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AREAS OF GROUND SUBSIDENCE DUE TO GEOFLUID WITHDRAWAL

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DISCLAIMER

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I. INTRODUCTION

The evaluation of the potential for subsidence of geothermal resource areas is an important consideration in resource development and exploitation. Subsidence, if it occurs, may cause a significant environmental impact as well as present problems in field operation. Consequently, methods for its prediction are required. As described in the SCI Geothermal Subsidence Handbook (Atherton, et al., Volume 1, Chapter 9, 1976), two approaches are currently available for predicting subsidence: the analysis method uses mathematical models; the analogy method relies on a subjective analysis and comparison of geological and hydrological features of the site under study with the corresponding features of other sites that have undergone subsidence in the past. The comparisons made in the analogy method thus require detailed information on sites which have already exhibited subsidence. This report provides such detailed information on four areas with histories of subsidence. This research, performed under Purchase Order 3003802, was a part of the ongoing Geothermal Subsidence Research Program being conducted by Lawrence Berkeley Laboratory of the University of California under the auspices of the Division of Geothermal Energy of the U.S. Department of Energy.

II. SUMMARY OF RESULTS

The project was divided into two major phases; 1) The selection of case history sites and 2) carrying out the case histories.

Selection of Case History Sites

Four subsidence sites were selected for detailed case studies. These selections were made on the basis of: 1) Physical relevance of subsidence areas to high priority U.S. geothermal sites in terms of withdrawn geofluid type, reservoir depth, reservoir geology and rock characteristics, and overburden characteristics; 2) Data completeness, quality, and availability.

A review of potential geothermal sites was made in order to determine the physical relevance (i.e., analogies) of areas with past subsidence to the potential geothermal sites. The geothermal areas were divided into six categories as follows:

Category 1: Caldera Structure - A caldera is a large, roughly circular, depression in volcanic terrain, typically caused by the explosion and subsequent collapse of a volcanic cone or vent. The depression is generally bounded by a series of arcuate faults known as "ring faults." Radial faults may also be present. The depression is typically filled with volcanic debris erupted after the collapse. Some alluvium may also be present in older calderas. Geothermal resources in caldera structures may be either hot water or vapor dominated, and springs often emerge along bounding faults.

Category 2: Active Volcanoes - Geothermal resources in this category are associated with active volcanism, and are in areas of widespread and thick volcanic rocks, with little or no alluvium.

Category 3: Block-Faulted Grabens of Basin and Range Province - Many geothermal resource areas are found in the basin and range geomorphic province, which includes Nevada, Southern New Mexico and parts of Oregon, California, Idaho, Utah, Arizona and Texas. This province is characterized by horst and graben structure. The many broad valleys of this province represent down-dropped fault blocks separated from each other by mountain ranges. The hot springs found in this region are commonly associated with range front faulting.

Category 4: Alluviated Valleys in Volcanic Terrain - Geothermal resources in this category are intermediate between the well developed basin and range structure of Category III and the volcanic terrain of Category I. Although some of the resource areas included may have a graven type structure, they are typically located in broad river valleys, where the volcanic rocks are overlain by alluvium.

Category 5: Deep Sedimentary Basins - This category includes areas of thick accumulations of sedimentary rocks, which may range from unconsolidated alluvium at the surface to hard sandstone and shale at depth. Fluids contained in these basins are sometimes geopressured such as along the U.S. Gulf Coast.

Category 6: Folded and Faulted "Hard" Rocks, With Little or No Alluvial Cover - While associated with volcanic areas, these resources are not located in volcanic rocks, and may therefore have different subsidence characteristics.

Subsidence areas were selected so that the case studies would cover as many of the geothermal site categories as possible. The four sites finally selected are 1) Chocolate Bayou oil and gas field, Texas; 2) Raft River Valley, Idaho; 3) Wairakei geothermal field, New Zealand; and 4) The Geysers geothermal field, California. Brief summaries of the case studies on each of these sites are presented below. A list of physical factors at each of the case study sites favoring, or not favoring subsidence is shown in Table 1.

