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Case Study Data Base Companion Report 3 to Simulation of Geothermal Subsidence (LBL-10571)

MASTER

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CASE STUDY DATA BASE
COMPANION REPORT 3
TO
SIMULATION OF GEOTHERMAL SUBSIDENCE
(LBL 10571)

PREPARED FOR LAWRENCE BERKELEY LABORATORY
✓ by GOLDER ASSOCIATES
UNDER SUBCONTRACT 3730302

Prepared by: I. Miller, W. Dershowitz, K. Jones,
L. Myer, K. Roman, and M. Schauer

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This report is the third in a series of three companion reports presenting the results of an investigation into the use of mathematical models for predicting subsidence caused by geothermal extraction. The simulation of results of the investigation are summarized in the report, "Simulation of Geothermal Subsidence" (LBL 10571). The titles of the other companion reports are listed below.

Report No.	Title	
1	Physical Processes of Compaction	LBL-10838
2	Detailed Report on Tested Models	LBL-10837

An additional report on the subject of reservoir models was generated as part of this project. The report was produced in 1979 by Dr. George F. Pinder under subcontract to Golder Associates and is titled "State-of-the-Art Review of Geothermal Reservoir Modeling" (Report LBL 9093).

ABSTRACT

This report presents the data base developed for selection and evaluation of geothermal subsidence case studies. Data from this data base was used in case studies of Wairakei, The Geysers, and Austin Bayou Prospect and are presented in the report, "Simulation of Geothermal Subsidence" (Report LBL 10571).

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1.0 INTRODUCTION

The data base presented in this report is a preliminary version only. Not all of the information included in this data base was used in the Case Studies. Also, some additional data used in the Case Studies is not included in this data base. Some data inconsistencies may also exist between information from different sources included in this data base. The data base should be considered a general source of information characterizing the sites rather than a definitive source. Definitive information can be found by referring to sources cited here and in "Simulation of Geothermal Subsidence" (Miller et al. 1980a).

2.0 WAIRAKEI

2.1 SYSTEM DEFINITION

2.1.1 Geologic Setting

The Wairakei geothermal field is located on the North Island of New Zealand just north of Lake Taupo (Figure 2-1) in the Taupo volcanic zone of the island's central volcanic district. The region is structurally characterized by a horst-and-graben structure formed by northwest- and northeast-trending faults of normal displacement. The stratigraphic sequence consists of rhyolitic ignimbrites, tuffs, and tuffaceous sediments with rhyolitic intrusions. Table 2-1 presents a summary of the stratigraphy.

In the geothermal field the Ohakuri Formation has been encountered in only one hole, though it is presumed to extend beneath the entire reservoir. The geothermal aquifer is located in the Waiora Formation, which consists of pyroclastic rocks, tuffaceous sandstones, silt sandstones, grey siltstone, ignimbrites, and interbedded intrusives. The intrusives, which have been encountered in the western and southwestern regions of the field, consist of the Waiora Valley andesite and the Karapiti rhyolite. Above the Waiora is the relatively impermeable Huka Mudstone. Figures 2-2 and 2-3 illustrate the variation in thickness of these units over the geothermal field. Below the Waiora are the Wairakei ignimbrites, also considered an impermeable formation. Figure 2-4 illustrates in cross section the structural relation of the Waiora Formation to the other units in the vicinity of the main bore field.

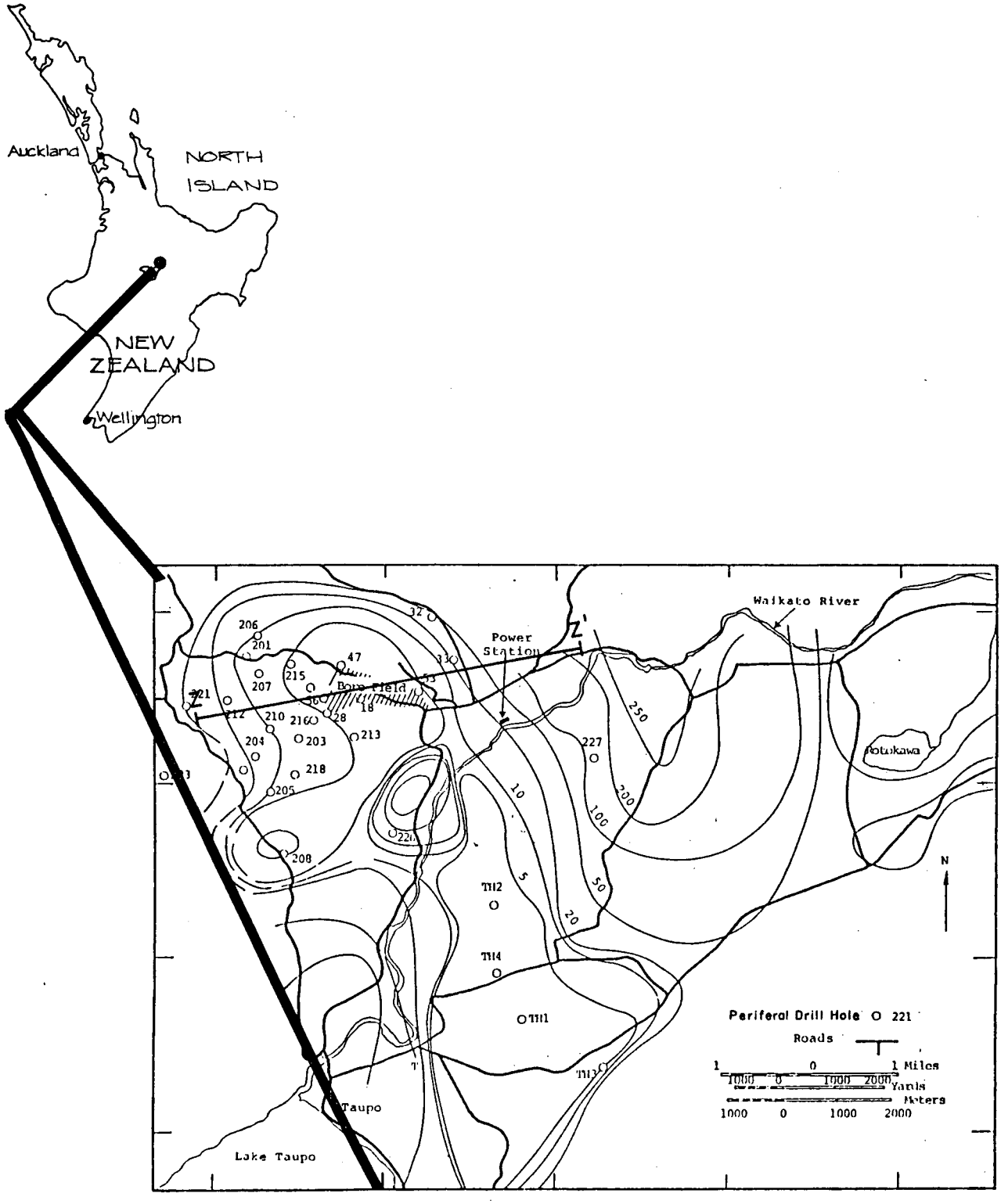


FIGURE 2-1 LOCATION OF WAIRAKEI GEOTHERMAL FIELD
After Pritchett et al. 1978

TABLE 2-1
GEOLOGIC STRUCTURE OF WAIRAKEI

NAME	LITHOLOGY	THICKNESS (FEET)
Taupo Pumice Alluviumm	Pumice alluvium, windblown pumice ash	Usually less than 100
----------UNCONFORMITY----------		
Wairakei Breccia	Mostly vitric lapilli tuff, with chalazoidite tuff and tuffaceous sandstone	Maximum preserved 550
Huka Falls Formation (Formerly Hula)	Tuffaceous mudstone and sandstone with interbedded vitric tuff, conglomerate, and diatomite	200 to 1000
Waiora Formation	Mostly pumice breccia and sandstone with minor interbedded siltstone and rhyolite breccia. Ingnimbrite at base and top. Lower part includes the Waiora Valley Andesite, a buried volcanic flow up to 600 feet thick	1500 to 3000
----------UNCONFORMITY----------		
Wairakei Ignimbrites	Ignimbrite, dense, hydrothermally altered at upper surface	400 to more than 1700
----------UNCONFORMITY----------		
Ohakuri Group	Tuffaceous sandstone and siltstone with interbedded pumice breccia	At least 600
----------UNCONFORMITY----------		
"Graywacke Basement"	Altered graywacke, argillite	At estimated depth of 6000; thickness unknown

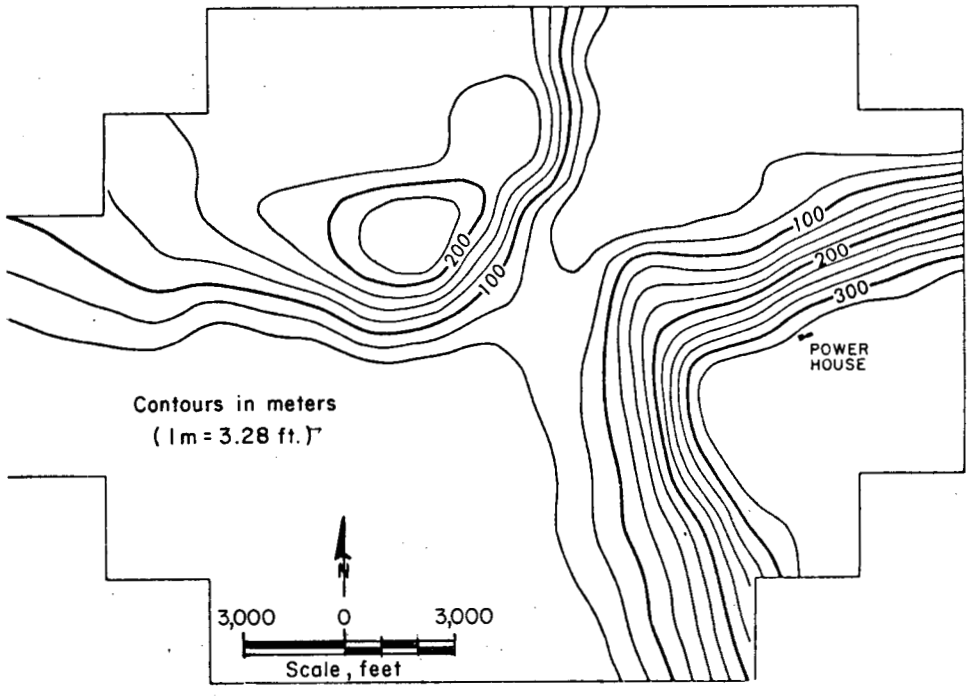


FIGURE 2-2
VARIATION IN THICKNESS
OF HUKA FALLS FORMATION, WAIRAKEI
After Mercer and Faust 1979

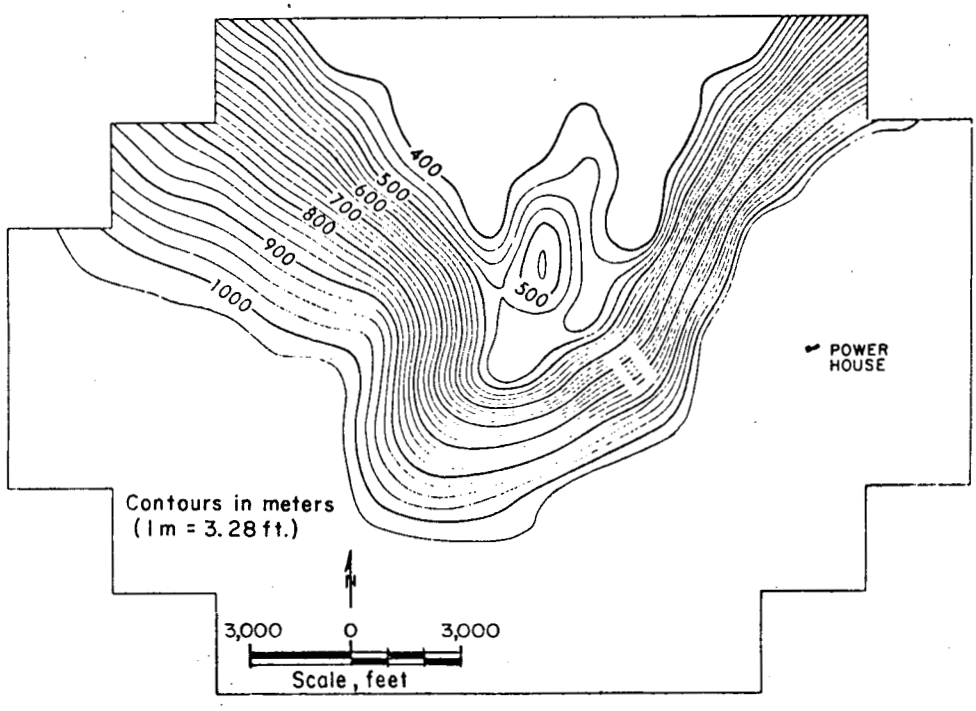


FIGURE 2-3

VARIATION IN THICKNESS
OF WAIORA FORMATION, WAIRAKEI
After Mercer and Faust 1979

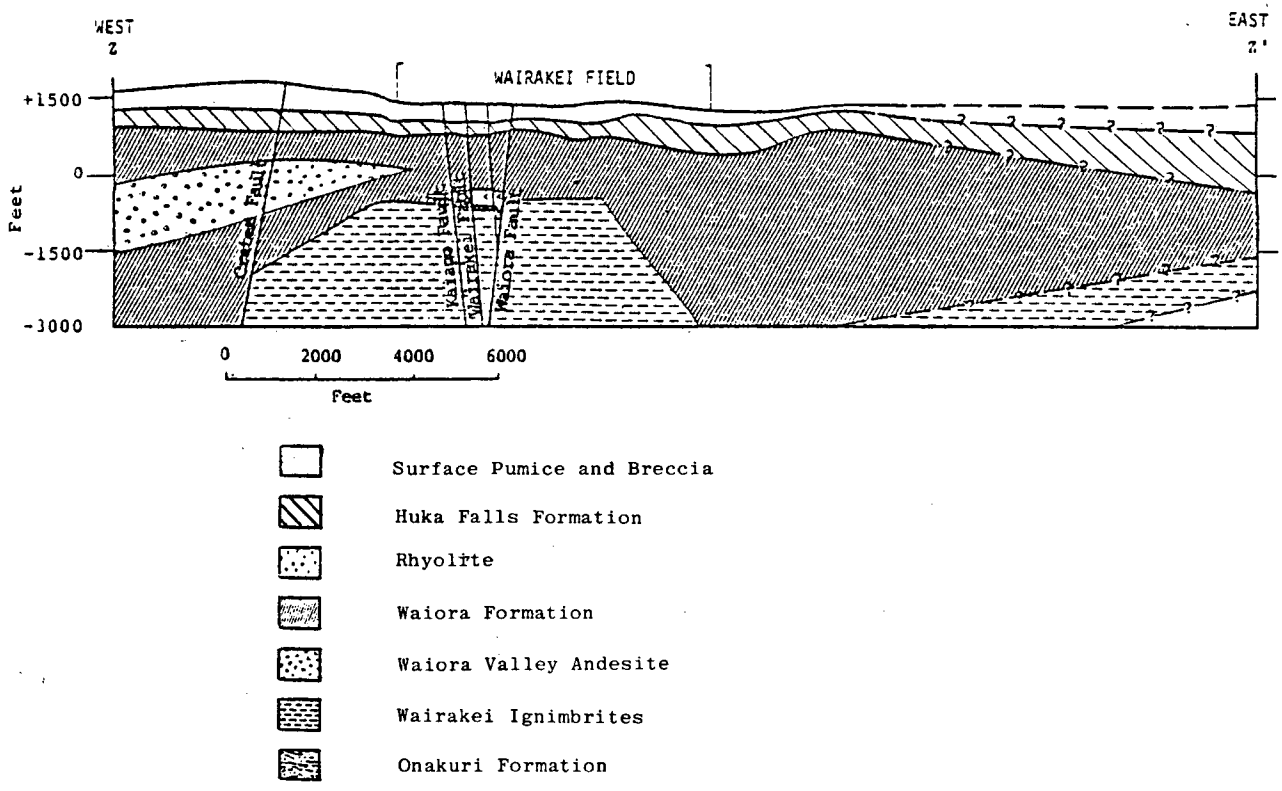


FIGURE 2-4 CROSS SECTION OF WAIRAKEI GEOTHERMAL FIELD SHOWING WAIORA FORMATION AND FAULTS
After Pritchett et al. 1978

Major faults, which heavily influence the hydrology of the production region of the geothermal field, are shown in Figure 2-5. The most productive wells, the highest measured permeabilities, and the highest fluid temperatures are associated with faults and fractures. Drilling results seem to indicate that the Waiora aquifer is fed from below through fractures associated with the Wairakei, Kaiapo, and upper Waiora faults (Grimsrud et al. 1978).

