cascades, and the Western (older) Cascades. The High Cascade crest, in the region where the drilling for this project took place, is marked by a line of young volcanoes which are Mount Jefferson (10,495 feet), Three-Fingered Jack (7,841 feet), and Mount Washington (7,802 feet). Numerous both large and small cinder and spatter cones also exist along and near this general crest line. These include Sisi Butte, Olallie Butte, Big and Little Nash craters, the Sand Mountain lineament with its several craters, the Pinhead buttes, and many others. The time line used to distinguish between High and Western Cascade rocks is commonly taken at the most recent magnetic reversal, or about 670,000 years.

The High Cascade province which exhibits these younger rocks consists of relatively unaltered volcanics ranging in composition from basalt to andesites and dacites, with numerous interculated zones of ash, cinders, and some minor stream and pond deposits; the pond deposits commonly have abundant diatom remains. A typical section of the High Cascades might be an andesitic columnarly jointed lava flow overlying a thin section of pond sediments which in turn overlies a thicker section of laharic breccias. Such a section is well exposed along the North Fork of the McKenzie River, and variations of that sort of rock and sediment assemblage are evident many places, and found also in drilled sections. An appreciable part of the High Cascade section has been reworked through slope wash and landslide movement, and then redeposited and consolidated. This is the origin of the laharic breccias which appear in great abundance both in the High Cascade and Western Cascade rock sequences, in places making up a third to half the rock section.

The Western Cascades are a substantially more weathered series of rocks, much like the High Cascades in composition, but reduced in relief. The physical boundary between these two provinces in the area of this drilling project appears to be a fault or zone of normal faulting trending approximately north-south, with the downthrown side to the east. A rough estimate of the displacement is on the order of 1000 to 2000 feet. A similar fault downthrown to the west is indicated equidistant on the east side of the Cascade crest in this region. Therefore, if these observations are correct, the High Cascades in this area at least would presumably be in a graben. Although this geological interpretation has considerable basis of fact in the region under consideration, it is uncertain as to how far either north or south of this area the concept might apply, and it is not presumed here to so extend it, and there is not entire agreement that the graben concept is valid for this area either.

Fracture Trends. The north-south trend of the volcanoes and attendant fractures in this region is striking and dominant, but there also exists a northwest-southeast fracture set, and a northeast-southwest trend. The major volcanoes are aligned along the north-south trend. Lesser volcanic activity is related to the other fracture sets.

Hot Springs. Several hot springs exist in this area, notably Belknap and Bigelow Hot Springs in the McKenzie River Valley , Breitenbush Hot Springs in the Breitenbush Valley, and Austin (also called Carey) Hot Springs in the mid-portion of the Clackamas River Valley. It is noteworthy that these hot springs are in a general north-south alignment, and are situated approximately along what some geologists believe to be the fault boundary (already cited) between the High and Western Cascades.

Bases for Well Locations. The geothermal gradient well locations (shown here on U. S. Forest Service base maps as Figures 2 and 3) were made on the basis of having a geographic spread over the area of interest, and the specific sites were determined by several factors including various geophysical investigations (where available), and regional and local structural patterns. Sites 1, 2, 3, and 4, were all located on the upland bench area which lies between the High Cascade crest and the boundary between the High and Western Cascades, in part marked by the north-south portions of the stream valleys of the McKenzie, North Santiam, and Clackamas Rivers. Site 5 is located on a prominence in a broad bend of the Clackamas River, and site 6 is located at the base of Sisi Butte a short distance up the valley wall of the Clackamas River.

It should be noted that all of these sites except site 1 have been glaciated, and greater or lesser depths of glacial debris were encountered in drilling these wells. Site 1 is located on a lava flow approximately 3,000 years old, and therefore unglaciated.

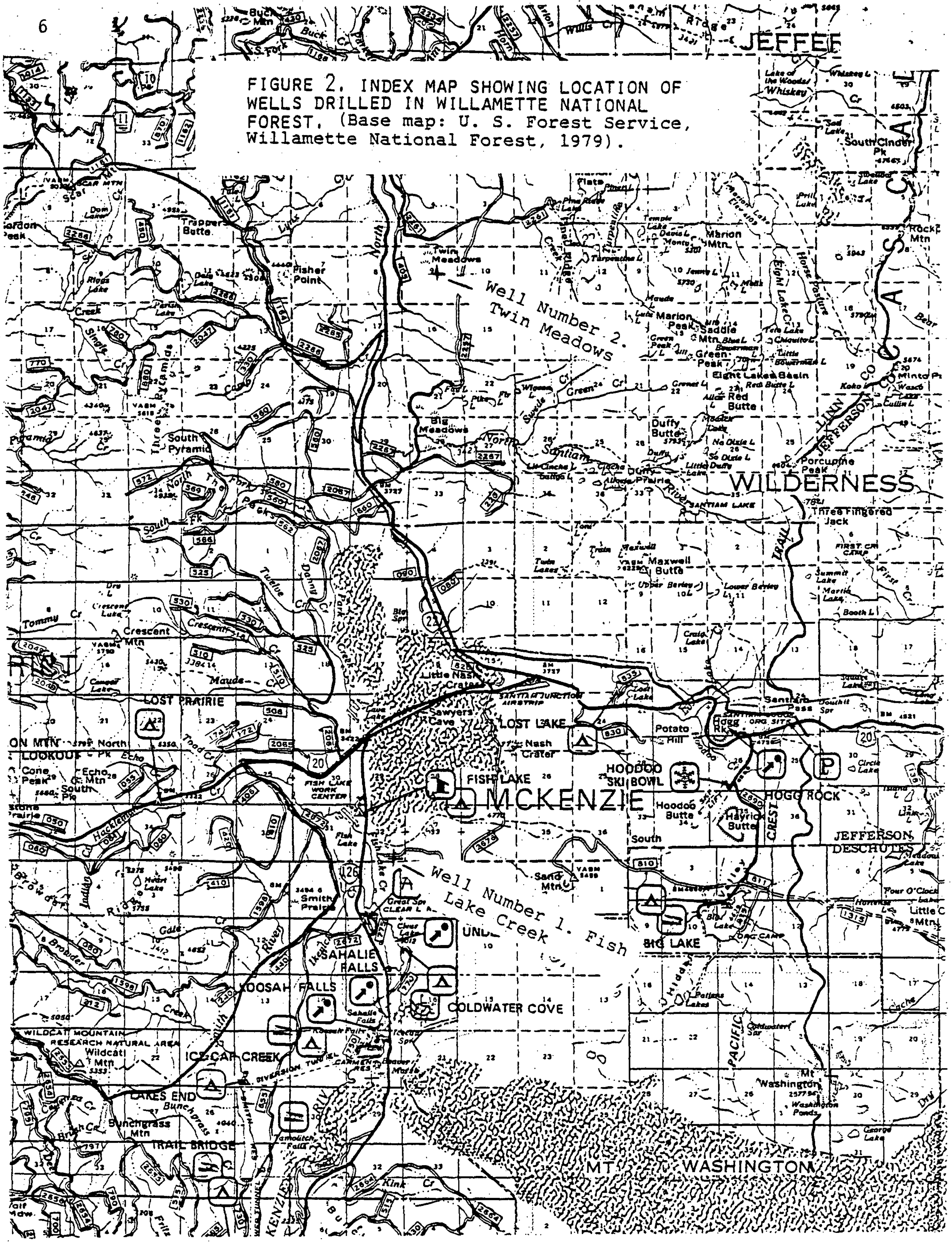


FIGURE 2. INDEX MAP SHOWING LOCATION OF WELLS DRILLED IN WILLAMETTE NATIONAL FOREST, (Base map: U. S. Forest Service, Willamette National Forest, 1979).

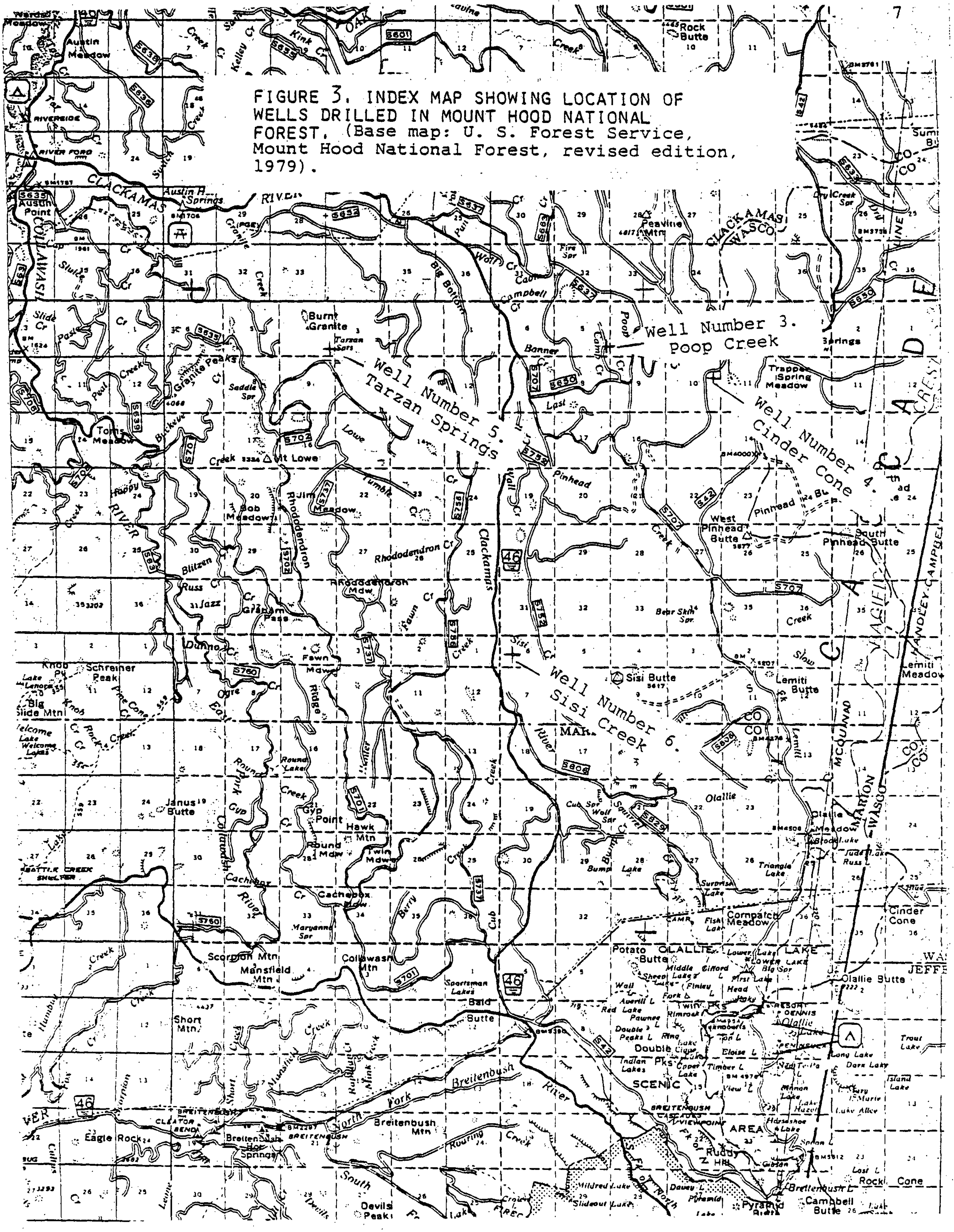


FIGURE 3. INDEX MAP SHOWING LOCATION OF WELLS DRILLED IN MOUNT HOOD NATIONAL FOREST. (Base map: U. S. Forest Service, Mount Hood National Forest, revised edition, 1979).

CASING PROGRAM, DRILLING EQUIPMENT, DRILL BITS, AND DRILLING PROBLEMS

Casing Program. The casing program was to drill 50 feet into the first competent formation and then set 8-inch casing and cement it in. A blowout preventer was then set on the casing, the cement drilled out, and a 6¼-inch bit was used to total depth. No intermediate strings of casing were set. A black iron two or two and one-half inch gradient pipe was set, sealed at the bottom, and filled with water.

Drilling Equipment. Rotary drilling equipment was used entirely. Initially a Chicago Pneumatic 1800 truck-mounted (including all pumps) drill rig with a 3500-foot capacity was brought in on the project. This was subsequently supplemented by a Portadrill (also truck-mounted) with a 2000-foot capacity. Mudpits were lined with plastic to prevent leakage, and fenced to prevent local wildlife from becoming entrapped in the pits during such times as the rig site might be temporarily unmanned.

Drill Bits. Both button-bits and medium-length-tooth rock bits were employed. However, it was found that a 6¼-inch Smith-Gruener medium-hard formation medium-length-tooth bit was the most efficient bit under most drilling conditions encountered in this project. Both basalt and other flows such as dacites and andesites could be drilled with these bits at a rate of 10 feet an hour or better, and the bits functioned well in ash, cinder, and pond and stream sediment sections also.

The sequence of rocks which is drilled at any given location in this portion of the Cascades is relatively unpredictable, as the complexity of the volcanic stratigraphy is great. In any one section laharic breccies usually make up the largest single element, but lava flows of different compositions, ash and cinder beds, and pond and stream sediments are also commonly present. The lava flows are usually less than 100 feet thick, and many are less than 25 feet thick, with the result that the drill encounters markedly different rock types in a relatively short vertical distance. It is, therefore, not possible to drill with the bit most adapted to each rock type, as it is impractical to change bits at relatively short drilling intervals. The optimum bit for drilling andesite is not the bit best designed for drilling pond sediments or weathered volcanic ash. It may be said, given the varied rock section, that regardless of what type of bit you start with, you are actually drilling with the wrong bit for a given rock type almost half the time. Therefore, a compromise has to be made, which, as previously stated, proved to be a medium tooth length rock bit. In the case of laharic breccias, the rock type changes almost foot by foot, as relatively solid boulders are drilled in a matrix of volcanic ash and cinders.

<u>Drilling Problems.</u> Drilling the section in which to set the surface casing proved to be a problem more often than not. This was due chiefly to the presence of a mantle of glacial debris, with boulders up to five feet or more in diameter being encountered. These boulders tended to cause the drill to deviate and the straight hole necessary to land a string of casing was not made. A 11 3/4-inch bit was used on occasion but the results were not appreciably better than those obtained by using a 10¼-inch bit. Also, deviation around the andesite and dacite boulders in the glacial drift tended to put undue strain on the bit and sub connection with the drill string, and on sites 2 (Twin Meadows) and 6 (Sisi Creek), the bit and sub broke off, and could not be fished, and the rig had to be moved in each case and the surface hole re-drilled.

In addition to the various rock types encountered, abundant fractures in the lava flows caused numerous lost circulation problems. Also, in some areas lava tubes are present which may or may not be carrying moving ground water. In lost circulation zones, drilling with air was attempted several times, but in all cases ultimately this procedure had to be abandoned because of the large volumes of water encountered which could not be handled by the pumps.

Lost circulation problems were severe, and as much as 21 tons of cement, and more than 200 sacks of lost circulation materials (cottonseed hulls, cedar fiber) were used in attempts to regain circulation in a given trouble zone. In additon, mud quality was frequently altered substantially by flows of ground water with the result that caving in the holes occurred causing drill strings to be stuck. In some instances, drill strings had to be blasted off. The laharic breccia zones were especially troublesome as large, hard, angular blocks of rock embedded in the soft ash and other sedimentary materials caused the drill string to deviate. Also, as the soft material was occasionally washed out by the action of the drilling mud from around the angular blocks, some of these blocks would move into the hole and stick the drill string so that the drill could neither be pulled nor pushed (hydraulic jack-hammers used in some cases to attempt to free the bit). Larger capacity draw-works would probably alleviate this problem to a considerable extent, but with the relatively light equipment with which we were working, this was a serious problem.

Noting again that the majority of wells were located on the bench area between the Cascade crest and the major valleys adjacent to the west, and that this is a region of high precipitation (80-100 inches annually), it became evident from experience that the bulk of the drilling problems were encountered in the zone of vadose (that is, free-flowing, downward moving) water above the regional water table. The regional water table is for all practical purposes represented by the streams in the major valleys. Once the drill reached the level of this regional water table, the drilling problems became less severe. In the vadose zone, however, through-flowing ground water has cleaned out and enlarged fractures and provides a hydraulic gradient all of which combine to produce an environment where lost circulation is almost a continual problem. In a major deep drilling situation with bigger draw-works to largely eliminate the stuck drill problems from caving, and a heavy mud combined with a casing program to carry a protective string of pipe below the regional water table, these relatively surficial problems would not be nearly so severe as they are when lighter drilling equipment is used, and no casing is carried below the initial few hundred feet.

WELL DATA

This section of the report presents a summary of drilling operations for each well, the generalized geologic section drilled, and petrographic and geochemical information supplied by the U. S. Geological Survey from their examination of the cuttings, together with the temperature gradient information for each hole. Preliminary logs were run on each well shortly after the time of each well completion in 1979. Final logs were run on each well in late spring 1980. Final geothermal gradient logs are plotted together for comparison on Figure 5 (page 27), and individual plots are shown as part of the basic data which makes up Table 1 at the end of this report. Pertinent observations of the technical personnel involved in obtaining the petrographic and geochemical information have also been included with the description of each well.

