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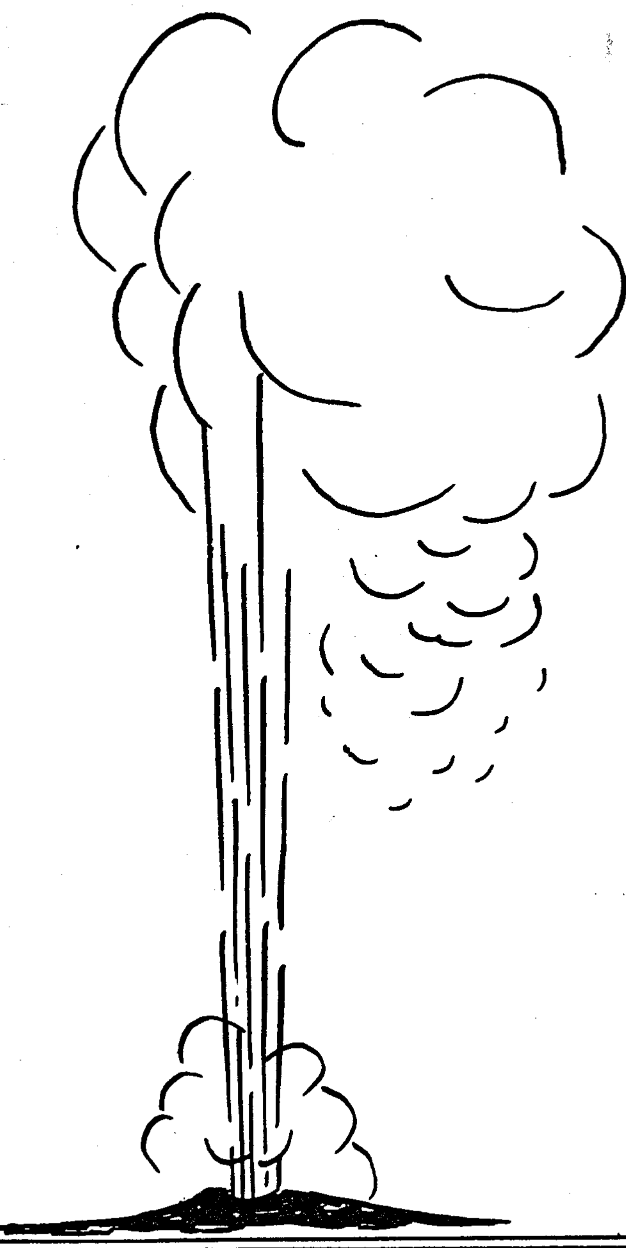

GEOTECHNICAL STUDIES OF GEOTHERMAL RESERVOIRS

By
H. R. Pratt
E. R. Simonson

January 1976

Work Performed Under Contract No. EY-76-C-07-1546

Terra Tek, Inc.
Salt Lake City, Utah

MASTER

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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Submitted to

Energy Research and Development Administration
Division of Geothermal Energy
#20 Massachusetts Avenue, N. W.
Washington, D. C. 20545

Attention: Mr. Morris Skalka

Submitted by

Terra Tek, Inc.
University Research Park
420 Wakara Way
Salt Lake City, Utah 84108

TR 76-2

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SUMMARY AND CONCLUSION

(1) Maximum temperatures found in the reservoir were approximately 700°F in the Imperial Valley, California, but drill bit temperatures may be considerably higher in the Geysers geothermal area. Temperatures reached up to 900°F because of frictional heating and possibly inefficient cooling.

(2) Rock types found in the high temperature environments range from hard abrasive granites and metamorphosed sandstones to unconsolidated sediments and friable sandstones. The rocks are highly fractured at reservoir depths.

(3) By far more wells drilled at higher temperatures are in the harder formations; this is primarily because the Geysers area is the only existing production field in the United States. Over 150 wells have been drilled there. There, drilling and drill bit problems are significant and costly. The reservoir at the Roosevelt Hot Springs area, Utah is also being drilled in hard fractured rock. The "hot dry rock" concept will also require drilling in a hard fractured granite.

(4) At the present time reservoir depths range from 2500 feet to greater than 10,000 feet but average 5000 to 7000 feet.

(5) The effects of reservoir characteristics on drill bit performance are complicated. Reservoir temperature alone is not the decisive factor controlling drill bit wear. As typified by the Geysers area, the mechanical properties of the rock (abrasiveness, strength, ductility) affect drill rates and lead to frictional heating which may significantly reduce life.

(6) The drilling fluids play an important role in drilling and bit performance. The highest reservoir temperatures are encountered in the Imperial Valley,

where temperatures reach 700°F, yet because of the use of cooled drilling muds and the soft non-abrasive nature of the reservoir media, few drill bit and drilling problems are encountered.

(7) A plot of total footage drilled as a function of temperature for all geothermal areas is not a valid measure of potential drill bit problems. The real temperature environment that the drill bit sees may be significantly modified by frictional heating and drilling fluids. Each geothermal area must be considered individually.

(8) There are little geophysical logging data available especially high temperature.

(9) There are little mechanical property data available on reservoir rocks and none of the tests are conducted at temperatures and pressures simulating *in situ* reservoir conditions.

TASK 1.1.2 GEOTECHNICAL STUDIES

The objectives of this task are (1) to delineate the important factors in the geothermal environment that will affect drilling; (2) to compile a detailed description of the geologic environments of producing and potential geothermal areas.

The nature of the geothermal resources that will be explored and developed over the next decade will be the following types:

1. Vapor dominated hydrothermal systems
2. Liquid dominated hydrothermal systems
3. Hot dry rock formations.

The depths of primary interest for current geothermal resources range between two and about 12,000 feet, although the hot dry rock reservoirs could be considerably deeper. We will not consider geopressured areas or magma sources as potential geothermal resources in this study. Important factors to be considered that will affect drilling are the rock type and its mechanical response, geologic structure, temperature, pressure and fluid chemistry. The important mechanical and physical properties include abrasiveness, strength, plasticity and permeability. All of these factors, as well as drilling parameters such as RPM, bit weight, and drilling fluid, will have an important bearing on the rates of penetration and bit life. The data base for this information will come primarily from drill holes in producing and potential geothermal areas. In addition, data such as regional heat flow, regional geologic studies and geophysical surveys can be used to make inferences about the geothermal environment. A cross section of a typical geothermal reservoir is shown in Figure 1 and consists of the following parts:

1. An impermeable cap which, in effect, seals the geothermal reservoir from the surface.

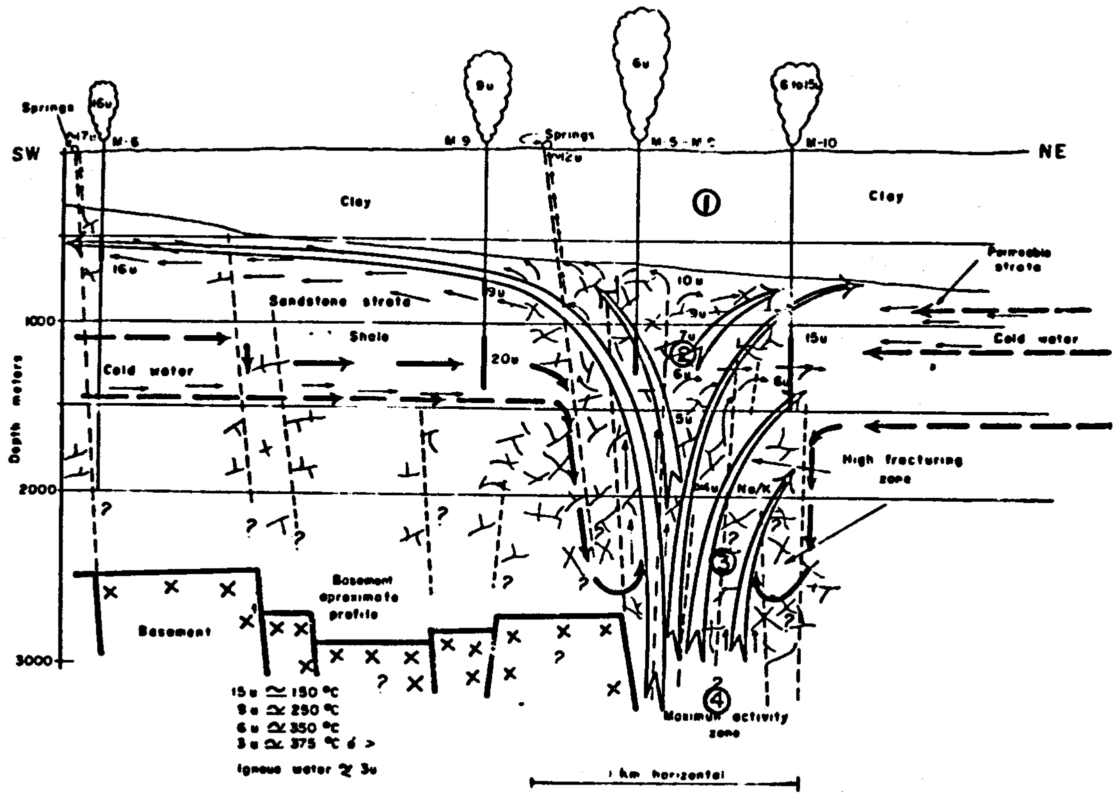


Figure 1. Geologic Structure and Stratigraphy of the Cerro Prieto Geothermal Resource (Reference 1)

2. A reservoir rock which is usually fractured and which serves as the aquifer system.
3. A conduit structure in the form of faults or shear zones along which the geothermal fluids can migrate from below, and
4. The heat source.

Figure 2 shows the areas in the western United States where geothermal data is available. Table 1 and Figure 3 show the known geothermal resource areas (KGRAs) in the western United States[2]. These areas will form the basis of the study of potential geothermal areas.

Several geothermal areas were visited and/or personnel from the corporations that are drilling at these geothermal areas were contacted during this course of study. We would like to thank these companies and these people for their cooperation without which this study would have been impossible. These include:

Union Oil Company

Carel Otte, Vice president and manager of Geothermal Division
Vane Suter, District Manager
Donald Ash, District drilling superintendent
John Bush, Engineer
Dick Dondanville, Geologist
Robert Sladowski, Geologist

Phillips Petroleum Company

William Berge, Exploration supervisor
Smokey Brethelot, Drilling supervisor

Republic Geothermal, Inc.

Robert Rex, President
William Smith, Vice president
Frank Welch, Drilling supervisor

Idaho Nuclear Engineering Lab

Jay Kunze, Aerojet Nuclear Co.

Battelle Northwest

William McSpadden

Rogers Engineering

James Kuwada
Winn Bott

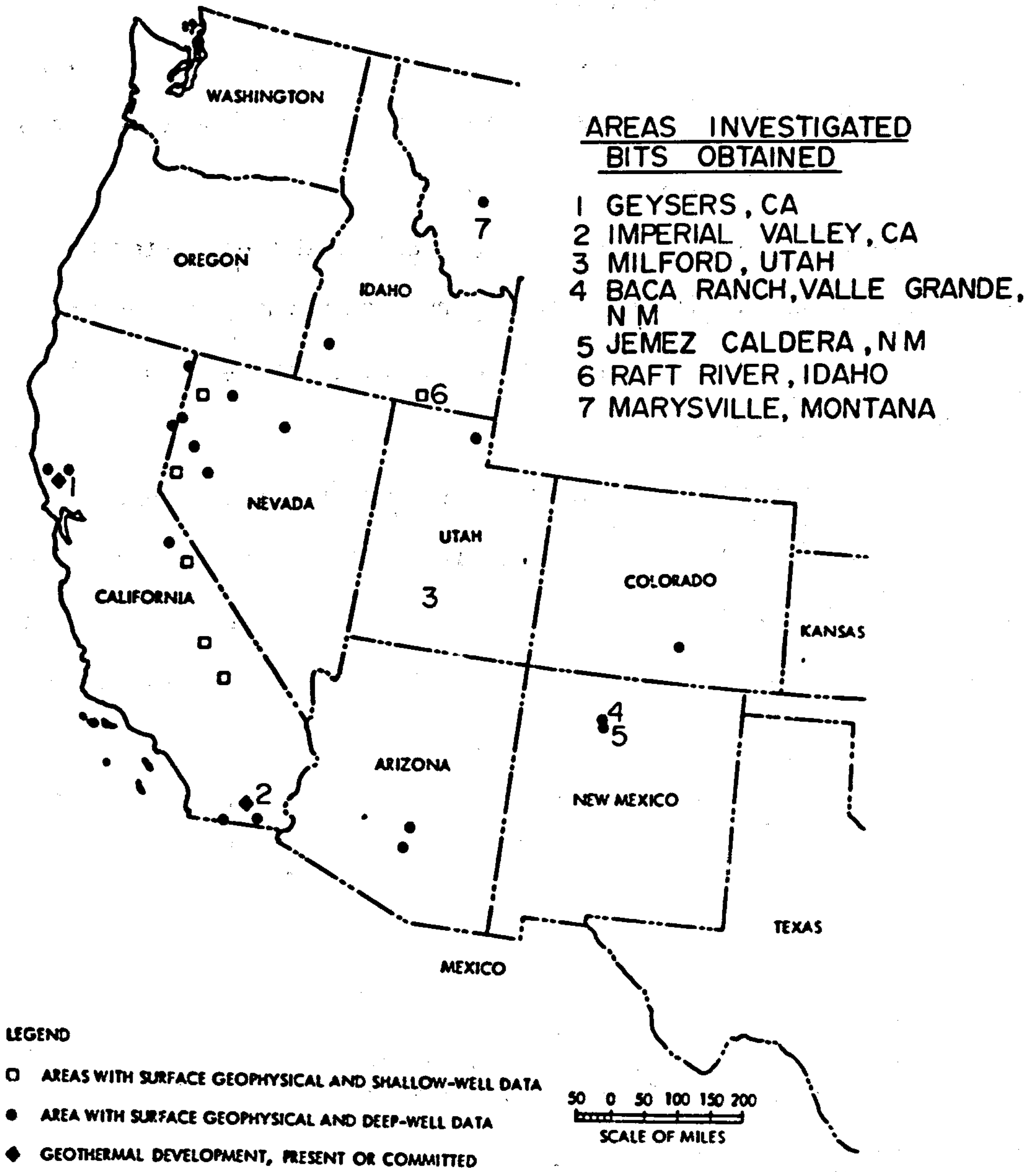


Figure 2. Areas in Western United States with Geothermal Well Data (Reference 2)

TABLE 1

List of Known Geothermal Resource Areas in the United States (Ref. 2)

Table 1. List of Known Geothermal Resource Areas (KGRAs) - western and central regions (USGS, Dec. 1974)

WESTERN REGION	
ALASKA	No. of Acres
Geyser Spring Basin	20,960
Okmok Caldera	44,800
Pilgrim Springs	22,400
ARIZONA	
Clifton	780
Gillard Hot Springs	2,460
CALIFORNIA	
Glass Mountain	15,371
Lake City-Surprise Valley	37,160
Lassen	78,641
Wendel-Amedee	17,292
Mono-Long Valley	460,256
Coso Hot Springs	51,760
Sespe Hot Springs	7,034
Salton Sea	95,824
Brawley	28,885
Glamis	25,505
Dunes	7,680
East Mesa	38,365
Heber	58,568
Lake City-Surprise Valley addition	35,091
Geysers-Calistoga	256,288
IDAHO	
Yellowstone	14,164
Frasier	7,680
NEVADA	
Double Hot Springs	10,815
Fly Ranch	5,125
Gerlach	8,972
Leach Hot Springs	8,957
Elko	8,960
Beowawe	12,712
Brady Hazen	79,426
Moana Springs	5,120
Steamboat Springs	8,914
Stillwater-Soda Lake	225,211

Table 1. (Contd)

NEVADA (Contd)	No. of Acres
Wabuska	11,520
Darrough Hot Springs	8,398
Monte Neva	10,302
Hot Springs Point	8,549
Beowawe addition	20,512
OREGON	
Mt. Hood	8,671
Carey Hot Springs	7,579
Breitenbush Hot Springs	8,960
Vale Hot Springs	8,940
Klamath Falls	17,300
Crump Geyser	21,304
Lakeview	12,165
McCredie Hot Springs	3,659
Belknap-Foley Hot Springs	5,066
Burns Butte	640
Vale Hot Springs addition	11,535
Vale Hot Springs addition	2,5[illegible]3
WASHINGTON	
Mt. St. Helena	17,622
Kennedy Hot Springs	3,311
CENTRAL REGION	
COLORADO	
Mineral Hot Springs	5,765
Valley View Hot Springs	5,099
Alamosa County	6,761
Poncha	3,200
MONTANA	
Yellowstone	12,763
NEW MEXICO	
Baca Location No. 1	152,863
UTAH	
Crater Springs	8,320
Roosevelt Hot Springs	5,201
Thermo Hot Springs	17,922
Cove Fort Sulphurdale	24,874
Roosevelt Hot Springs addition	24,590
TOTAL ACREAGE - (ALL REGIONS)	2,157,091