2.1.2 Hydrologic Boundaries

An indication of the boundaries of the reservoir may be given by the results of a resistivity survey shown in Figure 2-1, in which the contours of 10 ohm to 20 ohm are assumed to be the anomaly boundary. Also shown on Figure 2-1 are several of the peripheral wells with pertinent temperature and pressure data. The cooler temperatures and smaller pressure drops in wells 33 and 36 in the east and well 224 in the west indicate they may be outside the field.

As shown in Figure 2-6, steep pressure gradients that have been established in the east and west further indicate the presence of a low-permeability boundary (Bolton 1970). However, no geological feature has been found to account for this boundary (Grindley 1965). In the north and south, however, no boundaries have been indicated by the behavior of wells.

Wells designated as TH1, TH2, etc., in Figure 2-1 are part of the Tauhara geothermal field and were drilled in the later 1960's. Though Tauhara was once thought to be a separate field, it is now felt that the drawdown from Wairakei influences these wells (Pritchett et al. 1978).

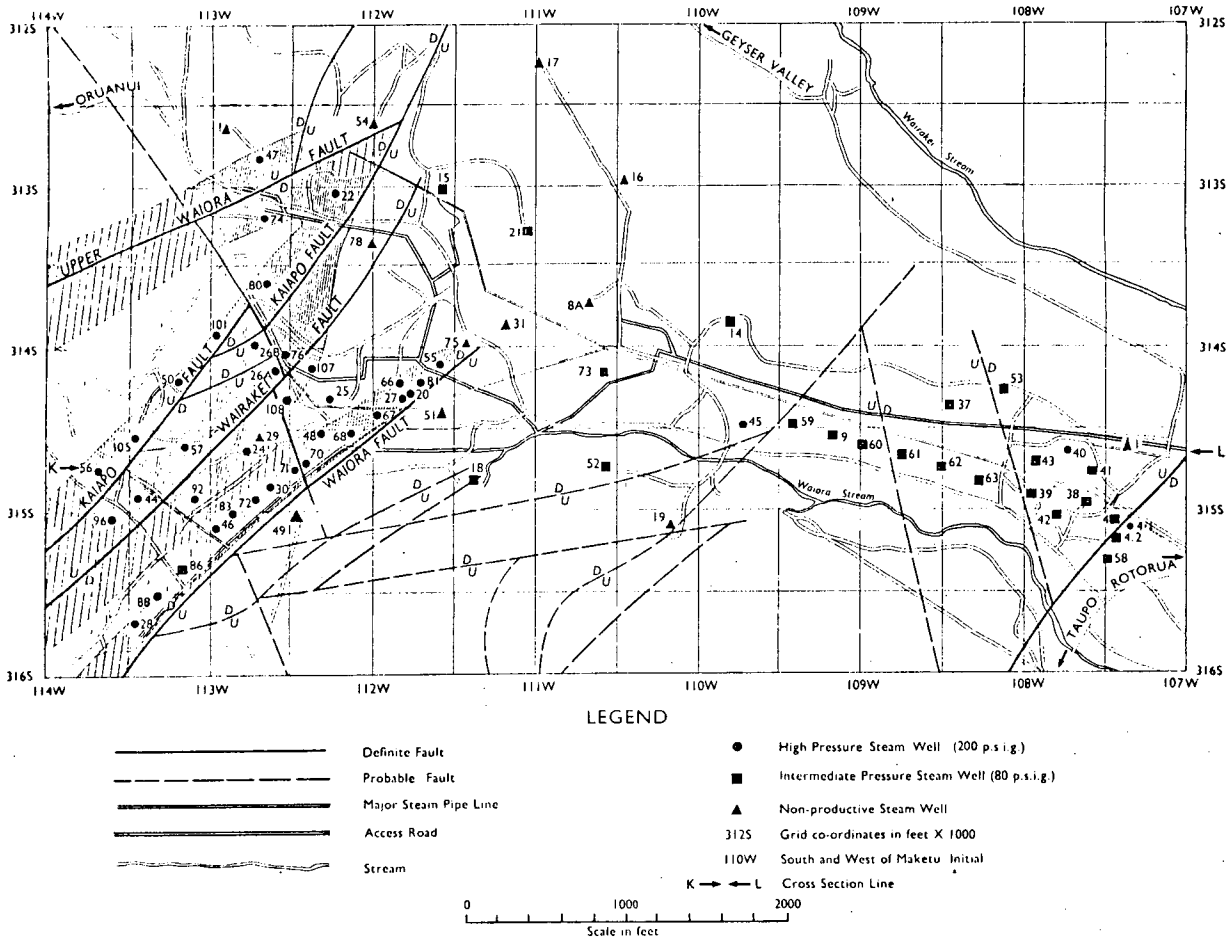


FIGURE 2-5 MAJOR FAULTS AND HIGH-PRESSURE STEAM ZONES AT WAIRAKEI GEOTHERMAL FIELD
After Grindley 1965

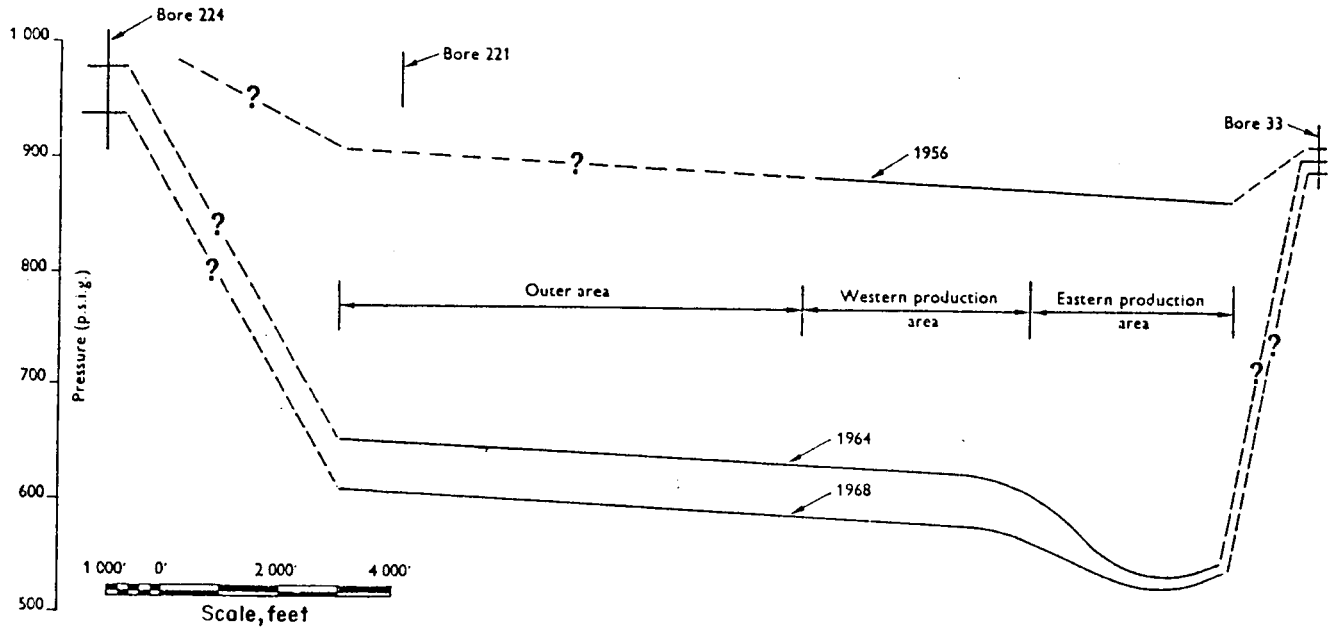


FIGURE 2-6 PRESSURE GRADIENTS DEFINING WAIRAKEI GEOTHERMAL FIELD
After Bolton 1970

2.1.3 Deformation Boundaries

As noted, the Wairakei field is quite heavily faulted, but there is no indication that the faulting constitutes a deformation boundary. The prevalent fracturing undoubtedly affects deformations, but the effect must be accounted for in the overall mass behavior of the system and not as a boundary condition.

As illustrated by the cross section shown in Figure 2-4, the various stratigraphic units differ considerably in thickness over the extent of the geothermal field. Because the units vary in compressibility, this variation in thickness would tend to cause more surface subsidence over the thickest accumulations of the most compressible layers.

2.1.4 Initial Conditions

It is believed that the reservoir was originally filled with water to the base of the Huka Falls Formation. From measurements made at the beginning of exploitation, the initial temperatures and pressures are assumed to be 250°C to 260°C and 574 psig (8.27×10^4 psf) at sea level datum. Apparently, the change in pressure with depth is essentially hydrostatic (Pritchett et al. 1978).

As will be discussed, temperature data from Wairakei are poor, but it appears that initial reservoir temperatures varied somewhat with depth. Data presented by Pritchett et al. indicate that initial temperatures in the upper part of the reservoir may have been between 10°C and 40°C lower than in the deep parts.

2.2 RESERVOIR DEVELOPMENT

Significant production began in 1953. Detailed records of individual bore mass and heat production have been compiled by Pritchett et al. (1978). The individual well records do not account for all discharge from the Wairakei field. Drilling mishaps, for example, resulted in three cases of uncontrolled discharge. However, estimates by Pritchett et al. (1978) of the quantity of uncontrolled discharge are less than 0.5 percent of the total field discharge.

The influence of faulting on field production is clearly seen; 40 percent of the total field production (in 1965) was from wells drilled along the Waiora Fault. Most of the HP wells (210 to 220 psi [3.02×10^4 to 3.17×10^4 psf] well-head pressures) are associated with faults in the western portion of the production area (Figure 2-5). Wells not located on faults in this area are usually IP wells (75 to 85 psi [1.08×10^4 to 1.22×10^4 psf] well-head pressure). East of the Waiora Fault, between holes 51 and 45, is an area useful only for IP production. No major faults are found in this area. East of hole 45 is a small area of higher temperatures and greater permeability where both IP and HP wells have been drilled.

Production wells in the Waiora range in depth from 450 to 4000 feet, though Grindley (1965) notes that most holes are less than 3000 feet deep. In addition, fissured zones for production are commonly below a 1600-foot depth. When drilling to intersect a known fault, casing is set as close as possible to the suspected intersection depth. In areas away from the major faults, holes are commonly cased to 1600 feet before drilling to depth is continued.

As noted above, the Tauhara field is considered to be hydrologically connected to the Wairakei field. Production from Tauhara, of which 95 percent is from well TH1, has amounted to only 0.5 percent of the total for the Wairakei/Tauhara system.

2.3 RESERVOIR RESPONSE

A substantial amount of bore-by-bore pressure data from 1953 to 1977 has been compiled by Pritchett et al. (1978). The pressures are recorded for two reference levels 500 and 900 feet below sea level. Only two datum levels are used because shut-in pressures are essentially hydrostatic. In addition, Bolton (1970) noted that pressure changes in outer bores responded very quickly to field discharge. This indicated that at any given time the pressure fall over the entire field was almost uniform. There is, however, some areal dependence of pressure reductions; the eastern part of the production area has experienced about 90 psi (1.30×10^4 psf) greater pressure decrease than the western part (Figure 2-5).

Prior to about 1962, most pressure measurements were made indirectly based on temperature profiles and water levels in the bores. The accuracy of these early measurements has been estimated as ± 20 psi (2.88×10^3 psf), while the accuracy of later direct measurements has been estimated at ± 10 psi (1.44×10^3 psf) (Pritchett et al. 1978).

Pritchett et al. (1978) have also compiled and presented in graphic and tabular form a considerable amount of temperature data. Those authors suggest, however, that those data be used "with great caution." Reasons for lack of confidence in available data include geothermograph errors, data recorded in cased holes, possible convective currents in the borehole, and frequent

insufficient intervals between drilling and temperature measurements.

Poor data prevent accurate quantitative description of temperature change. Bolton (1970) presented data which indicated that little temperature decrease has occurred in the deeper parts of the reservoir (deeper than 1200 feet below sea level). In the upper parts of the reservoir, data from Pritchett et al. (1978) indicate temperature decreases ranging from 5°C to 20°C. Reduction in reservoir pressure has led to the accumulation of flashed steam in the upper regions of the system.

2.4 SUBSIDENCE

Initial surface subsidence measurements were made in 1956, based on benchmarks placed in 1950. Data on both vertical and horizontal movements have been accumulated and presented by Pritchett et al. (1978). Most leveling has been second order, with periodic checks on the precise network. The maximum subsidence by 1974 was about 15.4 feet.