NAME OF WELL: Eugene Water & Electric Board No. 1. Fish Lake Creek.
LOCATION: Long. 121°59'33" W., Lat. 44°23'20" N. SE¼SE¼ section 32, Township 13 South, Range 7 East, Linn County, Oregon. (Willamette National Forest).
ELEVATION: 3135 feet (955.54 meters).
TOTAL DEPTH: 1837 feet (558.39 meters).
TOPOGRAPHIC/GEOLOGIC LOCATION: On outer apron of large series of basaltic flows from the Sand Mountain lineament; relatively flat-lying basalt with fragments up to two to three feet in diameter but most much smaller. Basalt dated as approximately 3000 years, no glacial debris present. Basalt came from a fissure about 3¼ miles east of the well, which fissure (Sand Mountain lineament) runs in a north-south direction for approximately six miles. Other fractures are also known in the area.
DRILLING DETAILS: Location of well site on a young ä ä lava flow was expected to cause initial drilling and lost circulation problems. Local surface geology indicated this young basalt flow was probably only about 60 to 80 feet thick at this place, overlying andesites (with a normal magnetic direction). This proved to be the case. Using heavy mud, lost circulation was a minor problem, and 150 feet of surface casing was landed into solid andesite with little difficulty. Frequent but minor lost circulation problems were encountered during drilling, but well was bottomed at 1837 feet with no major difficulties. A two-inch black iron gradient pipe was set. A total of four bits were used to drill the well. Estimated cost of drilling, including

proportionate rig-mobilization costs (from Nevada) was approximately $41,400, or $22.54/foot. This attractive figure, however, did not prevail for subsequent wells.

GEOLOGIC SECTION:

Interval (feet)	Lithology and Comments (USGS)
0-80	Basalt flow; black, vesicular basalt with groundmass of plagioclase and clinopyroxene, and phenocrysts of olivine, orthopyroxene, and plagioclase
80-160	Volcanic debris, mostly andesite
160-300	Flow, andesite, scarce hydrothermal minerals
300-330	Tuff, glass, zeolitized
330-340	Andesite flow
340-490	Volcanic debris
490-560	Andesite flow, scarce alteration minerals
560-820	Volcanic debris, mixed andesite and basalt, zeolitized throughout
820-830	Andesite flow
830-1370	Mixed andesite volcanic debris and interlayered thin flows. Zeolites and montmorillonite throughout
1370-1837	Mixed andesitic volcanic debris and interlayered thin flows; less alteration than in debris zone above

GENERAL OBSERVATIONS: (USGS) Hydrothermal alteration has resulted in depositing zeolites (phillipsite, chabazite, paulingite, thompsonite) montmorillonite, chalcedony, chlorite, and biggsite throughtout the older rocks of the Western Cascade Group. There is no evidence of hydrothermal alteration in the overlying flows of the High Cascade Group. Alteration minerals were first identified in this well at depth of 170 feet, and usually occur in vesicles and veinlets in volcanic rock fragments and are clearly of hydrothermal origin. Zeolitization occurs during hydrothermal alteration at temperatures generally between 20°C and 120°C. Hydrothermal alteration of this type has permeated the Western Cascades Group rocks in EWEB 1 drill hole below 170 feet. The date of this alteration is uncertain.

GEOTHERMAL GRADIENT: This is shown on the graph which is Figure 5, and also in the data in Table 1. Dr. Blackwell has commented on this temperature log as follows:

> Hole 13S/7E-32dc has an unusual temperature-depth curve. It is nearly isothermal through young basalts to a depth of 60 m, at which point the gradient is high and constant, with a value of 102°C/km. At a depth of 200 m, the gradient becomes isothermal and finally negative. It gradually increases and becomes positive again toward the bottom of the hole. The cause for this type of curve has been discussed in a previous letter: lateral flow of warm water along an aquifer between 200-220 m, superimposed on a background of relatively low heat flow. If more than one hole were available in this area, it would be possible to estimate the distance to the source and the possible temperature of the water coming up along the fracture zone and feeding this shallow aquifer. Based on a model similar to that discussed by Bodvarsson (1969), we estimate the initiation of the water flow in the age range of 1000 ± 500 years. This curve is typical of what one might expect to find associated with a geothermal system. It has already been recommended that the hole be perforated and samples be obtained from the aquifer at 200 m, in order for a chemical analysis to be performed and geochemical temperatures to be estimated.

Following the recommendation of Dr. Blackwell, an attempt was made, under the direction of James Robison of the U. S. Geological Survey, to sample the water at approximately 200 meters. The gradient pipe was perforated at that depth, and the water in the gradient pipe blown out for a considerable time by compressed air. The water flow obtained from these perforations was substantial. The water was subsequently sampled and analysis of this water was made by the U. S. Geological Survey (Dr. Robert Mariner) at Menlo Park, California. Results are tabulated here, with the note that the sample was not acidized, and was not filtered.

Sample no. GT-34JR80
Figures are in milligrams/liter

Na	32	Cl	4.2
K	2.6	SiO_2	48
Mg	0.1	B	1.0
HCO_3	73.0	Laboratory pH 7.95	
SO_4	1.0		

These data are rather inconclusive. If geothermal waters have been intercepted by perforations in the gradient pipe at approximately 200 meters it appears they may have been substantially diluted by vadose water.

NAME OF WELL: Eugene Water & Electric Board No. 2. Twin Meadows.
LOCATION: Long. 121°58'28" W., Lat. 44°32'20" N. NW¼SE¼ section 9, Township 12 South, Range 7 East, Linn County, Oregon. (Willamette National Forest).
ELEVATION: 3920 feet (1195 meters).
TOTAL DEPTH: 1965 feet (598.9 meters).
TOPOGRAPHIC/GEOLOGIC LOCATION: On upland bench area about 1¼ miles east of the canyon of the North Fork of the Santiam River. Upland has been glaciated and carries overburden of glacial debris with boulders up to five feet in diameter.
DRILLING DETAILS: Glacial boulders caused initial drilling problems. Drilled out of glacial debris about 60 feet, and into basalt. Major circulation loss at 85 feet and bit stuck at 90 feet while drilling blind (without mud). Eventually worked drill string free and pulled up to find bit and sub broken off. Did not attempt to fish. Moved rig 10 feet and drilled new hole. Considerable water flow encountered at 219 feet, eventually plugged off with cement. Drilled ahead with intermittent circulation losses to about 800 feet where drilling problems became less severe. Well drilled to total depth of 1965 feet (598.9 meters) with no additional serious lost circulation problems. Set two-inch black iron gradient pipe.
GEOLOGIC SECTION:

Interval (feet)	Lithology and Comments (USGS)
0-60	Overburden. Glacial debris, large boulders
60-120	Olivine basalt flow
120-410	Andesite flow
410-550	Basalt flow, with three textures: crystalline, vesicular, glassy. Lower 40 feet dominated by glassy layers
550-640	Volcanic debris unit, largely volcaniclastics

Interval (feet)	Lithology and Comments (USGS)
640-770	Volcanic debris unit, mostly olivine andesite
770-830	Volcanic debris unit, largely andesite, some volcaniclastics at base
830-840	Olivine andesite flow. Some hydrothermal alteration
840-890	Olivine andesite flow
890-980	Volcaniclastic unit, fine sand to silt
980-1020	Mixed volcaniclastics
1020-1260	Olivine andesite flow. White pumice ash zone 1180-1220
1260-1520	Volcaniclastic unit, 1260-1360 fine sand to silt; 1360-1430 dominant andesite, possibly a flow. 1430-1460 mixed white pumice. 1460-1520 coarser sand to silt
1520-1580	Mixed volcaniclastics and andesite
1580-1600	Andesite
1600-1670	Mostly andesite
1670-1700	Mostly volcaniclastics
1700-1740	Mostly andesite
1740-1750	Andesitic or basaltic glass flow with olivine phenocrysts
1750-1840	Volcanic debris unit with hydrothermal alteration
1840-1965	Volcaniclastics

GENERAL OBSERVATIONS: (USGS) There are two possible zones of hydrothermal activity evidenced at some time, one at 840 feet and one about 1800 feet. There is no alteration in the upper part of the drill hole.

GEOTHERMAL GRADIENT: The final temperature log was run on May 29, 1980, and the curve thereof and the data on which it is based are shown on Figure 5 and in Table 1. The log is isothermal down to about 787 feet (240 meters) which is approximately the depth of the regional water table, as evidenced by the adjacent valley of the North Santiam River a short distance to the west. Below that depth, the log shows a linear gradient of about 72°C/Km. Gradient data in Table 1, and on plot which is Figure 5.

NAME OF WELL: Eugene Water & Electric Board No. 3. Poop Creek.

LOCATION: Long. 121°50'45" W., 44°59'04" N., SE¼SE¼ section 5, Township 7 South, Range 8 East, Clackamas County, Oregon (Mount Hood National Forest).

ELEVATION: 3200 feet (975.6 meters).

TOTAL DEPTH: 960 feet (292.7 meters).

TOPOGRAPHIC/GEOLOGIC LOCATION: EWEB No. 3 is located on the intermediate bench area on the western slope of the Cascades between the crest of the Cascades and the adjacent valley of the Clackamas River approximately two miles to the west of the drill site.

DRILLING DETAILS: Two wells were drilled at this site. The first (EWEB 3) reached a depth of 960 feet (292.6 meters) with considerable difficulty. Lost circulation problems were encountered almost throughout the hole. Air-drilling was tried but the volumes of water were too great for the pumps to handle and the operation returned to drilling with mud. AT 960 feet the drill pipe stuck, and could not be freed. The drill string was blown off at 710 feet; a bit, sub, and about 250 feet of drill pipe including two drill collars were left in the hole. The string in the hole was cemented over with a view toward drilling around the fish and continuing the hole. In going back into the hole after the cement had been given time to harden, the drill did not reach the top of the cement, but stuck at 560 feet and could not be pulled. The drill string was reversed in rotation and the drill string separated at about 140 feet. Decision was made to abandon the hole and move the rig 100 feet east, which was done. The second well (EWEB 3A) was begun. Drill reached 640 feet, and was caving badly and it was decided to cement up the hole, and then drill out. This was done but drill got to 560 feet on drilling out and stuck again. Neither jacking up the rig nor using hydraulic jackhammers on the drill string could free the bit. After a day of continued circulation, however, the bit came free and drilling continued to 740 feet where circulation was again lost, and five mud pits of mud and lost circulation materials were lost down the hole. Additional mud and lost circulation materials were put in the hole and circulation eventually was regained and drilling proceeded to 840 feet where circulation was lost again. Two mud men from Nova Mud Corproation were called on the scene but were unable to regain circulation for the operation. Decision was made to switch to air-drilling, but again the pumps could not handle the formation water. Went back to mud drilling and reached depth of 870 feet with great difficulty where severe caving was encountered, and the heaviest mud the pumps could handle was not sufficient to prevent the caving. Drill was stuck several times and the driller could not get past this zone after two days of effort. Decision was made to bottom well at this point, and gradient pipe was set to 870 feet (265.1 meters). (Note: The lithologic section is that taken from the 1st--deeper well. The temperature gradient was run on the second well).

GEOLOGIC SECTION:

<u>Interval</u> (feet)	<u>Lithology and Comments</u> (USGS)
0-40	Overburden, consists of gray, tan, and reddish to orange amphanitic volcanic rock fragments. Darker fragments are andesite, reddish to orange fragments are oxidized basaltic cinders. A few fragments of chalcedony are in the overburden but none found deeper in the drill hole
40-140	Andesite flow, medium-gray, microporphyritic with groundmass of plagioclase
140-160	Porous layer of ash, probably andesitic
160-500	Andesite flow. A more careful study may show this unit actually consists of several flows, but there appears to be little variability and no indication of permeable or altered zones upon which the interval could be subdivided

Interval (feet)	Lithology and Comments (USGS)
500-670	Andesite flow, dark-gray and brown vesicular andesite fragments mixed with microporphyritic andesite. Groundmass consists of plagioclase, clinopyroxene, and cristobalite, and phenocrysts mostly plagioclase and clinopyroxene
670-690	Andesite flow, medium-gray, microporphyritic, fresh-appearing, described as "hard zone" in driller's log
690-820	Andesite flow, with lower part, 740-800 feet, having subordinate amount of gray amorphous obsidian chips mixed with the crystalline andesite chips of the rest of the flow section
820-960	Dacite, vapor-phase crystallization. This interval is significantly different from the overlying units. Vapor-phase tridymite is very abundant and vapor-phase hematite is moderately abundant. Traces of green staining and disseminated blue (azurite?) patches from 950 feet suggest copper mineralization

GENERAL OBSERVATIONS: (USGS) There is little material that can be ascribed to hydrothermal alteration. From 170 to 680 feet the cuttings consist mostly of unaltered gray andesite. Between 700 and 820 feet the proportion of yellowish-altered material to medium-gray unaltered andesite increases with depth. The interval from 830 feet to the bottom of the hole at 960 feet consists of light gray to light pink, and some white fragments of rhyodacite or dacite in contrast to the overlying units. Tridymite first appears in relative abundance at 820 feet. The abundance of tridymite and hematite indicate that the 830-960-foot interval is a zone of high-temperature vapor-phase crystallization. There are no vein of carvity deposits throughout the drill hole. The only possible hydrothermal deposit is very minor sulfides and azurite below 820 feet. The significant secondary crystallization is high temperature vapor-phase from 820-960 feet. Minor alteration activity causing Fe migration, oxidation, and leaching may be due to cooling of the lava flow, ground water circulation, or low temperature hydrothermal alteration.
GEOTHERMAL GRADIENT: The well was isothermal to total depth, temperature at 15 meters 7.44°C; temperature at 187 meters 7.06°C. Graph of gradient shown on Figure 5 and in Table 1.

NAME OF WELL: Eugene Water & Electric Board No. 4. Cinder Cone.
LOCATION: Long. 121°48'18" W., 44°58'34" N. SE¼NE¼ section 10, Township 7 South, Range 8 East, Clackamas County, Oregon. (Mount Hood National Forest).
ELEVATION: 3470 feet (1140 meters).
TOTAL DEPTH: 1160 feet (353.6 meters). Hole ultimately lost for most part and gradient pipe finally set to depth of 447 feet (see DRILLING DETAILS).
TOPOGRAPHIC/GEOLOGIC LOCATION: On south side of recent cinder cone located on the bench area between the Cascade crest and adjacent major valley of Clackamas River to the west. Well about ¼ mile west of pronounced fault scarp (traceable for several miles) with upthrown side apparently to the east.
DRILLING DETAILS: Drilling proceeded with little difficulty to

depth of 1015 feet where a major water zone was encountered. Circulation was lost at this point, and a very loud noise heard down the well (a roar like that of a freight train). Put in 140 sacks of cement and eventually plugged off trouble zone and drilled ahead to 1160 feet where circulation was again lost. Pulled drill back to 1100 feet while changing drilling mud, but in attempting to go back in, drill would not move although circulation was maintained. Used hydraulic jars very hard to try to move bit over period of several hours, but string could not be moved. Made decision to blast off bit at 1100 feet but blasting caps went off but not primer cord. Went in with second charge which stuck about 550 feet, and could not be pulled or pushed (with blasting caps, the amount of pushing is limited). Charge set off at that depth and drill string recovered to depth of 447 feet, and gradient pipe set to that depth. Drill pipe which was recovered had to be separated with aid of blowtorch because of pounding from jars. Drill string joints ruined.

GEOLOGIC SECTION:

<u>Interval</u> (feet)	<u>Lithology and Comments</u> (USGS)
0-110	Overburden, basalt cinders, red, oxidized, porous, unconslidated (south flank of adjacent cinder cone with local relief of about 150 feet)
110-200	Andesite flow, dark-gray, vesicular
200-220	"Soft zone" by driller's log. No recovery
220-290	Andesite flow. Multicolored fragments, gray, tan, red
290-300	Andesite flow
300-420	Andesite flow, massive
420-470	Andesite flow, gray, microporphyritic
470-750	Andesite flow. Massive, gray, occasional pink oxidized andesite
750-810	Andesite(?) flow. Oxidized flow top underlain by slightly coarser grained, massive andesite
810-880	Andesite(?) flow. Oxidized flow top
880-1010	Andesite flow. Dark-gray, massive
1010-1020	Masive, dark-gray andesite
1020-1100	No recovery
1100-1130	Andesite flow, massive, pinkish-gray andesite
1130-1160	No recovery

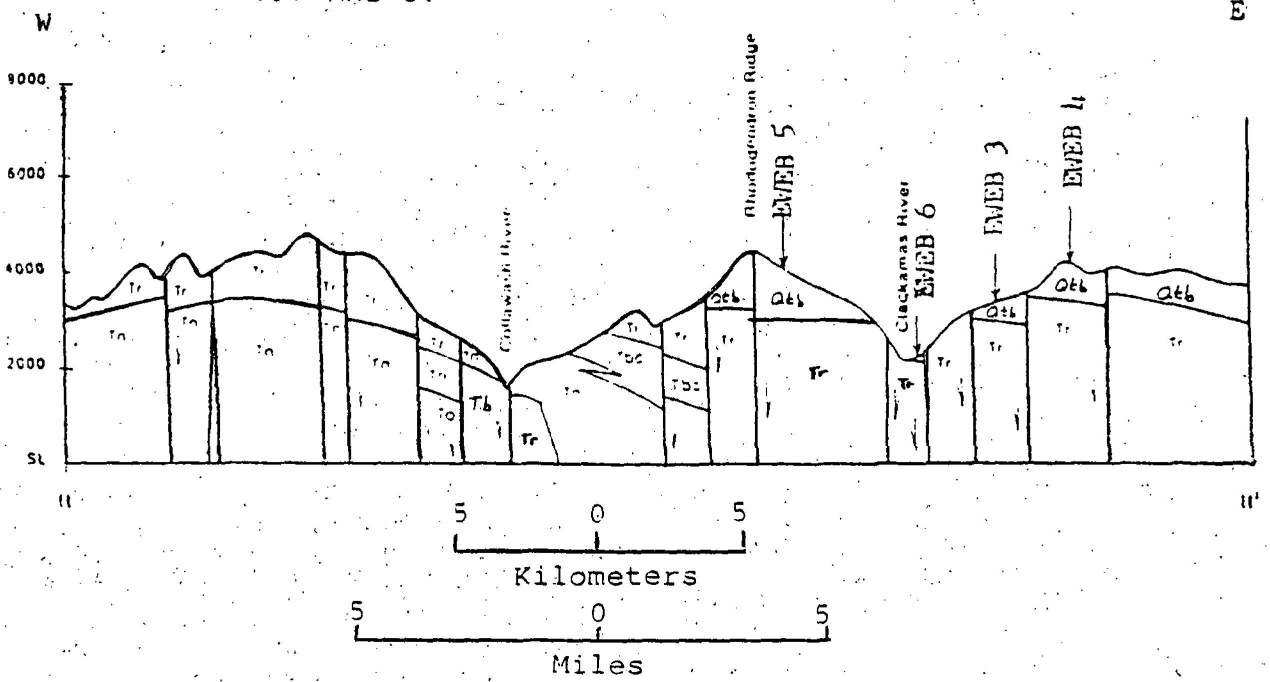
GENERAL OBSERVATIONS: (USGS) This drill hole penetrates twelve andesite flows and flow units. The flows are all similar in appearance and mineralogy. The cuttings show very little material which can be ascribed to hydrothermal alteration. The alteration is mainly Fe oxidation, leaching, and occasional redeposition on fracture surfaces as the mineral hematite. No vein or cavity deposits other than hematite are present in the cuttings.