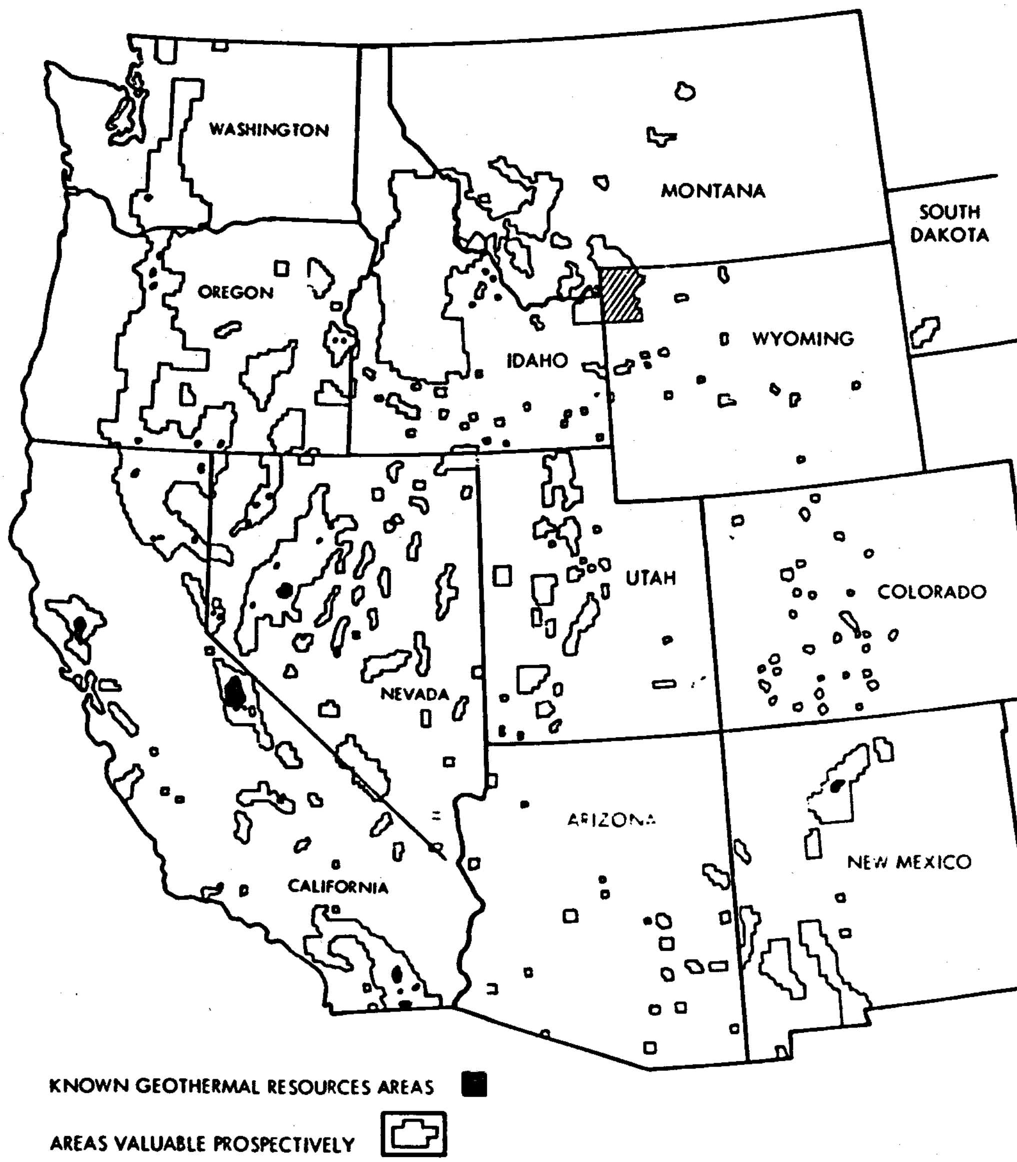


Figure 3. Areas Classified as Known Geothermal Resource Areas in Western United States (Reference 2)

Los Alamos Scientific Lab

John Rowley
Darrel Sims

U. S. Geological Survey

Patrick Muffler
William Diment
William Hardt
Robert McLaughin

Geodrilling

Bert McComack, President

Geothermal Kinetics

Michael O'Donnell

Geologic Environments

This section will describe the geologic environment of the particular areas of interest including rock types, geologic structure and other important parameters that help describe the reservoir and overlying cap rock. The geologic environment and reservoir characteristics of several geothermal areas were studied and drill bits were obtained from most of the areas (Table 2 summarizes the reservoir type, rock type, reservoir depth, geologic structure, temperature, pressure, salinity and if material properties are available for the rock in the reservoir). The geothermal areas studied in this program are: 1) Geysers Area, Geysers, California, 2) Imperial Valley, California, 3) Roosevelt Hot Springs, Utah, 4) Bacca Ranch, Valley Grande, New Mexico, 5) Jemez Caldera, New Mexico, 6) Raft River, Idaho and 7) Marysville, Montana (Figure 2).

Geysers Area, California

The Geysers geothermal area is located approximately 70 miles north of the San Francisco Bay area and lies in the Clear Lake geothermal area (Figures 3, 4). A detailed geologic map and cross section show

TABLE 2

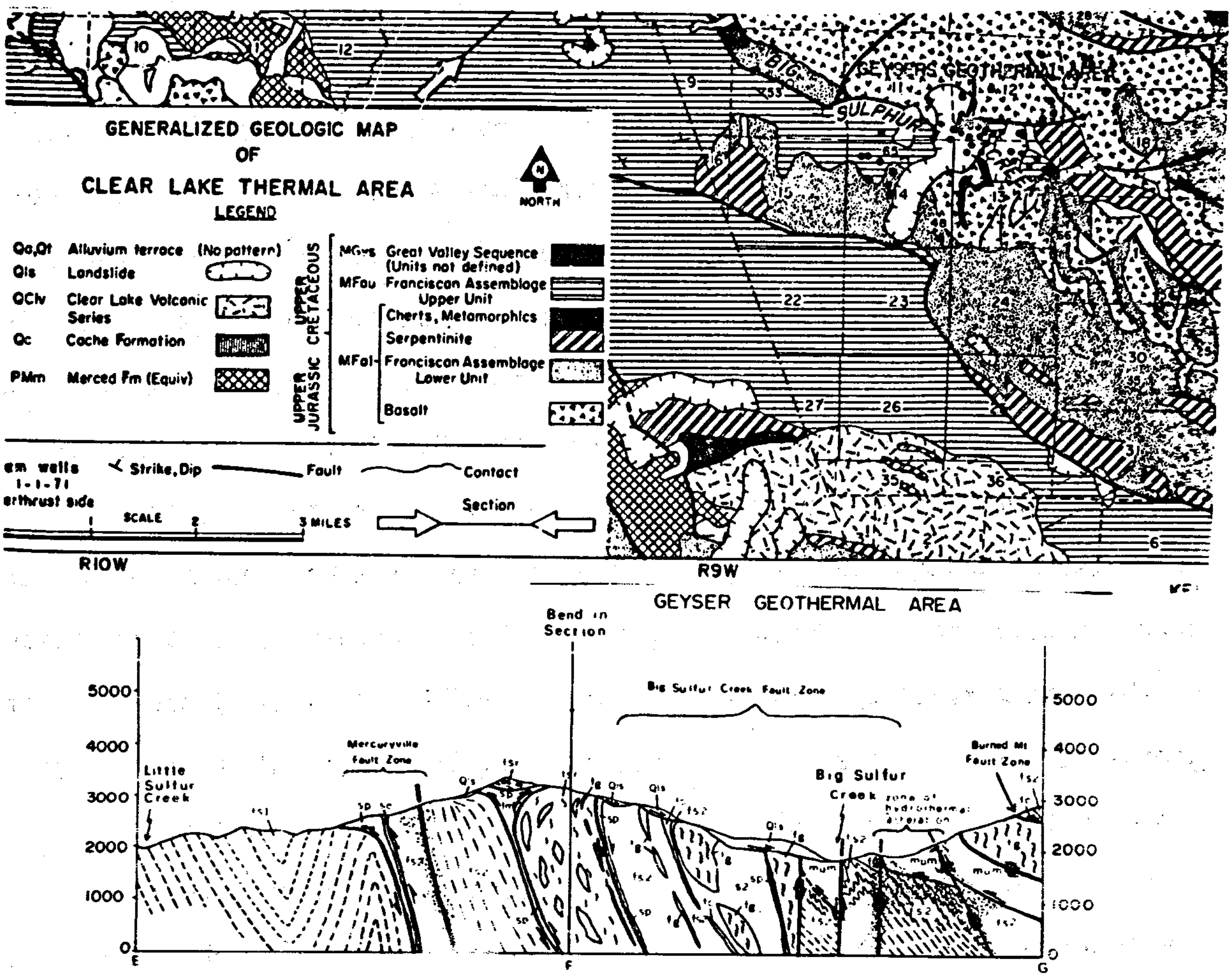
Reservoir Characteristics of the Geothermal Areas Investigated During the Terra Tek Program

Geothermal Areas	Principals	Reservoir Type	Rock Type	Reservoir Depth (ft) x 10^3	Geologic Structure	Temp. ° F	Pressure	Material Properties	Salinity
Geysers, Ca.	Union Shell Burma	Dry steam	Graywacke (ss)	5 - 7	Faulted, fractured	465	Subhydrostatic (500 psi)	Available core tested*	Low
Imperial Valley, Ca.									
Niland	Phillips, So. Cal. Ed.	Hot water	Alluvium, sandstone & shale; some metamorph. deep	2 - 4	Sedimentary basin, pore porosity	375-700	Hydrostatic	No core use existing data	High 20-30%
Brawley	Union	"		5 - 7	Pore, some fracture	"			
Heber	Chevron, Rep.	"		4 - 11	Pore, some fracture	"			High
East Mesa	Rep. Geo. USBR	"		7 - 9	Fractured faulted	"			Moderate 10%
Roosevelt Hot Springs, Utah	Phillips	Hot water & steam	Granite	2 - 4	Fractured, faulted	400-500	Hydrostatic	Available core tested*	Low to mod.
Baca Ranch, Valle Grande,	Union	Hot water	Tuff, welded & altered andesite	4 - 6	Fractured, faulted	400-500	Hydrostatic	No core, use existing data	Low to mod.
Raft River, Idaho	INEL	Hot water	Tuff, atzite qtz. monzonite	4 - 6	Fractured, faulted	290-300	Hydrostatic	No data except. perm.	Low
Jemez Caldera, New Mexico	LASL	Hot dry rock	Granite	6 - 9	Fractured	300-400	Hydrostatic	Data	Low
Marysville, Montana	Battelle (NSF)	Hot water	Granite	6 - 7	Fractured	200	Hydrostatic	Data	Low

* This program.

the location of the Big Sulphur Creek fault zone and the zone of hydrothermal alteration associated with the geothermal deposit (Figure 4)[3,4]. The reservoir rock types are Franciscan graywacke with minor shale, conglomerate and serpentinite. Metamorphism in the area ranges from weak to strong. Major high angle normal and thrust faults dissect the area. The major fault is the Big Sulphur Creek thrust. The reservoir depth ranges from 5,000 to 7,000 feet although wells have been drilled to depths greater than 9,000 feet. The conduits in the geothermal system are fractures and faults within the Franciscan graywacke sequence. Several generations of fractures were noted in the core specimen obtained from Union Oil Company. The reservoir fluid is dry steam so that the maximum temperature obtained is 465°F. An unusual aspect of this geothermal field is that the pressure is subhydrostatic. Reservoir pressures are only on the order of 500 psi at depths of 5,000 to 7,000 feet[5].

Mechanical property and permeability tests were run on core from a sample taken from the 3,900 foot depth in Union Oil Well, Ottoboni number 15. The stress-strain response indicates that the rock is strong and brittle (Figures 5 and 6). The elastic moduli are summarized in Figure 7. The failure envelope for the graywacke shows a rapid increase in strength with confining pressure (Figure 7). The permeability of the rock is very low, 0.02 microdarcies perpendicular to a fracture while the permeability parallel to the fracture is 40 microdarcies, a difference of factor of 2,000. The permeabilities were measured under conditions simulating *in situ* conditions: a confining pressure of 4900 psi and a pore pressure of 500 psi simulating the subhydrostatic pressure at reservoir depths. Because of the mineral composition of the rock, predominately quartz and feldspar, the rock will be abrasive. This is also substantiated by the fact that the drill bits used at depth go out of gage and reamers have worn tungsten carbide inserts after



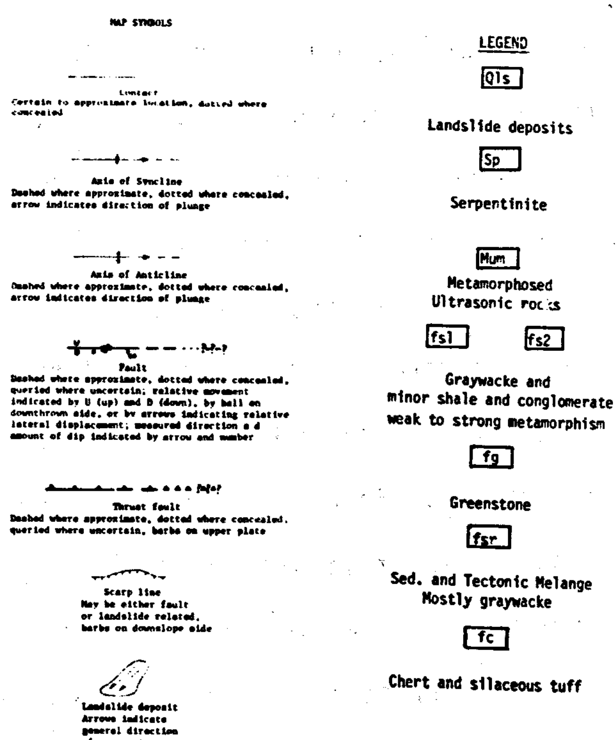


Figure 4. Generalized geologic map and cross section of the Geysers geothermal area (Ref. 3, 4).

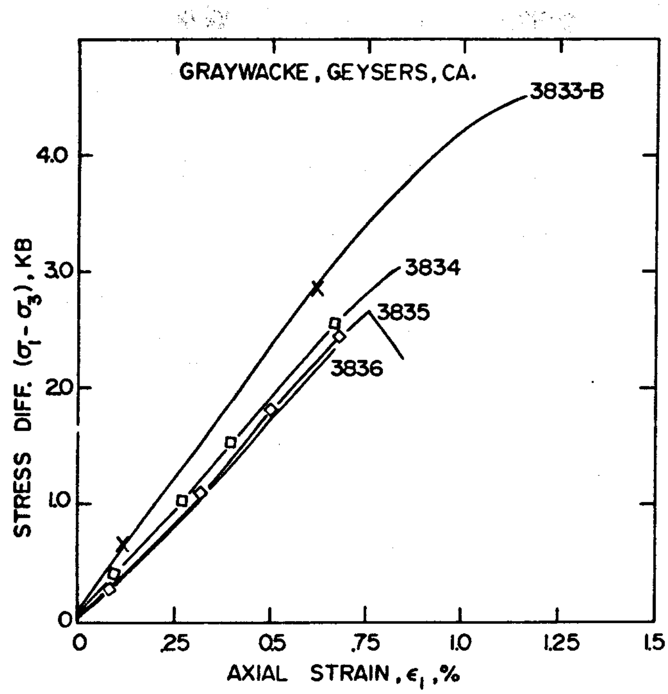


Figure 5. Stress-strain response of the graywacke sandstone, Geysers geothermal area (Ref. 3, 4).

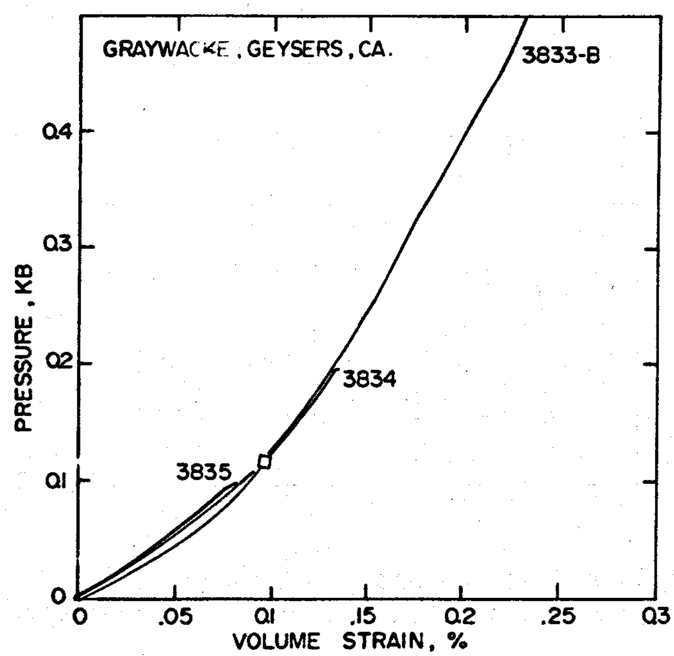
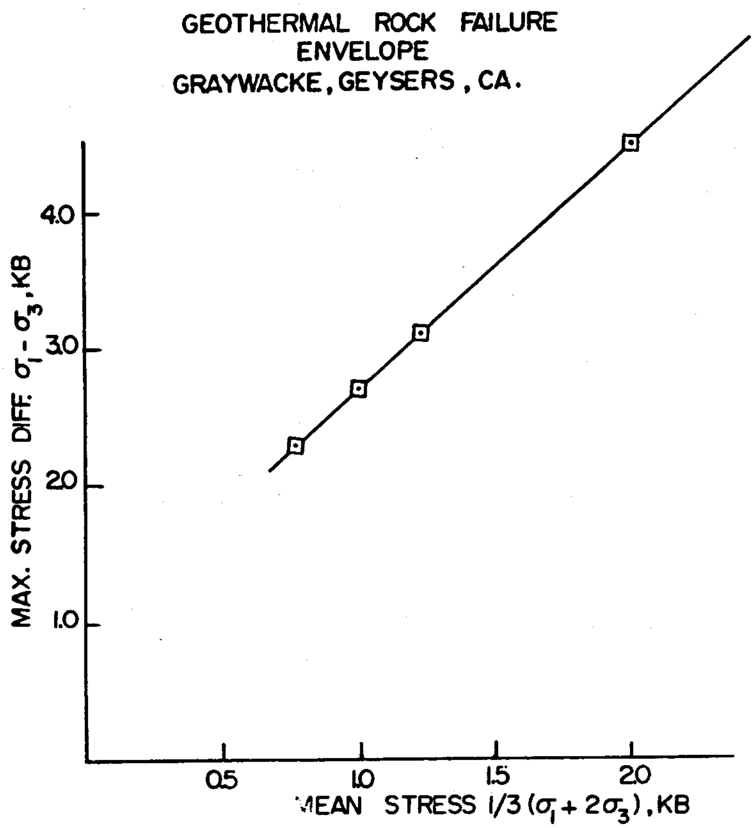


Figure 6. Pressure-volume response of the graywacke sandstone, Geysers geothermal area, California.