The subsidence pattern of Wairakei exhibits two peculiarities: the area of maximum subsidence occurs east of the major production area (Figure 2-7), and the rate of subsidence of some benchmarks has increased in recent years while the pressure decline rate has decreased. As yet, these peculiarities have not been definitely explained. Both the Huka Falls and the Waiora formations thicken in the eastern part of the production area. This increase in thickness in either one or both formations may have led to the increase in subsidence in the east. The non-linear relation between reservoir pressure drop and subsidence could be explained by assuming the Huka Falls Formation to be over-consolidated. However, the origin of the maximum past

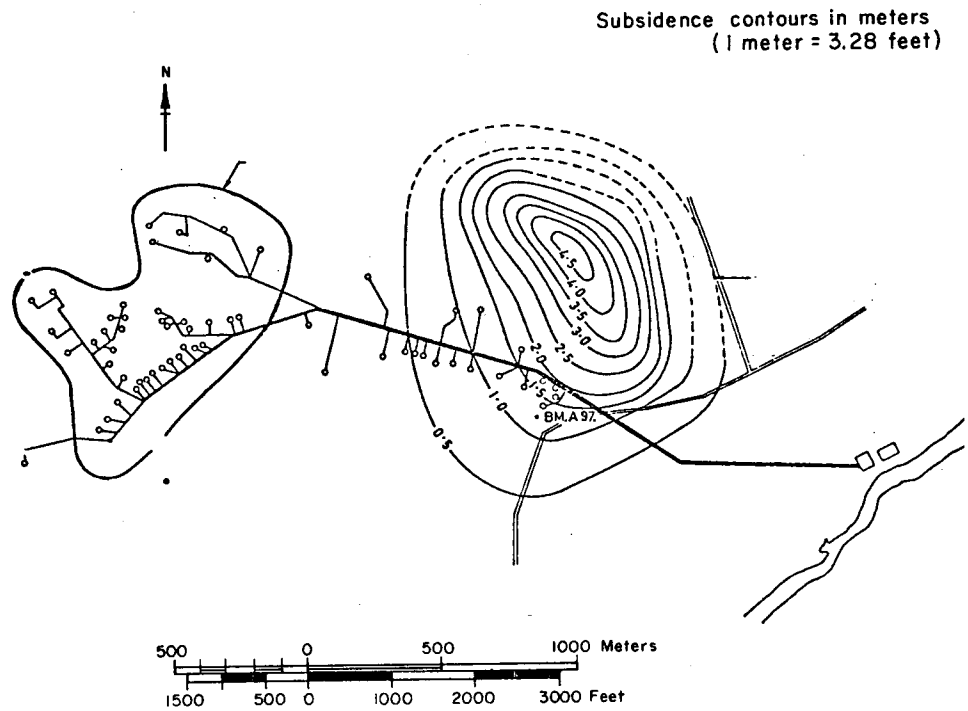


FIGURE 2-7
SUBSIDENCE ANOMALY AT WAIRAKEI GEOTHERMAL FIELD, 1964-1974
After Stillwell et al. 1975

consolidation pressure (greater than the present overburden pressures) is not clear. Grindley (1965) notes that the upper boundary of the Huka Falls is an authentic time horizon with the Wairakei breccia laid conformably on top. In addition, Flint (1971) notes that the North Island of New Zealand has experienced almost no glaciation. There is no available evidence from which inferences about previous reservoir pressures could be drawn.

2.5 PHYSICAL-MECHANICAL PARAMETERS

2.5.1 Permeability, Porosity

As noted above, most HP wells are sited to intersect faults or fissures. For such wells, Grindley (1965) found permeabilities of 1 darcy or more. Producing wells not located on faults are generally IP wells, and permeabilities determined from tests in such wells range from 0.005 to 0.03 darcies (5.3×10^{-14} to $3.2 \times 10^{-13} ft^2$). Grindley believes these IP wells are drawing upon aquifer storage, whereas the HP wells on faults have tapped aquifer feed zones. Some wells have been essentially nonproductive. Grindley found permeabilities of less than 0.001 darcy (1.06×10^{-14} ft^2) from tests in these wells.

Hendrickson (1976) reported the results of a suite of laboratory tests done on the Wairakei core. Permeabilities of only 50 x 10 darcies and 0.3 x 10 darcies (5.3×10^{-16} and $3.1 \times 10^{-18} ft^2$) were measured on pieces of intact rock from the Waiora and Huka Falls formations, respectively. Effective porosities of about 40 percent were measured.

Numerical simulations of the Wairakei reservoir have been performed by Mercer et al. (1975), Pritchett et al. (1978), and Mercer and Faust (1979). For the Waiora, assumed porosities of

0.20 to 0.25 in these studies were from 50 percent to 62 percent of those reported by Hendrickson (1976). Permeabilities assumed for the western production area of the Waiora Formation were greater by a factor of about 2000.

A permeability of 100 md (millidarcys) (1.06×10^{-12} ft^2) used by Pritchett et al. (1978) in the western region of the production area was 10 times that used in the eastern region. This permeability variation corresponds with the trends in permeabilities from well tests reported by Grindley (1965). Pritchett et al. also included a high permeability zone at the base of the Waiora to correspond with observations of Bolton (1970) and Grindley and Browne (1975).

In the Wairakei model of Mercer and Faust (1979), horizontal permeabilities varied from 120 to 300 md (1.27×10^{-12} to 3.19×10^{-12} ft^2) in parts of the production area to 0.6 md (6.37×10^{-15} ft^2) in peripheral zones. In the Huka Falls Formation, Pritchett et al. (1978) used a permeability of 10 md (1.06×10^{-13} ft^2). In the model of Mercer and Faust (1979), the Huka Falls' vertical permeability varied from 2 md (2.12×10^{-14} ft^2) in part of the production region to 0.01 to 0.05 md (1.06×10^{-16} to 5.31×10^{-16} ft^2) in peripheral areas.

2.5.2 Deformation and Thermal Parameters

The results reported by Hendrickson (1976) indicated that the Huka Falls Formation is 10 times more compressible than the Waiora Formation. In Table 2-2 these experimental results are compared with the values of material constants used in three models of the fluid-flow regime of Wairakei.

TABLE 2-2
DEFORMATION AND THERMAL PARAMETERS AT WAIRAKEI

REFERENCE	BULK MODULUS K BARS	POISSON'S RATIO	THERMAL CONDUCTIVITY W/W°C	SPECIFIC HEAT CAL/G°C	BULK MODULUS K BARS	POISSON'S RATIO	THERMAL CONDUCTIVITY W/M°C	SPECIFIC HEAT CAL/G°C
Hendrickson* (measured values)	1.9 Effective pressure 30 bars (saturated)	.17	1.28	.175	.20 Effective pressure 35 to 100 bars	.18	1.56 (saturated)	.177
Pritchett et al. 1978	-	-	1.55	.209	-	-	1.98-2.15	.183-.209
Mercer et al. 1975	.1**	-	-	-	34.0***	-	2.17	.220
Mercer & Faust 1979	-	-	2.18	-	20.0	-	21.8	.212

* Also mentioned Linear Coefficient of Thermal Expansion 8.2 x 10^6/C
** Confined modulus determined from value of specific storage
*** Confined modulus

3.0 THE GEYSERS

3.1 SYSTEM DEFINITION

3.1.1 Geologic Setting

The Geysers geothermal area is located in the Coast Ranges of northern California (Figure 3-1). Structurally, The Geysers area is characterized by a series of generally northwest-trending fault blocks and thrust plates. The complexity of the structure, however, has allowed only a partial understanding of the site geology. Four major geologic units are recognized: Franciscan assemblage, Ophiolite, the Great Valley sequence, and the Clear Lake volcanics. These units are described in Table 3-1. The reservoir rock is entirely Franciscan graywacke; reservoir overburden generally includes soils, landslides, and Franciscan units but locally may include rocks of the remaining units.

3.1.2 Hydrologic Boundaries

The Geysers is thought to be part of an extensive vapor-dominated region. Estimates of the area of this region range from 200 km (2.2 x 10^9 ft^2) (Goff et al. 1977) to 100 km (1.1 x 10^9 ft^2) (Reed and Campbell 1975). The area of proven reserves as of 1977 is about 50 km (5.4 x 10^8 ft^2), but the area containing the vast majority of producing wells (or wells capable of production) is roughly 25 to 30 km (2.7 x 10^8 to 3.2 x 10^8 ft^2).

Figure 3-1 shows the boundaries of the vapor-dominated region as postulated by Goff et al. (1977). The Collayonai Fault Zone may be the northeast boundary, because no steam

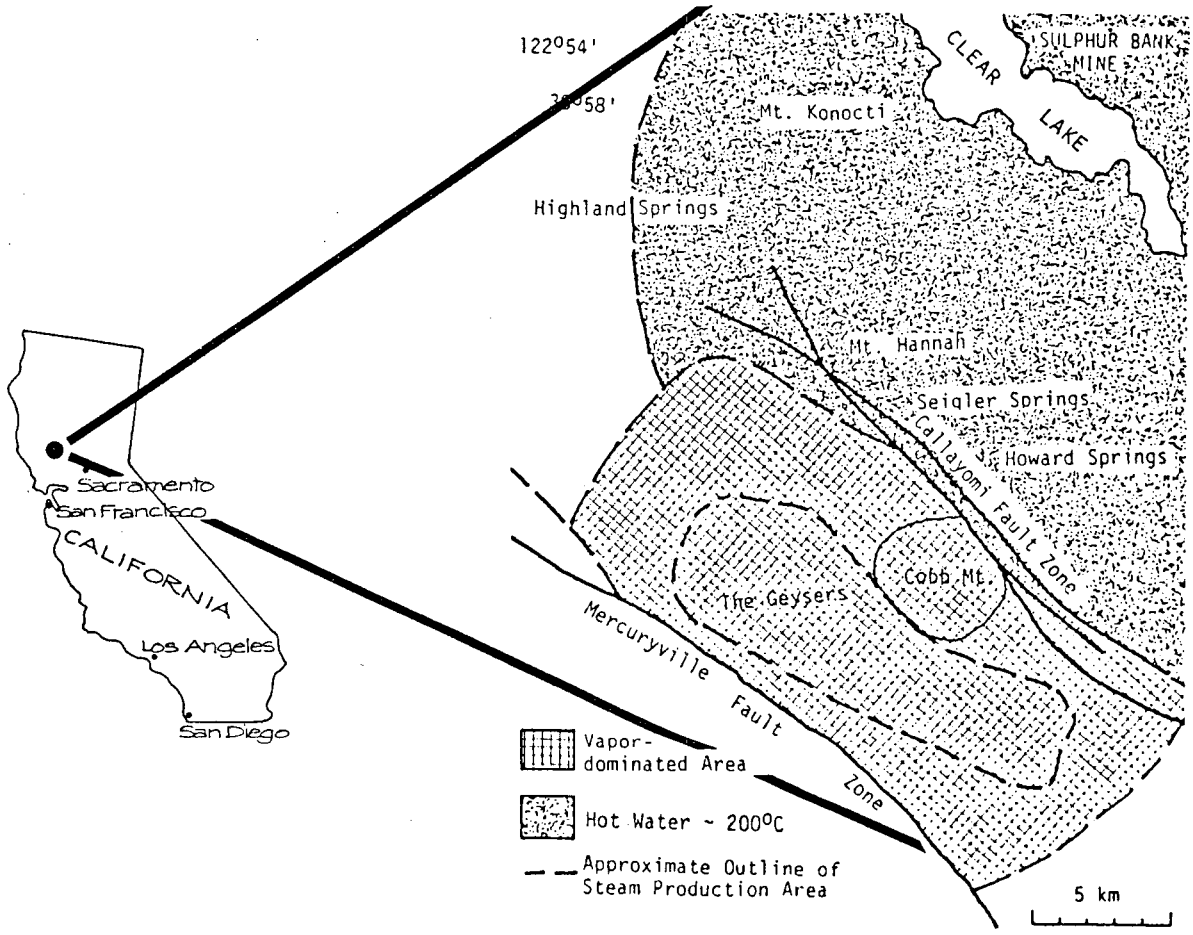


FIGURE 3-1 LOCATION OF THE GEYSERS GEOTHERMAL FIELD
After Goff et al. 1977

TABLE 3-1
GEOLOGIC UNITS OF THE GEYSERS AREA

NAME	DESCRIPTION
Clear Lake Volcanic	Cliff-forming flows (to 7500-ft thickness)
Great Valley Sequence	Well-bedded sandstone, shale, siltstones, mudstones. Some carbonates, lenses of conglomerates
Ophiolite	Igneous rocks: basaltic pillow lavas, breccias, quartz diabase, diorite gabbro, diabase, pyroxenite, serpentinite
Franciscan Assemblage	(Upper) graywacke sandstone, shale, minor greenstone, limestone, chert, conglomerate
	(Middle) Metagraywacke sandstone, minor metagreenstone, metachert
	(Lower) Scattered sandstones, melange: sheared shale plus metagraywacke, chert, greenstone, serpentine, and carbonates

Source: Grimsrud et al. 1978

condensate springs or water derived from such springs are found northeast of the fault. The Mercuryville Fault zone may act as the southeast boundary because it forms a boundary of hydrothermal alteration. A northwest boundary is indicated by chemical changes in the groundwater. The position of the southeast boundary is unknown. Hydrologic characteristics of the boundary faults have not been specifically investigated. The association of numerous hot springs and fumaroles with various fault zones at The Geysers (McLaughlin and Stanley 1975; Goff et al. 1977) indicates that faults act as conduits for vertical flow. On the other hand, Ramey (1970) and White et al. (1971) indicate that the natural recharge to the vapor-dominated system must be minimal for the system to exist in its present form. This in turn indicates that the bounding fault zones inhibit flow from the surrounding rock mass.

In addition to the system boundaries discussed above, Lipman et al. (1977) proposed the existence of a hydrologic boundary within the production area of the field. This boundary has been evidenced by the development of two independent pressure sinks resulting from production. Figure 3-2 shows these pressure sinks and indicates the position of the boundary between them.

The vertical extent of the reservoir is not well defined. Drilling indicates that a shallow, less extensive steam reservoir of lower temperature and pressure exists above the main reservoir. In some areas this upper reservoir is apparently separated from the lower reservoir by an impermeable layer, whereas in other areas some communication apparently exists. Figure 3-3 is a cross section illustrating the possible relationship of the two reservoirs. The elevation of the base of the main reservoir has not been determined; the deepest steam entry (as of 1977) is at a depth of 10,040 feet (Lipman et al. 1977).

Steam pressure isobaric contours in psi at mean sea level datum.