GEOTHERMAL GRADIENT: The gradient pipe could only be set to 447 feet, and to that depth the well was essentially isothermal, with 10 meter depth temperature of 5.84°C, and bottom temperature of 4.48°C. Graph of gradient is on Figure 5 and in Table 1.

NAME OF WELL: Eugene Water & Electric Board No. 5. Tarzan Springs.
LOCATION: Long. 121°57'03" W., Lat. 44°50'59" N. SE¼SE¼ section 4, Township 7 South, Range 7 East, Clackamas County, Oregon. (Mount Hood National Forest)
ELEVATION 4200 feet (1280.5 meters).
TOTAL DEPTH 730 feet (222.6 meters).
TOPOGRAPHIC/GEOLOGIC LOCATION: On a major ridge on the inside of a bend in the Clackamas River, and about ½ mile southeast of a prominence called "Burnt Granite" which is andesite. This is the highest of the six wells drilled in this project. The adjacent valley to the north and east is about 2000 feet lower than the drill site. A geologic cross-section prepared by the U. S. Geological Survey from work by Dr. Paul Hammond showing the site of this well and the sites of wells 3, 4, and 6 is here reproduced as Figure 4.

Figure 4

CROSS-SECTION SHOWING THE GENERALIZED GEOLOGIC RELATIONSHIPS (AFTER HAMMOND AND OTHERS, 1980) AND RELATIVE LOCATIONS OF EWEB DRILL HOLES 3, 4,5, AND 6.



Qtb - Older High Cascade basalt
Tr - Rhodendron Formation
Tbc - Beds of Bull Creek
Tn - Nohorn Andesite
Tb - Breitenbush Formation

(From: U. S. Geological Survey Open-File Report: Volcanic stratigraphy and alteration mineralogy of drill cuttings from EWEB 5 drill hole, Clackamas County, Oregon).

DRILLING DETAILS: Drilled with mud to about 500 feet but with considerable difficulty. Below 260 feet the section became highly variable with numerous permeable zones carrying water. Set surface casing in firm andesite and began to ream down hole to clear out debris which had fallen in with incoming water, and encountered a severe water flow at 260 feet. A loud roar could be heard down the well and at the same time a strong blast of cold air came out of the well bore. Lost several pits of mud down the hole including 105 sacks of lost circulation materials to no avail. Brought in commercial cement truck and put in 270 sacks of cement but failed to regain circulation. Went in again with lost circulation materials (cottonseed hulls. cedar fiber) and filled well to the top with these. Blizzard conditions forced abandonment of well site for two days. Re-entered well when weather conditions allowed access to site and continued to have drilling problems, drilling ultimately to 710 feet. In process a total of 21.15 tons of cement and 202 sacks of lost circulation material were placed in the hole during this drilling interval. Throughflows of ground water continued to wash out the hole. Abandoned drilling at 710 feet, and tried to set gradient pipe, but could only get it to 660 feet, where a two and one-half inch black iron pipe was set. Well was spudded on October 8 and completed November 7, 1979. It took approximately one month to go 730 feet at this site.

GEOLOGIC SECTION:

Interval (feet)	Lithology and Comments (USGS)
0-21	Overburden (swamp and glacial materials)
21-80	Andesite flow, very fresh, hard, with abundant small plagioclase phenocrysts in fine-grained gray groundmass.
80-120	Volcanic debris, much of it probably mudflow materials
120-130	Andesite flow. Fresh, fine-grained, with phenocrysts of plagioclase, clinopyroxene, and olivine
130-140	Volcanic debris. Dark-gray andesite with abundant white plagioclase phenocrysts is dominant rock type. Vapor-phase cavities are lined with pink oxidized rim, and hematite occurs in groundmass
140-150	Andesite flow. Dark-gray, massive, fine-grained with occasional phenocrysts of oliving, plagioclase, and orthopyroxene. Flow is very different from overlying flows
150-170	Volcanic debris. Mixed lithologies, with medium-gray andesite most abundant
170-300	Andesite flow. Probably more than one flow makes up this interval, but cuttings do not change significantly, except for minor oxidation and vapor-phase cavities increasing with depth

Interval (feet)	Lithology and Comments (USGS)
300-310	Andesite flow, fine-grained, medium-gray with occasional phenocrysts of plagioclase, olivine, and clinopyroxene. Hematite and cristobalite present in groundmass. Distinctive from the overlying flow
310-425	Volcanic debris. Mixture of volcanic fragments in varying proportions, indicating interval may consist of several thin flows between volcanic debris layers, or that several large volcanic boulders were encountered during drilling
425-450	Andesite flow, partly oxidized, with few phenocrysts of plagioclase, olivine, and clinopyroxene. Groundmass contains plagioclase, clinopyroxene, hematite, and cristobalite
450-500	Andesite flow, similar to overlying flow but two are separated by oxidized layer at 450 feet
500-530	Volcanic debris
530-550	Dacite. Fresh, light-gray, medium to fine-grained with scarce phenocrysts of plagioclase and clinopyroxene. Groundmass of plagioclase, cristobalite, clinopyroxene, and hematite
550-580	Volcanic debris
580-600	Andesite flow, medium-gray, to mottle pink porphyritic andesite with sporadic phenocrysts of plagioclase, clinopyroxene, orthopyroxene, and olivine. Vapor-phase hematite and tridymite occur in cavaties
600-660	Volcanic debris
660-720	Andesite flow, thin flow, medium-gray, dense, fine-grained, with few phenocrysts
720-730	Dacite flow, light-gray, fine-grained, equigranular

GENERAL OBSERVATIONS: (USGS) Much of this drill hole is probably in the upper Miocene Rhododendron Formation which is hydrothermally altered nearly everywhere it crops out. Alteration in EWEB 5 drill hole consists of two types:

(1) Fe oxidation which changes color of rock from gray to pink or reddish by staining. This process can occur during cooling of the flows and probably accounts for most of the oxidation described for these rocks.

(2) Alteration of thermal waters due to low-temperature circulation. The brick-red groundmass alteration of the nearby surface outcrops, and the volcanic debris units in the drill hole is probably due to low-temperature hydrothermal alteration.

GEOTHERMAL GRADIENT: The well was essentially isothermal over the entire depth. Temperature at 33 feet (10 meters) was 4.23°C, and at 635 feet (193.5 meters) was 5.31°C. Figures of final logging on May 28, 1980 are in Table 1, with graph of figures, and graph also of well temperature log is on Figure 5.

NAME OF WELL: Eugene Water & Electric Board No. 6. Sisi Creek.
LOCATION: Long. 121°52'52" W., 44°54'19" N., Clackamas County, Oregon. (Mount Hood National Forest).
ELEVATION: 2800 feet. (853.7 meters).
TOTAL DEPTH 1510 feet (460.4 meters).
TOPOGRAPHIC/GEOLOGIC LOCATION: On the west side base of Sisi Butte, on the east edge of the valley of the Clackamas River. Glacial debris mantles the area. Sisi Butte is a conspicuous young volcanic cone with the top about 1.9 miles east of the drill site.
DRILLING DETAILS: Drilling the coarse, boulder (up to 4 feet in diameter) surficial glacial debris was a problem and the drill stuck temporarily several times to base of glacial debris at 69 feet. Drilled into andesite and on to 90 feet where drill stick and twisted off sub and bit. Attempted to fish unsuccessfully. Moved rig 20 feet and began to re-drill. Drilled to 470 feet and then had lost circulation. Gunk plugs and lost circulation materials did not help and cement truck called in. 170 sacks of cement put into hole. Drilled out, and with minor lost circulation problems continued to total depth of 1510 feet. Hung two and one-half inch black iron gradient pipe in hole.
GEOLOGIC SECTION:

<u>Interval</u> (feet)	<u>Lithology and Comments</u> (USGS)
0-69	Glacial debris
70-80	Olivine basalt flow
80-140	Basalt flow, upper 20 feet somewhat vesicular. Small phenocrysts of clear to white plagioclase abundant
140-280	Basalt flow, nearly equigranular fine-grained orthopyroxene, clinopyroxene, plagioclase, and minor olivine
280-320	Flow consisting of interlayered obsidian and andesite
320-460	Volcanic debris; dominant rock types are dense, dark and medium-gray andesites
460-560	Interval of hydrothermal alteration. No recovery was obtained through much of this interval A small amount of material at 500 to 560 feet consists of fine-grained soft, pink to buff hydrothermally altered volcanic rock
560-1300	Dacite, fine-grained, with phenocrysts of plagioclase and partly oxidized reddish black altered hornblende
1300-1350	Volcanic debris, multicolored fragments of volcanic material
1350-1410	Andesite flow, dark-gray, dense, fine-grained
1410-1440	Andesite flow, dark-gray, with scattered clear plagioclase phenocrysts
1410-1510	Andesite flow, mostly pink oxidized, some dark-gray andesite

GENERAL OBSERVATIONS (USGS) Hydrothermal alteration in EWEB 6 is significant in two intervals:

(1) 470-560 feet where recovery consists of a few pieces of light pink altered dacite which has been extensively altered to montmorillonite. A possibility is that the 470-560 foot interval is a fault zone that formerly served as a channel for low-temperature hydrothermal fluid. Temperature data from the drill log give no indication of present hydrothermal fluids.

(2) 760-800 feet where there are red to orange iron-stained fracture surfaces. The driller's log at 800 feet mentions red clay, but nothing other than iron hydroxide appears in the cuttings.

GEOTHERMAL GRADIENT: Temperature data for this well in final log on April 29, 1980 are shown on Table 1, and plot of the geothermal gradient data is shown on Figure 5 and in a plot also in Table 1. The gradient for the first approximately 82 feet (25 meters) is essentially isothermal. This represents the vadose water zone. From 82 feet (25 meters) to total depth of 1510 feet (460 meters) the gradient is essentially linear at about 51.9°C/Km which is about average for this portion of the Cascades.

SUMMARY AND CONCLUSIONS

Six wells were drilled during this program, although in effect seven were drilled as two wells were drilled at site 3, the second well, however, actually going to a lesser depth than the first. Three of the wells (3, 4, and 5) were drilled in areas which topographically are subject to strong through-flows of ground water. None of these wells reached the regional ater table, and all showed essentially isothermal geothermal gradients. The single well which was started essentially at the water table (well 6) shows a linear temperature rise with depth essentially from the top of the well bore. Well number 2 (Twin Meadows) shows an isothermal gradient down to the level of the regional water table (the main stream valley adjacent to the well site on the west) and then shows a linear gradient of about 70°C/Km from the regional water table to total depth.

Well number 1 (Fish Lake Creek), which was drilled on a broad interstream divide between the headwaters of the North Fork of the McKenzie River, and the North Santiam River and is not immediately adjacent to any deep valleys, shows essentially an isothermal gradient in much of the lower part of the well, reflecting cold water saturation of this portion of the drilled section, but the upper part of the wells shows a high gradient (102°C/Km) which may be due to the presence at about 655 feet (200 meters) of a fracture which is carrying warm water from a geothermal system in the region. The most probable location of such a system is to the east and northeast, which is topographically up-slope and is a fracture line marked by several young (3000 years) volcanic cones (the Sand Mountain, and Nash Crater-Little Nash Crater lineaments). This area should be investigated further.

Little alteration was found in cuttings from any of the wells which could be ascribed to active geothermal systems. However, only two of the wells got below 1160 feet, so the sampling is from rather surficial rocks. It is likely that the continual flow of cold vadose waters through the surficial rocks of the Cascades (from the 80 to 100 or more inches of annual precipitation) does now and did also in the past preclude the the ability of thermal waters to reach these surficial rocks, and therefore evidence of geothermal systems is not likely to be found at shallow depths in the upland areas of these terrains.

Drilling with light equipment to depths of 2000 feet or less appears to be feasible and rewarding only where the well site can be located so that the regional water table can be found at shallow depth. Wells located where there is a thick interval of vadose waters to be penetrated are likely to have severe drilling problems, and unless the vadose zone is completely penetrated and the drill goes a reasonable distance below the regional water table, the wells will simply shown an isothermal gradient. This area where shallow wells are generally of little use is the broad upland bench-like area which lies west of the Cascade crest and east of the first major system of stream valleys.

DR. BLACKWELL'S OBSERVATIONS ON THESE GRADIENTS

Dr. David Blackwell of the Geothermal Laboratory at Southern Methodist University made conductivity tests on a complete suite of cuttings from all the wells and provided the data and graphs which are on Figure 5 and in Table 1. He also has provided a written summary of his observations on these data and his statement is here reproduced on the following three pages in its entirety.

HEAT FLOW AND GEOTHERMAL IMPLICATIONS OF THE EWEB CASCADE DRILL HOLES

David D. Blackwell

A series of holes drilled under the direction of Walter Youngquist, Ph.D., with the sponsorship of the Eugene Water and Electric Board and supported by DOE, represent the first intermediate-depth drilling information in the public domain in the central Oregon High Cascade Range. Temperature measurements have been made in these holes by personnel from the Oregon Department of Geology and Mineral Industries and from Southern Methodist University. In addition, gamma logs were obtained on the accessible holes. Thermal conductivity measurements were made in the SMU Geothermal Laboratory, and terrain corrections and heat flow calculations have also been made by this laboratory. A set of equilibrium temperature logs measured in the late spring of 1980 are shown in Figure 5 and a summary of location and thermal data are included in Table 1.

The holes fall into two different groups of "type" temperature-depth curves, with five of the holes associated with one type and one hole associated with the second type. The characteristic feature of temperature-depth curves drilled in the Western Cascade volcanic rocks in earlier years by DOGAMI has been linear temperature-versus-depth curves. It has become clear that the altered volcanic rocks of the Western Cascade province in general are relatively impermeable. It was also clear in the shallower drilling that, as sites were moved into the High Cascade rocks, the shallow temperatures would be swamped by copious water circulation in the porous young volcanic rocks at the surface, and that deeper holes would be necessary in order to investigate conditions below the young volcanic rocks. The EWEB series of holes illustrates the truth of these conclusions. Five of the drill holes indicate very low gradients to depths in excess of 100 m, and in four cases, to depths in excess of 150 m. The observed gradients approach the "regional" gradient (60-70°C/km) at a depth of approximately 150 m in 8S/8E-6dd, and rather abruptly at a depth of 220 m in hole 12S/7E-9da. The average temperature gradient below 150 m in hole 8S/8E-6dd is 63°C/km, corrected for topographic effects, while the average temperature gradient below 250 m in hole 12S/7E-9da is 69°C/km, corrected for topographic effects. Both of these mean gradients are typical background gradients similar to those observed in the Western Cascade Range east of the heat flow transition, which appears to mark the western thermal boundary of the High Cascade Range thermal anomaly (see Blackwell <u>et</u> <u>al.</u>, 1978, 1979).

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The very high gradients between 290 and 310 m in hole 8S/8E-6dd are either due to lithology or due to a slight fluid upflow in the borehole from near the bottom. Thermal conductivity measurements indicate a rock-type change in this depth range; however, the gamma log does not indicate a major change in the nature of K, U or Th content, although near the bottom of the hole, the gamma log does show more character, typical of interbedded basic volcanic rocks and tuffs or volcanoclastic rocks.

Even though the shallow gradients have been "swamped" to depths of 150-220 m in these holes, this effect might not be present everywhere. If active hydrothermal systems are present in High Cascade rocks, the rocks might be highly altered to a relatively impermeable state. In this case shallow holes might give conductive gradients.

The best heat flow values determined for holes 8S/8E-6dd and 12S/7E-9da are the same, 94 mW/m^2. Holes 7S/7E-4dd, 7S/8E-5dd and 7S/8E-10ad were drilled at the highest elevations, and failed to penetrate through the carapace of young, porous volcanic rocks. Consequently, the temperature-depth curves are essentially isothermal in these holes, and we are able to obtain no information about possible temperature gradients at depth.

Hole 13S/7E-32dc has an unusual temperature-depth curve. It is nearly isothermal through young basalts to a depth of 60 m, at which point the gradient is high and constant, with a value of 102°C/km. At a depth of 200 m, the gradient becomes isothermal and finally negative. It gradually increases and becomes positive again toward the bottom of the hole. The cause for this type of curve has been discussed in a previous letter: lateral flow of warm water along an aquifer between 200-220 m, superimposed on a background of relatively low heat flow. If more than one hole were available in this area, it would be possible to estimate the distance to the source and the possible temperature of the water coming up along the fracture zone and feeding this shallow aquifer. Based on a model similar to that discussed by Bodvarsson (1969), we estimate the initiation of the water flow in the age range of 1000 ± 500 years. This curve is typical of what one might expect to find associated with a geothermal system. It has already been recommended that the hole be perforated and samples be obtained from the aquifer at 200 m, in order for a chemical analysis to be performed and geochemical temperatures to be estimated.

In conclusion, the data have tended to confirm the ideas developed in drilling immediately to the west. The regional background gradient for the High Cascade Range is on the order of 60-70°C/km, with regional heat flow values of 95-110 mW/m^2. The high heat flow and geothermal gradients are maintained by a regional magma chamber at a depth of about 10 km. Superimposed on this background heat flow will be areas of low and high geothermal gradients and heat flow associated with groundwater and geothermal convective systems in the High Cascade Range. Groundwater convective systems obliterate shallow temperature gradients to the depths where groundwater penetration is rapid. Groundwater circulation, if as deep as 5 km, should generate temperatures high enough for commercial exploitation of the fluid in geothermal power production. Local hot spots may be associated with individual volcanoes, but the indications so far are that shallow magma chambers associated with the stratovolcanoes tend to be small. Commercial geothermal systems have not yet been directly identified in the results of the drilling.