Test #	Density (gm/cm^3)	Confining Pressure (kb)	Max Load (kb)	Young's Modulus (kb)	Shear Modulus (kb)	Permeability P_p = .034 kb (μ darcies) ⊥	∥
3833B	2.67	0.5	4.5	454	198		
3834	2.68	0.2	3.1	386	161		
3835	2.67	0.1	2.7	360	155		
3836	2.67	0	2.3	357	148		
3837		0.34				.02	
3838		0.34					40

Figure 7. Failure envelope and tabulated properties data for the graywacke sandstone, Geysers geothermal area, California.

only approximately 10 hours of use (Table 3). The bearings and races also wear at an abnormally high rate.

The thermal conductivity of the rock in the area ranges from 5×10^{-3} cal/cm sec°C for serpentinite to $10\text{-}12 \times 10^{-3}$ cal/cm sec°C for the graywacke[6]. The geothermal gradient in the reservoir area is about 200°C/km and the heat flow 10×10^{6} cal/cm^{2}sec[6].

Imperial Valley, California

The geothermal areas in the Imperial Valley are located in northwest-southeast trending line from the Salton Sea in the north to the Cerro Prieto geothermal field 25 km across the border in Mexico, Figure 8[7]. The Salton Sea geothermal areas are characterized by high temperatures and high salinities although both temperature and concentration of dissolved solids vary over the Imperial Valley area, Figures 9, 10 and 11[8]. The generalized geologic structure consists of a large alluvial filled block faulted valley typical of the basin and range physiographic province. Normal faulting is also part of the internal structure of the valley (Figure 12)[7]. Two cross sections of the area, Figures 13 and 14, illustrate the temperature contours with depth and location of deeper wells. The temperature at a given depth decreases from the Salton Sea to the Holtville (East Mesa anomaly) area, but then increases in the Cerro Prieto area within the United States. Thus, reservoir depth increases from the Niland field in the north to the East Mesa field in the south. The Imperial Valley is laced with northwest southeast trending normal faults which exist to depths of at least 15,000 to 20,000 feet; the depth of the alluvial filled valley. The stratigraphy consists of a sequence of poorly consolidated sediments and intermittant sandstone, shales and volcanics (Figure 15)[7]. At depths of 9,000 to 11,000 feet in the Heber and East Mesa areas the sandstones and shales

TABLE 3

Drill Bit and Well Data Collected for the Terra Tek Drilling Project

Location	Lessor	Bit Size	Make	Type	Depth Out	Feet	Hours	Ft/Hr	Drilling Media	Bit Condition T	B	G	Temp.* ° F	Rock Type	Comments
Geysers, Ca.	Union	8 3/4	Smith	JJA	5182	250	11.5	21.7	Air	2	3	I	285	Graywacke	Dev. 18°, insert bit
		"	Reed	YF3JA	3877	282	15.7	18.8	"	3	5	1/16	240		18°
		"	"	73JA	5139	257	14.25	18.0	"	2	6	1/16	340		17°
		"	"	"	5754	262	14	19.9	"	2	6	3/8	330		15°
		"	"	"	5070	296	17.5	17	"	3	5	1/16	300		16°
		"	Sec	H8J	4380	210	18	11.7	"	2	3	5/8	325		20°
		"	HTC	A44	3595	252	19.75	12.7	"	3	4	1/4	190		17°
		12 1/4	Smith	V2HJ	1611	78	8.5	9.2	"	8	8	1/2			7° Dynadrill (400 rpm), tooth bit
Imperial Valley, Ca.	Rep. Geo.	8 3/4	Smith	F3		1400			Cooled mud				325	Alluvium, sandstone & shale	Journal bearing
Baca Ranch Valley Grande, New Mexico	Union	8 3/4	Reed	73JA	5764	501	24.75	20.4	Air & water				190	Tuff(welded)	(400-500)
Jemez Caldera, New Mexico	LASL	9 5/8	Smith	9JS	5234	313	65.0	4.8	W,a,w+a, m,m+a				387	"Granite"	T. D. 9619'
			Sec	H10J	8842	225	33.5	6.7							
Roosevelt Hot Springs, Utah	Phillips	7 7/8							Water				400-500	"Granite"	
Raft River, Idaho	INEL	12 1/4	Smith	DGHJ	3054	584	20.5	28.5	Mud				290-300	Tuffaceous sandstone & shale, quartzite	
		12 1/4	Smith	9JS	5523	188	32.0	5.9	Water						
Marysville, Montana	Battelle (NSF)	7 7/8	Smith										200	"Granite"	Journal bearing T. D. 6723'
		7 7/8	Hughes												

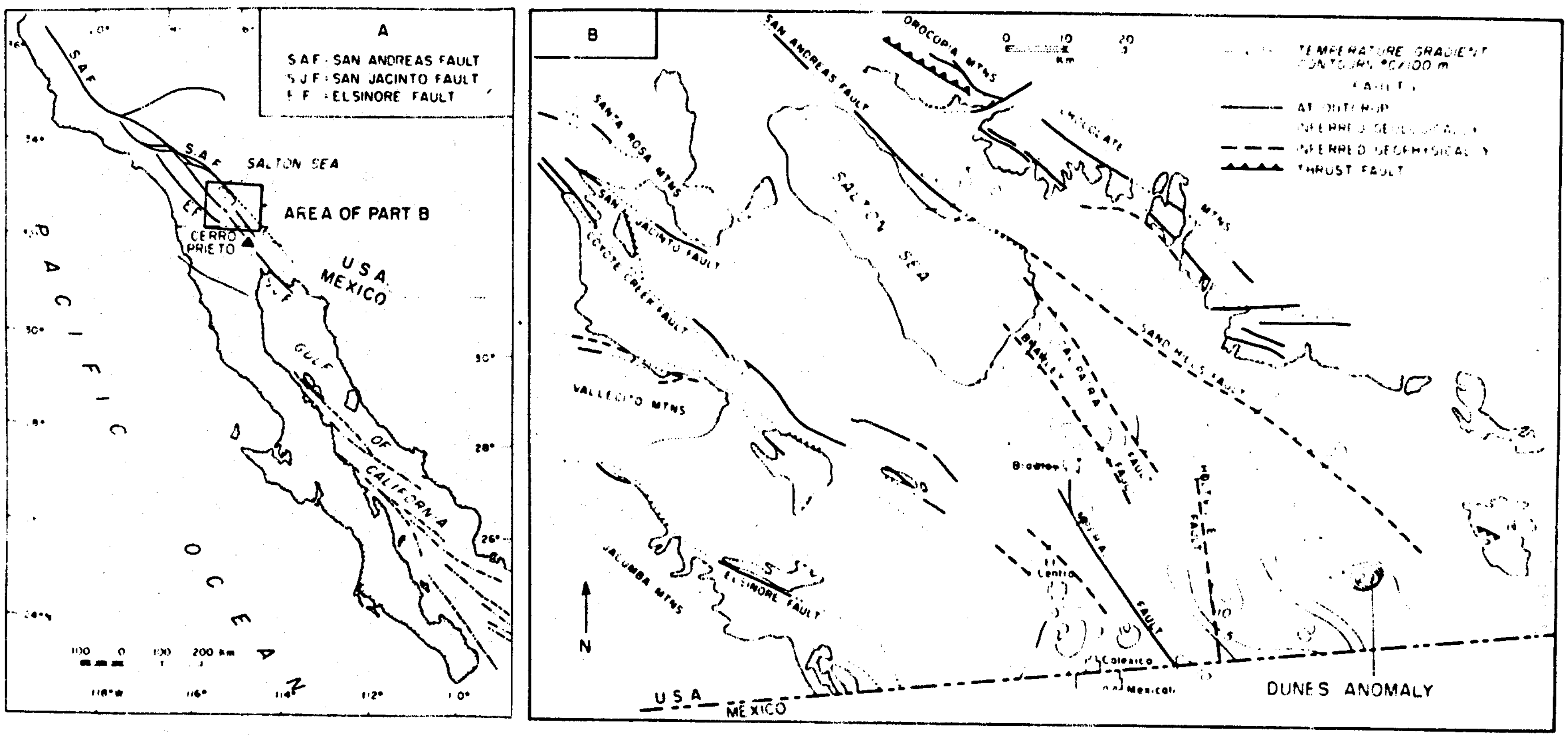


Figure 8. Location of the Salton Sea Geothermal Areas and Associated Geologic Structures (Reference 8)

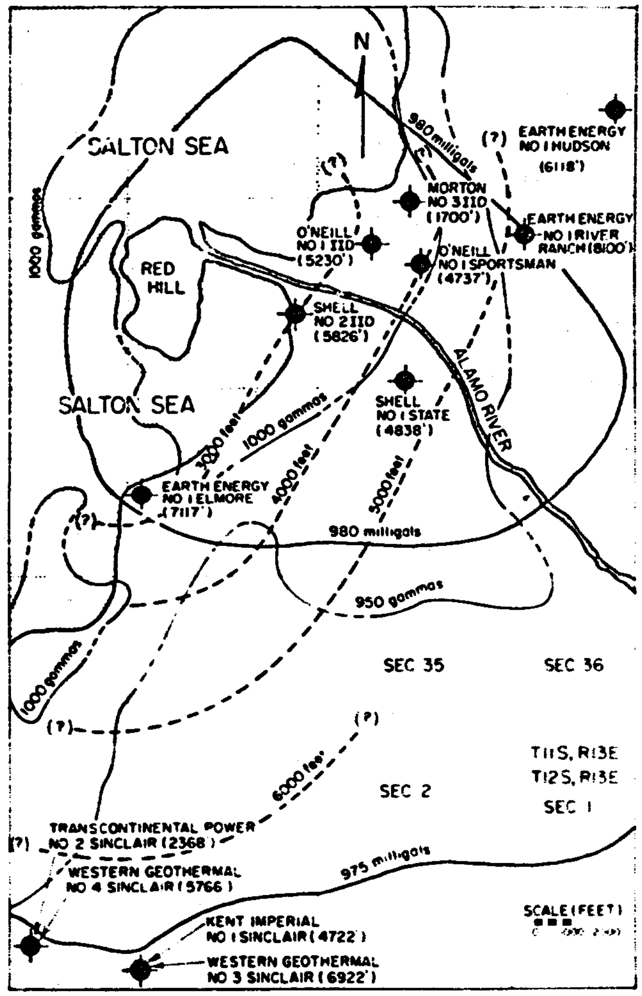


Figure 9. Well Location Map of Salton Sea Geothermal Area (Reference 8)

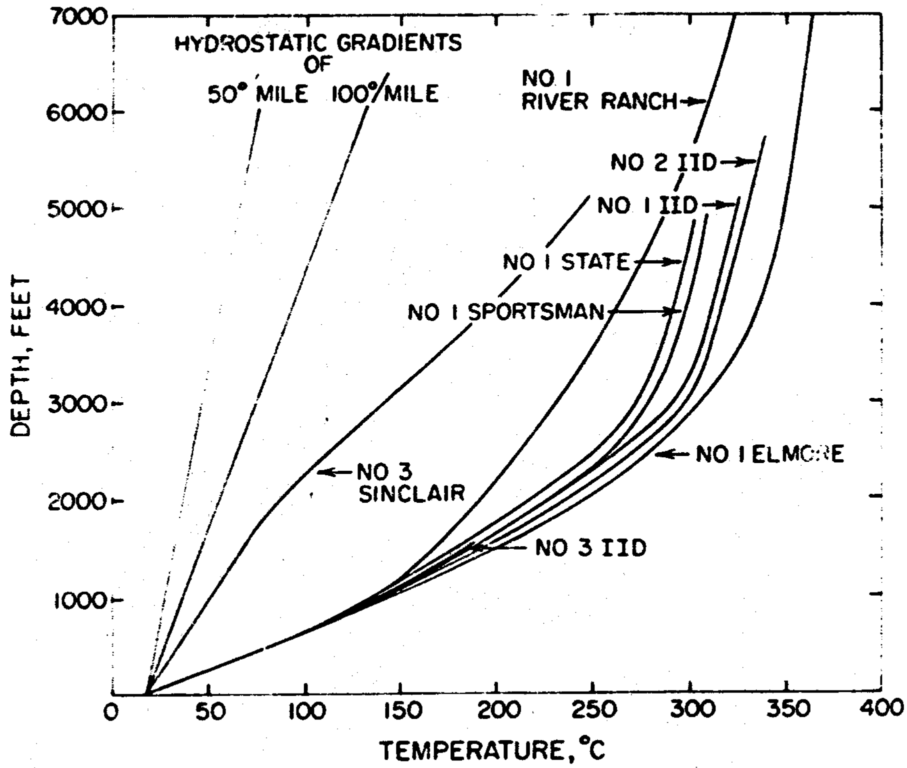


Figure 10. Temperature as a Function of Depth for Salton Sea Geothermal Wells (Reference 8)

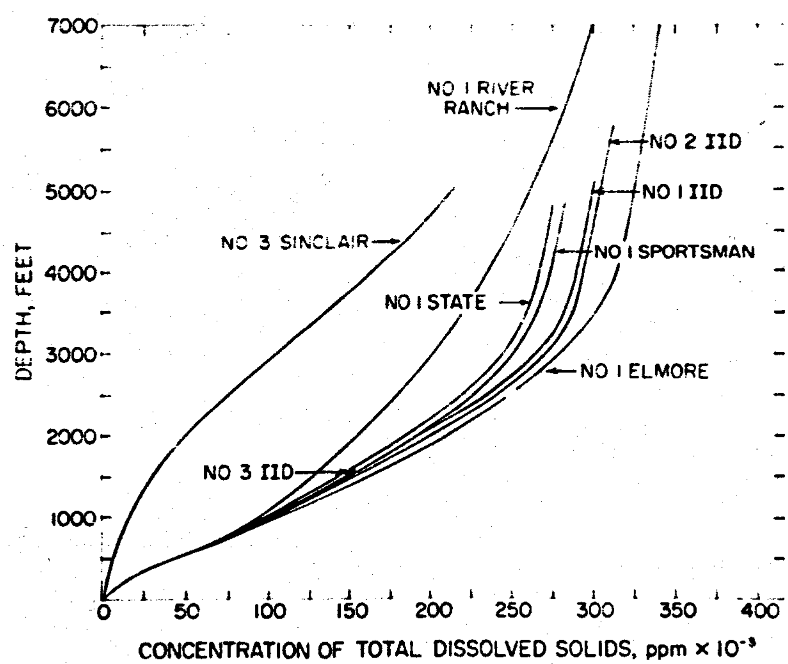
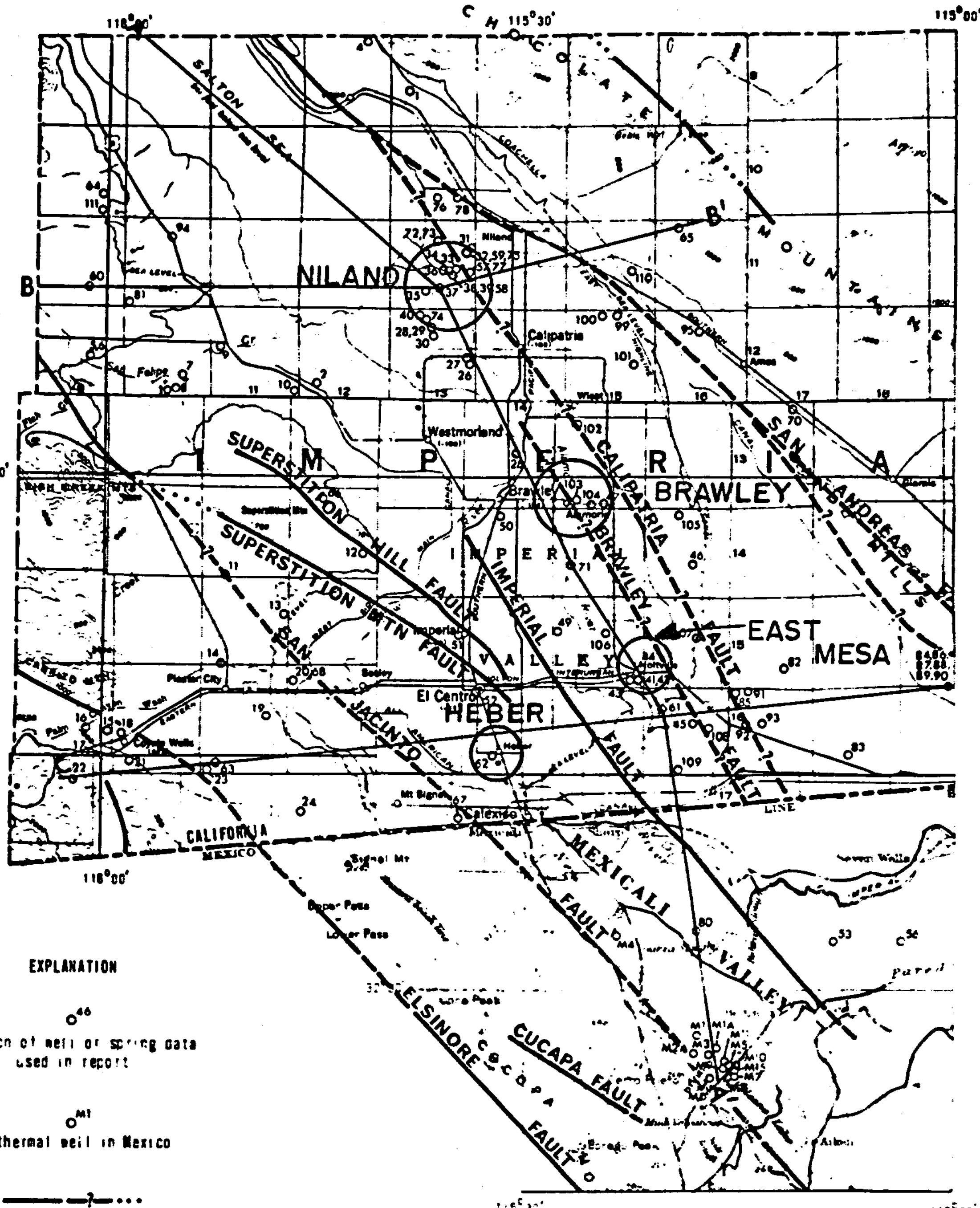


Figure 11. Concentration of Total Dissolved Solids as a Function of Depth for Salton Sea Geothermal Wells (Ref. 8).