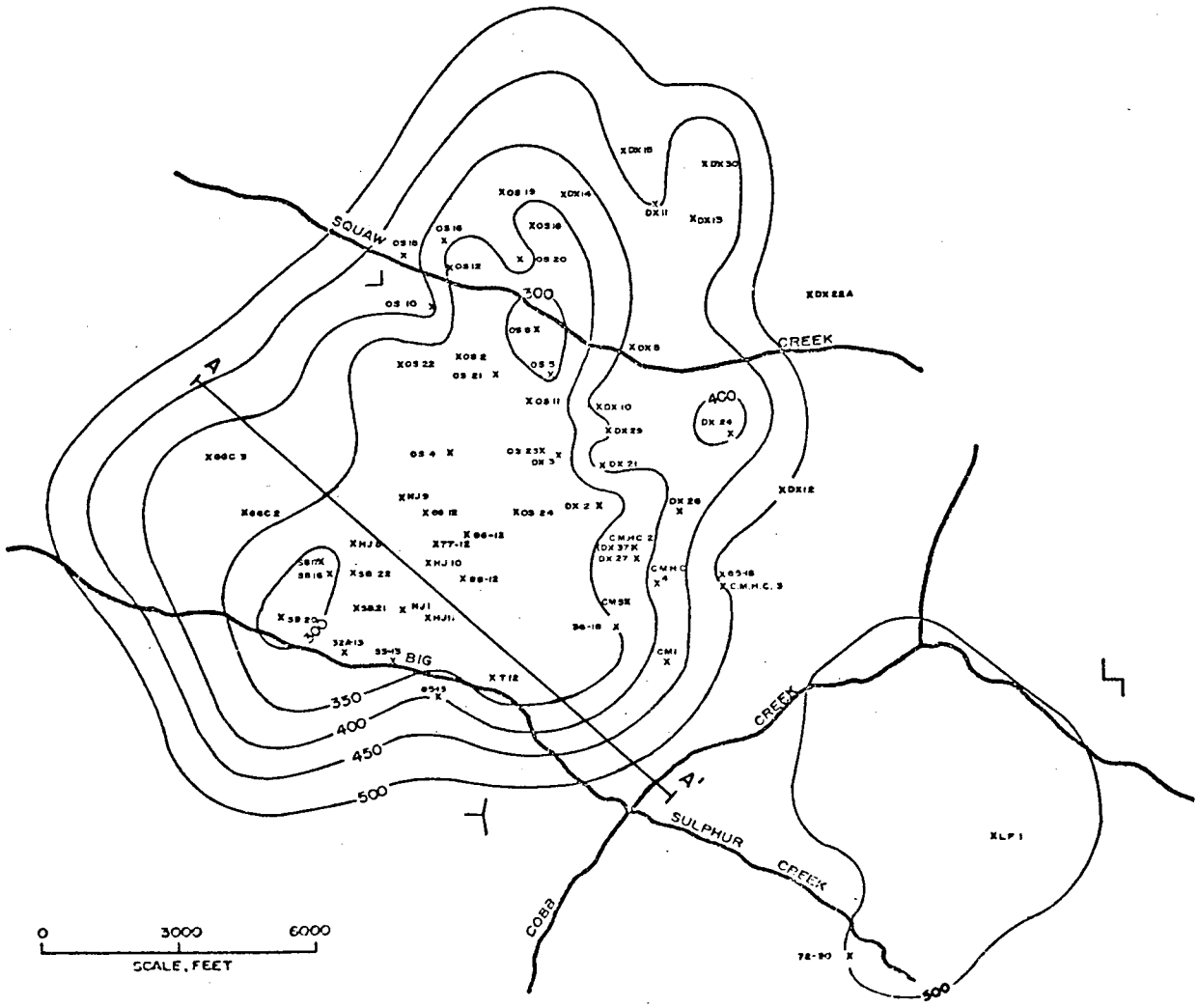


FIGURE 3-2 PRESSURE CONTOUR OF THE GEYSERS GEOTHERMAL FIELD
After Lipman et al. 1977

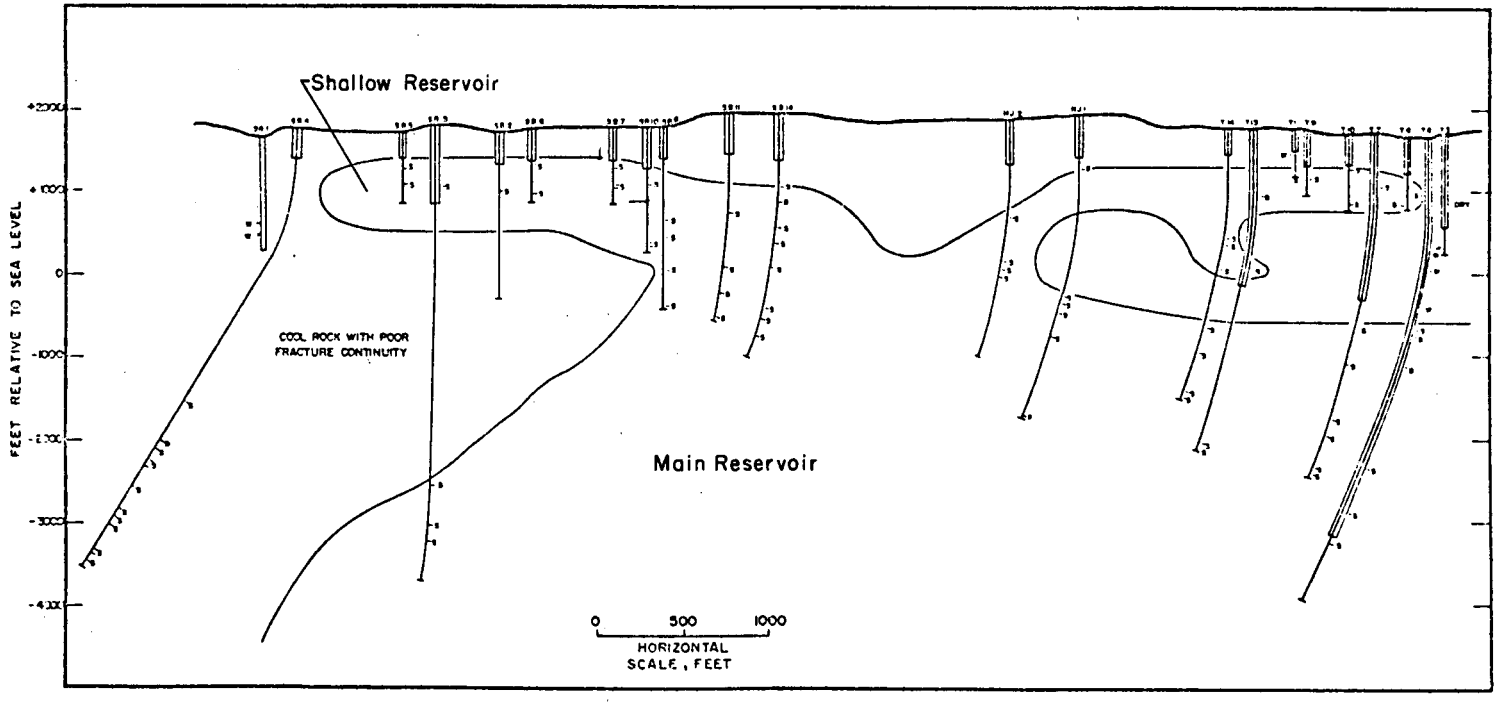


FIGURE 3-3 CROSS SECTION OF THE GEYSERS GEOTHERMAL FIELD ILLUSTRATING SHALLOW AND DEEP RESERVOIRS
After Lipman et al. 1977

The position of the reservoir top has been estimated from data by Lipman et al. (see Figure 3-3) and from drill data from 23 bores. Wells are left uncased in the steam production intervals; thus, the beginning of the open hole can be assumed to roughly correspond to the reservoir top. This information indicates the top of the reservoir is near sea level. At least three theories have been proposed to describe the nature of the upper boundary: (1) impermeable Franciscan rocks, (2) permeable but chemically sealed Franciscan rocks, or (3) a high, meteorite water table (Grimsrud et al. 1978).

3.1.3 Factors Affecting Deformation Behavior

Faults, representing persistent planes of shear strength lower than surrounding rock, influence deformation behavior of a rock mass. At The Geysers, the pervasiveness of faulting probably reduces the significance of any particular fault plane, and the rock mass consequently deforms as a homogeneous medium. Faulting and fracturing still affect the bulk deformation properties of this medium, but it is not necessary to consider effects of each fault plane.

Different rock types have different deformational characteristics and thus also affect the deformation behavior of the system. At The Geysers the predominant reservoir rock is Franciscan greywacke (Grimsrud et al. 1978), but the rock mass overlying the reservoir consists of greywacke with a mixture of other types, including volcanics and serpentine. Because of the complex geology, the extent, relative position, and thickness of these various rock types are unknown.

3.1.4 Initial Conditions

The initial pressure and temperature of wells drilled in the main reservoir is 514 psi (7.40×10^4 psf) and 240°C, respectively, at sea level datum. Increased pressure with depth seems to be limited to the increase due to the additional weight of the steam column.

The Geysers is considered to be vapor-dominated; thus, the vapor is the pressure-determining phase. It is apparent that the reservoir used to contain water that has since boiled off to produce the steam. The most popular concept at present is that a deep water table still exists below the reach of present wells and continues to drop due to steam production.

3.2 RESERVOIR DEVELOPMENT

Production history of The Geysers dates to the early 1920's, when several holes up to 500 feet deep were drilled. Static pressures in these wells ranged from 67.5 to 291 psi (9.72×10^3 to 4.19×10^4 psf). No further drilling took place until 1955, when development began which led to exploitation for power generation. Prior to 1968 the shallow reservoir was the source of steam for power production. By the early 1970's most production was from the more extensive deep reservoir, with most well depths from 2500 feet to 5000 feet.

Detailed steam production records are not available because this information is considered proprietary by the owners. If one knows the power generated and the amount of steam required per kilowatt hour generated, however, estimates of steam used for power generation can be made. However, significant quantities of steam are lost in ways such as continuous venting of wells and blowouts (Grimsrud et al. 1978). Weres et al. (1977)

estimated total man-caused steam production for the years 1960 to 1977. For early production years, these estimates are as much as 70 percent greater than the estimates based on power generation, but the difference decreases in later years. This trend probably reflects the fact that in the early 1970's more wells were drilled than were produced for power, while in later years fewer wells were idle.

Reinjection of steam condensate was begun in 1969. Koenig et al. (1975) noted that condensate reinjection quantities were about 20 percent of production. Chasteen (1976) reported that 5.54×10^8 ft^3 had been reinjected between 1969 and 1975. The depth of the reinjection wells ranges from 2364 feet to 13,450 feet; injection depths are generally greater than nearby producing wells.

3.3 RESERVOIR RESPONSE

The available data on the response of the reservoir to steam withdrawal are summarized on figures 3-2 and 3-4. Figure 3-2 is an isobaric map of the pressure drop in the production area. Figure 3-4 shows the growth of the 500-psi (7.2×10^4 psf) isobar over time.

In constructing these figures, it is assumed that the initial pressure in the reservoir is 514 psi (7.40×10^4 psf)--a pressure which is much less than hydrostatic. As discussed previously, the reservoir may have been filled with liquid prior to exploitation. In this case, the total pressure drop would be substantially greater than that shown in Figure 3-2. It is not known when the reservoir became vapor-dominated; for the purposes of this study, it is assumed that the initial pressure was 514 psi (7.40×10^4 psf).

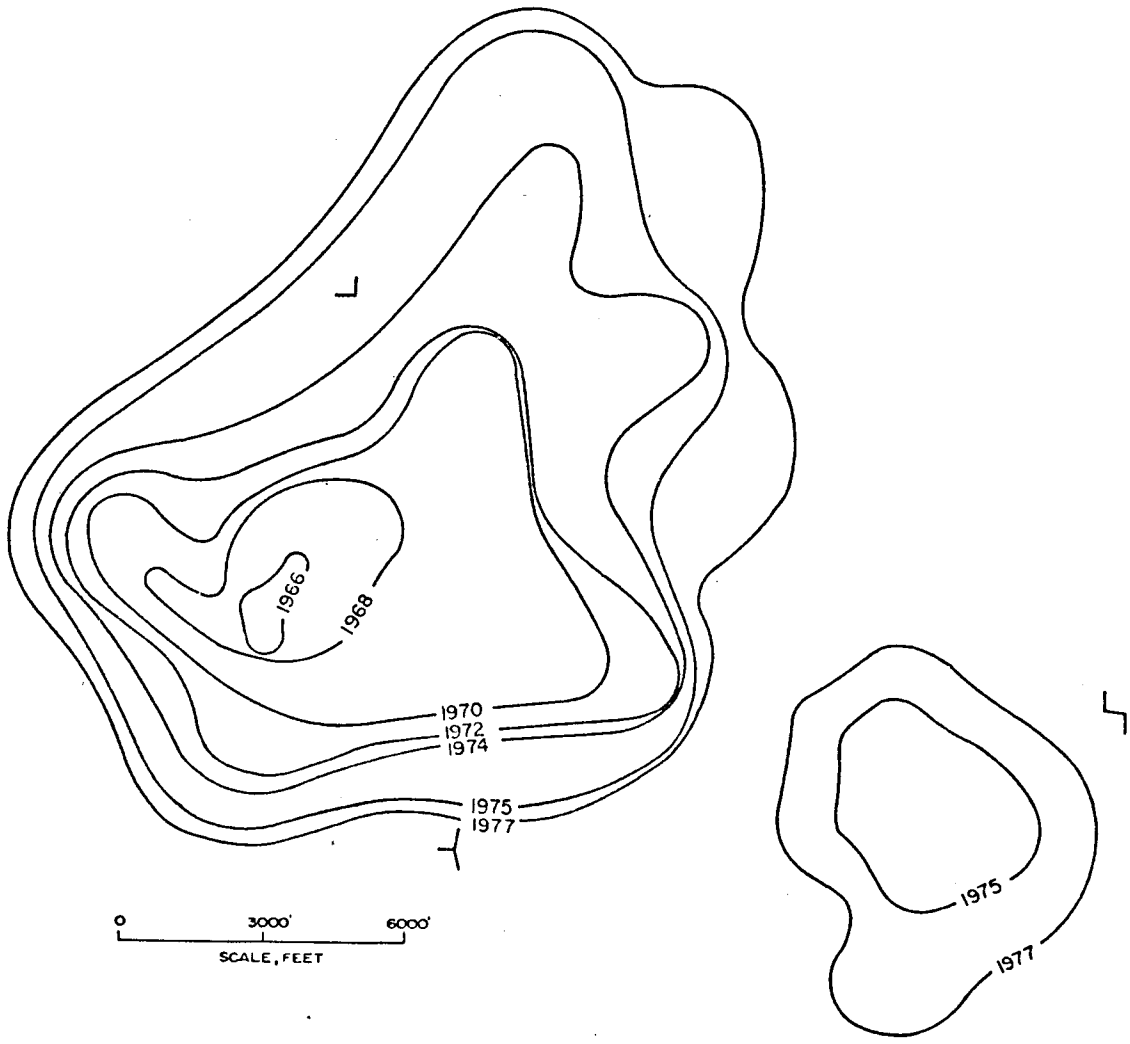


FIGURE 3-4 GROWTH OF THE 500-PSIA PRESSURE SINK WITH TIME SEA LEVEL DATUM, THE GEYSERS GEOTHERMAL FIELD
After Lipman et al. 1977

3.4 SUBSIDENCE

In 1974, a 150-gravity-station network was established in The Geysers area to attain data for evaluation of reservoir changes accompanying subsidence. Vertical surface subsidence measurements for a portion of the production area assuming 1973 as a base year are summarized in Figure 3-5. Maximum movements of 0.45 feet have been observed in the vicinity of power plants 1 through 8.

Measurements of horizontal movement have been made over the same time period. Lofgren (1978) reported horizontal deformation rates ranging from 0.05 feet per year in areas of heaviest fluid withdrawal to 0.013 feet per year in peripheral areas.