CHOCOLATE BAYOU, TEXAS

The Chocolate Bayou oil and gas field near Houston, Texas was selected for a case study because it is large, has produced for over 35 years, largely from the geopressured zone, good geological data are available, and subsidence has been documented across part of the field. The stratigraphy at the site is typical of the region and consists of interbedded deltaic sand and shale wedges from Cretaceous to Recent age with major hydrocargon production from the Tertiary sands. The Chocolate Bayou field is a faulted anticlinal structure from which oil is produced from about 8000 to 10,000 foot depth. From 10,000 to over 15,000, the field produces geopressured gas.

TABLE 1

FACTORS TENDING TO INFLUENCE GEOTHERMAL SUBSIDENCE FOR EACH CASE STUDY

FACTOR TYPE	FACTORS WHICH MAY CONTRIBUTE TO SUBSIDENCE SUSCEPTIBILITY	WAIRAKEI	CHOCOLATE BAYOU	RAFT RIVER	GEYSERS
1. RESERVOIR FLUID					
Phase	All-liquid	Mostly	Part Gas	Yes	No
Pressure	Geopressured (overpressured)	No	Partly	No	Yes
Density	High	No	Yes	No	No
2. PRODUCTION FLUID					
Volumes	Large	Yes	Yes	No	Yes
Fluid levels[1]	Large drops, long time, extensive areas	Some	Yes	Yes	?
Pore pressures[1]	Large drops, long time, extensive areas	Yes	Yes	?	No?
Formation flashing	None	No[6]	Yes[6]	Yes[6]	No[6]
3. GEOHYDROLOGY					
Natural recharge[1]	Low rates	Partially	Yes	No	Yes
4. RESERVOIR MATERIALS					
Type	Sediments	Yes	Yes	Yes	No
Predominant grain size	Coarse	?	No	Yes	No
Grain shape	Angular	Yes	Yes	Partly	Yes?
Porosity	High	Yes	No	Yes?	No
Consolidation/cementation	Unconsolidated, lacking cementation (loose or friable)	Yes	Some	Yes	No
Preconsolidation[2]	None	Yes	Some	Yes	No
Hydrothermal alteration	Present	Yes	No	No	Yes
Admixed mineral content	High mica, montmorillonitic clays	Some	Yes	?	No?
Age	Micocene and younger	Yes	Some	Yes	No
Thickness (in communication)	Great vertical section	Yes	Yes	Yes?	Yes
Deformation properties[3]	Highly deformable	Partly	Partly	Yes	No
5. ASSOCIATED MATERIALS					
Type	Clays, siltstones, shales	Some	Yes	Some	Some
Occurrence	Many thin strata of large total vertical thickness, interbedded with reservoir materials but not impairing communication between them (less susceptible if distributed in few thick strata)	No	Yes	No?	No?
6. RESERVOIR GEOMETRY					
Width/thickness ratio[4]	Large	No	Yes	Yes	No
7. OVERBURDEN					
Thickness	Small (< 3000 ft)	Yes	No	Yes	Yes
Competence	Incompetence, unconsolidated sediments	Yes	Partly	Yes	No
Deformation properties[5]	Highly deformable	Yes	No	Yes	No
Density	High	No	No	No	Yes
8. SITE GEOLOGY, STRUCTURE					
Folding	Gentle, broad, synclinal	Yes	Yes	Yes	No
Flank dips	Less than 25°	No	Yes	Yes	No
Faulting	Normal, graben blocks	Yes	Yes	Yes	No
Fracturing	Much, recent	Yes	Yes	No	Yes
Regional stresses	Tensional	Yes	Yes	Yes	No

1. Depend(s) upon formation properties, which may be studied by preliminary well tests.
2. Preconsolidated materials have previously experienced loads greater than their present load.
3. Elastic constants, compaction coefficient, yield stress, etc.
4. Of the producing zone.
5. Can the overburden materials possible respond more slowly than the reservoir materials below.
6. No, meaning subsidence susceptibility under this factor does not occur, this formation flashing does occur. Similarly, a yes means formation flashing does not occur.
7. Question marks signify not adequate data to tell.