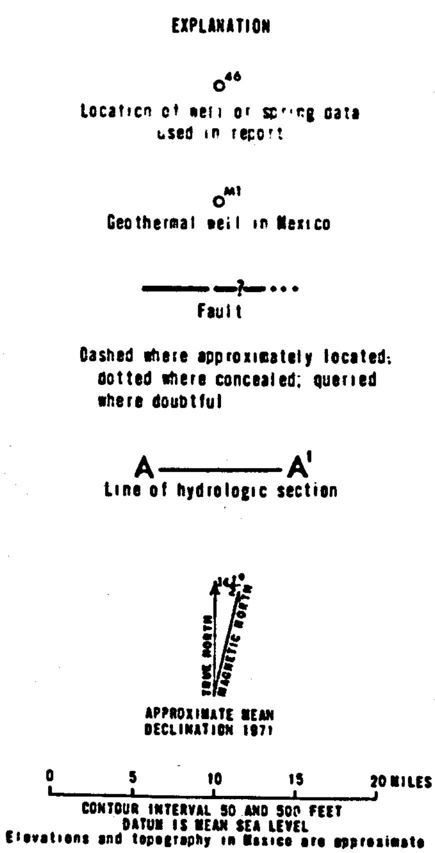


Figure 12. Generalized map of the Imperial Valley area showing major structural features (Ref. 7).

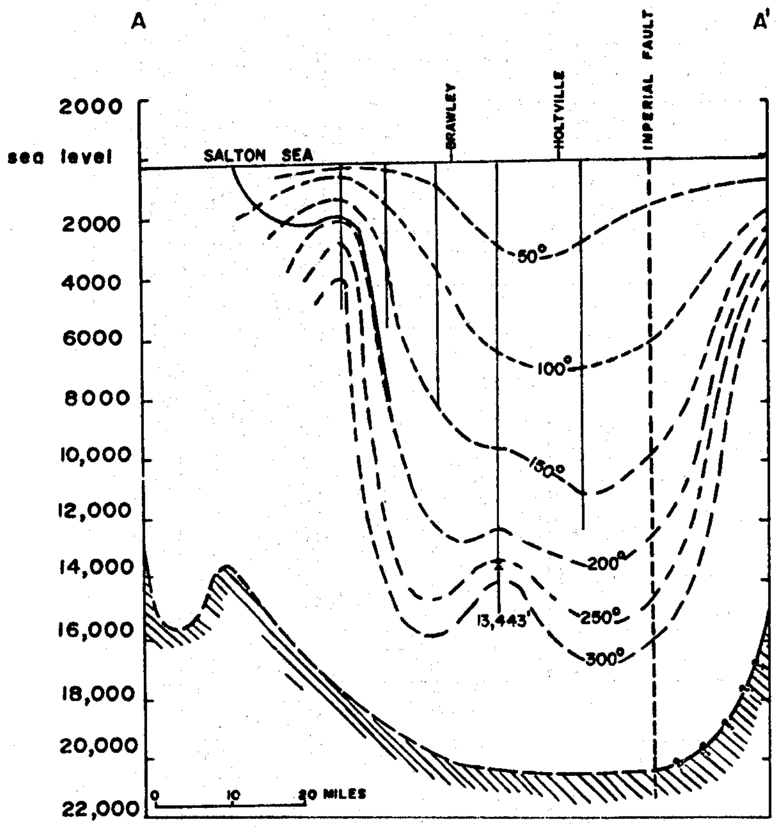


Figure 13. Northwest-southeast trending cross section from the Salton Sea to the Mexican border showing temperature contours as a function of depth in the Imperial Valley area (Ref. 7). Temperature in degrees centigrade.

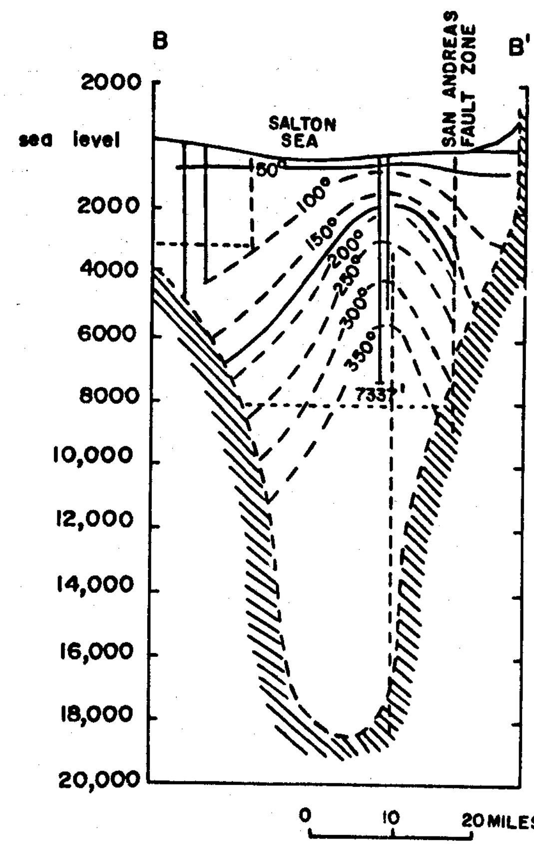
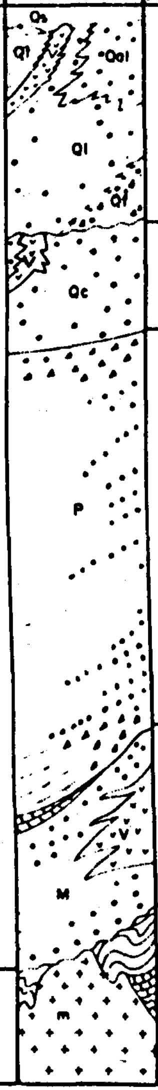


Figure 14. East-west cross section across the Imperial Valley showing temperature contours in the Imperial Valley area in California (Ref. 7). Temperature in degrees centigrade.



Geologic Age	Stratigraphic column	Stratigraphic unit and symbol	Stratigraphic nomenclature*	Maximum thickness (feet)	DESCRIPTION
QUATERNARY		Dune Sand (Qs)	Recent Dune Sand	80	Wind blown sand, local dunes. Locally distributed around Salton Sea
		Alluvial Deposits (Qal)	Recent Alluvium		Gravel, sand, silt, and clay. Occurs along river channels and at foothills above the ancient shoreline of Lake Coahuila
		Volcanic Rocks (V)	Recent Volcanic Rocks		Obsidian, rhyolite, and pumice composing volcanic domes on the southeast shore of Salton Sea. Locally interbedded [illegible] flows and lake deposits
		Lake Deposits (Ql)	Lake Coahuila (Cahuilla) Deposits		Clay, silt, sand, beach gravel, and evaporite deposits of the former extensive lake. Includes older lake beds above ancient shoreline of Lake Coahuila and locally undifferentiated alluvial deposits
		Terrace Deposits (Qt)	Quaternary Nonmarine Terrace Deposits		Extensively dissected and locally folded stream terrace deposits of fanglomerate, gravel, and sand in Borrego Valley
		UNCONFORMITY			
		Nonmarine Sediments (Qc)	Brawley Formation	2,000	Red grey claystone, siltstone, sandstone, and pebbly gravel deposits
			Ocotillo Conglomerate	2,500	Grey, poorly consolidated boulder conglomerate, grading basinward into pink sandstone and claystone. Distributed generally in forebay areas along foothills
		Volcanic Rocks (V)	Pleistocene Volcanic Rocks	- -	Quaternary rhyolite plugs along Salton Creek
TERTIARY		Pliocene Formations (P)	Unnamed Pliocene Pleistocene Nonmarine Sedimentary Deposits		Moderately deformed fanglomerate in the northern Chocolate Mountains, consisting of unsorted, poorly consolidated, pale grey yellow sediments containing mostly angular volcanic clasts
			Canebrake Conglomerate	[illegible]	Grey conglomerate and fanglomerate of granitic and metamorphic debris. Unsorted and poorly consolidated. Continental origin
			Palm Spring Formation	7 000	Light grey arkosic sandstone and reddish claystone, grading into Canebrake conglomerate. Continental origin. Contains Pliocene and/or Pleistocene vertebrate fossils west of Salton Sea
			Borrego Formation	6 000	Light grey claystone and minor amounts of buff sandstone of lacustrine origin; contains a few [illegible] fauna of minute mollusks, ostracods and rare foraminifera; grades laterally into Palm Spring Formation
			Mecca Formation	1,000	Greyish red to yellowish brown basal conglomerate, overlain by a loose and arkosic conglomerate of granitic and metamorphic debris. Continental origin.
			Imperial Formation	4 000	Light grey claystone and lesser interbedded arkosic sandstone with calcerous oyster-shell "reefs." Shallow water, marine in origin
		Miocene--Eocene Formations (M)	Split Mountain Formation	2 700	Red or grey cemented basal conglomerate or fanglomerate and sandstone of granitic and metamorphic debris. Overlain locally by gypsum and anhydrite beds (Fish Creek Gypsum member). The upper member is marine, while the middle and lower members are nonmarine in origin
			Unnamed Oligocene Nonmarine Sedimentary Rocks	- -	Conglomerate, sandstone, breccia, mudstone, and evaporite rocks (Orocopia Mountains)
			Maniobra Formation	- -	Marine Eocene, siltstone, sandstone, conglomerate, and breccia with some sandy limestone (Orocopia Mountains)
		Volcanic Rocks (V)	Undifferentiated Tertiary Volcanic and Intrusive Rocks	- -	Local lava flows and tuffs. Flows are andesitic, rhyolitic, or basaltic rocks of various ages. Also includes intrusive acidic rocks and related diabasic dikes. Alverson andesite dated as Miocene
		UNCONFORMITY			
PRE-TERTIARY		Granitic and Metamorphic Rocks (m)	Undifferentiated Mesozoic Granitic Rocks	-	Granitic rocks
			Orocopia Schist	- -	Pre Cretaceous schist
			Other Pre Cenozoic Granitic and Metamorphic Rocks	- -	Gneiss, limestone, schist, and granitic rocks, ranging in age from Mesozoic to Precambrian.

Total maximum thickness of the Quaternary and Tertiary units (arrow spanning the thickness column): 20 000

*After California Division of Mines and Geology, Salton Sea (1967) and Santa Ana (1966) Geologic Map Sheets. Does not conform to U.S. Geological Survey stratigraphic nomenclature

From California Department of Water Resources (1970)

Figure 15. Generalized stratigraphic column in the Imperial Valley, California (Ref. 7).

become metamorphosed and rhyolite flows are encountered. According to some existing models of the geothermal area, the shales are thought to form impermeable barriers to fluid flow within which convection cells operate (Figure 16)[9]. The temperatures at these depths range from 480 to 700°F (250 to 350°C) depending on the location.

The sediments which filled the basins are weak and should be similar in mechanical response to that of the alluvium from the Nevada Test Site which is found in the same type of geologic environment; that is, a basin and range alluvial filled basin. Axial stress-longitudinal strain and the compressibility of the NTS alluvium illustrate the large amount of deformation that occurs in very low stress regions (Figures 17 and 18)[10]. The strength of the alluvium is very sensitive to the degree of the saturation (Figure 19) and is much stronger under the dry conditions than under saturated conditions. The strength under saturated conditions is low at the pressures equivalent to reservoir depths. The depths to water table in this area can be significant although the sediments will be saturated at reservoir depths. The material will probably be drilled with normal oil field techniques and refrigerated drilling mud. The sandstone and shale units encountered at depth will be weak and friable. An upper bound for the stress-strain response of the sandstone can be extrapolated from the porous Kayenta sandstone data (Figures 20, 21 and 22)[11]. It should be noted that the strength and stress-strain response of the sandstone is a function of the initial porosity; more porous material has lower strength and modulus and significantly more strain to failure (Figure 21). The strength envelope for Kayenta sandstone at confining pressures comparable to overburden stresses in the reservoir is shown in Figure 22[11]. Only a small percentage of material in the Salton Sea area should be abrasive until significant depths are reached where the rock may be metamorphosed. Both Union Oil Company and Republic Geothermal have encountered

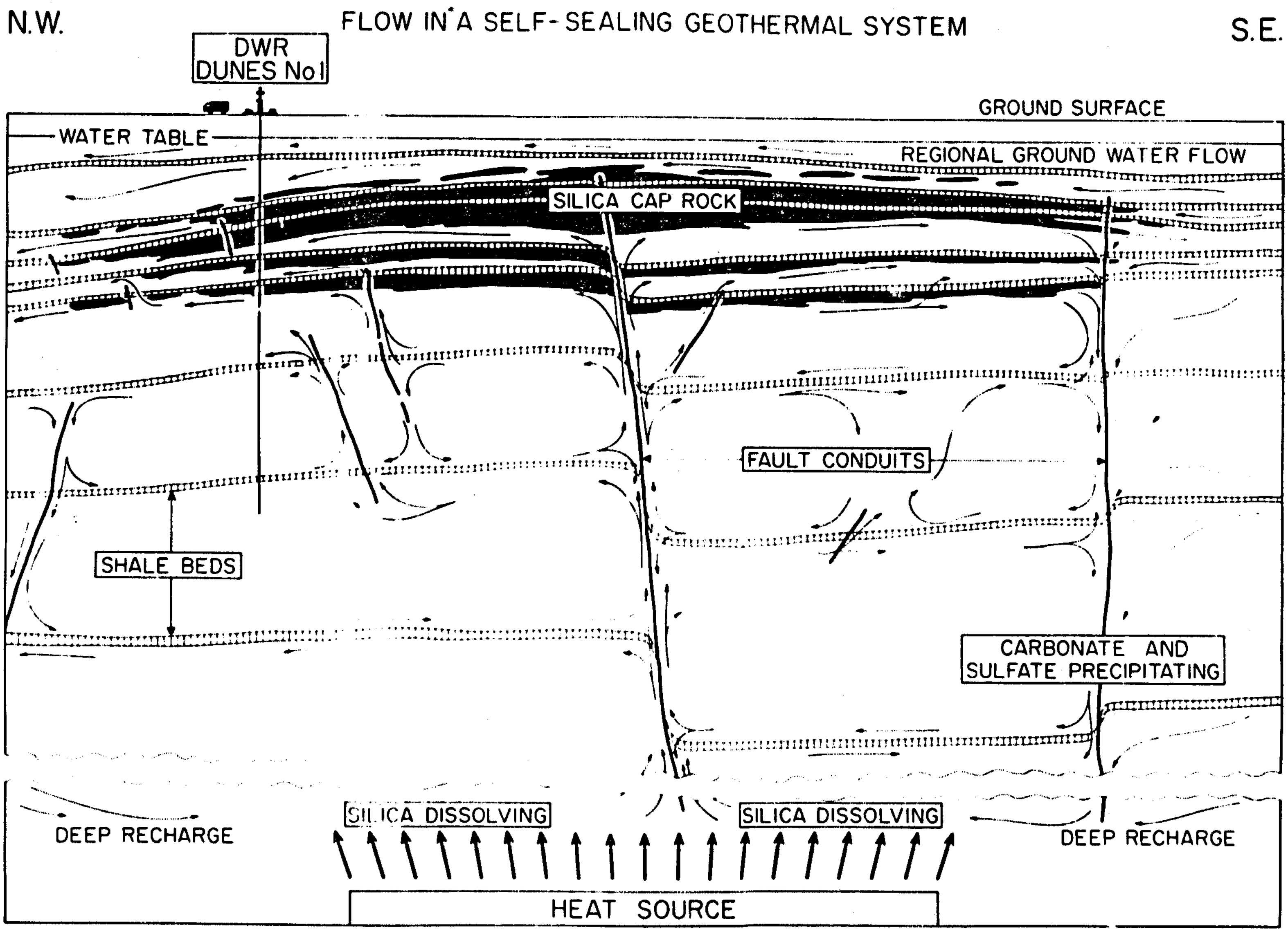


Figure 16. Schematic representation of the self-sealing mechanism in the Imperial Valley geothermal area, California (Ref. 9).