REFERENCES

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Blackwell, D.D., and J.L. Steele, Heat flow modeling of the Mount Hood volcano, Oregon, pp. 190-264, in Geothermal Resource Assessment of Mount Hood, Final Report, D.O.E. #AC06-77-ET-28369, 1979.

Bodvarsson, G., On the temperature of water flowing through fractures, Journal of Geophysical Research, 74 (8), p. 1987-1992, 1969.

FIGURE 5. Equilibirum temperature-depth plots for all six Eugene Water & Electric Board drill holes. (Supplied by Dr. David Blackwell, Geothermal Laboratory, Southern Methodist University, Dallas, Texas).

FIGURE 5

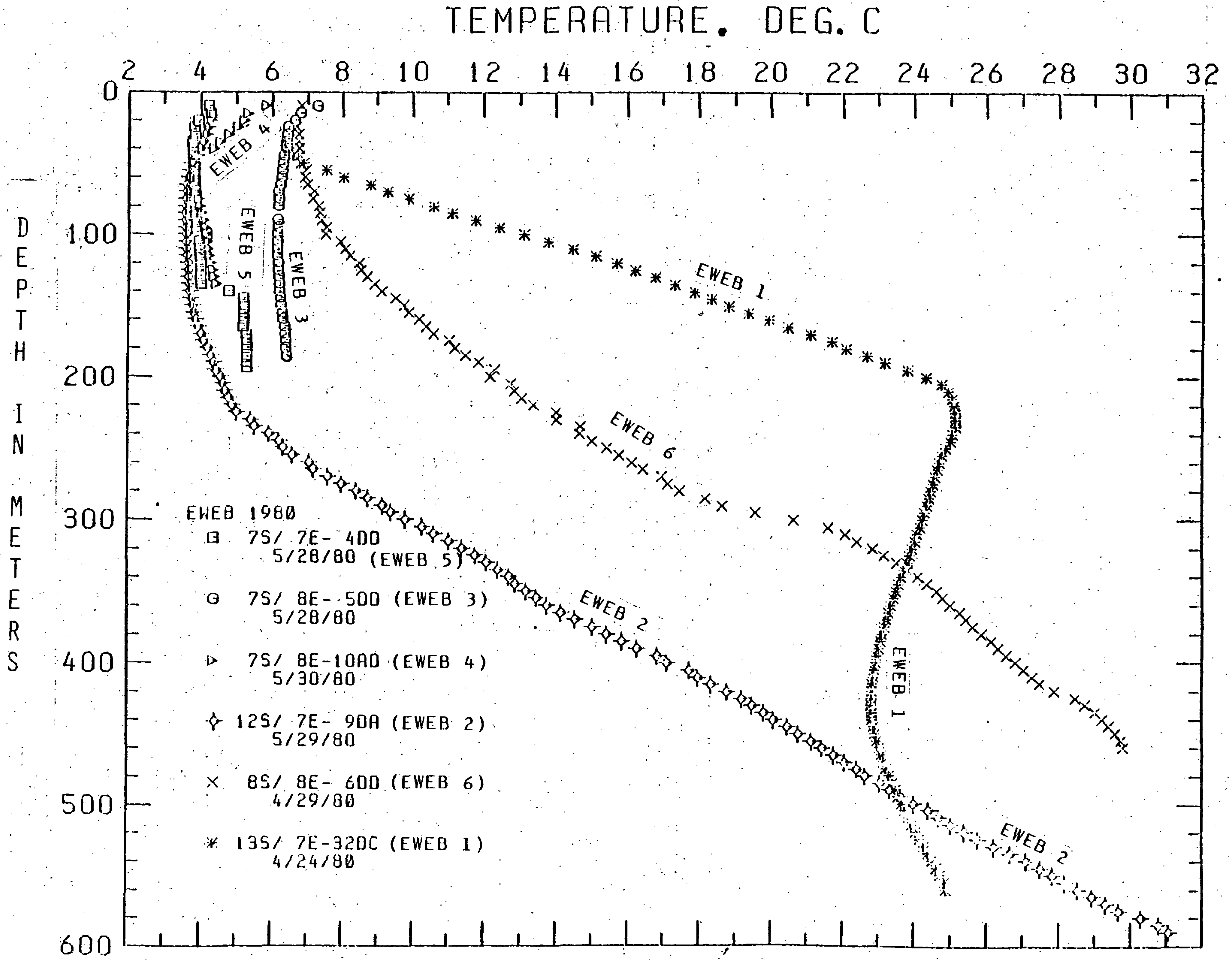

TEMPERATURE. DEG. C
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
DEPTH IN METERS
0
100
200
300
400
500
600
EWEB 4
EWEB 5
EWEB 3
EWEB 1
EWEB 6
EWEB 2
EWEB 1
EWEB 2
EWEB 1980
⊟ 7S/ 7E- 4DD 5/28/80 (EWEB 5)
⊖ 7S/ 8E- 5DD (EWEB 3) 5/28/80
▷ 7S/ 8E-10AD (EWEB 4) 5/30/80
✧ 12S/ 7E- 9DA (EWEB 2) 5/29/80
× 8S/ 8E- 6DD (EWEB 6) 4/29/80
✳ 13S/ 7E-32DC (EWEB 1) 4/24/80

FIGURE 6. Gamma ray log on EWEB no. 5. Tarzan Springs.

GAMMA RAY LOG

HOLE NAME: EWEB-TS EWEB NO. 5
TARZAN SPRINGS
LOCATION: 7S/7E-4DD
BEND AMS, OREGON
DATE: 11/13/79
DEPTH LOGGED: 190 METERS
SPEED LOGGED: 6 METERS/MINUTE
TIME CONSTANT: 3 SECONDS
FULL SCALE: 100 COUNTS/SECOND

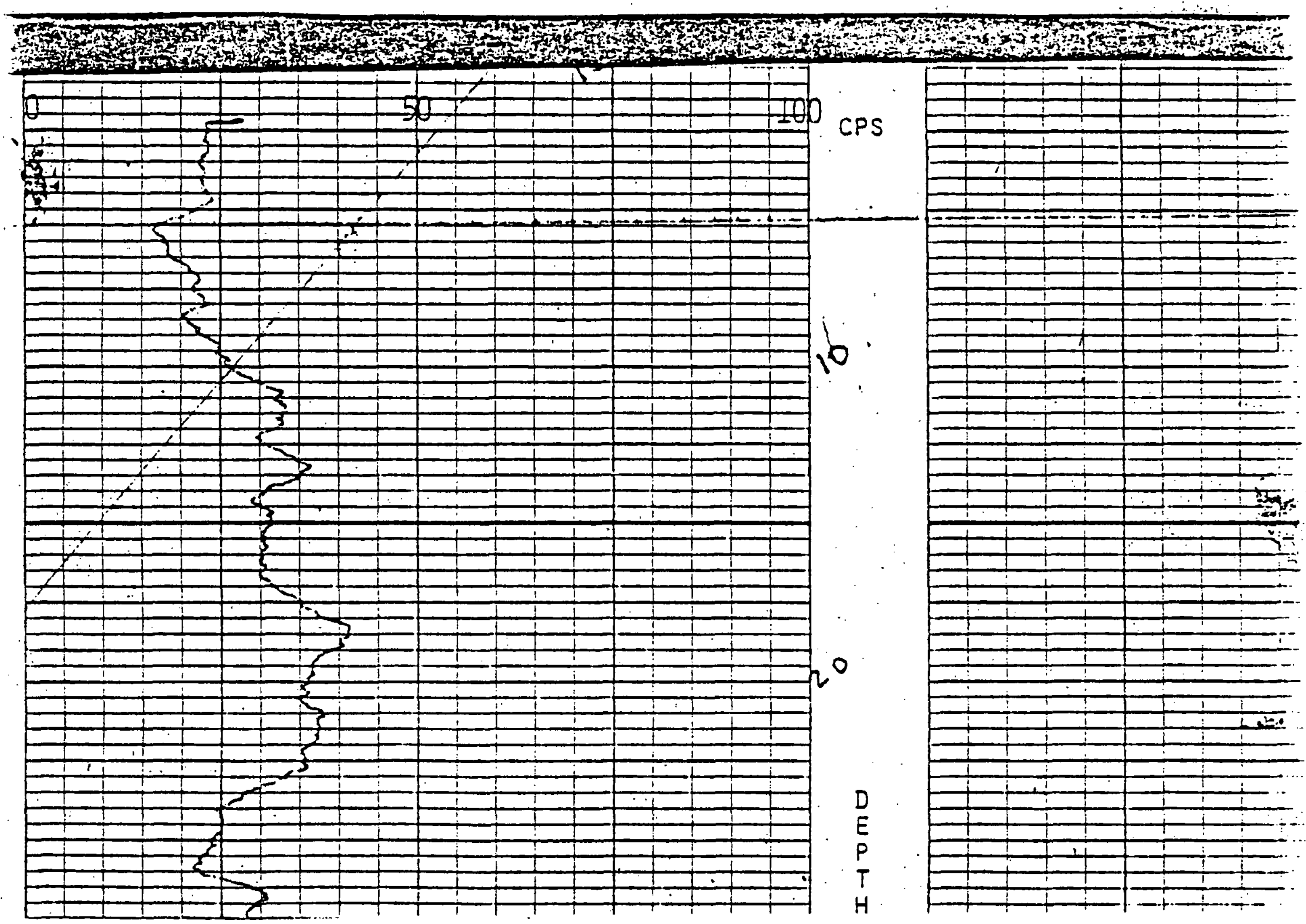


FIGURE 7. Gamma ray log on EWEB no. 6. Sisi Creek.

GAMMA RAY LOG

SOUTHERN METHODIST UNIVERSITY
DALLAS, TEXAS

HOLE NAME: EWEB-SB EWEB NO. 6 SISI CREEK
LOCATION: 8S/8E-6DD
BEND AMS, OREGON
DATE: 11/13/79
DEPTH LOGGED: 457.5 METERS
SPEED LOGGED: 6 METERS/MINUTE
TIME CONSTANT: 3 SECONDS
FULL SCALE: 100 COUNTS/SECOND

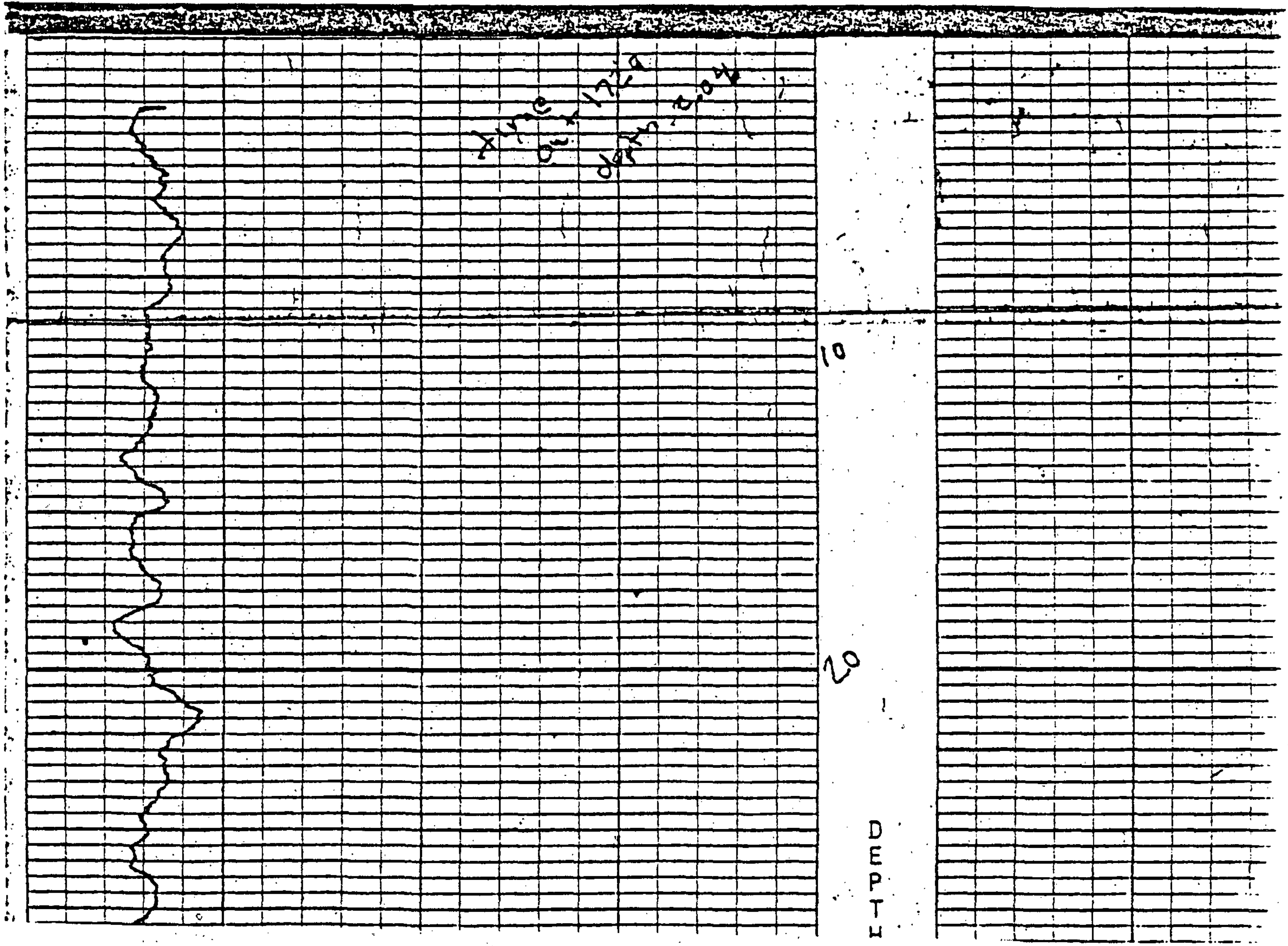
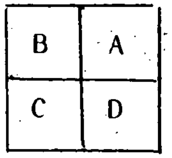


TABLE 1. Equilibrium temperature-depth data for EWEB drill holes, with plots of individual well data. (Supplied by Dr. David Blackwell, Geothermal Laboratory, Southern Methodist University, Dallas, Texas).

TABLE 1. Geothermal data for EWEB holes. (Summary)

Twn/Rng- Section	Prov.	N Lat. Deg.Min.	W Long. Deg.Min.	Hole # Date	Collar Elev. (m)	Depth Interval (m)	Avg. TC $Wm^{-1}K^{-1}$	# TC	Uncorr. Gradient °C/km	Corr. Gradient °C/km	Corr. HF mWm^{-1}	HF Qual.	Lithologic Summary
(EWEB 3) 7S/ 8E- 5DD	HC	44-59.0	121-50.8	EWEB-PC 10/30/79	975	70.0 185.0	1.58 .04	10	4.5 .8			X	BASALT (Q)
(EWEB 5) 7S/ 7E- 4DD	HC	44-59.0	121-57.0	EWEB-TS 11/13/79	1273	165.0 190.0	1.62 .04	10				X	BASALT (Q)
(EWEB 4) 7S/ 8E- 10AD	HC	44-58.5	121-48.4	EWEB-CC 10/18/79	1140	110.0 137.0	1.45 .10	10				X	BASALT (Q)
(EWEB 6) 8S/ 8E- 6DD	HC	44-54.3	121-52.9	EWEB-SB 11/13/79	860	150.0 460.0	1.49 .13	20	71.5 1.1	63.3	94	B	BASALT AND ANDESITE
(EWEB 2) 12S/7E- 9DA	HC	44-32.7	121-57.8	EWEB-TM 10/31/79	1195	300.0 600.0	1.36 .08		71.4 1.3	69.4	94	B	VOLCANICS
(EWEB 1) 13S/7E- 32DC	HC	44-23.3	121-59.7	EWEB-CL 10/30/79	955	50.0 205.0	1.44 -	10	112.0 2.2	102.8	148	B	ANDESITE & VOLCANICS
						.0 555.0	1.40	19	25.6 11.4	23.9	33	C	