Four fluids are extracted at Chocolate Bayou: ground water (from the upper 1000 feet), oil, gas, and brine associated with hydrocarbon production. Production records for these four fluids were compiled and compared with leveling data showing subsidence at the field. Benchmarks on a first order level line crossing the NW part of the field have been releveled at least four times since 1918. A profile along this line of benchmarks shows a progressive increase in rate of elevation change with time, and also across the field.

Correlation of subsidence data with production figures shows that although ground water withdrawal has caused some subsidence, brine and oil production appear to have caused 0.5 to 1.2 feet of the maximum observed subsidence of 1.8 feet since 1943. A lag time of several years is indicated, and as of the period 1964-73, subsidence rates were still increasing despite much lower production rates at Chocolate Bayou.

Within the scope of our study, certain data were not obtained either because they did not exist or would have been too costly to compile. Such data include brine production for the first 25 years of operation, casing-head gas production prior to 1970, rock properties for reservoir sandstones and interbedded shales, consolidation characteristics of clays in the upper 1000 feet, production data by well and by depth zone, and large scale mapping showing surface traces of growth faults. It would also have been desirable to have a level line crossing the field in a N-S direction, particularly across the area where production has been principally from the gas pressured zone.

RAFT RIVER VALLEY, IDAHO

The Raft River Valley in southern Idaho is unlain by saturated, slightly consolidated sediments and lava flows in a basin formed in essentially impermeable older rock. Agricultural development began in the 1860s and has evolved into a predominantly grain and cattle raising industry. Use of ground water for agricultural purposes essentially began in the 1920s, and has been increasing since. Ground water use has exceeded recharge of the basin resulting in a decline of the water table of as much as 50 feet, and local ground surface subsidence probably exceeding the maximum measured amount of 2.6 feet.

The Raft River geothermal development, operated by EG&G-Idaho at the head of the valley, will use large quantities of ground water. The reservoir system envisioned for this KGRA assumes meteoric waters percolate downward, become heated by a deep heat source, then rises to the surface along more permeable fault zones or where wells tap into it.

The subsidence effects of water use by this geothermal development are presently unknown, but could be assessed with additional data, including: 1) the correlation of geologic units between the known subsidence area and the geothermal area; 2) physical properties including void ratio and consolidation potential of sediments in the geothermal area from ground surface to the production zone; 3) hydraulic continuity between the near surface, cool water reservoir and the geothermal reservoir; and 4) the predicted changes of water levels and pore pressures in these reservoirs. Additional, or more detailed base-line data on leveling and subsurface compaction should also be obtained.

WAIRAKEI, NEW ZEALAND

Wairakei is a geothermal production field on the New Zealand North Island, central volcanic region. The bulk of the steam production at Wairakei is obtained from permeable pumice breccias (Waiora Formation). Overburden materials (from deepest to shallowest) are a rhyolite intrusion from the west (Haparangi Rhyolite), an impermeable series of sedimentary and pyroclastic rocks (Huka Falls Formation), and permeable breccia and pumice alluvium covers (Wairakei Breccia and Recent Pumice Alluvium). The Waiora Reservoir is underlain by a thick section of impermeable ignimbrites (Wairakei Ignimbrites).

Production at Wairakei started in the early 1950s; however, major increase in production began in 1958 when power generation was started. In the early years of production, prior to 1963, recharge to the reservoir was much less than production volume ($\sim$10%), thus causing large pressure drops in the reservoir (in the order of 250 psig in the western production area and over 300 psig in the eastern production area). After 1963 pressure decline in the reservoir leveled off to less than 10 psig per year. First and second order leveling since 1956 has shown that grown subsidence went relatively slow prior to 1960, and then increased to a sustained maximum subsidence rate from 1962 through 1971. By 1974, the maximum subsidence of the Wairakei area reached over 15 feet. Through 1974 the rate of subsidence continued to be high, even though reservoir pressures have remained nearly constant since 1968.

Maximum subsidence at Wairakei occurs away from the main production area, in the eastern part of the field. There are a number of possible explanations for this unusual phenomenon. Probably the most important explanation is the much greater thickness of the Waiora Formation reservoir under the eastern area. In addition, the groundwater pressure gradient falls strongly from west to east in the Waiora aquifer. As a result, pressure drops due to production would tend to be greater in the east.