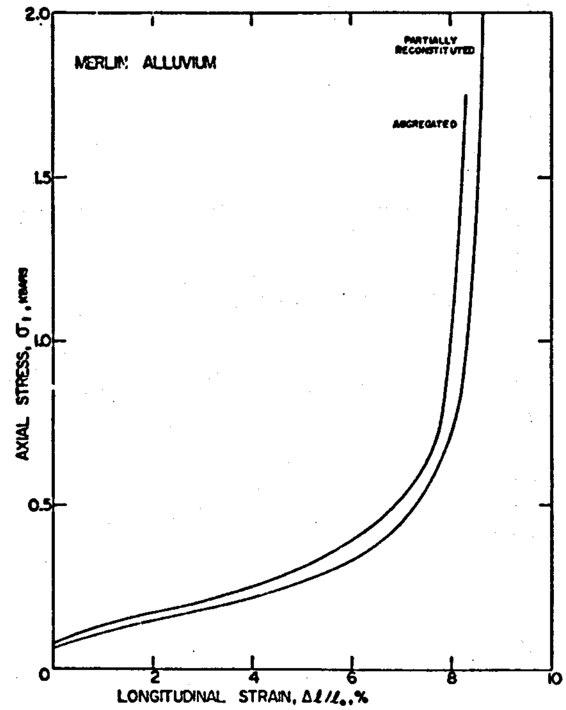


Figure 17.. Shortening strain as a function of axial stress for aggregated and partially reconstituted alluvium.

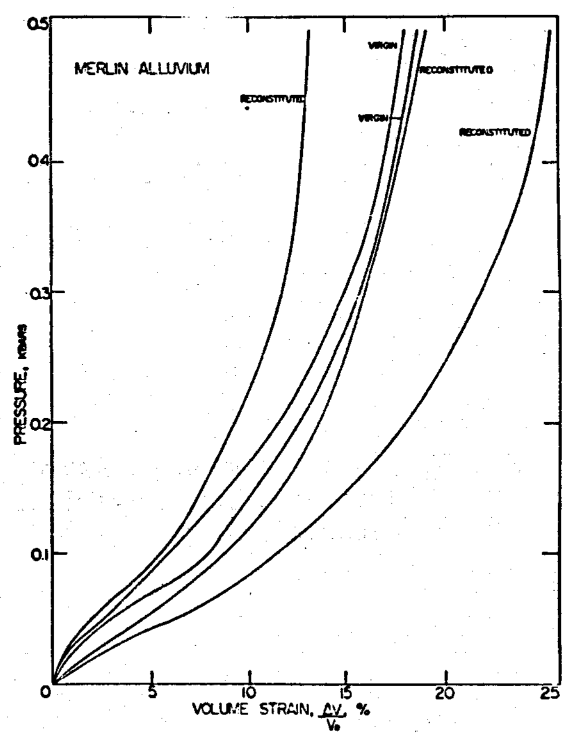


Figure 18. Pressure-volume response of reconstituted and virgin alluvium to .5 kbars.

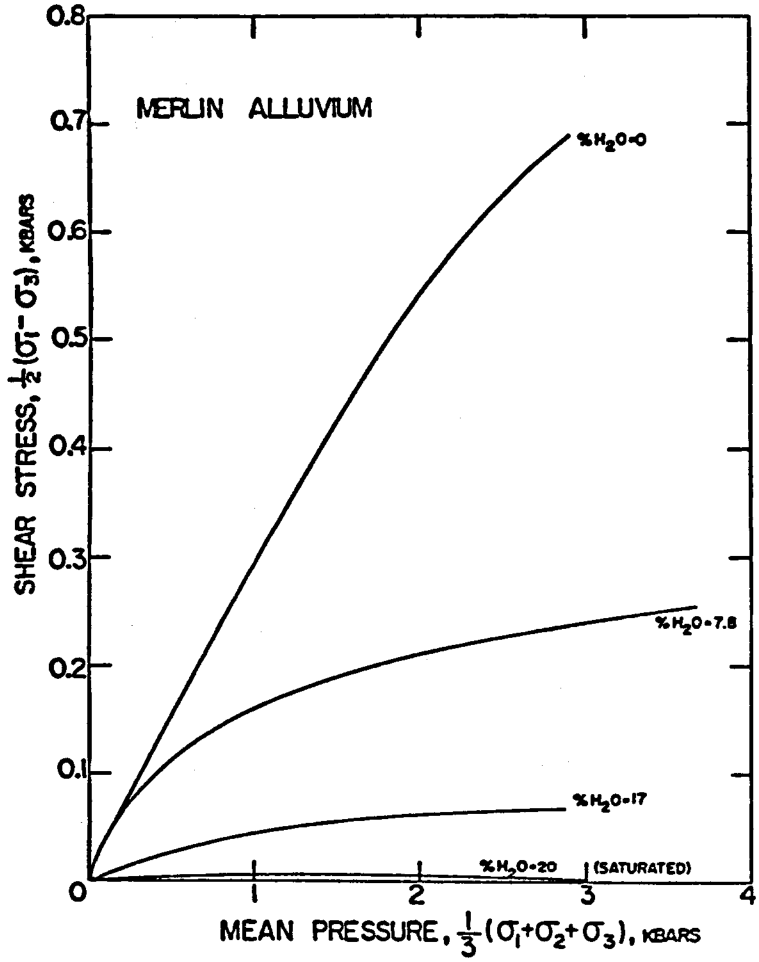


Figure 19. Shear stress mean pressure relationship of alluvium at various degrees of saturation.

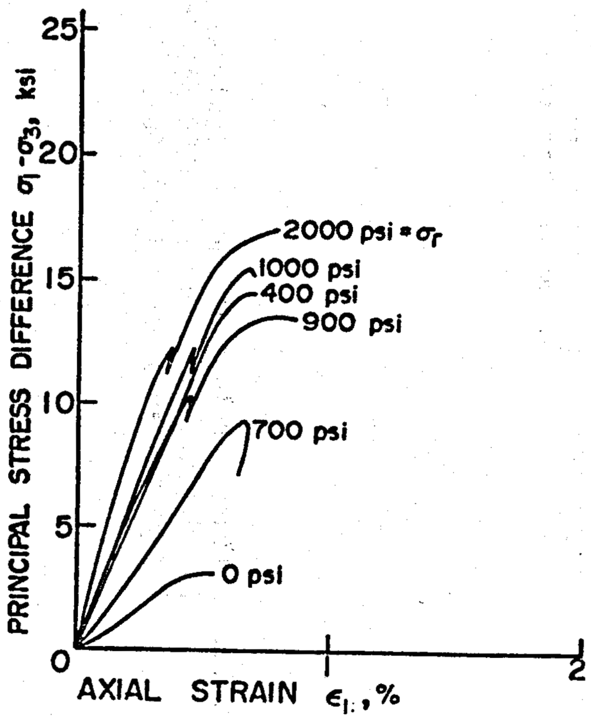


Figure 20. Stress difference -vs- axial strain for confining pressure between 0 and 2000 psi. (Ref. 66).

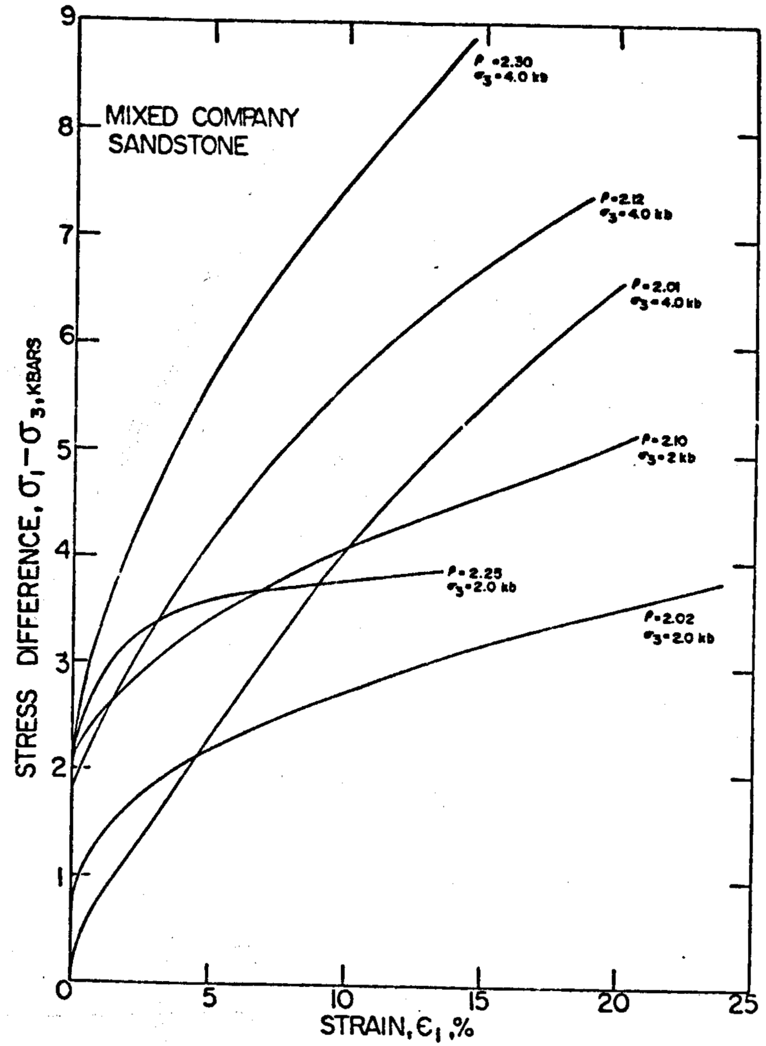


Figure 21. Strain as a function of stress difference for confining pressures between 2 and 4 kbars for samples of various densities of Kayenta sandstone. (Ref. 22).

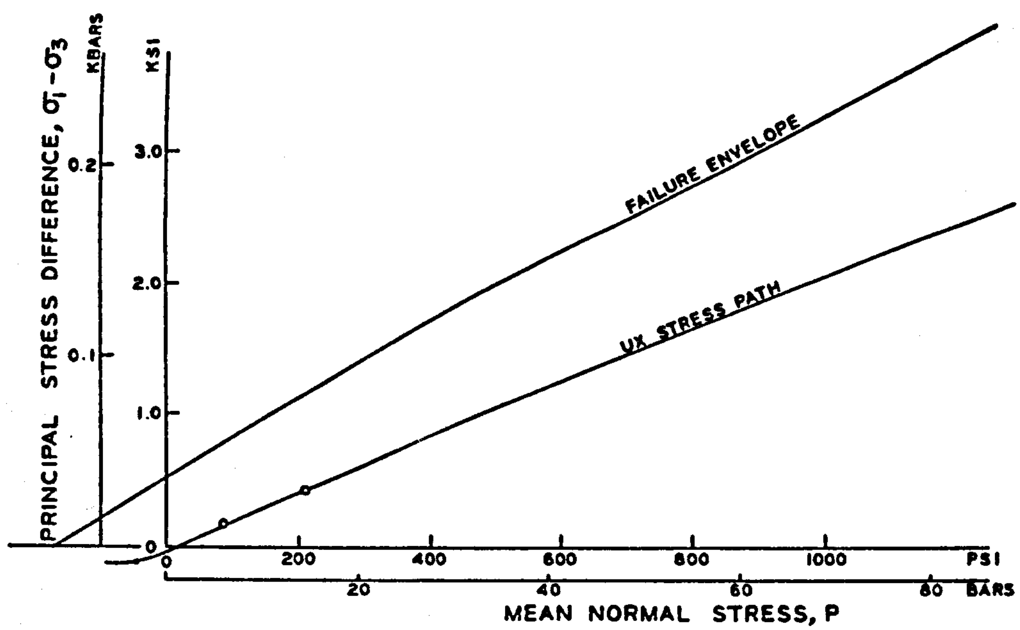


Figure 22. Failure envelope and uniaxial stress path for triaxial shear to P = 1200 psi for layer 4 Kayenta sandstone. (Ref. 66).

only a small amount of lithified material in this section at depths to 9,000 feet[12]. The strength of the rock media will increase if metamorphism has taken place at depth and it is expected that the permeability within the geothermal environment at those depths will be a fracture permeability. For depths down to 9,000 feet most of the permeability will be as a pore type permeability with fluids percolating through the porous sediments[13]. The permeability at these depths ranges from 600 to 1,200 millidarcies[7]. No core has been taken to date in the Salton Sea geothermal although an attempt was made by Republic Geothermal to obtain core at a depth of 11,000 feet in the Heber field. The caustic nature of the geothermal fluids in the Salton Sea area will probably not be a significant problem to the drilling because the bits are essentially isolated from the caustic fluids due to the use of cooled drilling mud. The geothermal fluids have up to 30 percent dissolved solids near the Niland geothermal field[8] but decrease away from the Salton Sea area.

Except for some temperature measurements, few geophysical measurements have been made at depth in boreholes. On the basis of mineral constituents and porosity, thermal conductivity of the unconsolidated material is estimated to be 3 to 5 x 10^{-3} cal/cm sec°C; for the heat flow on the order of 4 to 6 x 10^{-6} cal/cm^{2}sec[6]. The pressures encountered are hydrostatic, about 0.0295 atm/ft.

Roosevelt Hot Springs, Utah

The Roosevelt Hot Springs area is a potential producing geothermal field located in southwestern Utah (Figure 2). The area is located in the basin and range physiographic province in a structurally complex area on the western side of the Mineral Range Mountains (Figure 23)[14]. A schematic cross section of the area shows that the stratigraphy consists of alluvium underlain by a fractured grantic rock probably of Tertiary age (Figure 23). Some of the rock

GEOLOGIC MAP OF THE ROOSEVELT HOT SPRINGS AREA,
BEAVER COUNTY, UTAH

J. A. Whelan & C. A. Petersen

December 1974

Scale

1 : 24,000

(1 inch = 2,000 feet)

Correlation of Map Units

Alluvial Deposits: Qal

Hot Spring Deposits: Qhs, Unit C — Order does not reflect age

Bedrock:
- Holocene
- Unit B, Unit A — Pleistocene (Quaternary)
- Tva, Tvg, Tg — Tertiary
- Pcm — Precambrian

Description of Map Units

Qal — Quaternary alluvium.-- Gravel, pebbles, and cobbles derived from granite and silicic volcanic rocks. Unconsolidated. Most of the unit is Holocene of Pleistocene in age, but some parts may be Pliocene in age.

Qhs — Quaternary hot-spring deposits.-- Tan to white soliceous sinter; and layers of white, red, and brown opal.

Unit C — Unit C.-- Fragments of granite in siliceous matrix. Stratified or unstratified. White or tan but orange or purple streaks of hematite staining are common.

Unit B — Unit B.-- Fragments of granite in glassy matrix. Pale or green or white.

Unit A — Unit A.-- Fragments of granite in glassy matrix. Tan or medium brown.

Tva — Tertiary volcanic ash.-- Stratified white ash. Possibly water-laid.

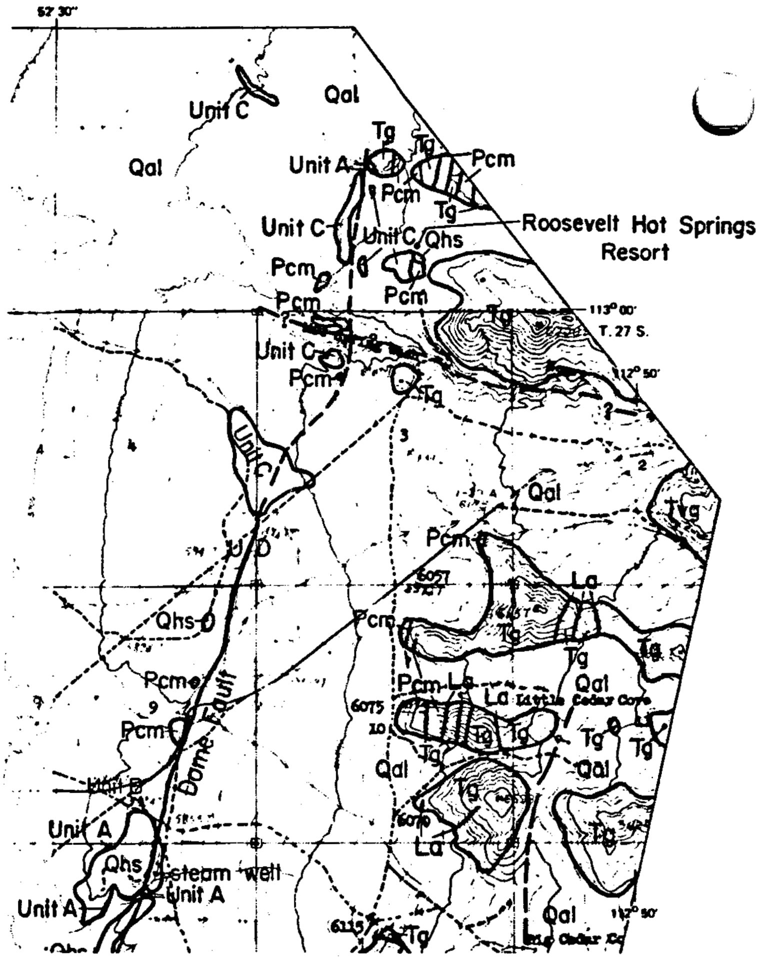
Tvg — Tertiary glassy volcanics.-- Silicic flow rocks. Tan to gray glassy rock, or obsidian.