Location System



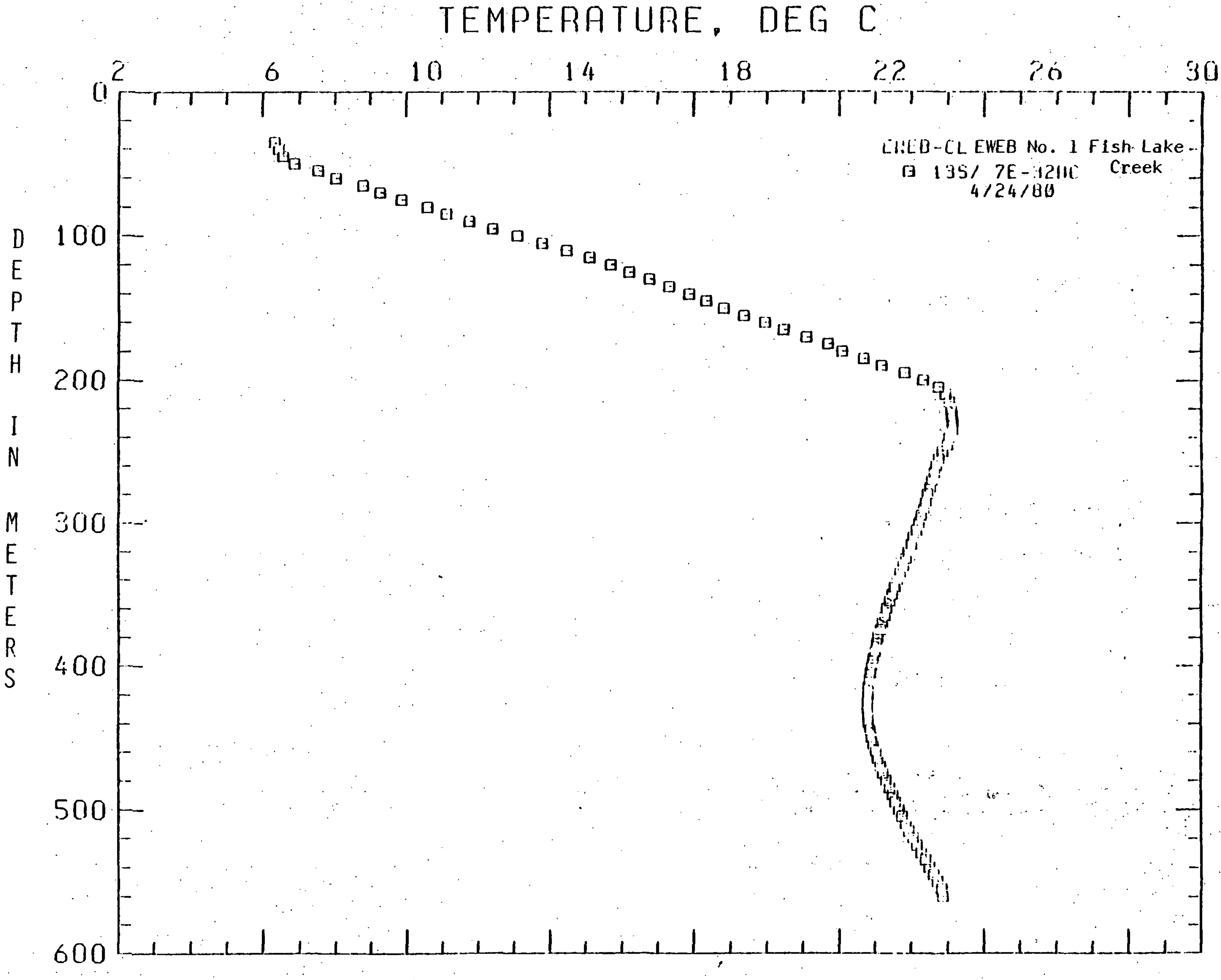
Section

LOCATION: BEND AMS, OREGON
13S/ 7E-32DC
HOLE NAME: EWEB-CL EWEB No. 1 Fish Lake Creek
DATE MEASURED: 4/24/80

DEPTH	DEPTH	TEMPERATURE		GEOTHERMAL GRADIENT	
METERS	FEET	DEG C	DEG F	DEG C/KM	DEG F/100 FT
35.0	114.8	6.340	43.41	0.0	0.0
40.0	131.2	6.450	43.61	22.0	1.2
45.0	147.6	6.580	43.84	26.0	1.4
50.0	164.0	6.880	44.38	60.0	3.3
55.0	180.4	7.530	45.55	130.0	7.1
60.0	196.8	8.040	46.47	102.0	5.6
65.0	213.2	8.610	47.86	154.0	8.5
70.0	229.6	9.290	48.72	96.0	5.3
75.0	246.0	9.880	49.78	118.0	6.5
80.0	262.4	10.610	51.10	146.0	8.0
85.0	278.8	11.130	52.03	104.0	5.7
90.0	295.2	11.770	53.19	128.0	7.0
95.0	311.6	12.430	54.37	132.0	7.2
100.0	328.0	13.110	55.60	136.0	7.5
105.0	344.4	13.790	56.82	136.0	7.5
110.0	360.8	14.480	58.06	138.0	7.6
115.0	377.2	15.120	59.22	128.0	7.0
120.0	393.6	15.700	60.26	116.0	6.4
125.0	410.0	16.210	61.18	102.0	5.6
130.0	426.4	16.770	62.19	112.0	6.1
135.0	442.8	17.320	63.18	110.0	6.0
140.0	459.2	17.870	64.17	110.0	6.0
145.0	475.6	18.330	64.99	92.0	5.0
150.0	492.0	18.810	65.86	96.0	5.3
155.0	508.4	19.360	66.85	110.0	6.0
160.0	524.8	19.940	67.89	116.0	6.4
165.0	541.2	20.470	68.85	106.0	5.8
170.0	557.6	21.100	69.98	126.0	6.9
175.0	574.0	21.700	71.06	120.0	6.6
180.0	590.4	22.090	71.76	78.0	4.3
185.0	606.8	22.690	72.84	120.0	6.6
190.0	623.2	23.190	73.74	100.0	5.5
195.0	639.6	23.820	74.88	126.0	6.9
200.0	656.0	24.340	75.81	104.0	5.7
205.0	672.4	24.760	76.57	84.0	4.6
210.0	688.8	24.960	76.93	40.0	2.2
215.0	705.2	25.060	77.11	20.0	1.1
220.0	721.6	25.110	77.20	10.0	0.5
225.0	738.0	25.130	77.23	4.0	0.2
230.0	754.4	25.150	77.27	4.0	0.2
235.0	770.8	25.140	77.25	-2.0	-0.1
240.0	787.2	25.050	77.09	-18.0	-1.0
245.0	803.6	25.000	77.00	-10.0	-0.5
250.0	820.0	24.860	76.75	-28.0	-1.5
255.0	836.4	24.760	76.57	-20.0	-1.1
260.0	852.8	24.690	76.44	-14.0	-0.8
265.0	869.2	24.640	76.35	-10.0	-0.5
270.0	885.6	24.580	76.24	-12.0	-0.7
275.0	902.0	24.520	76.14	-12.0	-0.7
280.0	918.4	24.460	76.03	-12.0	-0.7
285.0	934.8	24.410	75.94	-10.0	-0.5
290.0	951.2	24.350	75.83	-12.0	-0.7
295.0	967.6	24.290	75.72	-12.0	-0.7
300.0	984.0	24.230	75.61	-12.0	-0.7
305.0	1000.4	24.160	75.49	-14.0	-0.8
310.0	1016.8	24.080	75.34	-16.0	-0.9
315.0	1033.2	24.020	75.24	-12.0	-0.7
320.0	1049.6	23.940	75.09	-16.0	-0.9
325.0	1066.0	23.870	74.97	-14.0	-0.8
330.0	1082.4	23.800	74.84	-14.0	-0.8
335.0	1090.8	23.720	74.70	-16.0	-0.9
340.0	1115.2	23.640	74.55	-16.0	-0.9
345.0	1131.6	23.570	74.43	-14.0	-0.8
350.0	1148.0	23.490	74.28	-16.0	-0.9
355.0	1164.4	23.420	74.16	-14.0	-0.8
360.0	1180.8	23.350	74.03	-14.0	-0.8
365.0	1197.2	23.290	73.92	-12.0	-0.7
370.0	1213.6	23.220	73.80	-14.0	-0.8
375.0	1230.0	23.170	73.71	-10.0	-0.5
380.0	1246.4	23.110	73.60	-12.0	-0.7
385.0	1262.8	23.060	73.51	-10.0	-0.5
390.0	1279.2	23.010	73.42	-10.0	-0.5
395.0	1295.6	22.970	73.35	-8.0	-0.4
400.0	1312.0	22.930	73.27	-8.0	-0.4
405.0	1328.4	22.900	73.22	-6.0	-0.3
410.0	1344.8	22.860	73.15	-8.0	-0.4
415.0	1361.2	22.830	73.09	-6.0	-0.3
420.0	1377.6	22.820	73.08	-2.0	-0.1
425.0	1394.0	22.810	73.06	-2.0	-0.1
430.0	1410.4	22.810	73.06	0.0	0.0
435.0	1426.8	22.820	73.08	2.0	0.1
440.0	1443.2	22.830	73.09	2.0	0.1

LOCATION: BEND AMS, OREGON
13S/ 7E-32DC
HOLE NAME: EWEB-CL EWEB No. 1 Fish Lake Creek (continued)
DATE MEASURED: 4/24/80

DEPTH METERS	DEPTH FEET	TEMPERATURE DEG C	TEMPERATURE DEG F	GEOTHERMAL GRADIENT DEG C/KM	GEOTHERMAL GRADIENT DEG F/100 FT
445.0	1459.6	22.880	73.18	10.0	0.5
450.0	1476.0	22.920	73.26	8.0	0.4
455.0	1492.4	22.970	73.35	10.0	0.5
460.0	1508.8	23.030	73.45	12.0	0.7
465.0	1525.2	23.080	73.54	10.0	0.5
470.0	1541.6	23.150	73.67	14.0	0.8
475.0	1558.0	23.230	73.81	16.0	0.9
480.0	1574.4	23.310	73.96	16.0	0.9
485.0	1590.8	23.410	74.14	20.0	1.1
490.0	1607.2	23.490	74.28	16.0	0.9
495.0	1623.6	23.570	74.43	16.0	0.9
500.0	1640.0	23.660	74.59	18.0	1.0
505.0	1656.4	23.750	74.75	18.0	1.0
510.0	1672.8	23.850	74.93	20.0	1.1
515.0	1689.2	23.950	75.11	20.0	1.1
520.0	1705.6	24.060	75.31	22.0	1.2
525.0	1722.0	24.170	75.51	22.0	1.2
530.0	1738.4	24.280	75.70	22.0	1.2
535.0	1754.8	24.400	75.92	24.0	1.3
540.0	1771.2	24.510	76.12	22.0	1.2
545.0	1787.6	24.620	76.32	22.0	1.2
550.0	1804.0	24.730	76.51	22.0	1.2
555.0	1820.4	24.850	76.73	24.0	1.3
560.0	1836.8	24.880	76.78	6.0	0.3

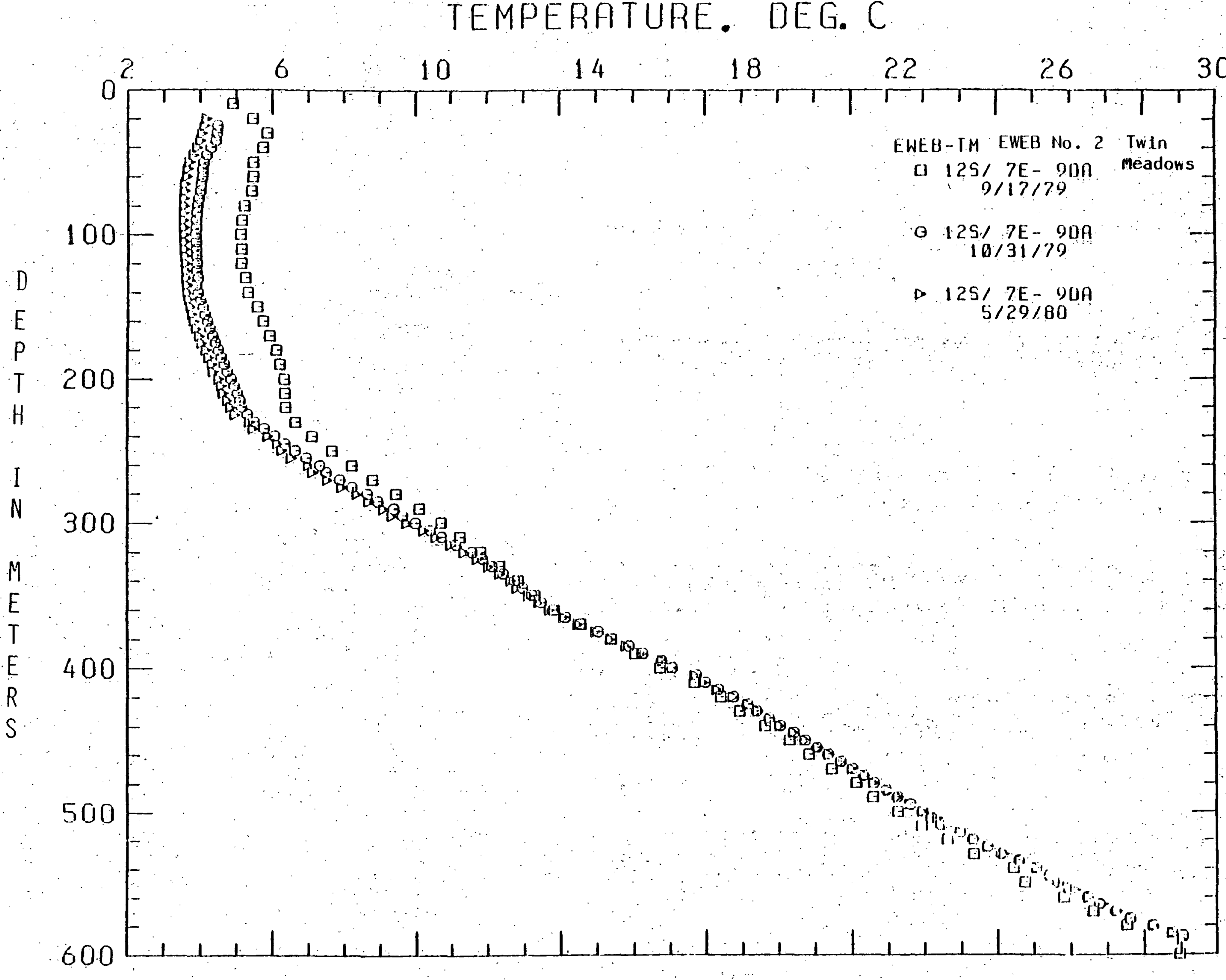

TEMPERATURE, DEG C
2
6
10
14
18
22
26
30
0
100
200
300
400
500
600
DEPTH IN METERS
CHEB-CL EWEB No. 1 Fish Lake Creek
⊟ 13S/ 7E-32DC
4/24/80

LOCATION: BEND AMS, OREGON
12S/ 7E- 9DA
HOLE NAME: EWEB-TM EWEB No. 2 Twin Meadows
DATE MEASURED: 5/29/80

DEPTH METERS	DEPTH FEET	TEMPERATURE		GEOTHERMAL GRADIENT	
		DEG C	DEG F	DEG C/KM	DEG F/100 FT
20.0	65.6	4.190	39.54	0.0	0.0
25.0	82.0	4.150	39.47	-8.0	-0.4
30.0	98.4	4.080	39.34	-14.0	-0.8
35.0	114.8	4.030	39.25	-10.0	-0.5
40.0	131.2	3.930	39.07	-20.0	-1.1
45.0	147.6	3.840	38.91	-18.0	-1.0
50.0	164.0	3.710	38.68	-26.0	-1.4
55.0	180.4	3.660	38.59	-10.0	-0.5
60.0	196.8	3.640	38.55	-4.0	-0.2
65.0	213.2	3.600	38.48	-8.0	-0.4
70.0	229.6	3.590	38.46	-2.0	-0.1
75.0	246.0	3.580	38.44	-2.0	-0.1
80.0	262.4	3.570	38.43	-2.0	-0.1
85.0	278.8	3.560	38.41	-2.0	-0.1
90.0	295.2	3.560	38.41	0.0	0.0
95.0	311.6	3.560	38.41	0.0	0.0
100.0	328.0	3.570	38.43	2.0	0.1
105.0	344.4	3.570	38.43	0.0	0.0
110.0	360.8	3.580	38.44	2.0	0.1
115.0	377.2	3.590	38.46	2.0	0.1
120.0	393.6	3.610	38.50	4.0	0.2
125.0	410.0	3.620	38.52	2.0	0.1
130.0	426.4	3.630	38.53	2.0	0.1
135.0	442.8	3.640	38.55	2.0	0.1
140.0	459.2	3.660	38.59	4.0	0.2
145.0	475.6	3.700	38.66	8.0	0.4
150.0	492.0	3.740	38.73	8.0	0.4
155.0	508.4	3.780	38.80	8.0	0.4
160.0	524.8	3.840	38.91	12.0	0.7
165.0	541.2	3.910	39.04	14.0	0.8
170.0	557.6	3.990	39.18	16.0	0.9
175.0	574.0	4.050	39.29	12.0	0.7
180.0	590.4	4.170	39.51	24.0	1.3
185.0	606.8	4.270	39.69	20.0	1.1
190.0	623.2	4.350	39.83	16.0	0.9
195.0	639.6	4.390	39.90	8.0	0.4
200.0	656.0	4.530	40.15	28.0	1.5
205.0	672.4	4.610	40.30	16.0	0.9
210.0	688.8	4.650	40.37	8.0	0.4
215.0	705.2	4.770	40.59	24.0	1.3
220.0	721.6	4.870	40.77	20.0	1.1
225.0	738.0	4.960	40.96	22.0	1.2
230.0	754.4	5.380	41.68	80.0	4.4
235.0	770.8	5.480	41.86	20.0	1.1
240.0	787.2	5.890	42.60	82.0	4.5
245.0	803.6	6.160	43.09	54.0	3.0
250.0	820.0	6.290	43.32	26.0	1.4
255.0	836.4	6.540	43.77	50.0	2.7
260.0	852.8	7.020	44.64	96.0	5.3
265.0	869.2	7.140	44.85	24.0	1.3
270.0	885.6	7.550	45.59	82.0	4.5
275.0	902.0	7.950	46.31	80.0	4.4
280.0	918.4	8.370	47.07	84.0	4.6
285.0	934.8	8.710	47.68	68.0	3.7
290.0	951.2	9.110	48.40	80.0	4.4
295.0	967.6	9.360	48.85	50.0	2.7
300.0	984.0	9.760	49.57	80.0	4.4
305.0	1000.4	10.240	50.43	96.0	5.3
310.0	1016.8	10.580	51.04	68.0	3.7
315.0	1033.2	11.010	51.82	86.0	4.7
320.0	1049.6	11.380	52.48	74.0	4.1
325.0	1066.0	11.730	53.11	70.0	3.8
330.0	1082.4	12.040	53.67	62.0	3.4
335.0	1098.8	12.360	54.25	64.0	3.5
340.0	1115.2	12.670	54.81	62.0	3.4
345.0	1131.6	12.840	55.11	34.0	1.9
350.0	1148.0	13.140	55.65	60.0	3.3
355.0	1164.4	13.430	56.17	58.0	3.2
360.0	1180.8	13.730	56.71	60.0	3.3
365.0	1197.2	14.120	57.42	78.0	4.3
370.0	1213.6	14.510	58.12	78.0	4.3
375.0	1230.0	15.000	59.00	98.0	5.4
380.0	1246.4	15.390	59.70	78.0	4.3
385.0	1262.8	15.820	60.48	86.0	4.7
390.0	1279.2	16.250	61.25	86.0	4.7
395.0	1295.6	16.810	62.26	112.0	6.1
400.0	1312.0	17.080	62.74	54.0	3.0
405.0	1328.4	17.700	63.86	124.0	6.8
410.0	1344.8	17.950	64.31	50.0	2.7
415.0	1361.2	18.310	64.96	72.0	4.0
420.0	1377.6	18.740	65.73	86.0	4.7
425.0	1394.0	19.160	66.49	84.0	4.6