THE GEYSERS

The Geysers is a vapor-dominated geothermal system in central California first used for commercial power generation in 1960. Exploitation of the resource has increased since then with the present production being about 80 X 10^5 lb/hr. Well-head pressure declines of about 180 psi have been observed with steam production

The Geysers area is underlain by northwest-trending fault bounded wedges of Jurassic and Cretaceous consolidated rocks of the Great Valley Sequence and the Franciscan assemblage. It is an area of moderately high seismicity with several major active faults nearby. The steam reservoir rocks are believed to be dominantly fractured Franciscan metagraywacke overlying a hot brine reservoir at a depth of about 5 km. The system is probably heated by a deep (about 30,000 feet) magma chamber.

Geodetic surveys since 1972-73 reveal that significant vertical and horizontal subsidence has occurred in the Geysers region. Two types of subsidence in the area are indicated by the data: 1) a regional subsidence due to fault movement; and 2) local subsidence directly related to the area of principal steam production. A maximum subsidence of 13 centimeters has occurred over a 4-1/2 year measured period in the area of most concentrated steam withdrawals. Horizontal ground movement as much as two centimeters per year, was also measured during this period.

III. SUBSIDENCE SITE SELECTION

The selection of case history sites was done by examining both promising geothermal sites in the United States, and a wide range of historically measured subsidence sites throughout the world, and comparing their various characteristics. The results of this process are presented in this section.

Investigation of U.S. Geothermal Sites

In order to seek proper analogues to geothermal areas, the geological environments of 38 geothermal resource areas in the western and southwestern United States were studied. The purpose of this study was to establich "categories" of geological settings for comparison with geofluid production areas where subsidence occurred.

In this subtask, the project team fucused its efforts on the 37 geothermal areas studied by the MITRE Corporation as prospective sites for geothermal developemnt. We felt that these sites were most important because they would be of very high interest in future DOE geothermal studies. To look for categories of geological settings, we researched the geology, structure and resource type for each of the 37 areas (plus Klamath Falls, Oregon, which we felt belonged on the list). Because of the importance of subsurface geology, in determining subsidence potential, a special effort was made to acquire this type of data, where available.

Summarizing the geology of each area in tabular form enabled us to look for similarities between the different resource areas. Once the categories were established, a large scale table of geology, structure and resource type was prepared, as shown in Table 2, with the geothermal areas grouped by category. Key references on geology and hydrology are also given in this table.

The following is a brief discussion of each category, and a list of the geothermal areas which belong in that category on the basis of what we know about their geological settings.

Table 2. GENERAL CHARACTERISTICS OF GEOTHERMAL SITES

GEOTHERMAL SITE	GEOLOGIC ENVIRONMENT (SETTING)	ESTIMATED DEPTH TO TOP OF RESERVOIR	OVERBURDEN CHARACTERISTICS	RESERVOIR CHARACTERISTICS	RESOURCE TYPE AND SUBSURFACE TEMP.	PRINCIPAL SOURCES OF GEOLOGIC AND HYDROLOGIC DATA
Baker H.S., WA	Active volcanic area	?	Quarternary and Tertiary volcanic flows; (mainly andesite) some pyroclastic rocks.	Granite, overlain by Tertiary lava flows.	Hot water convection 165°C	• Waring, G.A., 1965 USGS Prof. Ppr. 492 • Schuster, J.E., 1974 • Livingston, V.E., Jr. 1972
Mt. Hood, OR	Active volcano	1000 m.	Andesite and basalt flows with some Quaternary mudflows and glacial deposits.	Quaternary and Tertiary lava flows and tuffaceaous rocks.	Hot water convection 125°C.	• Peck & others, 1964 • Waters, A.C., 1968
Glass Mtn., CA	Active volcano	?	Holocene to Late Tertiary Volcanics—rhyolite andesite, basalt and pyroclastic rocks	Probably fractured Quaternary and Tertiary volcanics	Probably hot water convection, with temp. < 100°C.	• California Division of Mines & Geol., 1958, Geologic Map of California, Alturas sheet.
Puna, HI	Active volcano	?	Quaternary basalt flows and ash beds	Fractured basaltic flow rocks and ash beds.	Probably hot water convection, with temp.	• Greeley, R. ed., 1974 • Stearns, H.T., 1966
Lassen, CA	Probable caldera structure with associated ring faulting	1000 m.	Quaternary volcanic rocks, mostly dacite; some andesite and basalt.	Quaternary and possibly Late Tertiary volcanics.	Vapor dominated 240°C.	• Williams, H., 1932
Mono-Long Valley, CA (Casa Diablo)	Caldera with associated ring faulting and normal faults.	1000 m.	Interbedded tuff, flow rocks and alluvium of Quaternary age.	Bishop tuff and Glass Mtn. Rhyolite of Pleistocene age.	Hot water convection 220°C	• California Div. of Mines & Geol., 1967 Geologic Map of Cal., Mariposa Sheet. • California Div. of Mines & Geol., 1963, Geol. Map of Calif., Walker Lake Sheet • Recent work by USGS Pub. in Journal of Geophysical Research