Tg — Tertiary granite.-- White or gray, medium grained.

Pcm — Precambrian(?) metamorphic rocks.-- Biotite gneisses, schists, phyllites, quartzites.

Symbols

- Doubtful or probable fault (dotted where concealed).
- Contact
- La — Lamprophyric dike
- Ap — Aplitic dike
- Tg — Granite dike in metamorphic rock
- V-shaped embankment



ROOSEVELT HOT SPRINGS
DIAGRAMMATIC CROSS SECTION

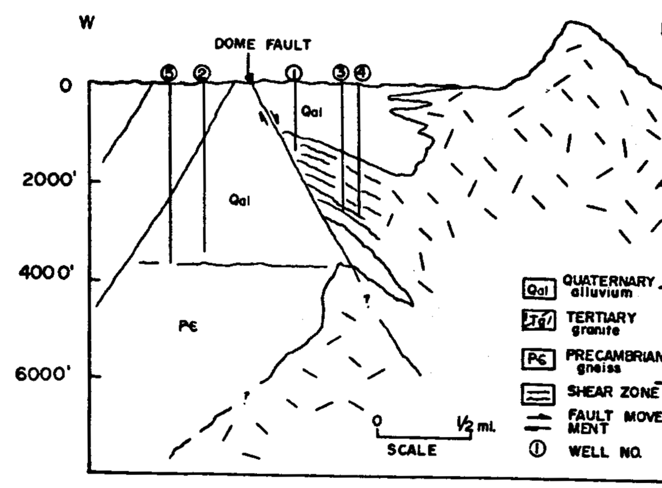


Figure 23. Generalized geologic map and cross section, Roosevelt Hot Springs geothermal area, Utah.

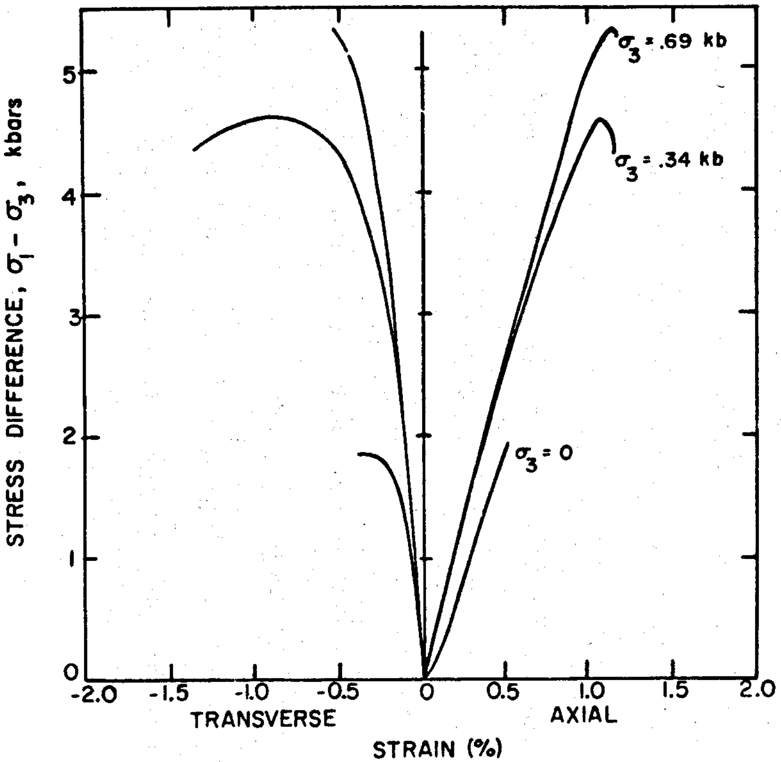
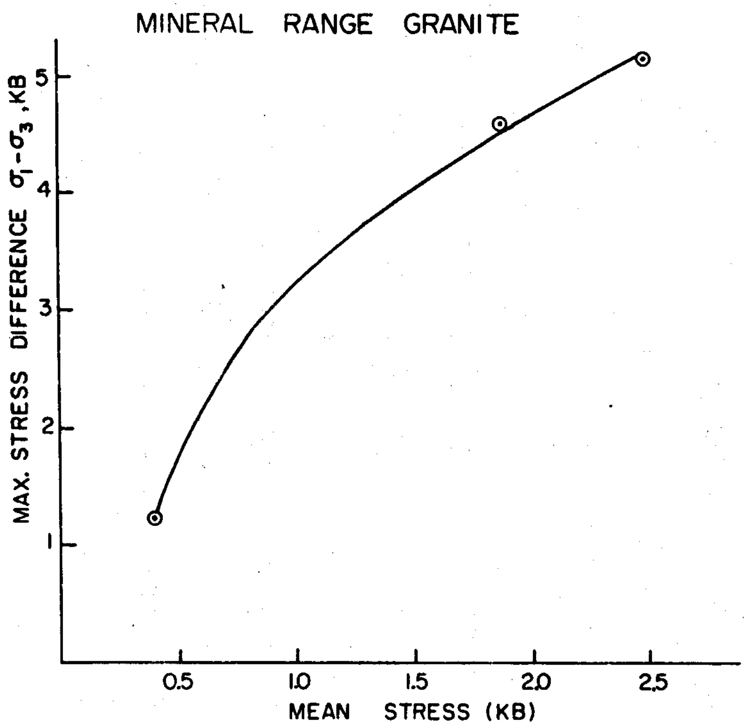


Figure 24. Stress-strain response of the Mineral Range granite, Roosevelt Hot Springs, Utah.



σ_3 (KB)	$\sigma_1 - \sigma_3$ (KB)	$\frac{\sigma_1+\sigma_2+\sigma_3}{3}$	E (KB)	ν
UNC	1.21	0.4	440	.32
.34	4.55	1.86	504	.28
.69	5.38	2.48	504	.28

Figure 25. Failure envelope and elastic properties, Mineral Range granite Roosevelt Hot Springs, Utah.

is altered and fractured and at least the upper part has been silicified[15]. To date, six exploratory geothermal wells have been drilled into the reservoir by Phillips Petroleum Co. as part of a program to delineate this geothermal deposit. The reservoir rock is highly fractured granite and granite wash. Reservoir depths range between 2,000 and 6,000 feet; the deepest well to date drilled in the field has been a "dry" hole on the order of 8,000 feet. The field appears to be structurally controlled by the Dome fault, located two to three miles to the west of the front of the Mineral Range Mountains. The exact structural nature of this geothermal deposit or the scope of the deposit is not known at this time. The reservoir parameters for this field are given in Table 2. Temperatures of 400 to 500°F have been encountered and the fluid permeability of the rock will be primarily along fractures. Drilling in the reservoir will be through granite wash and fractured granite at fairly high temperatures. The salinity of the area appears to be moderate to low[15].

A hand specimen of unaltered granite was obtained from the Mineral Range Mountains and has been tested to obtain mechanical properties. The rock is quite hard, brittle and strong as indicated by the small amount of strain to failure once the ultimate strength has been reached (Figure 24). The failure envelope of the Mineral Range Mountains indicates a strong rock with significant increase in strength with confining pressure (Figure 25). The rock will be abrasive since quartz and feldspar dominate. The exact nature of the material, however, is not fully known since no core has been taken from the reservoir zone. The pressure in the area is approximately hydrostatic. No geophysical logs have been conducted in the holes drilled to date. Heat flow has been measured and core has been taken in shallow 200 foot-deep holes[16]. A detailed study of the geothermal area by geologic and geophysical techniques is being conducted by the University of Utah[16].

Bacca Ranch, Valle Grande, New Mexico

The Bacca Ranch, Valley Grande geothermal area being explored by Union Oil Company is located in the Jemez Caldera approximately 70 miles northwest of Albuquerque, New Mexico, Figure 3. The geologic map and cross section of the area shows that the center of the volcanic caldera consists of interbedded tuff flows and andesites which have been highly faulted (Figure 26)[17]. The primary reservoir rock is the Bandelier tuff which is generally welded at depths of interest which are on the order of 5,000 to 7,000 feet[18]. Temperatures range from 400 to 500°F. Reservoir characteristics are summarized in Table 2. The primary permeability is along fractures because even though the rock is porous it is very low in permeability (microdarcy range). Fracture ranges from a few feet to a few inches at reservoir depths[18].

Drilling in the reservoir area is accomplished with aerated mud and normal oil field techniques. Only a small amount of core has been obtained by the Union Oil Company but no material property has been published. The author feels that material property data can be extrapolated from the Mt. Helen welded tuff in central Nevada to approximate the mechanical response of the welded tuff in the reservoir. The elastic moduli and seismic velocity derived from laboratory tests are summarized in Table 4. The stress-strain response of the welded tuff shows that the rock is ductile at hydrostatic pressures of equivalent to depths within the reservoir, .25 to .5 kilobars (Figures 27 and 28)[19]. No data is available at elevated temperature. The failure envelope for the welded tuff shows that the strength of the rock is drastically affected by the amount of water present. The lowest curve, approximately at saturation (8 percent), would be representative of strength values under *in situ* conditions (Figure 29). Note that the strength of the tuff does not increase significantly with confining pressure as it had for the graywacke

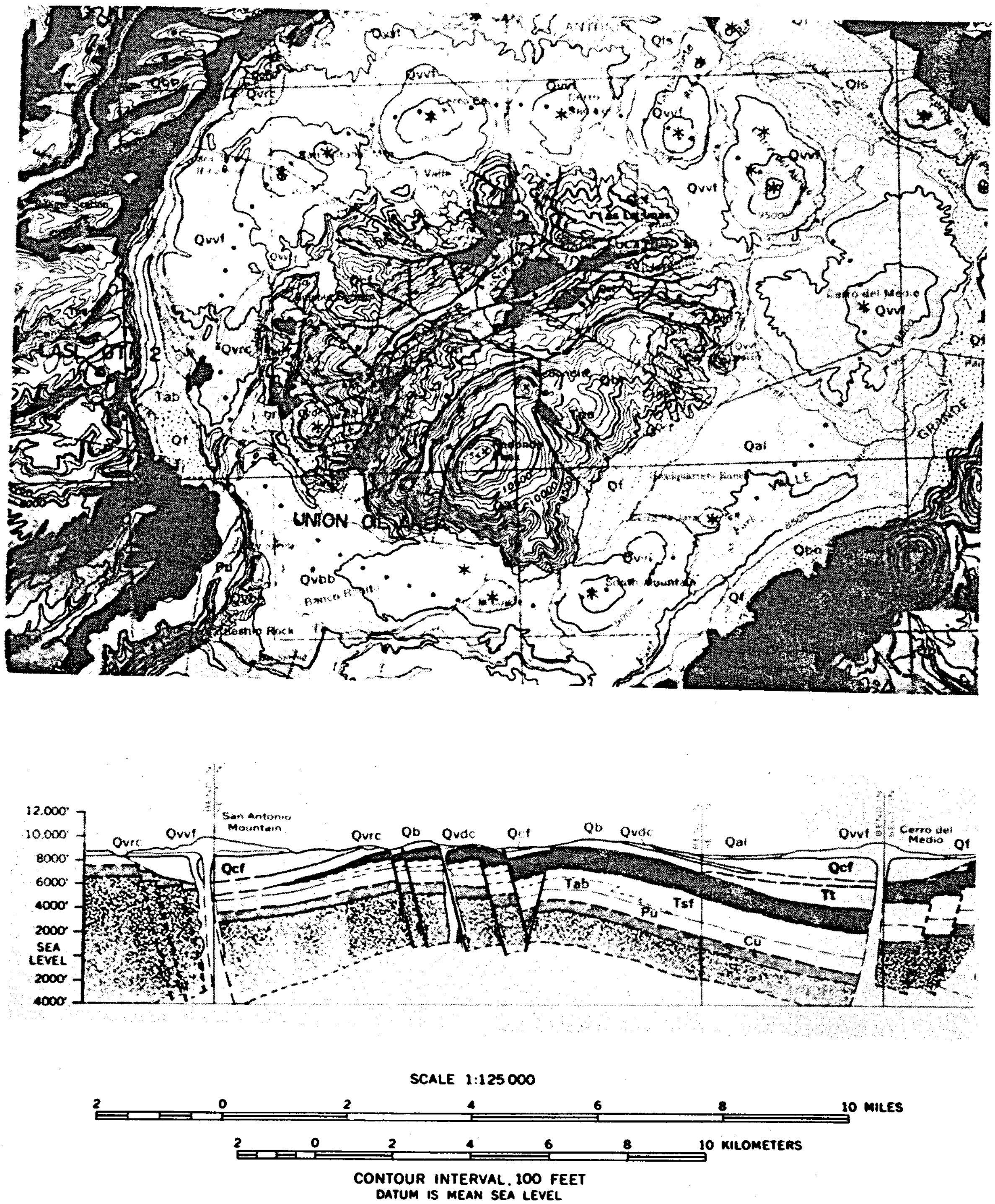


Figure 26. Generalized geologic map and cross section of Union Oil geothermal field and Los Alamos GTH Well #2, Sandoval County, New Mexico.

TABLE 4

Elastic Moduli from Seismic Velocities, Ultrasonic Data and Mechanical Tests, Mt. Helen Welded Tuff

Derived from:	Constrained Modulus (B) KB	Bulk Modulus (K) KB	Shear Modulus (G) KB	Young's Modulus (E) KB	Poisson's Ratio (ν)
Velocities					
Ultrasonic (0-15')	198±40	97±20	77±10	180±30	0.19±0.05
Seismic (0-15')	130	---	---	---	---
Hydrostatic Compression (4'-8')					
Initial Slope	---	50	---	---	---
Linear Region	---	110	---	---	---
Uniaxial Strain (4'-8')					
Initial Slope	50	[23]	[20]	[47]	0.16
Linear Region	190	[83]	[73]	[170]	0.20
Triaxial Compression (4'-8')					
$\sigma_3 = 0$ loading	[130]	[56]	[55]	124 average (120-165)	0.13 average (0.11-0.15)
unloading	---	---	---	---	---
$\sigma_3 = 0.25KB$ loading	[205]	[93]	[80]	190	0.18
unloading	[270]	[167]	[77]	200	0.30
$\sigma_3 = 0.50KB$ loading	[251]	[131]	[90]	220	0.22
unloading	[311]	[206]	[86]	210	0.33
$\sigma_3 = 2.70KB$ loading	[267]	[142]	[94]	230	0.23
unloading	[470]	[333]	[103]	280	0.36

*The moduli for the velocities were calculated from the density and the longitudinal and shear velocities. The moduli from the mechanical tests were either scaled directly from the stress-strain and stress-stress curves (unbracketed numbers) or calculated from the direct measurements (square brackets). The numbers in circular brackets represent the range of values for several tests. The moduli are all considered representative of material with 1.5% water by wet weight.

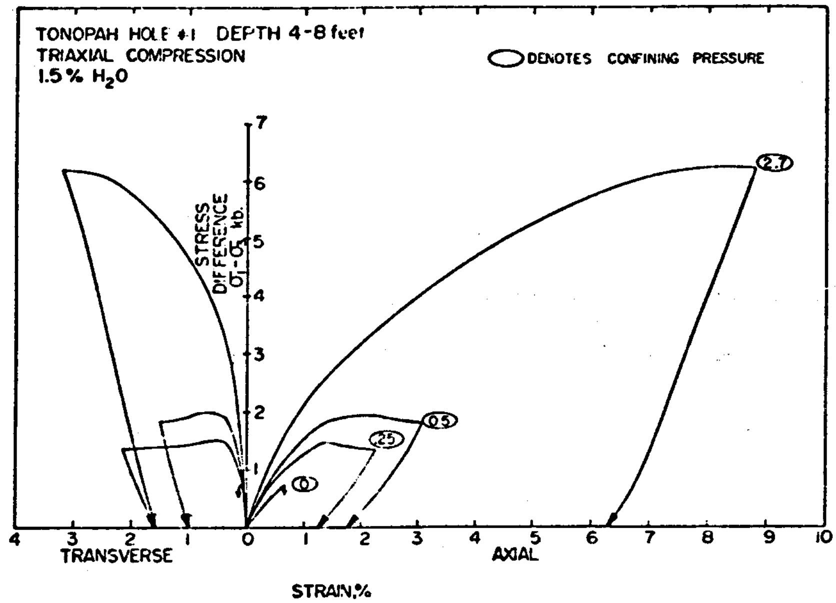


Figure 27. Triaxial Compression Tests -- Stress Difference versus Individual Strains, Mt. Helen Welded Tuff.