12S/ 7E- 9DA
HOLE NAME: EWEB-TM EWEB No. 2 Twin Meadows (continued)
DATE MEASURED: 5/29/80

DEPTH METERS	DEPTH FEET	TEMPERATURE DEG C	TEMPERATURE DEG F	GEOTHERMAL GRADIENT DEG C/KM	GEOTHERMAL GRADIENT DEG F/100 FT
430.0	1410.4	19.450	67.01	58.0	3.2
435.0	1426.8	19.770	67.59	64.0	3.5
440.0	1443.2	20.050	68.09	56.0	3.1
445.0	1459.6	20.420	68.76	74.0	4.1
450.0	1476.0	20.730	69.31	62.0	3.4
455.0	1492.4	21.090	69.96	72.0	4.0
460.0	1508.8	21.380	70.48	58.0	3.2
465.0	1525.2	21.720	71.10	68.0	3.7
470.0	1541.6	22.020	71.64	60.0	3.3
475.0	1558.0	22.360	72.25	68.0	3.7
480.0	1574.4	22.600	72.68	48.0	2.6
485.0	1590.8	23.020	73.44	84.0	4.6
490.0	1607.2	23.290	73.92	54.0	3.0
495.0	1623.6	23.600	74.48	62.0	3.4
500.0	1640.0	23.960	75.13	72.0	4.0
505.0	1656.4	24.370	75.87	82.0	4.5
510.0	1672.8	24.660	76.39	58.0	3.2
515.0	1689.2	24.990	76.98	66.0	3.6
520.0	1705.6	25.370	77.67	76.0	4.2
525.0	1722.0	25.750	78.35	76.0	4.2
530.0	1738.4	26.180	79.12	86.0	4.7
535.0	1754.8	26.630	79.93	90.0	4.9
540.0	1771.2	27.080	80.74	90.0	4.9
545.0	1787.6	27.450	81.41	74.0	4.1
550.0	1804.0	27.800	82.04	70.0	3.8
555.0	1820.4	28.140	82.65	68.0	3.7
560.0	1836.8	28.510	83.32	74.0	4.1
565.0	1853.2	28.890	84.00	76.0	4.2
570.0	1869.6	29.270	84.69	76.0	4.2
575.0	1886.0	29.640	85.35	74.0	4.1
580.0	1902.4	30.250	86.45	122.0	6.7
585.0	1918.8	30.770	87.39	104.0	5.7
590.0	1935.2	31.040	87.87	54.0	3.0


TEMPERATURE, DEG. C
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22
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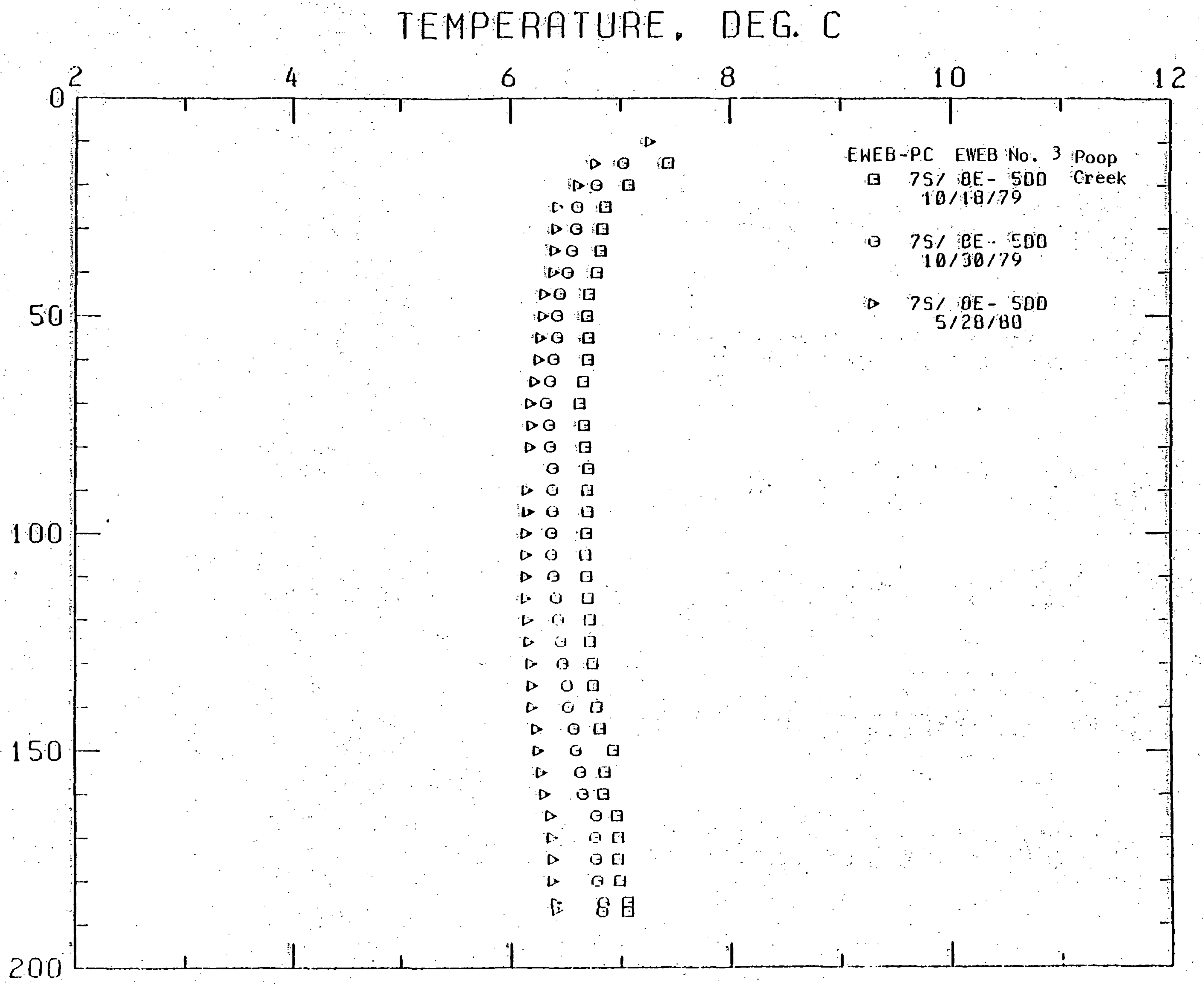
300
400
500
600
DEPTH IN METERS
EWEB-TM EWEB No. 2 Twin Meadows
□ 12S/ 7E- 9DA 9/17/79
⊙ 12S/ 7E- 9DA 10/31/79
▷ 12S/ 7E- 9DA 5/29/80

LOCATION: BEND AMS, OREGON
7S/ 8E- 5DD
HOLE NAME: EWEB-PC EWEB No. 3 Poop Creek
DATE MEASURED: 5/28/80

DEPTH METERS	DEPTH FEET	TEMPERATURE DEG C	DEG F	GEOTHERMAL GRADIENT DEG C/KM	DEG F/100 FT
10.0	32.8	7.280	45.10	0.0	0.0
15.0	49.2	6.780	44.20	-100.0	-5.5
20.0	65.6	6.630	43.93	-30.0	-1.6
25.0	82.0	6.440	43.59	-38.0	-2.1
30.0	98.4	6.430	43.57	-2.0	-0.1
35.0	114.8	6.410	43.54	-4.0	-0.2
40.0	131.2	6.400	43.52	-2.0	-0.1
45.0	147.6	6.320	43.38	-16.0	-0.9
50.0	164.0	6.310	43.36	-2.0	-0.1
55.0	180.4	6.280	43.30	-6.0	-0.3
60.0	196.8	6.260	43.27	-4.0	-0.2
65.0	213.2	6.230	43.21	-6.0	-0.3
70.0	229.6	6.190	43.14	-8.0	-0.4
75.0	246.0	6.200	43.16	2.0	0.1
80.0	262.4	6.190	43.14	-2.0	-0.1
95.0	311.6	6.170	43.11	-1.3	-0.1
90.0	295.2	6.160	43.09	2.0	0.1
95.0	311.6	6.160	43.09	0.0	0.0
100.0	328.0	6.150	43.07	-2.0	-0.1
105.0	344.4	6.150	43.07	0.0	0.0
110.0	360.8	6.150	43.07	0.0	0.0
115.0	377.2	6.150	43.07	0.0	0.0
120.0	393.6	6.160	43.09	2.0	0.1
125.0	410.0	6.170	43.11	2.0	0.1
130.0	426.4	6.190	43.14	4.0	0.2
135.0	442.8	6.200	43.16	2.0	0.1
140.0	459.2	6.200	43.16	0.0	0.0
145.0	475.6	6.240	43.23	8.0	0.4
150.0	492.0	6.250	43.25	2.0	0.1
155.0	508.4	6.280	43.30	6.0	0.3
160.0	524.8	6.310	43.36	6.0	0.3
165.0	541.2	6.360	43.45	10.0	0.5
170.0	557.6	6.370	43.47	2.0	0.1
175.0	574.0	6.380	43.48	2.0	0.1
160.0	590.4	6.380	43.48	0.0	0.0
185.0	606.8	6.410	43.54	6.0	0.3
186.5	611.7	6.420	43.56	6.7	0.4


TEMPERATURE, DEG. C
2
4
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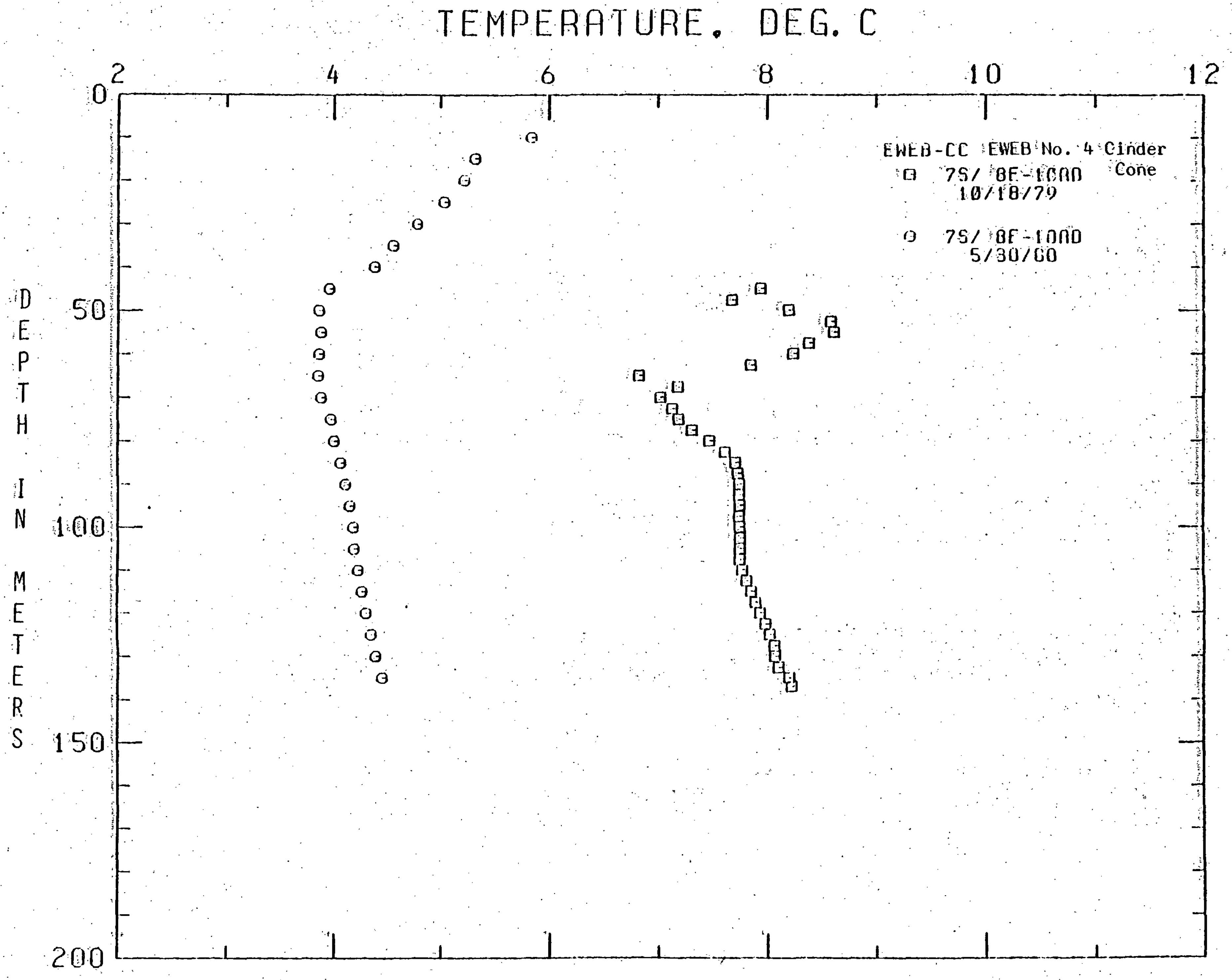
12
0
50
100
150
200
EWEB-PC EWEB No. 3 Poop Creek
⊟ 7S/ 8E- 5DD 10/18/79
⊖ 7S/ 8E- 5DD 10/30/79
▷ 7S/ 8E- 5DD 5/28/80

LOCATION: BEND AMS, OREGON
7S/ 8E-10AD
HOLE NAME: EWEB-CC EWEB No. 4 Cinder Cone
DATE MEASURED: 5/30/80

DEPTH METERS	DEPTH FEET	TEMPERATURE DEG C	TEMPERATURE DEG F	GEOTHERMAL GRADIENT DEG C/KM	GEOTHERMAL GRADIENT DEG F/100 FT
10.0	32.8	5.840	42.51	0.0	0.0
15.0	49.2	5.320	41.58	-104.0	-5.7
20.0	65.6	5.220	41.40	-20.0	-1.1
25.0	82.0	5.040	41.07	-36.0	-2.0
30.0	98.4	4.790	40.62	-50.0	-2.7
35.0	114.8	4.560	40.21	-46.0	-2.5
40.0	131.2	4.380	39.88	-36.0	-2.0
45.0	147.6	3.960	39.13	-84.0	-4.6
50.0	164.0	3.860	38.95	-20.0	-1.1
55.0	180.4	3.880	38.98	4.0	0.2
60.0	196.8	3.860	38.95	-4.0	-0.2
65.0	213.2	3.850	38.93	-2.0	-0.1
70.0	229.6	3.880	38.98	6.0	0.3
75.0	246.0	3.970	39.15	18.0	1.0
80.0	262.4	4.000	39.20	6.0	0.3
85.0	278.8	4.060	39.31	12.0	0.7
90.0	295.2	4.110	39.40	10.0	0.5
95.0	311.6	4.150	39.47	8.0	0.4
100.0	328.0	4.180	39.52	6.0	0.3
105.0	344.4	4.190	39.54	2.0	0.1
110.0	360.8	4.230	39.61	8.0	0.4
115.0	377.2	4.260	39.67	6.0	0.3
120.0	393.6	4.300	39.74	8.0	0.4
125.0	410.0	4.350	39.83	10.0	0.5
130.0	426.4	4.390	39.90	8.0	0.4
135.0	442.8	4.450	40.01	12.0	0.7


TEMPERATURE, DEG. C
2
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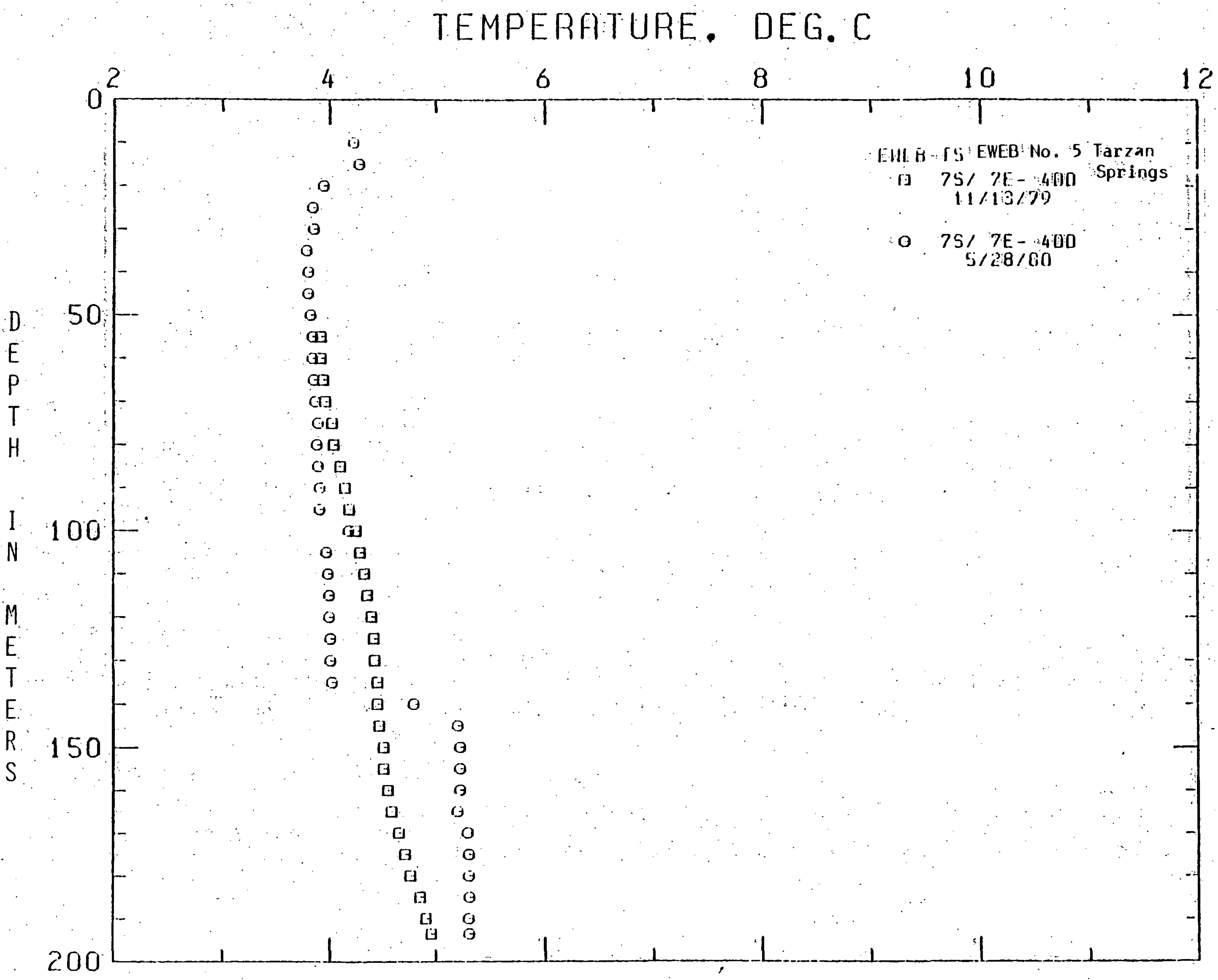
200
DEPTH IN METERS
EWEB-CC EWEB No. 4 Cinder Cone
□ 7S/ 8E-10DD 10/18/79
ʘ 7S/ 8E-10DD 5/30/80