Table 2 Continued

GEOTHERMAL SITE	GEOLOGIC ENVIRONMENT (SETTING)	ESTIMATED DEPTH TO TOP OF RESERVOIR	OVERBURDEN CHARACTERISTICS	RESERVOIR CHARACTERISTICS	RESOURCE TYPE AND SUBSURFACE TEMP.	PRINCIPAL SOURCES OF GEOLOGIC AND HYDROLOGIC DATA
Valles Caldera, NM	Caldera with associated ring faulting	1000 m.	Quaternary volcanics and some lake beds. Principal unit is the Bandolier tuff, a welded ash flow. Extensive hydrothermal alteration.	Oldest volcanics are Pliocene basalt. Volcanic pile includes basalt, andesite, dacite, quartz, latite, and rhyolite.	Hot water convection 240°-280°C	• Smith, R.L., and others, 1970 • Summers, W.K., 1965 • GSA Memoir 116 (1968) • Griggs, R.L., 1964 • Smith, R.L., and others, 1961, USGS Prof. Ppr. 340-D • Titus, F.B., Jr. 1961
Coso H.S., CA	Probable caldera with associated ring faulting	Shallow zone<200m Deeper zone probably 1000 m.	Quaternary alluvium (~50m. ?) and acidic volcanics.	Granite and associated rhyolitic volcanics	Hot water convection 220°C	• Austin, C.F. and J.K. Pringle, 1970 • Duffield, W.A., 1975 • Lanphere, M.A. and others, 1975
West Yellowstone MT	Old caldera	?	Quaternary alluvium overlying Quaternary and Tertiary volcanics	Probably fractured volcanics.	Possibly vapor dominated	• A.A.P.G. Geological Highway Map Northern Rocky Mtn. Region • Smedes, H.W. and H.J. Prostka, 1972, USGS Prof. Ppr. 729-C • Ross, C.P. and others, 1955
Brady H.S., NV	Basin & Range; graben bounded by normal or strike-slip faults.	500 m.	Alluvial fan, lake bed and pediment deposits of Quaternary age; Tertiary sandstone, basalt, diatomite and tuff. Resource is fault controlled.	Tertiary basalt, tuff, and diatomite with interbedded shale and sandstone.	Hot water convection 214°C.	• Willden, C.R. and R.C. Speed, 1968 • Garside, L.J., 1974 • Nev. Bureau of Mines and Geol., Rpt. 21. • Olmsted, F.H. and others, 1975
Surprise Valley, CA	Basin & Range; graben bounded by normal faults with over 1500 m. offset	1000 m	Quaternary alluvium and Tertiary-Quaternary volcanics up to ~2000 m. thick accumulated in down-dropped basin.	Tertiary sediments and volcanic debris with related rhyolite flows and plugs. Most hot springs are near rhyolite plugs or flows.	Hot water convection 175°C	• Duffield, W.A. and R.O. Fournier, 1974 • Ford, R.S. and others 1963, DWR Bull. 98 • White, D.E., 1955 GSA Bull. vol. 56