3.5 PHYSICAL-MECHANICAL PARAMETERS

Very little data are available on the necessary model input parameters describing the physical-mechanical characteristics of the reservoir. Chasteen (1976) reported the permeability thickness product ranged from 6 darcy-m (2.09×10^{-10} ft^3) to 0.45 darcy-m (1.57×10^{-11} ft^3). Several examples of well-test data from The Geysers are presented by Ramey (1975) and Ramey and Gringarten (1975). Computed permeability thickness products (permeability to steam) based on these data ranged from 4 darcy-m to 18 darcy-m (1.34×10^{-10} to 6.27×10^{-10} ft^3). Williams et al. (1978) reported a porosity for The Geysers of 0.05 to 0.1.

Values for formation compressibility determined from in situ tests were not available. Initial input parameters for compressibility and rock mass moduli were chosen based on values reported in Birch (1966) and Wuerker (1963) for intact specimens of serpentinite and a variety of sandstones.

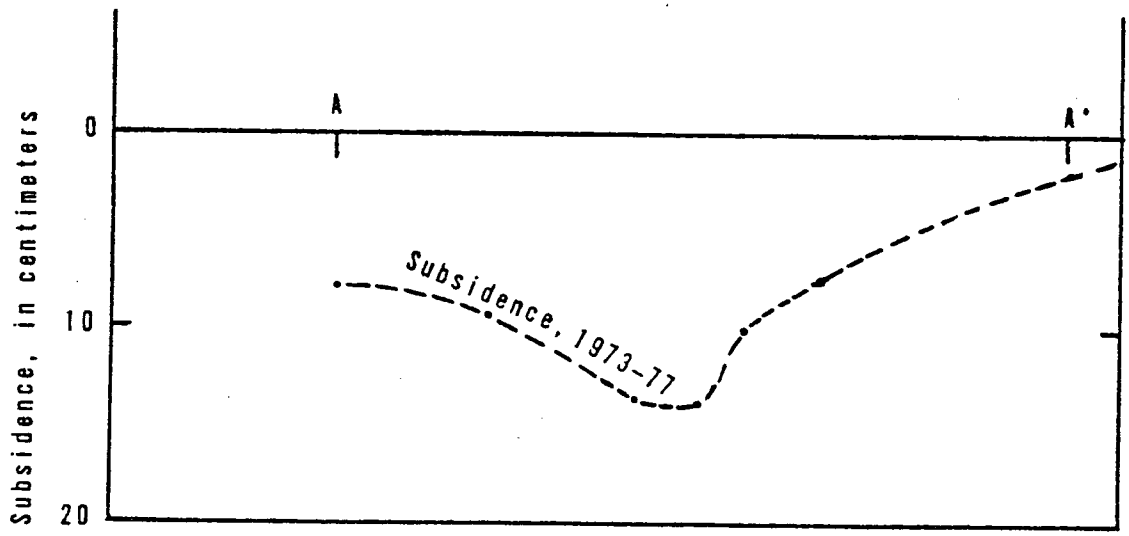


FIGURE 3-5
SUBSIDENCE PROFILE OF THE GEYSERS GEOTHERMAL FIELD
AT CROSS SECTION A-A OF FIGURE 3-2
After Lofgren 1978

4.0 CHOCOLATE BAYOU: AUSTIN BAYOU PROSPECT

4.1 SYSTEM DEFINITION

Chocolate Bayou is an oil and gas field in Brazoria County, Texas. Austin Bayou Prospect is a geothermal exploration site about 5 miles southwest of the Chocolate Bayou field (Figure 4-1). These sites share essentially the same geohydrology and thus are discussed in the same section of this report. Both sites are part of the Brazoria Fairway, a 10-mile-wide, 20-mile-long strip of land identified as an area of potential geothermal development.

The geology of the Brazoria Fairway, as well as much of the Gulf coast in general, is characterized by thick sequences of interbedded deltaic shales and sandstones. A complex system of growth faults divide the sediments into blocks and wedges.

Also characteristic of the region are abnormally high fluid pressures at depth. These pressures probably resulted from a number of mechanisms, including rapid sediment deposition and fault entrapment (Bruce 1973). As sediments were deposited, water loss from underlying sediments dissipated excess pore pressures. In the shales, however, the rate of dissipation lagged behind the rate of deposition and led to abnormal pore pressures in the shales. In the absence of faulting, sandstone permeability would have been great enough to prevent abnormal pressure development in the sandstones. Relative fault movement, however, brought low-permeability shales into contact with the sands and prevented communication between the sandstones and the lower-pressure sediments.

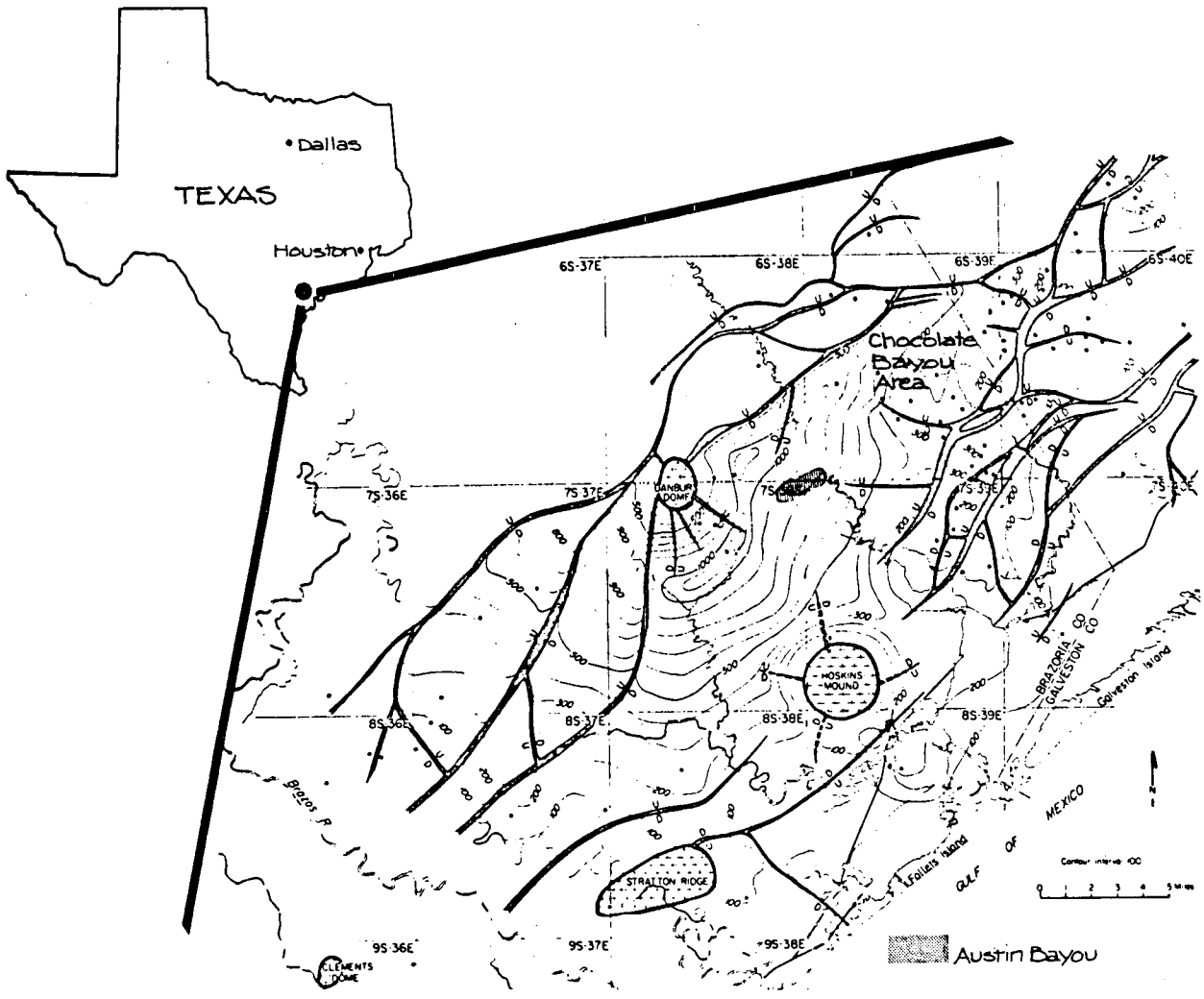


FIGURE 4-1 LOCATION OF CHOCOLATE BAYOU AND AUSTIN BAYOU GEOTHERMAL PROSPECT
After Bebout et al. 1978

Marker beds have allowed good statigraphic correlation throughout the Fairway. In the Frio Formation, these markers have been designated by T_0, T_1, etc., with T_0 designating the top of the Frio. The T5 to T6 units (from about 13,500 to 16,500 feet in depth) have been selected as potential geothermal reservoirs because of increased section thickness and sandstone percentage below the T5 marker. Within the T5 to T6 interval are several depositional shale-sandstone sequences. The base of each sequence is marked by an apparently "pure" shale which grades upward into more coarse-grained sediments. Consequently, only 800 to 900 feet of the 3000-foot reservoir interval is sandstone. Due to the nature of the depositional environment, Bebout et al. (1978) feel that the extent along strike of any sandstone unit would not be more than 2 miles.

The sedimentary sequence above the Frio consists of the Oligocene-Miocene Anahuac Shale up to about a depth of 7000 feet, Miocene and Pliocene sandstones and shales to about 2500 feet, and Pliocene and Holocene sand and clay beds to the surface.

4.1.1 Hydrologic Boundaries

Figure 4-1 illustrates the fault pattern throughout the Brazoria Fairway as it would be found at the elevation of the T5 marker bed. It should be noted that the growth faults in general do not extend to the surface. Gustavson and Kreitler (1976) note that the faults found in the Chocolate Bayou field act as complete or partial hydrologic barriers. (It seems reasonable to believe they act as barriers throughout the region.) As seen in Figure 4-1, the Fairway is bounded on the northwest and southeast by major growth fault networks. Those on the southeast do not extend above the T5 correlation unit (Bebout et al. 1978). Austin Bayou Prospect is in a syncline, the axis of which extends

roughly from Chocolate Bayou through the test area and between Danbury Dome and Hoskins Mound. Though the synclinal area is bordered by faults, there appear to be few, if any, major faults within the syncline.

Hydrologic barriers have also resulted from the depositional process. As a result of the deltaic depositional environment, the sedimentary structure is perhaps best defined as numerous sand lenses in an overall shale mass. This is illustrated in Figure 4-2, which is a generalized cross section through the T4 and T5 correlation units in South Texas. Low-permeability shale would inhibit fluid flow between sandstone lenses. Extensive drilling has defined the distribution of sand and shale in the Chocolate Bayou field, but there has been little drilling in the Austin Bayou Prospect Area; consequently, not much is known of the detailed sandstone/shale distribution.

4.1.2 Factors Affecting Deformation

Two factors affecting deformation due to fluid withdrawal are rock type (including distribution and thickness) and faulting. The entire section consists of sands and clays in various degrees of induration. As discussed above, details of the distribution of sandstone and shales in the Austin Bayou Prospect are not known (results of the drilling currently being conducted at Austin Bayou were not available at the time of this study), but overall percentages of sand and shale can be estimated from regional considerations. From data presented by Bebout et al. (1978), the following estimates were made:

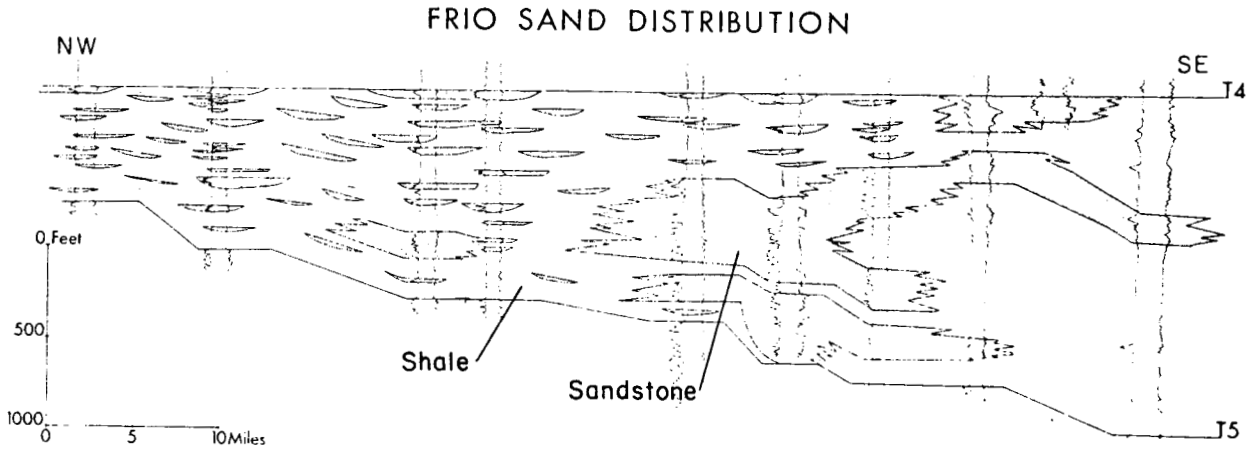


FIGURE 4-2
CROSS SECTION OF AUSTIN BAYOU PROSPECT
SHOWING STRATIGRAPHY
After Bebout et al. 1978

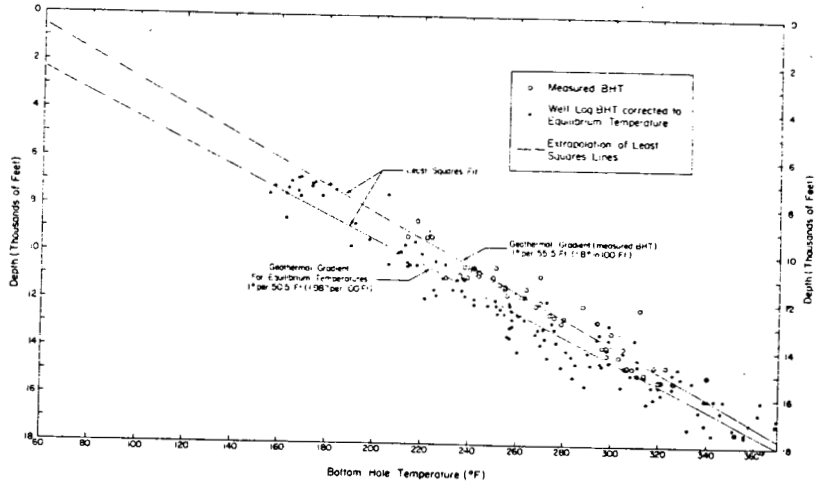
Formation	Percentage Thickness Of Sandstone
Frio (reservoir interval)	40
Frio (above and below reservoir)	10
Anahuac shale	10
Miocene/Pliocene sandstones and shales	35

Faulting may definitely affect deformation in Austin Bayou. Acting as hydrologic barriers, fluid pressures may drop on one side of the fault but not on the other. Differential fluid pressure drops would lead to differential compaction and possibly fault activation. Gustavson and Kreitler (1976) have documented fault movement related to fluid withdrawal from shallower sediments in the Gulf Coast region. Differential subsidence, though not accompanied by fault movement, has also been observed in the Chocolate Bayou as a result of oil and gas production (Gustavson and Kreitler 1976).