LOCATION: BEND AMS, OREGON
7S/ 7E- 4DD
HOLE NAME: EWEB-TS EWEB No. 5 Tarzan Springs
DATE MEASURED: 5/28/80

DEPTH METERS	DEPTH FEET	TEMPERATURE DEG C	TEMPERATURE DEG F	GEOTHERMAL GRADIENT DEG C/KM	GEOTHERMAL GRADIENT DEG F/100 FT
10.0	32.8	4.230	39.61	0.0	0.0
15.0	49.2	4.280	39.70	10.0	0.5
20.0	65.6	3.940	39.09	-68.0	-3.7
25.0	82.0	3.840	38.91	-20.0	-1.1
30.0	98.4	3.850	38.93	2.0	0.1
35.0	114.8	3.780	38.80	-14.0	-0.8
40.0	131.2	3.800	38.84	4.0	0.2
45.0	147.6	3.800	38.84	0.0	0.0
50.0	164.0	3.820	38.88	4.0	0.2
55.0	180.4	3.840	38.91	4.0	0.2
60.0	196.8	3.840	38.91	0.0	0.0
65.0	213.2	3.850	38.93	2.0	0.1
70.0	229.6	3.860	38.95	2.0	0.1
75.0	246.0	3.890	39.00	6.0	0.3
80.0	262.4	3.880	38.98	-2.0	-0.1
85.0	278.8	3.890	39.00	2.0	0.1
90.0	295.2	3.910	39.04	4.0	0.2
95.0	311.6	3.910	39.04	0.0	0.0
100.0	328.0	4.180	39.52	54.0	3.0
105.0	344.4	3.970	39.15	-42.0	-2.3
110.0	360.8	3.990	39.18	4.0	0.2
115.0	377.2	4.000	39.20	2.0	0.1
120.0	393.6	4.000	39.20	0.0	0.0
125.0	410.0	4.010	39.22	2.0	0.1
130.0	426.4	4.010	39.22	0.0	0.0
135.0	442.8	4.020	39.24	2.0	0.1
140.0	459.2	4.790	40.62	154.0	8.5
145.0	475.6	5.200	41.36	82.0	4.5
150.0	492.0	5.220	41.40	4.0	0.2
155.0	508.4	5.220	41.40	0.0	0.0
160.0	524.8	5.220	41.40	0.0	0.0
165.0	541.2	5.200	41.36	-4.0	-0.2
170.0	557.6	5.290	41.52	18.0	1.0
175.0	574.0	5.300	41.54	2.0	0.1
180.0	590.4	5.300	41.54	0.0	0.0
185.0	606.8	5.310	41.56	2.0	0.1
190.0	623.2	5.300	41.54	-2.0	-0.1
193.5	634.7	5.310	41.56	2.9	0.2


TEMPERATURE, DEG. C
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4
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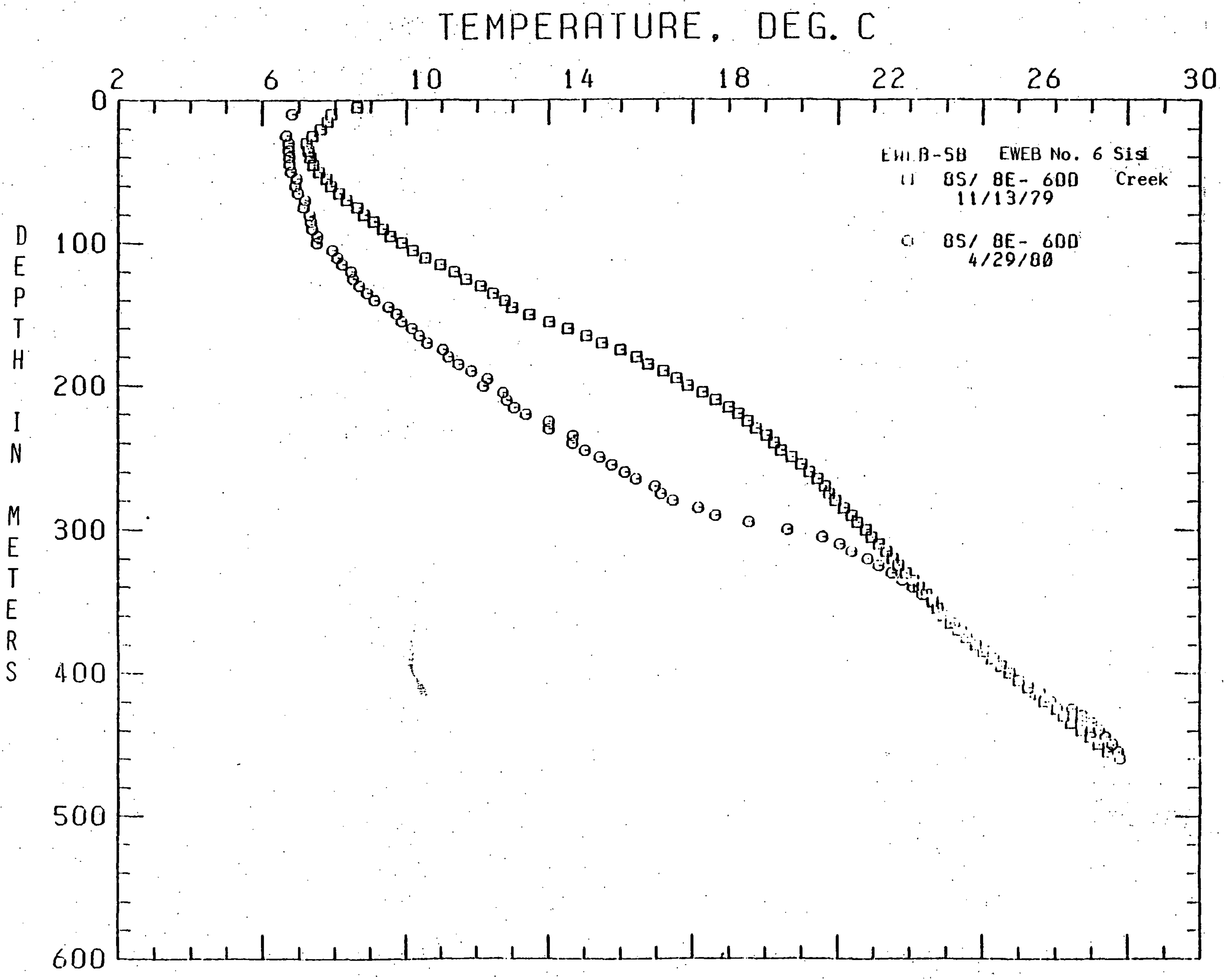
8
10
12
0
50
100
150
200
DEPTH IN METERS
EWEB-FS EWEB No. 5 Tarzan Springs
⊡ 7S/ 7E- 400
11/13/79
ʘ 7S/ 7E- 400
5/28/80

LOCATION: BEND AMS, OREGON
8S/ 8E- 6DD
HOLE NAME: EWEB-SB EWEB No. 6 Sisi Creek
DATE MEASURED: 4/29/80

DEPTH	DEPTH	TEMPERATURE		GEOTHERMAL GRADIENT	
METERS	FEET	DEG C	DEG F	DEG C/KM	DEG F/100 FT
10.0	32.8	6.820	44.28	0.0	0.0
25.0	82.0	6.660	43.99	-10.7	-0.6
30.0	98.4	6.730	44.11	14.0	0.8
35.0	114.8	6.730	44.11	0.0	0.0
40.0	131.2	6.750	44.15	4.0	0.2
45.0	147.6	6.760	44.17	2.0	0.1
50.0	164.0	6.800	44.24	8.0	0.4
55.0	180.4	6.950	44.51	30.0	1.6
60.0	196.8	6.920	44.46	-6.0	-0.3
65.0	213.2	6.980	44.56	12.0	0.7
70.0	229.6	7.170	44.91	38.0	2.1
75.0	246.0	7.140	44.85	-6.0	-0.3
80.0	262.4	7.320	45.18	36.0	2.0
85.0	278.8	7.350	45.23	6.0	0.3
90.0	295.2	7.380	45.28	6.0	0.3
95.0	311.6	7.520	45.54	28.0	1.5
100.0	328.0	7.510	45.52	-2.0	-0.1
105.0	344.4	7.930	46.27	84.0	4.6
110.0	360.8	8.060	46.51	26.0	1.4
115.0	377.2	8.200	46.76	28.0	1.5
120.0	393.6	8.460	47.23	52.0	2.9
125.0	410.0	8.510	47.32	10.0	0.5
130.0	426.4	8.690	47.64	36.0	2.0
135.0	442.8	8.910	48.04	44.0	2.4
140.0	459.2	9.110	48.40	40.0	2.2
145.0	475.6	9.510	49.12	80.0	4.4
150.0	492.0	9.740	49.53	46.0	2.5
155.0	508.4	9.890	49.80	30.0	1.6
160.0	524.8	10.170	50.31	56.0	3.1
165.0	541.2	10.390	50.70	44.0	2.4
170.0	557.6	10.600	51.08	42.0	2.3
175.0	574.0	11.050	51.89	90.0	4.9
180.0	590.4	11.210	52.18	32.0	1.8
185.0	606.8	11.490	52.68	56.0	3.1
190.0	623.2	11.850	53.33	72.0	4.0
195.0	639.6	12.310	54.16	92.0	5.0
200.0	656.0	12.190	53.94	-24.0	-1.3
205.0	672.4	12.740	54.93	110.0	6.0
210.0	688.8	12.850	55.13	22.0	1.2
215.0	705.2	13.050	55.49	40.0	2.2
220.0	721.6	13.390	56.10	68.0	3.7
225.0	738.0	14.020	57.24	126.0	6.9
230.0	754.4	14.020	57.24	0.0	0.0
235.0	770.8	14.680	58.42	132.0	7.2
240.0	787.2	14.660	58.39	-4.0	-0.2
245.0	803.6	15.010	59.02	70.0	3.8
250.0	820.0	15.430	59.77	84.0	4.6
255.0	836.4	15.760	60.37	66.0	3.6
260.0	852.8	16.130	61.03	74.0	4.1
265.0	869.2	16.430	61.57	60.0	3.3
270.0	885.6	16.960	62.53	106.0	5.8
275.0	902.0	17.130	62.83	34.0	1.9
280.0	918.4	17.470	63.45	68.0	3.7
285.0	934.8	18.160	64.69	138.0	7.6
290.0	951.2	18.640	65.55	96.0	5.3
295.0	967.6	19.570	67.23	186.0	10.2
300.0	984.0	20.640	69.15	214.0	11.7
305.0	1000.4	21.590	70.86	190.0	10.4
310.0	1016.8	22.070	71.73	96.0	5.3
315.0	1033.2	22.400	72.32	66.0	3.6
320.0	1049.6	22.850	73.13	90.0	4.9
325.0	1066.0	23.160	73.69	62.0	3.4
330.0	1082.4	23.520	74.34	72.0	4.0
335.0	1098.8	23.800	74.84	56.0	3.1
340.0	1115.2	24.090	75.36	58.0	3.2
345.0	1131.6	24.350	75.83	52.0	2.9
350.0	1148.0	24.630	76.33	56.0	3.1
355.0	1164.4	24.790	76.62	32.0	1.8
360.0	1180.8	24.990	76.98	40.0	2.2
365.0	1197.2	25.260	77.47	54.0	3.0
370.0	1213.6	25.440	77.79	36.0	2.0
375.0	1230.0	25.620	78.12	36.0	2.0
380.0	1246.4	25.860	78.55	48.0	2.6
385.0	1262.8	26.140	79.05	56.0	3.1
390.0	1279.2	26.320	79.38	36.0	2.0
395.0	1295.6	26.550	79.79	46.0	2.5
400.0	1312.0	26.800	80.24	50.0	2.7
405.0	1328.4	27.020	80.64	44.0	2.4
410.0	1344.8	27.260	81.07	48.0	2.6
415.0	1361.2	27.470	81.45	42.0	2.3
420.0	1377.6	27.880	82.18	82.0	4.5
425.0	1394.0	28.460	83.23	116.0	6.4

8S/ 8E- 6DD
HOLE NAME: EWEB-SB EWEB No. 6 Sisi Creek (continued)
DATE MEASURED: 4/29/80

DEPTH METERS	DEPTH FEET	TEMPERATURE DEG C	DEG F	GEOTHERMAL GRADIENT DEG C/KM	DEG F/100 FT
430.0	1410.4	28.750	83.75	58.0	3.2
435.0	1426.8	29.020	84.24	54.0	3.0
440.0	1443.2	29.220	84.60	40.0	2.2
445.0	1459.6	29.400	84.92	36.0	2.0
450.0	1476.0	29.590	85.26	38.0	2.1
455.0	1492.4	29.730	85.51	28.0	1.5
460.0	1508.8	29.790	85.62	12.0	0.7


TEMPERATURE, DEG. C
2
6
10
14
18
22
26
30
0
100
200
300
400
500
600
DEPTH IN METERS
EWEB-58 EWEB No. 6 Sisi Creek
8S/ 8E- 600
11/13/79
8S/ 8E- 600
4/29/80

U. S. GEOLOGICAL SURVEY OPEN-FILE REPORTS

U. S. Geological Survey open-file reports prepared on each of the Eugene Water & Electric Board drill holes, based on cuttings and driller's logs supplied to the Branch of Field Geochemistry and Petrology, U. S. Geological Survey, Menlo Park, California. Information in these open-file reports has been extracted and used in this present report.

Keith, Terry E. C., and Boden James R., 1980. Volcanic stratigraphy and alteration mineralogy of drill cuttings from EWEB 1 drill hole, Linn County, Oregon.
-----------, 1980. Volcanic stratigraphy and alteration mineralogy of drill cuttings from EWEB 2 drill hole, Linn County, Oregon.
-----------, 1980. Volcanic stratigraphy and alteration mineralogy of drill cuttings from EWEB 3 drill hole, Clackamas County, Oregon.
-----------, 1980. Volcanic stratigraphy and alteration mineralogy of drill cuttings from EWEB 4 drill hole, Clackasmas County, Oregon.
-----------, 1980. Volcanic stratigraphy and alteration mineralogy of drill cuttings from EWEB 5 drill hole, Clackamas County, Oregon.
-----------, 1980. Volcanic stratigraphy and alteration mineralogy of drill cuttings from EWEB 6 drill hole, Clackamas County, Oregon.

These are preliminary draft reports which, as of this writing, have not been assigned open-file numbers.

* * *

REGISTERED PROFESSIONAL GEOLOGIST
OREGON
Walter Youngquist
Walter Youngquist
No. G 452

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MEMORANDUM

TO: Marshall Reed
P. M. Wright

FROM: H. P. Ross

SUBJECT: 9/23/86 Meeting of Steering Committee PSDC
Brief Summary of Meeting and Topics Discussed

DATE: September 24, 1986

This is a short form summary of the Steering Committee Meeting, PSDC held at Portland State University on September 23, 1986. A more complete record will be compiled by Norm Goldstein, LBL in his new role as Executive Secretary, PSDC.

Persons Attending

George Priest	DOGAMI
John Beaulieu	DOGAMI
John Rowley	LASL
Norm Goldstein	LBL
Michael Korosec	WA-DNR
Dave Blackwell	SMU
Dick Couch	OSU
Jerry Patchett	USFS
Harvey Waff	UO
Gordon Goles	UO
Howard Ross	UURI

Topics Discussed

1. Relative priority for completion of the science plan versus writing specific proposals. Many members favored completing the science plan prior to submitting any proposals.

2. A strategy for funding the PSDC project as a whole, and in increments (unresolved).

3. New responsibilities for George Priest within DOGAMI. In addition to his role as Geothermal Specialist, George will be responsible for the Portland Field Office and be involved in a forthcoming Hanford review. Thus, it is necessary to split up the workload George is now carrying at PSDC.

4. As a result of (3) it was agreed to form a group of officers for PSDC. Those selected and agreeing to serve are:

David Blackwell	Chairman
George Priest	Vice Chairman (will also handle mailing responsibilities)
Norman Goldstein	Executive Secretary
John Rowley	Project Coordinator (informal basis-telephone contacts)

5. Discussion of the need for proposals to address specific funding sources.

   * George Priest agreed to write a proposal in response to a forthcoming State Cooperative RFP (FY-86 Funds), at a level of about $75,000. The proposal will address geologic and geophysical work preliminary to sitting PSDC drillholes.