Table 2 Continued

GEOTHERMAL SITE	GEOLOGIC ENVIRONMENT (SETTING)	ESTIMATED DEPTH TO TOP OF RESERVOIR	OVERBURDEN CHARACTERISTICS	RESERVOIR CHARACTERISTICS	RESOURCE TYPE AND SUBSURFACE TEMP.	PRINCIPAL SOURCES OF GEOLOGIC AND HYDROLOGIC DATA
Stafford, AZ	Basin & Range graben. Faults not well known. Tertiary and Quaternary volcanics in Gila Mtns. to NE.	?	Alluvial gravel, sand and silt with some gypsum, marl, diatomite, limestone and interbedded volcanics, looselv to firmly consol.	Tertiary and Quaternary volcanics, basalt to interm. composition, crop out in mtns to NE, and are probably present at depths of up to 3000 m.	Hot water convection Probably >200°C.	• Wilson, E.D. and others, 1969. Geologic Map of Arizona • Cushman, R.C. and R.S. Jones, 1947
Chandler, AZ	Basin & Range graben. Faults not well known.	?	Alluvium, evaporites, other sedimentary rocks. May also be some interbedded basalts.		Hot water convection 184°-200°C	• Wilson, E.D., and others, 1969. Geol. Map of Arizona • McDonald, H.R. and others, 1947
Bruneau-Grandview, ID (Castle Creek)	Alluvial valley in volcanic terrain; may be part of large graben structure. Many subparallel high angle faults.	300 m	150-900 m Pliocene to Holocene fluvial and lacustrine deposits (Idaho Group) with intercalated basalt and ash; underlain by Pliocene basalt.	Pliocene Idavada volcanics silicic, latite, chiefly layered of devitrified welded tuff but includes some vitric tuff, lava flows, and some rhyolitic rocks.	Hot water convection >200°C.	• Young, H.W. and R.L. Whitehead, 1975 IDWS Bull. 30, part 2 • Young, H.W. and J.C. Mitchell, 1973 IDWS Bull. 30, part 1
Weiser-Crane Creek, ID	Alluvial valley in volcanic terrain. Region characterized by closely spaced NW-trending folds with some sub-parallel faults	1000 m	Quaternary alluvium (in valley portions) underlain by Pliocene and Pleistocene sediments of Idaho group.	Basalts of Columbia River Group (Miocene and Pliocene).	Hot water convection 180°C.	• Young, H.W. and R.L. Whitehead, 1975, IDWS Bull., part 3 • Young, H.W., and J.C. Mitchell, 1973, IDWS Bull. 30, part 1 • Newcomb, R.C., 1970 USGS Misc. Geol. Inv. Map I-587
Vale H.S., OR	Alluvial valley in volcanic terrain with N-S trending faults.	1000 m	Semiconsolidated to well consolidated tuffaceous sandstone, siltstone, claystone of Cenozoic age, with some interbedded basalt flows.	Basalts of Columbia River Group.	Hot water convection 180°C .	• Corcoran, R.E. and others, 1968 • Walker, G.W., 1977
Klamath Falls, OR	Alluvial valley in volcanic terrain; probable graben structure with numerous NW-trending faults.	500 m	Tuffaceous sediments and interbedded flow rocks.	Quaternary and Tertiary lava flows.	Hot water convec- ~100-150°C.	• Peterson, N.V. and E.A. Groh, 1967 • Lund, J.W. and others 1974
Alvord, OR	Basin & Range; graben bounded by normal faults.	1500 m	Alluvium and lake beds over rhyodacite, andesite, and basalt with some interbedded tuffs and flow breccias.	Rhyodacite, andesite, and basalt.	Hot water convection 200°C	• Groh, E.A., 1966 • Walker, G.W., 1977 • Walker, G.W., and C.A. Repenning, 1965