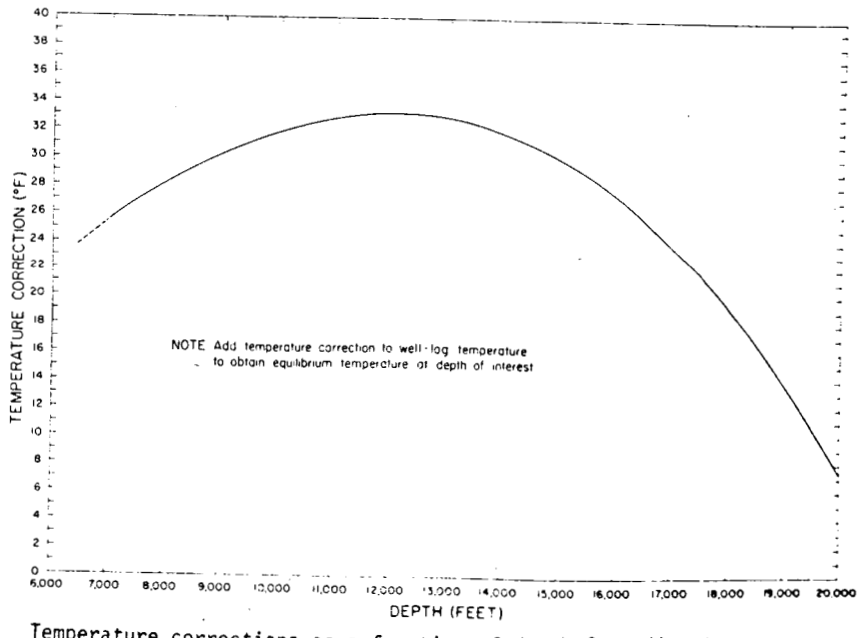
4.1.3 Initial Conditions

Initial temperatures are quite consistent over the region of interest. Figure 4-3 shows the thermal gradient to be in the range of 1.8°F to 2°F (1.0°C to 1.1°C) per 100 feet.

First occurrence of abnormal pressures (i.e., fluid gradient in excess of 66.96 psf/ft = 0.465 psi/ft) is variable between fault blocks but generally is below 10,000 feet in depth (Figure 4-4). In Chocolate Bayou the geopressured zone begins at depths greater than 12,000 feet. Within this zone gradients of 122 psf/ft (0.85 psi/ft) are found (Myers 1968).



Comparison between measured bottom hole temperatures (BHT) and temperatures calculated from well logs, Brazoria County, Texas.



Temperature corrections as a function of depth for adjusting well-log temperatures to approximate equilibrium temperatures.

FIGURE 4-3 THERMAL GRADIENT AT AUSTIN BAYOU PROSPECT

After Bebout et al. 1978

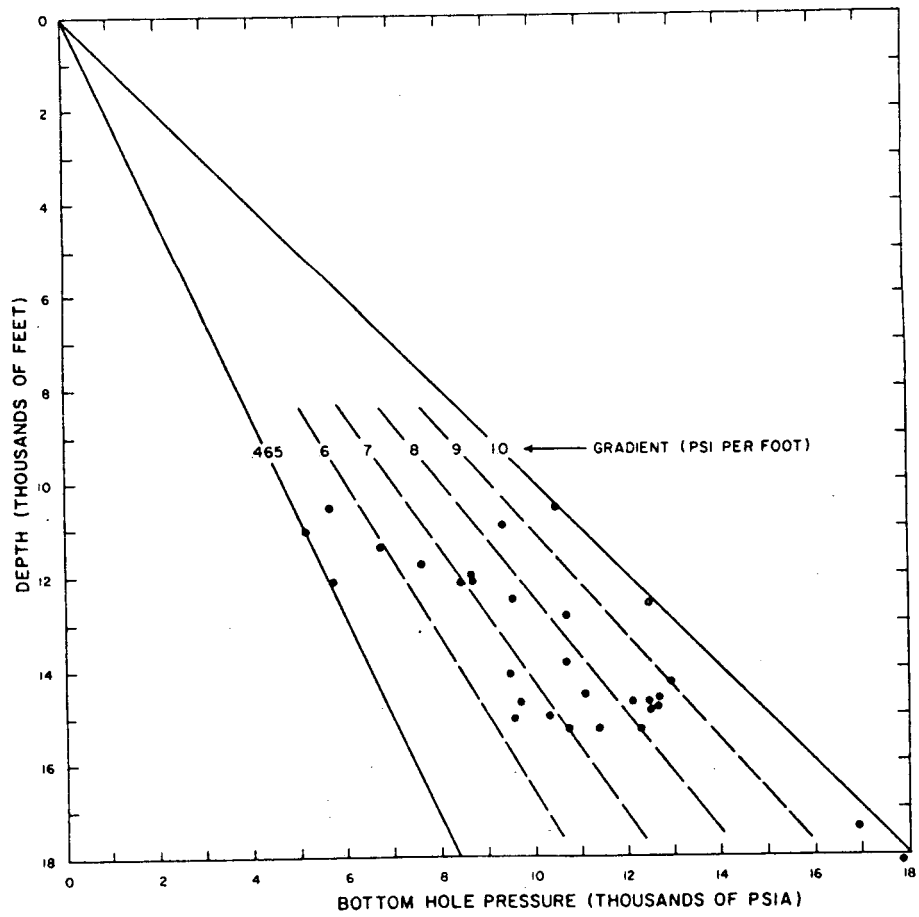


FIGURE 4-4 PRESSURE GRADIENT AT AUSTIN BAYOU PROSPECT

After Bebout et al. 1978

4.2 RESERVOIR DEVELOPMENT

The producing zone of the Chocolate Bayou field ranges in depth from about 8600 feet to more than 13,000 feet. There are more than 20 different pay sands separated by shale sections of various thicknesses (Grimsrud et al. 1978). Reservoir sands below about 10,000 feet produce mainly gas.

Oil was discovered at Chocolate Bayou in 1941. Production of oil peaked in the 1950's, but production of gas peaked in the mid 1960's. Current total production of hydrocarbons is less than 0.5×10^6 barrels per year. Oil, gas (plus condensate), and brine are produced in the field. Very detailed, well-by-well production histories are available at the Texas Railroad Commission. These data include well location, depth, completion interval, and monthly production of oil and/or gas. The data, however, have not yet been compiled into an easily workable form. The Railroad Commission does not keep records of brine production and available data relating to this are not detailed. Brine has also been reinjected into the Chocolate Bayou field but, again, details as to well-by-well injection rates are not available.

4.3 RESERVOIR RESPONSE

Pressure and temperature histories for five wells are provided by Bebout et al. (1978). This is the extent of the readily accessible information about reservoir temperature and pressure change data at Chocolate Bayou. Presumably, more such data would be available either at oil companies or the Texas Railroad Commission.

4.4 SUBSIDENCE

Subsidence data for Chocolate Bayou is limited to information from a survey line that extends from Angelton to Algoa and crosses the western region of the field. This line has been surveyed to first-order precision with a 1943 survey taken as base. Along this line, the maximum subsidence of 1.8 feet has occurred over the Chocolate Bayou field (Figure 4-5). Subsidence at Chocolate Bayou is complicated by regional groundwater withdrawal. Groundwater withdrawal has led to significant subsidence in the Houston-Galveston area and has probably contributed to the subsidence at Chocolate Bayou. The magnitude of this contribution is not definitely known. Its prediction could constitute an entire study in itself.

It is felt that there is significant potential for subsidence at the Austin Bayou Prospect due to withdrawal of geothermal fluids that exist at abnormally high pressures. The abnormally high pore-water pressures have led to abnormally high porosities of the shale interbeds. Upon depressurization of the reservoir, this porosity would decrease in accordance with increased effective stress and lead to compaction of the reservoir and possible surface subsidence.

4.5 PHYSICAL-MECHANICAL PROPERTIES

4.5.1 Permeability, Porosity

Values of permeability for the geopressured sands in the Brazoria Fairway were discussed by Bebout et al. (1978). These authors reported core permeabilities up to thousands of millidarcies for sands in Chocolate Bayou. Permeability (and porosity) decreases to the southwest of Chocolate Bayou. Thus,

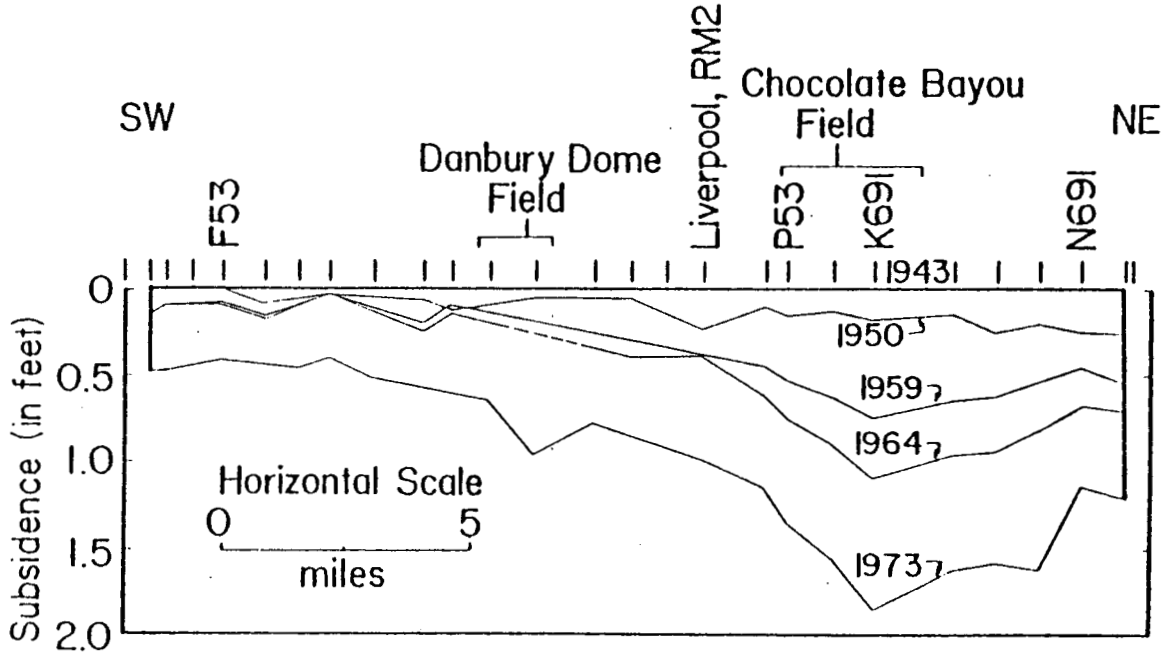


FIGURE 4-5 SURFACE SUBSIDENCE AT CHOCOLATE BAYOU OIL/GAS FIELD
After Grimsrud et al. 1978

Bebout et al. (1978) estimated that 30 percent of the sandstone in the T5 to T6 section would have core permeabilities of 20 to 60 md (2.1 to 6.4 x 10^{-13} ft^2). Bebout et al. (1978) also reported permeabilities of geopressured gas reservoirs in Chocolate Bayou measured from the well tests that ranged from 2 md to 10 md (2.1x 10^{-14} to 1.1 x 10^{-13} ft^2). These authors felt that the producing zones of the Austin Bayou prospect would be more permeable than the gas sands of Chocolate Bayou, but they also concluded that permeabilities obtained from unconfined cores would substantially overestimate true permeabilities.

Reservoir studies of a geopressured reservoir in the Texas Gulf Coast region have been reported by various authors, including Garg et al. (1977), Papadopoulos (1975), Wilson et al. (1975), and Bebout et al. (1978). Assumed values of sandstone permeability in these analyses ranged from 20 md to 415 md (2.1 x 10^{-13} to 4.4 x 10^{-12} ft^2). Garg et al. (1977) assumed anisotropic permeability of the sands with the vertical permeability of 2 md (2.1 x 10^{-14} ft^2).

Bebout et al. (1978) estimated that 250 feet of the sandstones in the T5 to T6 interval would have a porosity of 20 percent. They estimated the remaining sands to have an average porosity of 15 percent, varying from 5 percent to 20 percent. A porosity of 20 percent was generally assumed in the various geothermal reservoir studies reviewed.

No measured values of permeability of the abnormally pressured shales adjacent to the sandstone reservoirs were available. However, porosities of about 20 percent have been measured at various points along the Gulf Coast (Hottman and Johnson 1965; Schmidt 1973; Jones 1975). The Kozeny-Carman equation states

that the permeability is proportional to $n^3/(1-n)$ where n is porosity, but Mitchell (1976) has indicated that this equation is inappropriate for fine-grained sediments, particularly for porosities below 40 percent. Little data are available relating porosity and permeability of shales and clays; Olsen (1962) reports the permeability of illite with a porosity of 20 percent to be on the order of 10^{-4} md (1.06×10^{-15} ft^2). Values of permeabilities assumed in reviewed analyses (Garg et al. 1977; Papadopoulos 1975) ranged from 10^{-4} to 10^{-5} md (1.06×10^{-15} to 1.06×10^{-16} ft^2)

4.5.2 Temperature, Pressure Effects

Ramey (1975) presented data relating reduction in permeability to changes in temperature and pressure for Berea 17 sandstone (Figure 4-6). At a reservoir temperature of 300°F (150°C), these data indicate that an increase in effective confining pressure from 260 psi (3.74×10^4 psf) to 3810 psi (5.49×10^5 psf) would result in a decrease of permeability of about 50 percent. McLatchie et al. (1958) showed that change in permeability for a given pressure change was greater in low-permeability than in high-permeability rocks (Figure 4-7). For rocks of low-permeability, an increase of 4000 psi (5.76×10^5 psf) in effective confining pressure could result in a 95-percent decrease in permeability.

Changes in porosity also occur as a result of pressure changes. This will be discussed in Section 4.5.3.