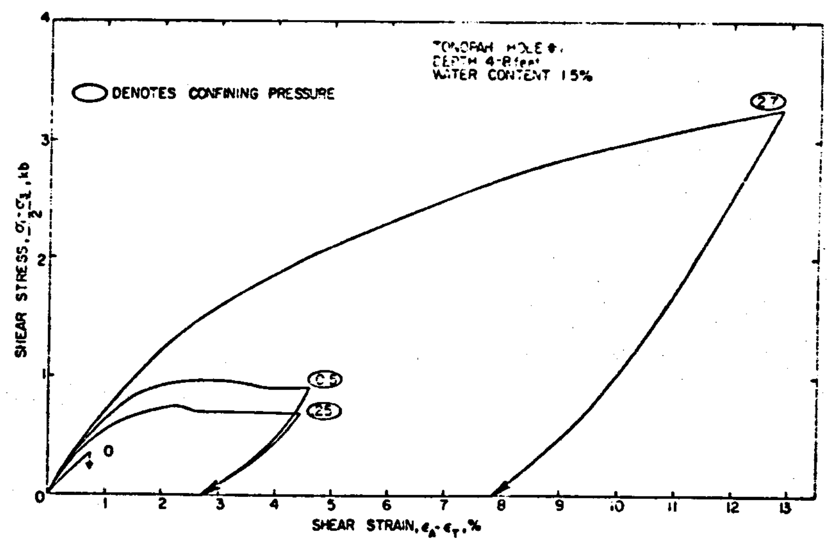


Figure 28. Triaxial Compression Tests -- Shear Stress versus Shear Strain, Mt. Helen Welded Tuff.

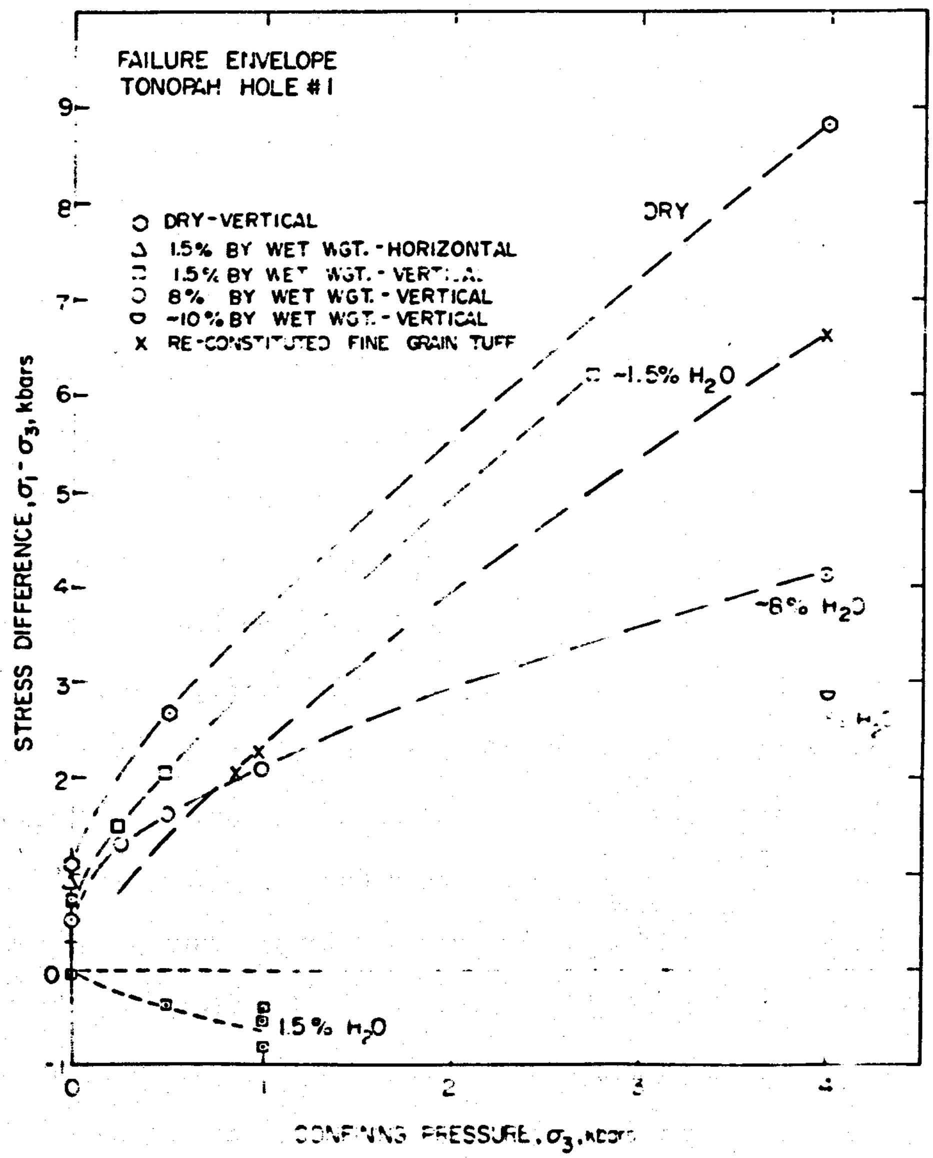


Figure 29. Failure envelope of the Mt. Helen welded tuff as a function of saturation (Ref. 19).

at the Geysers area California and for the granite at Roosevelt Hot Springs, Utah. The tuff will not be an abrasive rock because of high porosity, glassy texture and its mineralogic composition. The rock is comprised of a fine-grained matrix made up of glass and glassy fragments with phenocrysts of quartz and feldspar. The rock is soft, not abrasive and did not present difficult drilling although Union indicated problems were associated with the aerated mud drilling fluid which corrodes the drill stem pipe[21]. Geophysical logs have been run in the Los Alamos Scientific Laboratory test wells located five miles northwest of the Union oil field. These wells penetrated the Bandelier tuff. The logs include 3-D velocity, gamma-caliper, electric (SP-resistivity), temperature, density and gamma-neutron[20].

Jemez Caldera, Sandoval County, New Mexico

The hot dry rock geothermal program of the Los Alamos Scientific Lab has consisted of drilling a series of deep holes into a hot crystalline basement with subsequent hydr racturing to produce the necessary surface area and communication between holes. To date three deep holes have been drilled through a volcanic and paleozoic sedimentary sequence into an underlying crystalline basement. These wells are located on the flank of the Jemez Caldera about 70 miles northwest of Albuquerque, New Mexico (Figures 3 and 26). The deepest well has been drilled to 9,619 feet. Complete geologic, geophysical and drilling logs were run on these holes including rock type fracture spacing, drilling rates, etc.[20,22], Figure 30. The geophysical logs included 3-D velocity, gamma-neutron, density, electric and temperature. The temperature at the bottom of this hole is 387°F. The drilling fluids used to drill vary from mud to air to water to mud plus water. There is no reservoir per se except to say that hot granite is needed. The depth of interest will depend on the local geothermal gradient. The granite will have to be hydrofractured

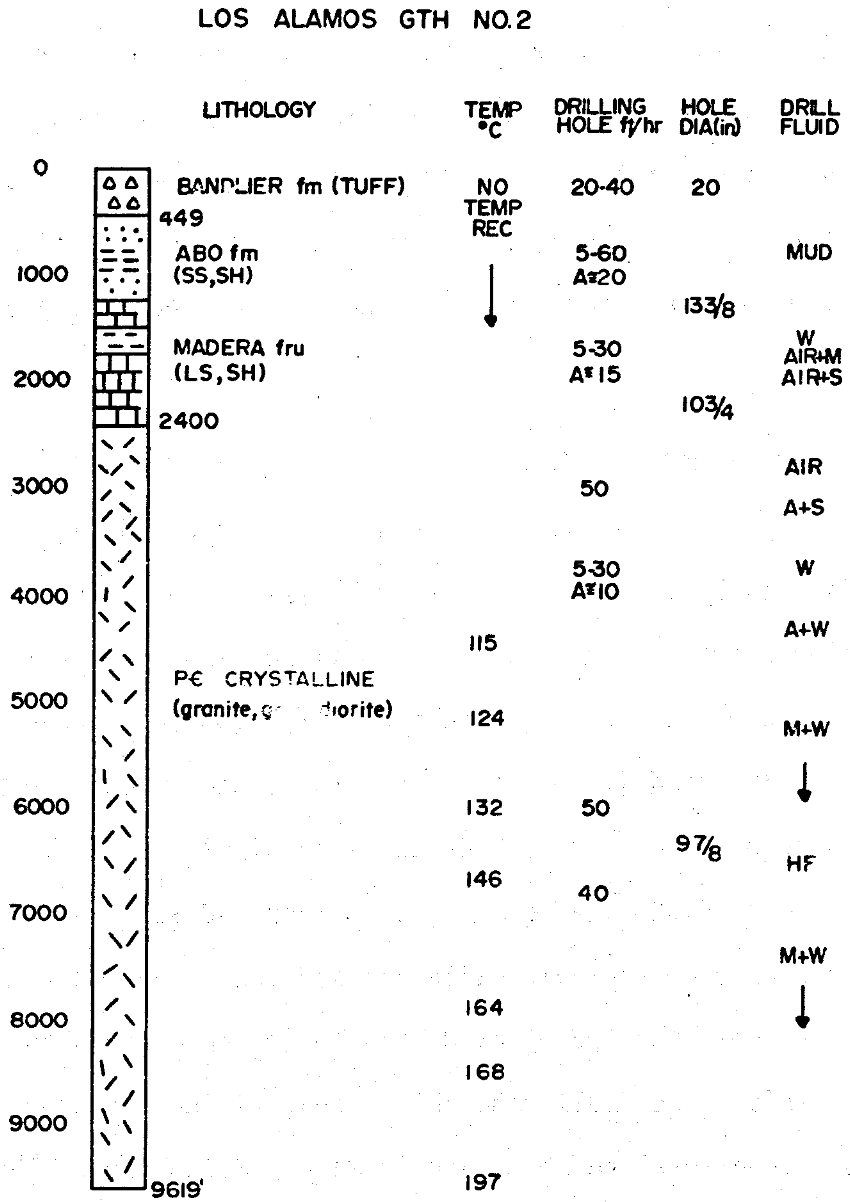


Figure 30. Stratigraphic section, temperature profile, drilling rates and drilling fluid; Los Alamos GTH #2 well.

to produce the necessary surface area to allow fluid to percolate along the fractures to withdraw the heat. The reservoir rock consists of Precambrian crystalline rock ranging from granite to granodiorite. The fracture spacing of the granite ranges from a few inches to feet. The intact rock is hard and brittle[20]. Drilling rates of 5 to 30 ft/hr indicate the rock is moderately abrasive. The drill bit life seems to be correlative with the quartz content of the granitic rock with the quartz-rich rocks wearing the bits significantly faster than the more feldspar-rich rocks which were found at greater depths[23].

Raft River

The raft River geothermal area is located at approximately 50 miles south-east of Rupert in southeastern Idaho, Figures 3 and 31[24]. The Raft River site is located in a basin and range physiographic province within an alluvial filled block faulted basin. A cross section of the area shows the two wells that have been drilled into the quartz monzonite reservoir rock (Figure 32)[25]. The conduit for the geothermal fluid appears to be the Bridge fault zone, a zone approximately 230 feet wide dipping at 60°. The wells penetrated 4,000 to 4,500 feet of the Raft River and Salt Lake formations consisting of poorly consolidated alluvial sediments and underlying soft volcanics. The wells then penetrated hard metamorphic rocks consisting of quartzite and shist; the fault zone and the underlying Precambrian quartz monzonite rock to a total depth of approximately 6,000 feet. The temperatures at reservoir depths were on the order of 290 to 300°F. The nature of the materials in the fault zone will be highly variable and are undoubtedly extensively fractured. Some core was taken in both holes, RRGE1 and RRGE2. Permeability measurements have been made by Terra Tek on some of the overlying volcanic media, but no material property tests have been run. Permeability is on the order of microdarcies (Table 5). It is expected that the quartzite and

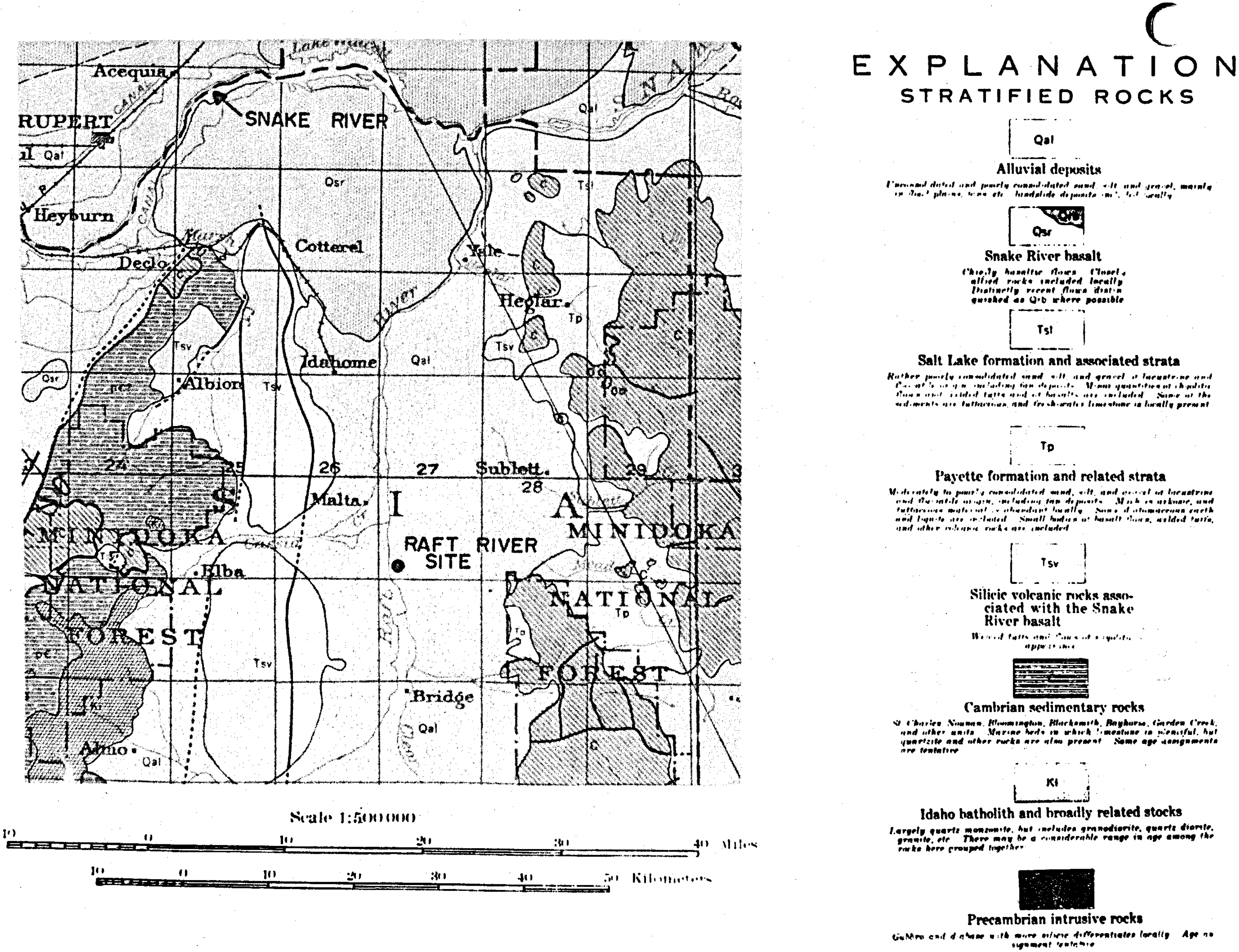


Figure 31. Generalized geologic map of the Raft River geothermal area.