   * David Blackwell will write a proposal to be submitted to the State Cooperative Program - FY 87 funds for an undetermined amount. The proposal will be for an initial drill hole in the Santiam Pass area.

   * Proposals will be drafted at a future time to seek funds from DOE-BES or DOSEC.

   * Proposals will be consistent with, and supported by, the science plan.

6. Coordination with U.S. Forest Service. Jerry Patchett, USFS emphasized the need to identify possible drill sites, and survey areas as soon as possible and to coordinate with the USFS. He noted that the Pacific Trail passes through the immediate Santium Pass area, and that primitive, non-road areas are common throughout the High Cascades. The status of land with respect to geothermal leases should also be determined. Land permit times may vary between 2 months and 1 year.

7. Blue Lake Geothermal has offered a $100K cost share match for a hole on their site in Santium Pass. The location appears to be about 5 miles west of the crest of the volcanic arc.

8. Discussion of the Science Plan. Considerable discussion regarding the main and secondary objectives and how they should be stated. George Priest will evaluate comments in

finalizing the Plan, and will put substantial effort on the plan in the next few months.

9. Discussion over the various elements in Phase I; how many holes are really required, to what depths, etc. What are the number versus depth cost tradeoffs.

Howard

Howard P. Ross

HPR:leo

PMW –
Handouts
from 9-23-86
meeting.
VR

NOTES - 9-23-1986 MEETING OF STEERING COMMITTEE - PSDC

UMMARY OF PROGRESS TO DATE on PSDC

. Geothermal research program of DOGAMI-USGS-SMU-USDOE-BPA-EWEB-NWNG
    a. Mount Hood project: USGS, DOGAMI, USDOE, NWNG = 16 @ 150 m; 8 @ 300-400 m; 1 @ 1836; 2 @ 1220 m
    b. Cascades project: DOGAMI, USDOE = ~30 @ ~152 m
    c. EWEB Cascades program: EWEB, USDOE, DOGAMI = 6 @ ~600 m.; one at Santiam Junction.
    d. Low-Temp project - USDOE, DOGAMI (Powell Buttes, Willamette Pass, Belknap-Foley)= 1 @ 335 m, 1 @ 457 m, 8 @ ~150 m

Th. Pwr.
NE Britenbush
4800'

    e. Newberry project - USGS, Sandia, DOGAMI, BPA, USDOE, industry: 1 @ 457 m; 1 @ 914 m; 2 @ 1219 m; 1371 m; 2 @ 1219 in progress (one private); 1 @ 1524 in progress

1. Started with exploratory letters in 1982 to CSDP - Wash.
2. First organizational meeting on Dec. 8, 1983 - AGU
3. 2nd " " 1984 - AGU
4. 3rd " " 1985 - USGS Cascade Workshop

ident. Santiam Pass area.

5. First rough draft of Sci. Plan sent for review 8-85
6. 2nd rough of main body " " " " " 8-86
7. <u>Articles published</u> in EOS, USGS open-file report, Oregon Geology, Geo-Heat Center News, GRC Bulletin, GRC Transactions, DOSECC proceedings - twice, Non-tech. summary printed by DOGAMI and distributed free.

→ outline of science pla

8. Rapid City presentation - spring 1986; DOSECC-USDOE response indicates need for more focus. Mixed signals from the reviewing committee (informal vs. formal response are quite different).
9. Technical Science Plan to be published in Winter 1986-1987 as DOGAMI open-file report (with USDOE financial support).
10. Grant proposal for ~$75,000 needed this fall.
11. " " " $500,000 ±

STATE OF OREGON **INTEROFFICE MEMO**

TO: Cascade Drilling File

DATE: September 22, 1986

FROM: John D. Beaulieu

SUBJECT: Necessary Future Tasks

At the meeting scheduled for September 23, it will be necessary that several tasks and assignments be addressed. These include:

(1) Completion of the scientific plan.
(2) Assignment of executive secretary duties to an individual
(3) Designation of a chairman.
(4) Identification of a proposal writer.

- Scribe
- Correspondence
- Mailman
- Coordinator - Duncan?"
- Scientific Plan. - Chairman

In addition, it will be necessary to develop concepts for two proposals. The first proposal should be on the order of $75,000.00 for Fiscal Year 86 money in the State coupled program. For this particular proposal, a match of about ten to one (State) is required. The second proposal for Fiscal Year 87 monies can be for a larger sum. It, too, will be in the State coupled program for which a national budget of $2,000,000.00 is anticipated. We have no specific knowledge of a cap for individual states.

Both proposals should fit into a context which leads towards our deeper drilling plan as it has been described in earlier documents.

JDB:eed

81-125-1387

Department of Geology
University of Oregon
Eugene, Oregon 97403

23 September 1986

Response to
"PROGRAM FOR SCIENTIFIC DRILLING IN THE CASCADES"

Please note that this response is not a carefully formulated critique of George Priest's "Program ...". Harve Waff asked me to review the document only yesterday; as a consequence, the comments below are very much "top of the head". I hope that they will be useful nevertheless.

Gordon Goles
Gordon Goles

I. Overall impression

The aim of the structural re-organization that, according to George's memo of 11th August 1986, must have been done between the first draft (which I have not seen) and this one is laudable. This version seems to me, however, to have serious flaws. I urge that these be corrected, before publication as an open-file report and if feasible, **before beginning preparation of even the first draft of a formal proposal to CSDP.** It seems likely that whoever is writing the successive drafts of the proposal shall find it easier to come up with something that is likely to be funded, if they start from a science plan that has been substantially revised from this version.

II. Specific criticisms

This document does not convince me that objective 1, estimation of the rate of magmatic heating of the Cascades axis, can be accomplished. Fundamental difficulties in attacking this objective are rife. For instance, because of the propinquity of the Basin-and-Range province to the southern and central High Cascades and the strong possibility that the Cascades Graben is itself **a B-and-R structure,** much like other major grabens associated with voluminous volcanism around the margins of the northern B-and-R, it would be exceptionally difficult to disentangle heat flow associated with subducted-plate magmatism from that which arises from other sources, many of them also magmatic. The other approach that seems to leap out on first encounter, that of estimating the volume of mafic magma added to some segment of the Cascades Axis as a function of time, is surely beyond our present capabilities and will remain so for considerable time to come.

Another relevant objection, and one that applies not only to objective 1 but also elsewhere in this draft document, is how to decide what is "typical"? I am not convinced that criteria for deciding this question exist. If they exist, they have not been clearly stated in this document. It would seem more prudent to restate the criteria relevant to choice of areas within the Cascades in which to drill in some other, more easily defensible, way (see below).

Objectives 2 and 3 seem achievable to me. It would be prudent, in stating them, to qualify what might be viewed by reviewers as an unduly ambitious and therefore unrealistic scope to these objectives. For instance, in the ABSTRACT it would be prudent to write something like: "2) Investigate in carefully selected areas the nature of the heat source responsible for the regional heat flow anomaly. 3) Characterize, in the same areas, regional hydrothermal circulation."

Objective 4 requires **very** comprehensive data, **almost all of which does not yet exist.** For starters, there are fundamental disagreements among students of the problem on the question of what is the rate and direction of plate convergence between the North American and Juan de Fuca Plates. There is general agreement that both the nature and the volume-per-unit-length and -time of volcanic products in such a province should reflect the angle of subduction and the character of the subducting plate. Some recently published isotopic studies suggest that interactions of magmas generated in association with the subducted plate beneath the Cascades with the overlying lithosphere cannot be ignored. We are not sure of the subduction angle; we know little about the subducted Juan de Fuca Plate; and we have only vague hints about magma-lithosphere interactions in the Cascades.

Objective 5, as stated, seems unrealistic to me. Even if objectives 1 and 4 can be addressed (a premise that, as outlined above, seems dubious), it is important to remember that published interpretations of plate convergence rates in the PNW may be presented with far more apparent assurance of their validity than is really warranted. (This comment is not intended to disparage the valiant efforts of those making such interpretations. We all are tempted to argue past our data, I think.) It might be more prudent to restate objective 5 as that of obtaining reliable data on volume of volcanic products added to the crust as a function of time in selected areas of the High Cascades. That is "do-able", and as I read the document is not explicitly addressed elsewhere.

Objective 6, like objective 4, requires exceptionally comprehensive data. In this instance, however, I doubt that it is at all realistic to claim, implicitly or explicitly, that such data can be obtained from a small number of drill holes, no matter how cleverly sited and exhaustively studied. Inclusion of such an objective is likely to be counter-productive: one risks convincing preceptive reviewers that this science plan was prepared too hastily.

Note that I vigorously support the need for the kinds of investigations cited on p. 20 as those that would be done to address objective 6. My concern is that the objective itself is framed in terms that are far too broad and unrealistic. The investigations should be done, but they should be linked to a properly-framed objective.

Objective 7 seems to me to be both very important and attainable.

Objective 8 is clearly impractical for a **drilling program.** It should be addressed, but by seismic and other geophysical approaches. If this is to remain as a stated objective of this science plan (which I recommend), it must be made clear that there are two categories of objectives, those related to drilling and those related to support activities. Otherwise, one risks inducing the impression of muddled thinking.

III. Suggestions for improvement

As briefly indicated in the introductory note, above, I am diffident about making suggestions for improvement because I have had little time to think about what kind of program should be done and how to present a plan to do it. Nevertheless, I recognize the obligation to make constructive criticisms, not merely negative ones.

First, re-think the objectives. Ruthlessly weed out all those, and the phrasing of those which remain, that could lead a careful reviewer to wonder about the realism of the plan and its component parts. (The need for this is easily read between the lines of the parts of the CSDGR report to which I have access.)

Put the objectives in a logical order. It might be very effective to state explicitly that the plan incorporates two kinds of objectives, those directly related to drilling and those expressing aims of related activities. If this distinction is explicitly drawn, the order in which the objectives are stated and perhaps even how they are designated (for instance, by use of "1A", "1B", etc., to designate non-drilling objectives related to drilling objective "1") should be adjusted to ensure an orderly presentation.

Make more logical and defensible the choice of areas in which to drill. Breitenbush is an obvious choice because of the existing drill hole. However, Brian Baker and I pointed out ten years ago that it is a poor choice for a geothermal test drill hole (along with other sites along and near the western boundary fault system of the High Cascades Graben marked by hot springs) because of the hydrologic flow regime of the region. It has required a distressingly long time for this simple argument to "sink in", but I think it is now generally recognized that we are unlikely to find economic geothermal resources where the prominent hot springs are located. Thus, although I agree wholeheartedly that deepening of the Breitenbush hole should be in the plan, I **strongly urge** that the criteria for choice of drilling sites be explicitly designed to state why.

A possible logical structure of criteria is the following: A) There are at least three distinguishable types of volcanic edifices in the High Cascades Province. They are: 1) basaltic (or basaltic andesitic) shield volcanoes and their associated cinder cones, etc.; 2) composite cones of intermediate to silicic composition (by the way, **don't** use the term "stratovolcano" to describe what is now generally referred to as a "composite cone"); 3) volcanic platforms dominated by basaltic andesite but incorporating some intermediate and silicic materials. Of course, these categories are in reality blurred by transitions from one to another, and may in addition be linked in an evolutionary sequence ("1" evolving through "3" to examples of type "2"). I cite them here simply to provide a framework for rethinking parts of George's document.

The first of these overwhelmingly predominate in the High Cascades. In most areas they fill the High Cascades Graben and constitute the High Cascades Platform, as is well known and clearly indicated in the present draft of the science plan. Because they constitute the graben filling, they are inevitably targets of deep drill holes. You can't miss them! Thus, although one needs to characterize such rocks and edifices in any logically designed deep drilling program in the High Cascades, it is pointless to adjust the siting of deep drill holes so as to sample shield edifices. Furthermore, **it would be grossly unrealistic to claim as an objective of this science plan the characterization on a regional scale of such edifices.** *A few deep drill holes cannot do more than* suggest what the internal structures of a few of these edifices might be. This is an unpalatable fact, because the structures of these edifices may well dictate the details of flow of both cold groundwaters and geothermal fluids in the High Cascades Graben, but the fact does not go away if ignored.

Composite cones are poor targets for deep drilling because of the distribution of Wilderness Areas in the High Cascades. (The work done near Hood some years ago was very valuable, and might eventually be extended, but I have the impression that it makes more sense at this time to investigate other areas in the High Cascades. Perhaps this question should be debated, however.) Also, at least at some of them, their recent geologic history suggests that "live" magmas may exist only at very substantial depths. An example is Jefferson, where simple arguments based on assumptions of a close approach to "magmatostatic" equilibrium during eruption and a "guesstimate" of the crustal structure beneath the volcano suggested that the chambers whence the Santiam basalts and the Forked Butte series erupted are located at depths of about 30 km.

This line of reasoning leaves category three, volcanic platforms with at least some andesites and dacites, as principal targets. These do not seem to have been explicitly recognized in previous publications, but may well be relatively abundant. The Santiam Pass area is such a platform, although a poorly developed one according to the results of work done there in 1980 and 1981 by Baker and myself. (That work was done under contract to industry. The contract specified that the data were to be considered proprietary for a period of five years. Thus, it is only very recently that I have begun to plan publications reporting it.) Drilling in the Santiam Pass area, as proposed in the present draft of the science plan, might be justified on the basis both that it is a platform of type 3 and that quite a bit is known about the area already. There is at least one substantial contraindication, however: I think much of what we know about the area suggests that magma reservoirs at depths of less than 25 or 30 km are rare, perhaps almost entirely absent. Thus, I urge that the focus on a transect of the Santiam Pass area be re-considered.

A better target for a transect might be the Pinhead Buttes Platform, NE of Breitenbush. There are relatively abundant post-glacial lavas there, ages of some of which have been estimated by a U-disequilibrium technique, and andesites and dacites seem to be substantially more abundant than in the Santiam Pass area. It is also relevant to this decision that the proposed deepening of the Breitenbush hole would provide important information on a nearby area.

Implicit in the two paragraphs above is the concept that a criterion for selection of areas in which to propose drilling is that of how much we know about them already. It would be prudent to strike a balance between focussing sharply on a very limited set of areas when we clearly are ignorant about most of the Cascades, and risking an unproductive drill hole by choosing a site about which too little is known.

This comment brings me to my final suggestions for improvement: Although the proposal for funds may well be fairly sharply focussed on exactly where to drill and what to do with the cores and any downhole logging that may be done, the science plan **must**, in my view, present a comprehensive and defensible overview of the entire program of study of this part of the PNW. The plan should be re-written to incorporate, and in some instances emphasize, the need for and potential benefits of closely related activities. A partial list of such activities includes: A) Seismic studies of the region, and explicitly of the High Cascades. These probably should include detailed investigations of microseisms along and near the Cascades Axis. It is especially necessary to obtain information from which one may infer details of regional-scale crustal structure, as an important aid to diverse modelling exercises. B) MT investigations such as those being done by Harve Waff and his group. From a summary presented at the meeting entitled "Oregon Lithospheric Traverse - I" a couple of weeks ago, it is clear that this kind of work has great potential for "seeing" deep structure in ways at least partly orthogonal to those of other geophysical techniques. C) Continuation and extension of mapping, geochronological studies, and petrological and geochemical (including isotopic) investigations of selected areas in the High Cascades.

Kinds of investigations that should be part of the deep drilling program, but are not appropriately covered in the present draft of the science plan, include detailed studies of the petrologic, compositional, and isotopic features of recovered cores, and detailed studies of the compositions and, via thermodynamic modelling, temperature histories of fluids recovered from various levels of the holes. Lacking discussion of these investigations, the present draft gives an impression to a knowledgeable reviewer of being incomplete or hastily put together.

Program for Scientific Drilling in the Cascades (PSDC)

At its LBL meeting of May 1-2 the Review Group heard George Priest outline the scientific rationale for an extensive CSD program in the Cascades area. The first phase of this program was further elaborated by Priest at the Rapid City workshop. It calls for an east-west geology-geophysics transect across the Cascades range as well as drilling near Santiam Pass and the Breitenbush Hot Springs area in Oregon. In the most general terms the scientific objective of the overall PSDC is " ... to develop a reliable theoretical model for processes of mass and energy transfer which occur in the volcanic mountain range above a subduction zone ..." (p. 45 of the abstracts volume from the CSD workshop at Rapid City). Without a doubt this is a significant objective, but, in the context of the CSD program, it must be distilled down to the specific drilling steps proposed to get us there.

The Review Group believes that the PSDC is now, in fact, much better defined then when it was presented at the first CSD workshop in Houston last year. Nevertheless, it needs sharper focus still. In our view the next step indicated for the Cascade consortium is to develop a proposal outlining the specific scientific goals for drilling in this area. Among the general possibilities we have heard discussed so far, we think that (1) establishing the temperature profile below the Cascade "rain curtain" effect with intermediate depth drilling, and (2) eventually identifying the (magma?) heat source below the Cascades with a deeper drilling effort are the most promising. We encourage the PSDC science team to consult with the Geosciences Program while developing such a proposal so that the proposed drilling costs are kept in phase with developing programmatic possibilities.

While we are on the subject we wish to thank Dennis Nielson for keeping us current on GTD-Industry jointly sponsored drilling in the Cascades. Thanks to his briefing during the May 1-2 LBL meeting, his talk at Rapid City and the timely EOS article of July 22 by Swanberg and Combs we and, more importantly, the geoscience community are informed about the recent results and imminent plans of the cooperative Cascade Deep Thermal Gradient Drilling Program. Although the immediate purpose of this program is to support the geothermal industry's efforts in the Cascade region, there is much obvious overlap of interest with the PSDC in particular and the CSD-thermal regimes scientific goals in general. We hope that the PSDC team will be able to put the results of this program to good use as they develop their proposal. We commend the management and scientists of this program for the prompt way in which they have announced the opportunity for further work in the holes, on core samples, and with the collected data that has been placed on open file.