4.5.3 Compressibility

Unpublished results of compressibility tests on sandstone cores from Austin Bayou (Pleasant Bayou well 1) showed a value

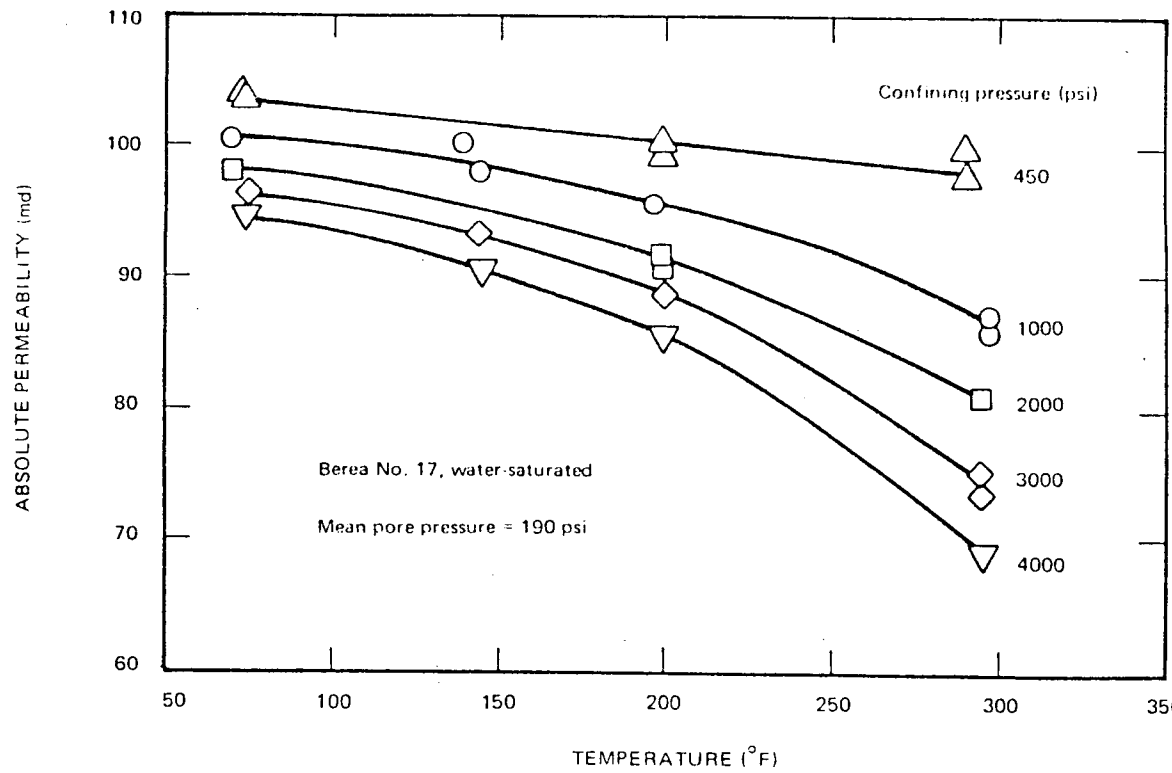
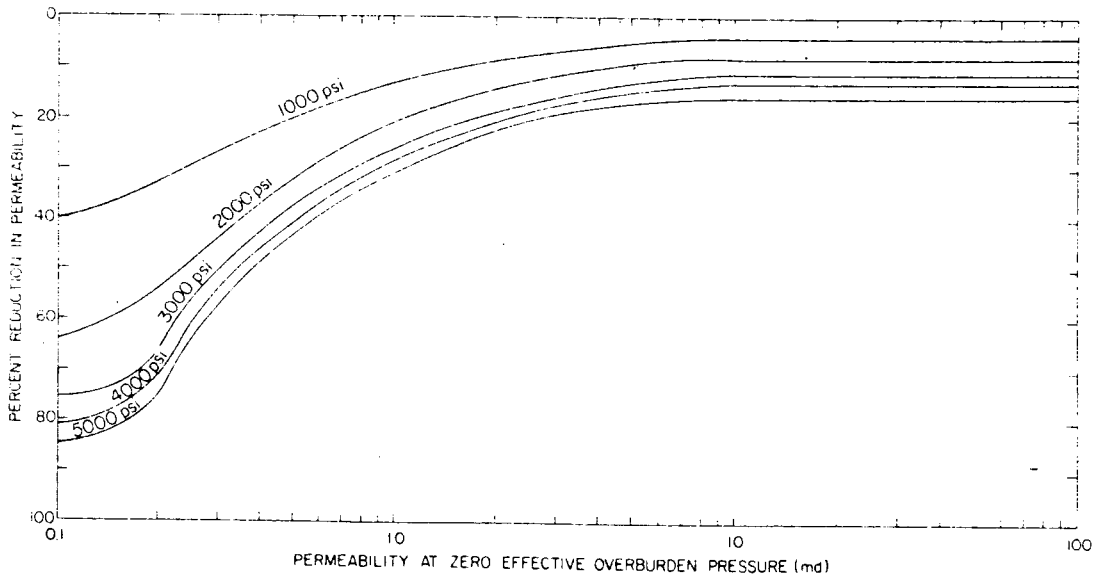


FIGURE 4-6

PERMEABILITY - TEMPERATURE/PRESSURE RELATIONSHIPS OF RAMEY ET AL.(1975)

After Ramey et al. 1975



Reduction in oil permeability versus effective overburden pressure (McLatchie, Hemstock, and Young, 1958).

FIGURE 4-7

PERMEABILITY - TEMPERATURE/PRESSURE RELATIONSHIPS OF MCLATCHIE ET AL. (1958)

for bulk compressibility of 0.8×10^{-6} psi^{-1} (5.55×10^{-9} psf^{-1}) under an effective confining pressure of 7500 psi (1.08×10^{6} psf). When unconfined, the bulk compressibility ranged from 2×10^{-6} to 3×10^{-6} psi^{-1} (1.4×10^{-8} to 2×10^{-8} psf).

Knutson and Bohar (1962) reported pore compressibilities for various Louisiana and Texas sandstones for a wide range of effective confining pressures. Using reported porosities and assuming negligible rock grain compressibility, the pore compressibility data were converted to bulk compressibility. Thus, for an effective confining pressure of 1.3×10^{6} psf, the average value of reported data was about 2.1×10^{-8} psf^{-1}. At 4.32×10^{5} psf effective confining pressure, a value of 2.78×10^{-8} psf^{-1} represented an average of the presented data.

As a comparison with previous Gulf Coast modeling efforts, Bebout et al. (1978) reported an assumed sandstone "matrix" compressibility of 8.33×10^{-8} psf^{-1}, and Garg et al. (1978) used 5×10^{-8} psf^{-1}.

No measurements of the compressibility of fine-grained sediments from the Gulf Coast region were available and, in general, very little information was available on the compressibility of any fine-grained sediments at the effective pressure expected at Austin Bayou. Chilingarian and Rieke (1969) reported the results of one-dimensional (no lateral movement) compressibility tests on various wet and dry clays. By assuming elastic properties and a Poisson's ratio (ν) of 0.2, their data showed average values of bulk compressibility at 9000 psi and 3000 psi (1.3×10^{6} psf to 4.3×10^{5} psf) effective confining stress to be about 2×10^{-5} psi^{-1} and 10×10^{-5} psi^{-1} (1.4×10^{-7} and 6.9×10^{-7} psf^{-1}), respectively.

Roberts (1969) reported data from one-dimensional consolidation tests of some shale at applied pressure up to 1.44×10^6 psf. These data yielded a compression index of about 0.22. Again assuming elastic parameters and a ν of 0.2, a value of bulk compressibility of about 3×10^{-5} psi^{-1} (2.08×10^{-7} psf^{-1}) is obtained.

Comparing this with published modeling efforts, Bebout et al. (1978) reported an assumed shale compressibility of 2×10^{-5} psi^{-1} (1.39×10^{-7} psf^{-1}) and Garg et al. (1978) used 1×10^{-4} psi^{-1} (6.94×10^{-7} psf^{-1}).

4.5.4 Pressure Dependence of Compressibility

The compressibility of sandstones is pressure-dependent. Teeuw (1971) suggested that the volumetric strain (e) was related to the hydrostatic component of effective stress (σ_e) by:

$$e = a\sigma_e^{\,n}$$

Van der Knaap (1959) found the value of the exponent n for numerous sandstones to be 0.7. The data presented by Knutson and Bohar (1962), however, do not seem to conform to such a simple relation.

For fine-grained soils under moderate loads, it is generally acknowledged that the Terzaghi e-log p-type relation adequately describes the dependence of compressibility upon pressure. For shales under high effective stress, however, it is not clear that the same relationship is valid. Data presented by Chilingarian and Rieke (1969) fit the following relation between bulk compressibility (C_b) and effective confining pressure p:

$$C_b = ap^{-b}$$

For many clays $b \approx 1$.

In lieu of experimental data, some knowledge of the volume change behavior of shales at high pressures can be obtained from data on void ratio (or porosity) changes with depth. Knowing the pressure at depth, a void ratio versus pressure curve can be constructed. Assuming the sediments are normally consolidated, it can be argued that such a curve would be very similar to that obtained from a standard laboratory isotropic consolidation test (neglecting differences in the time frame). Bulk compressibility is related to the slope of this curve by the relation:

$$C_b = \frac{1}{1+e_o} \frac{e_o - e}{Po - P}$$

(assuming compressibility of the mineral grains is negligible). Athy (1930) plotted shale porosity data over the depth range of 0 to 16,000 feet and found an approximately exponential relationship between porosity and depth of the form:

$$n = n_o e^{-bx}$$

where: b = constant
n_o = average porosity of surface clays
x = depth
n = porosity

Hedberg (1936), however, noted that in the pressure range of 1.15×10^5 to 8.64×10^5 psf (total overburden pressure) the relation is nearly linear. Data presented by Schmidt (1973) and Jones (1975) for shales of the Louisiana Gulf Coast also showed a linear relationship between porosity and depth from 4000 feet to the top of the geopressured zone (in excess of 10,000 feet). From the slopes of these curves, values of C_b from 2.08×10 psf^{-1} to 2.78×10 psf^{-1} were obtained.

5.0 EAST MESA

5.1 SYSTEM DEFINITION

This discussion of East Mesa is based on a report done in 1976 by TRW and thus reflects only what was known until that date. We are aware that further work has been done at East Mesa since 1976, but results of this work were not available at the time of our review.

East Mesa geothermal area lies in the eastern part of the California Imperial Valley, about 100 miles east of San Diego (Figure 5-1). Drilling of deep exploration wells began in about 1972; by 1976, 10 deep wells had been drilled in the area.

East Mesa, as part of the Salton Trough, is underlain by thick deltaic sediments. Alternating layers of sands, silts, and clays grade into sandstone, siltstone, and shale at depth. As of 1976, the geologic structure had not been very well defined. Based on data available at that time, the geothermal reservoir was envisioned as lying on a southwest-plunging nose transversed by a northwest-southeast trending normal fault (TRW 1976) (see Figure 5-2). No stratigraphic markers have been determined, so inter-well correlations were based on geophysical logs. These correlations were minimal and suggested considerable lateral variability in rock type and thickness. Because of the minimal inter-well correlation, distribution of sandstone was characterized by arbitrarily dividing wells into 500-foot intervals and determining the sand percentage in each interval. The distribution of sandstone was mapped over the area based on these percentage figures.