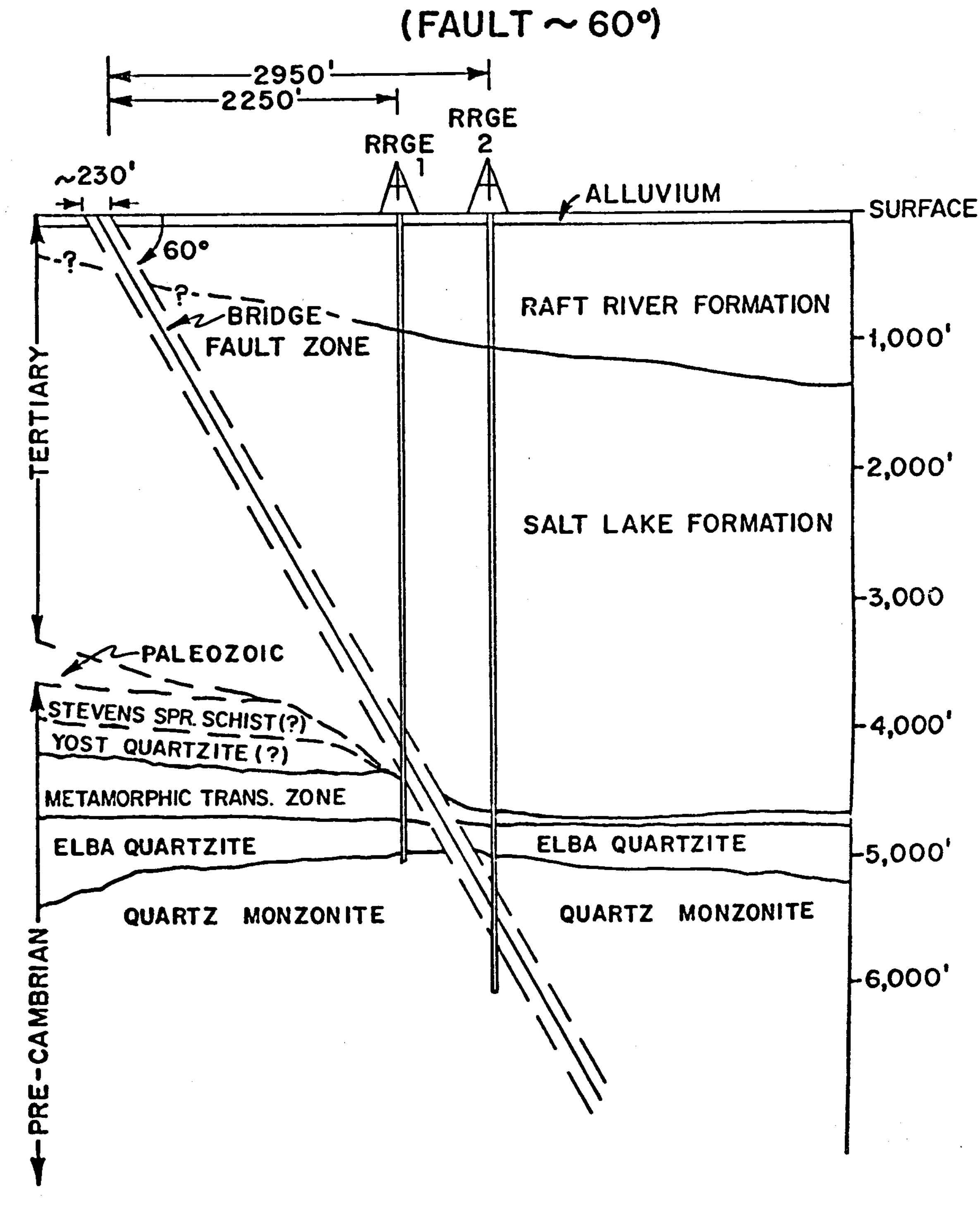


Figure 32. Cross section of the Raft River geothermal area showing locations of the two wells drilled in the area.

TABLE 5

Results of Permeability Tests Performed for ERDA
on Samples Taken From the Raft River Geothermal Well

Sample Depth	4,227	4,372	4,506
Axial Stress - Vertical (psi)	4,855	5,025	5,175
Lateral Stress (psi)	3,480	3,265	3,710
Pore Pressure (psi)	1,880	1,945	2,005
Temperature (^{o}F)	220^{o}	200^{o}	210^{o}
Permeability (millidarcies)	.003	.002	5

(Stress levels and temperatures were chosen to simulate *in situ* conditions)

TABLE 6

Raft River Geothermal Project
(Bottom Hole Temperature 290 - 300° F)

BIT	FORMATION	DEPTH DRILLED* (FEET)	TIME (HOURS)	DRILLING FLUID	LOAD (1000 LBS)	RPM
Smith Tool Company 12 1/4" DGHJ bit	Tuffaceous Siltstone & Sandstone	2470 thru 3054	[illegible]	Mud+	[illegible]	[illegible]
Smith Tool Company 12 1/4" 9JS bit	Extremely hard Quartzite	5335 thru 5523	32	Water	40	[illegible]

* Ground level 4845 ft. elevation

+ Input mud temperature 160° F
Return mud temperature 180° F

the quartz monzonite will be strong, abrasive and brittle. The material property data from the granite in the Milford geothermal area can probably be extrapolated to the quartz monzonite (Figures 24 and 25). However, it is expected that the overlying Salt Lake formation consisting of sediments and volcanics which will be much softer. The drilling rates are summarized in Table 6.

Marysville, Montana

The Marysville, Montana geothermal area is located in west central Montana approximately 50 miles west of Helena, Figures 3 and 33[26]. The geologic map of the area shows that the geothermal area is underlain by Precambrian shale and igneous rocks of cretaceous age. This geothermal deposit was delineated on the basis of the heat flow data[23], and the hole was part of a National Science Foundation (RANN) program[26]. The single hole, 6,720 feet deep, was drilled through a section of shale and quartzite into quartz feldspar porphyry (Figure 34). Only 975 feet is metamorphosed sediments; the bottom 5,748 feet is crystalline rock. The temperature profile is also given in the Figure 34 and indicates a maximum temperature of 200°F. The coring summary for the Marysville project is given in Figure 35. The footage per drill bit ranged between 300 to 400 feet at depths of between 2,000 feet and the bottom of the hole at 6,709 feet using a 7 7/8 inch drill bit (Figure 36). There were not significant drill bit problems because of the low temperatures encountered, even at greater than 5,000 feet. However, journal bearing bits gave better bit performance than unsealed roller bearing bits[27].

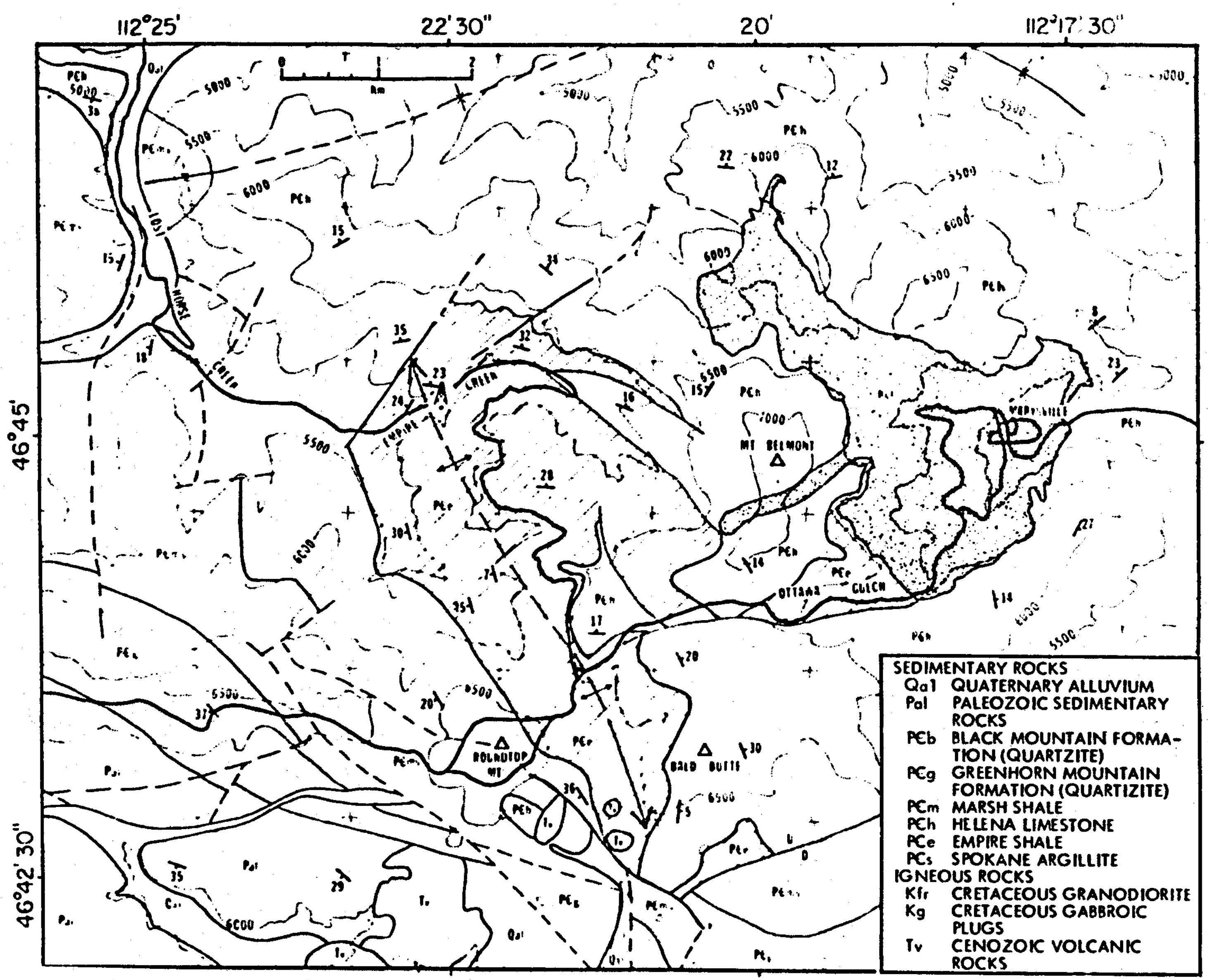


Figure 33. Topography and geologic map of Marysville geothermal area: contour interval = 500 ft (152 m); location of deep drill hole indicated by derrick symbol; many Cenozoic dikes and sills omitted from map.

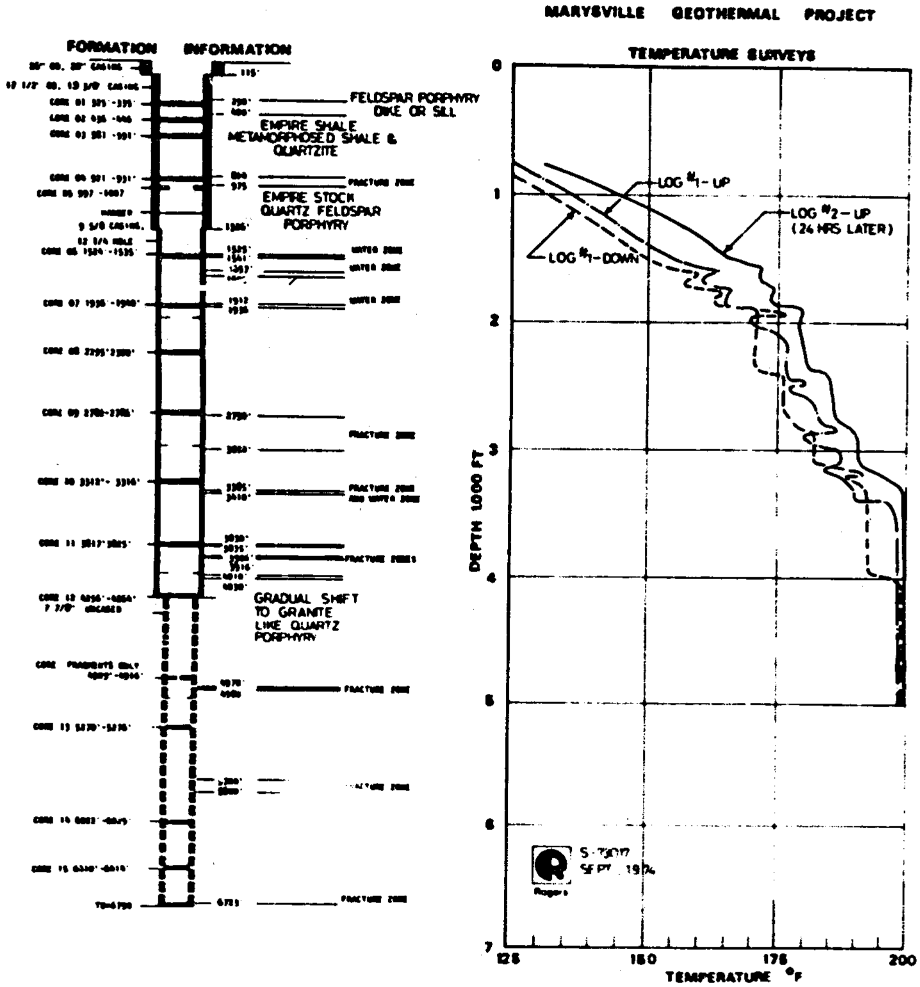


Figure 34. Geologic section and temperature profile as a function of depth in the Marysville, Montana geothermal well.

Coring Interval		Cored	Coring Rate Ft/Hr	Core Recovered	Core Diameter	Remarks
No.	Depths					
1	325 - 335	10'	2.1	10'	4"	
2	436 - 446	10'	5.0	6'-10"	4"	
3	581 - 591	10'	2.2	9'-8"	4"	
4	921 - 931	10'	3.3	10'	4"	
5	997 - 1007	10'	1.7	10'	4"	
6	1524 - 1530	6'	0.9	5'-10"	4"	
7	1936 - 1940	4'	1.4	7"	4"	Core head broke.
8	1942 - 1943	1'	0.3	0	4"	Metal in hole.
9	2042 - 2042.5	0.5'	0.3	0	4"	Damaged core head.
10	2295 - 2300	5'	0.7	4'-7"	4"	
11	2782 - 2786	4'	0.5	2'-8"	5-1/4"	
12	3312 - 3316	4'	0.7	3'	5-1/4"	
13	3817 - 3825	8'	0.8	5'-2"	4"	Undersized core.
14	4256 - 4264	8'	1.5	5'	5-1/4"	
15	4909 - 4916	7'	1.0	0	4"	Fragments recovered in junk snatcher.
16	5270 - 5276	6'	1.0	3'	4"	
17	6022 - 6029	7'	1.3	4'-1"	4"	
18	6410 - 6414	4'	1.1	2'	4"	
		114.5'	1.2 Avg	82'-5"		

Total Rig Time Spent on Coring: 89 Hours

Total Rig Time Spent on Core Round Tripping: 114 Hours

Average Cost of Cores Per Foot Recovered $1.636

Cost of Rig Time for Cores Recovered: $71.781

Cost of Coring Tools, Bits & Services: $64.219

Rogers

S-73017
SEPT , 1974

Figure 35. Core information and drilling rates for the Marysville, Montana geothermal well, Montana.

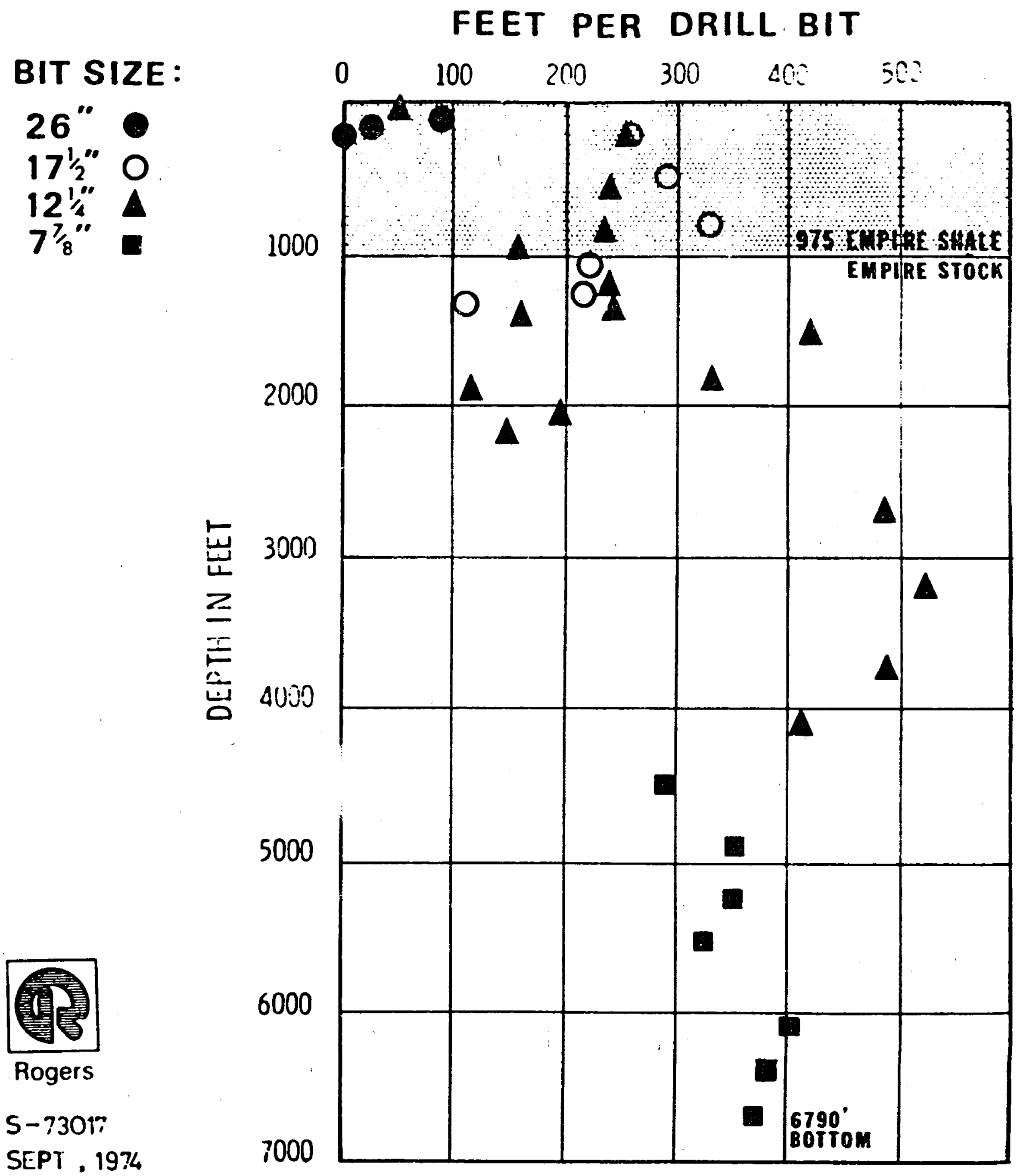


Figure 36. Feet per drill bit for the Marysville, Montana geothermal area.

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