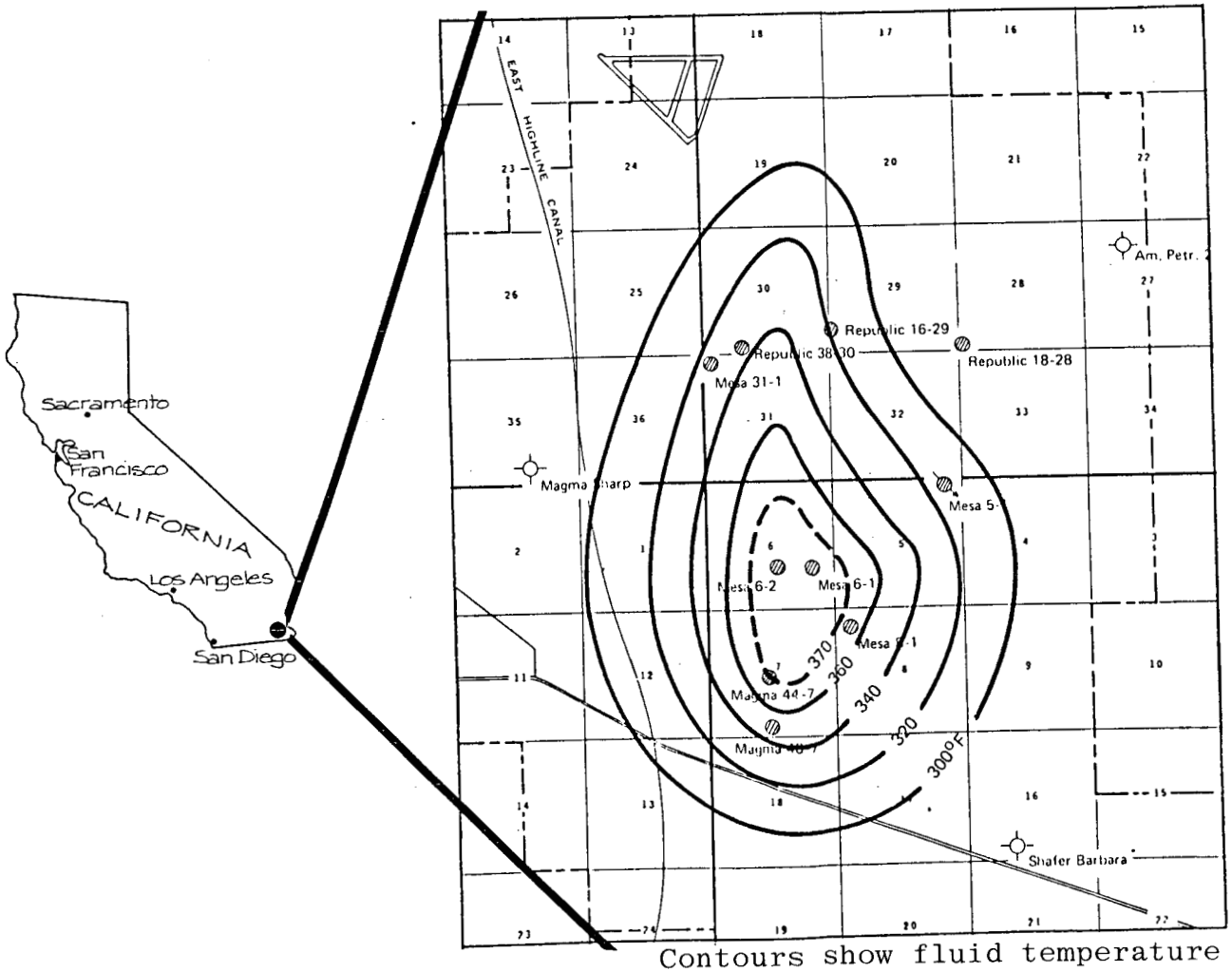


FIGURE 5-1 LOCATION OF EAST MESA GEOTHERMAL PROSPECT
After TRW 1976

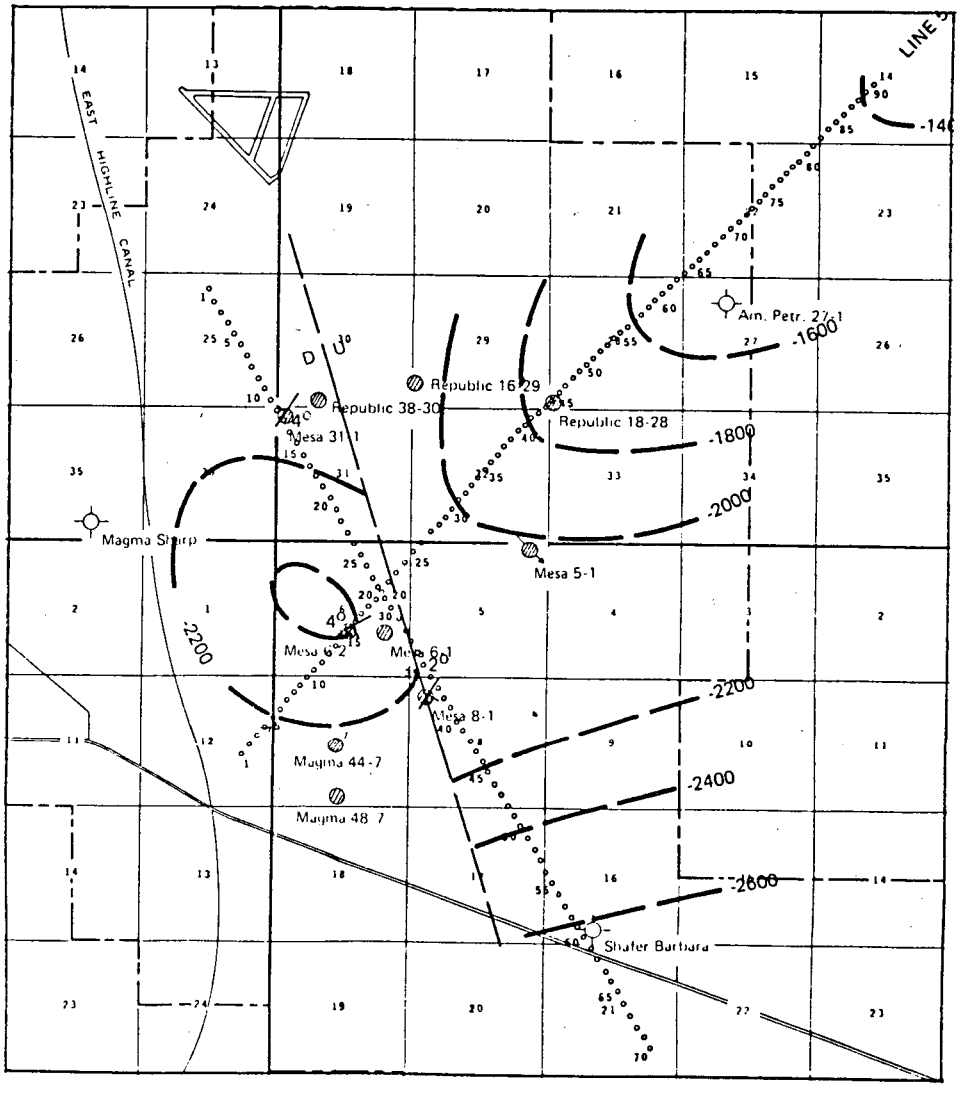


FIGURE 5-2

FAULTS DEFINING EAST MESA GEOTHERMAL PROSPECT

After TRW 1976

The effective reservoir is assumed to be defined by the 150°C (300°F) isotherm (Figure 5-1). The base has been assumed to be at 600 feet below sea level, though there are indications that this is conservatively shallow (TRW 1976). The approximate top of the reservoir is 2000 feet below sea level. Well-pressure tests have also indicated the presence of hydrologic boundaries in the reservoir. Maximum reservoir temperature is about 190°C (370°F).

5.2 PHYSICAL-MECHANICAL PARAMETERS

Porosities and horizontal and vertical permeabilities for reservoir sandstone have been measured from core samples and correlated to geophysical logs. In addition, several drawdown and/or recovery and interference well tests have been performed. Data for determination of hydrologic or mechanical parameters of the specific shale units in the reservoir and above are not available. No deformation moduli for any of the rock units are available.

5.3 SUBSIDENCE POTENTIAL

The presence of shale units within the reservoir increases the potential for subsidence at East Mesa. As reservoir pressures decrease, these units may exhibit additional consolidation which may be evidenced on the surface as subsidence.

6.0 RAFT RIVER VALLEY

6.1 SYSTEM DEFINITION

A geothermal exploration area is located in the southern part of the Raft River Valley, Cassia County, south-central Idaho (Figure 6-1). Four exploration wells have been drilled.

Structurally, the Raft River Valley is a down-dropped graben. Two of the faults in the valley (the Bridge Fault and the Narrows Structure) are significant because the geothermal wells were sited to penetrate their intersection. The geologic units consist of sediments and volcanic flows. These are summarized on Table 6-1. The lower part of the Salt Lake group is considered the geothermal aquifer. Data on rock type are available from the logs of the geothermal wells but are insufficient to clearly define the geology of the reservoirs (Figure 6-2).

The extent and shape of the geothermal reservoir have not been clearly defined. Estimates are that it has an average thickness of 1200 feet with an effective permeable, producing thickness of 600 feet (Grimsrud et al. 1978). The area is about 5 square miles. Temperatures in three experimental wells were about 300°F (150°C), and artesian pressures ranged from 140 to 175 psig (2.02×10^4 to 2.52×10^4 psf).

6.2 PHYSICAL-MECHANICAL PARAMETERS

Tests were performed on core for the test wells to determine densities, porosities, and permeability. In addition, some short-term pump tests were done.

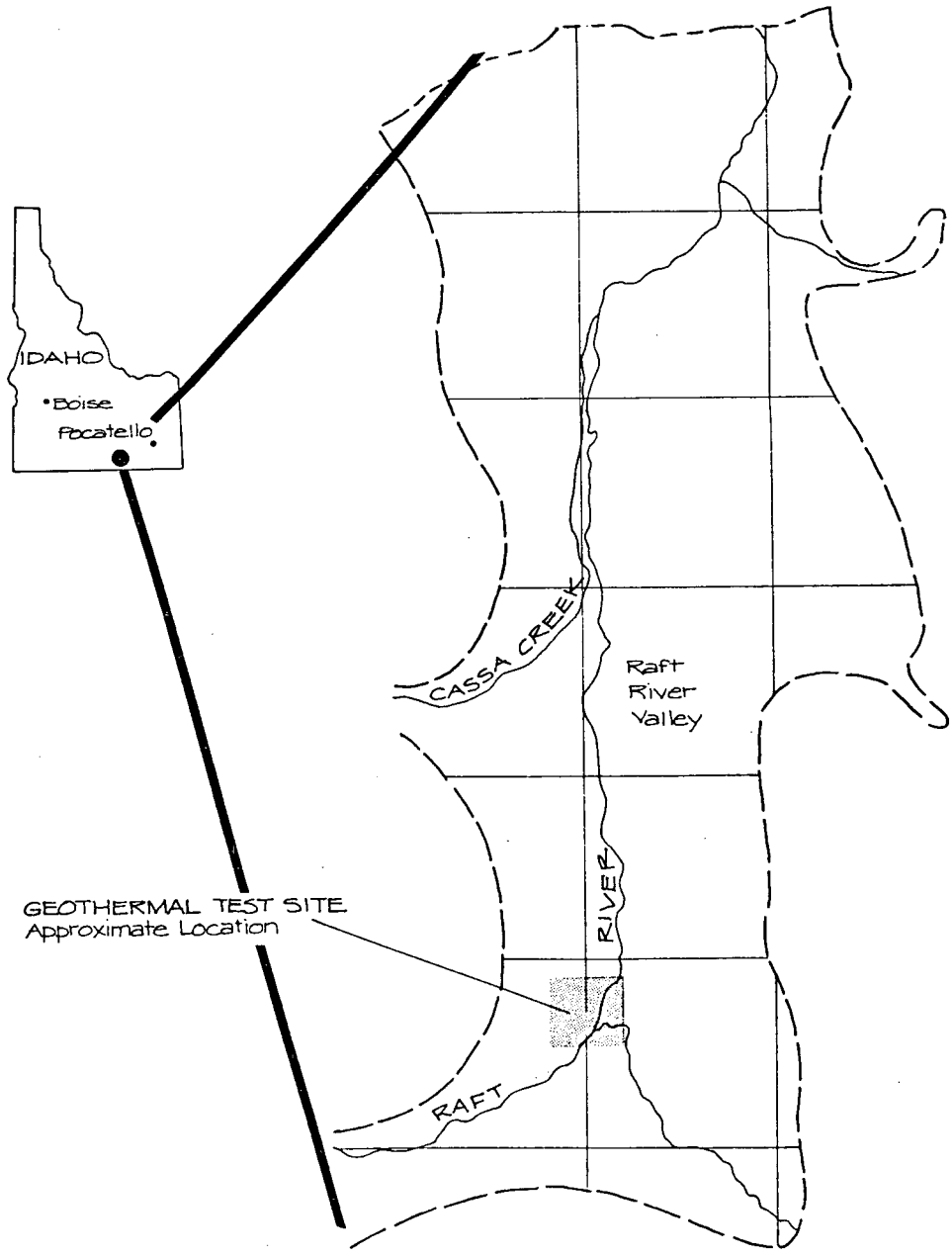


FIGURE 6-1 LOCATION OF RAFT RIVER VALLEY GEOTHERMAL PROSPECT
After Grimsrud et al. 1978

TABLE 6-1
GEOLOGIC UNITS OF THE RAFT RIVER VALLEY AND THEIR WATER-BEARING PROPERTIES

Era	Period	Epoch	Rock Unit	Physical Characteristics & Distribution	Water-Bearing Properties
Cenozoic	Quaternary	Holocene and Pleistocene	Quaternary Sedimentary deposits	Clay, silt, sand, gravel & boulders underlying valley floors & hillslopes; includes alluvium, alluvial fans, windblown silt & landslide deposits; unconcolidated; loose to well compacted; massive to well bedded	Sandy & gravelly alluvium yields considerable ground water to wells, especially where pumping induces recharge; windblown silt & landslide deposits are not important aquifers but transmit precipitation to underlying material
		Holocene (?) and Pleistocene	Snake River basalt	Olivine basalt; dense to vesicular; fine-grained; irregular & columnar jointing; includes beds of cinders, rubbly basalt & interflow deposits; locally intertongued with Pleistocene & Holocene deposits; crops out at mouth of Raft River Valley	Formational permeability high because of jointing & rubbly contacts; rock permeability low; yields large amounts of unconfined water to wells where it lies below the water table; receives & transmits recharge readily; interflow sediments yield little or no water
		Pleistocene	Raft Formation	Partly consolidated clay, silt, sand, & gravel; underlies much of Raft River Valley floor; crops out near mount of river	Lacustrine facies yields small amount of water to domestic wells; elsewhere is a good aquifer.
	Tertiary	Pliocene and Miocene	Salt Lake Group	Stratified sedimentary & volcanic rock including clay, sandstone, conglomerate, ash, and volcanic flow rocks; exposed mainly as blanket on highland areas	Joints & faults in flows, welded tuff, coarse-grained ash beds, sand & gravel yield small to moderate amounts of water; nonpermeable altered beds & some faults control ground water movement; important artesian aquifer locally
Proterozoic to Mesozoic			Pre-Tertiary Rocks	Well-indurated sedimentary rocks, metamorphosed sediments & granitics; folded & faulted; crop out in hills surrounding valley	Generally very low permeability; fractured rock yields small amounts of water; important chiefly as basement rock transmitting water from catchment area to lowlands.

Source: Grimsrud et al. 1978

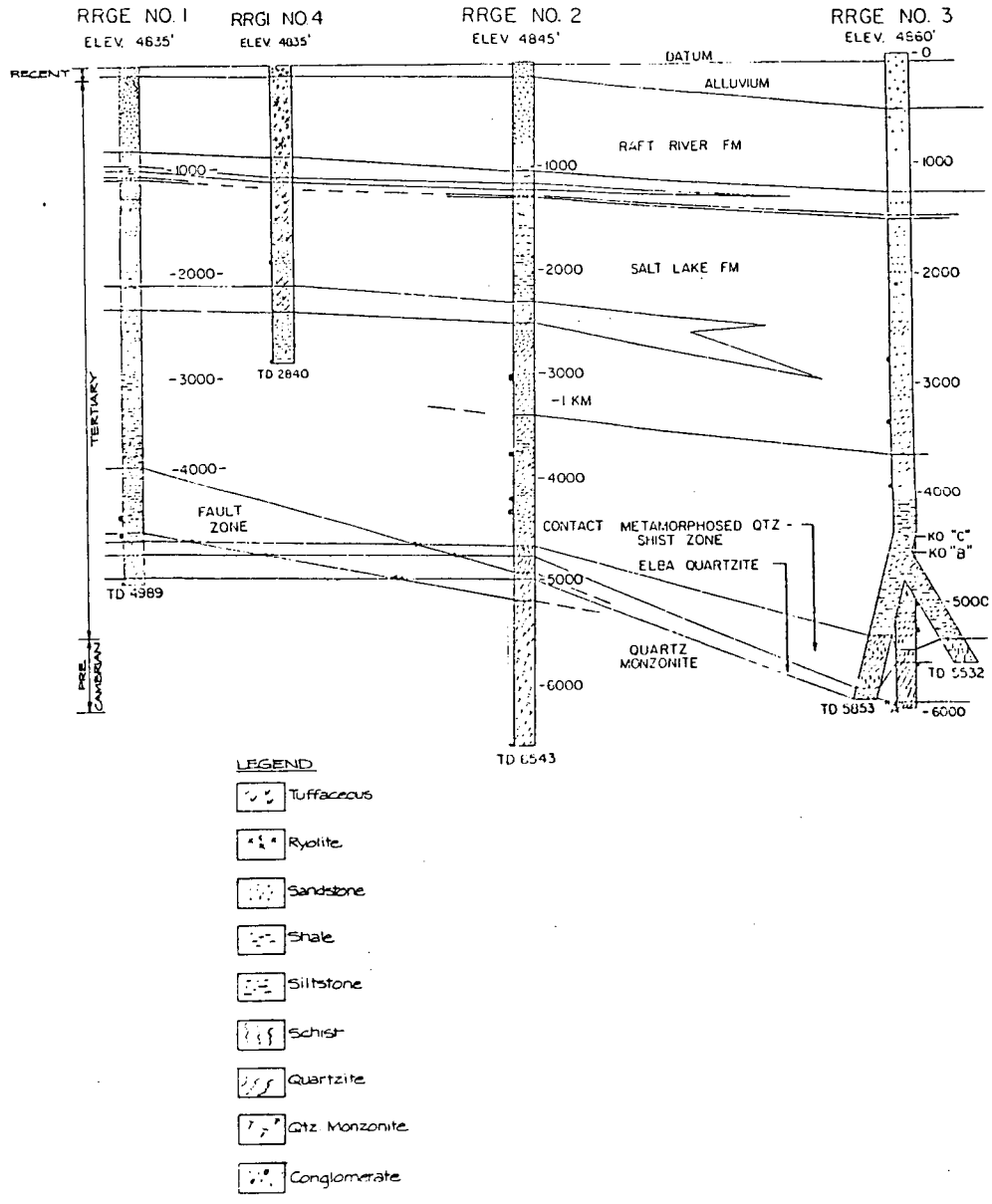


FIGURE 6-2

GEOLOGIC STRUCTURE OF RAFT RIVER VALLEY GEOTHERMAL PROSPECT

After Grimsrud et al. 1978

6.3 SUBSIDENCE POTENTIAL

Subsidence has occurred in the Raft River Valley, but it is attributed to groundwater withdrawal from near-surface sediments. From the general description given of the Salt Lake Formation rock, there appears to be little shale in the reservoir region. The presence of shale may increase the potential for subsidence, but the absence of shale does not preclude the possibility of subsidence. The controlling factor is the compressibility of the rock unit.

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