Table 2 (continued

GEOTHERMAL SITE	GEOLOGIC ENVIRONMENT (SETTING)	ESTIMATED DEPTH TO TOP OF RESERVOIR	OVERBURDEN CHARACTERISTICS	RESERVOIR CHARACTERISTICS	RESOURCE TYPE AND SUBSURFACE TEMP.	PRINCIPAL SOURCES OF GEOLOGIC AND HYDROLOGIC DATA
Steamboat Springs NV	Basin & Range; graben bounded by normal faults.	300 m	Siliceous sinter over Pleistocene alluvium, tuff breccia & trachyte flows. Sinter deposits occur along trace of major E-dipping faults with apparent normal displacement.	Granodiorite	Hot water convection 210°C.	• White, D.E., G.A. Thompson and C.H. Sandberg, 1964; USGS Prof. Ppr. 458-B • White, D.E., 1968
Raft River, ID	Basin & Range; graben bounded by normal faults.	1500 m. (Silica caprock found at 1200 m. during drilling.) Could be shallow if used for other than power gen.	Less than 150 m. of Quaternary alluvium, fans and loess over Tertiary tuff, breccia and flow rocks.	Pre-Cenozoic Metamorphic rocks at approx. 1350 m., overlain by Tertiary volcanics.	Hot water convection 140-150°C.	• Nace, R.L. and others 1961, USGS Wat. Supply Paper 1587 • Lofgren, B.E., 1975 • Williams, P.L., 1975
Roosevelt H.S., UT	Basin & Range graben bounded by normal faults.	830 m.	Quaternary fan deposits along W side of Mineral Mtns. Tertiary intrusives and volcanics & Paleozoic metamorphics cropout to E. Springs related to normal faulting along mtn. front.	Probably Precambrian schist gneiss, and migmatite intruded by Tertiary granite overlain by volcanics.	Hot water convection 230°-260°C.	• Mundorff, J.C., 1970 • Peterson, C.A., 1973
Thermo, UT	Basin & Range; graben bounded by normal faults.	1500 m	Unconsolidated and silica cemented alluvium of Quaternary age (including sand dunes). Mtns. to NW and S. have many faults which may continue under alluvium.	Probably Tertiary volcanics	Hot water convection 200°C.	• Mundorff, J.C., 1970 • Peterson, C.A., 1973
Cove Fort/ Sulphurdale, UT	Basin & Range; graben bounded by normal faults.	1500 m	Unconsolidated Quaternary alluvium and fan deposits probably underlain by consolidated sedimentary rocks with some volcanics	Paleozoic sedimentary and metamorphic rocks. Tertiary volcanics.	Probably hot water convection 200°C but may be vapor dominated.	• Hintze, L.F., 1963 • Mundorff, J.C., 1970
Leach, NV	Basin & Range; graben bounded by normal faults.	?	Quaternary and Late Tertiary sediments overlying Mesozoic and Paleozoic rocks with some interbedded volcanics.	Tertiary and older sedimentary rocks. Possibly some volcanics. Springs are related to normal faulting.	Hot water convection 170°-200°C.	• A.A.P.G. Geological Highway Map, Pacific Southwest Region. • Olmsted, F.H. and others, 1975
Beowawe, NV	Basin & Range; graben bounded by normal faults.	1000 m.	Young and old alluvium overlying Tertiary volcanics on top of Paleozoic Valmy Fm. (quartzite chert and shale). Active fault along valley margin.	Near mountain front, resource probably in hard rocks; in valley, geofluids may be in mod. hard sedimentary rocks.	Hot water convection 240°C.	• Roberts, R.J., K.M. Montgomery, and R.E. Lehner, 1967, Nevada Bureau of Mines, Bull. 64 • Stewart, J.H. and E.H. McKee, 1970 • Huse, R.K. and B.E. Taylor, 1974

Table 2 Continued

GEOTHERMAL SITE	GEOLOGIC ENVIRONMENT (SETTING)	ESTIMATED DEPTH TO TOP OF RESERVOIR	OVERBURDEN CHARACTERISTICS	RESERVOIR CHARACTERISTICS	RESOURCE TYPE AND SUBSURFACE TEMP.	PRINCIPAL SOURCES OF GEOLOGIC AND HYDROLOGIC DATA
Mexicali-Imperial Rift Valley including Brawley, East Mesa, Heber, Salton Sea, Glamis Dunes	Deep sedimentary basin cut by NW trending faults.	1000-1500 m.	Typical profile: 0-180 m unconsolidated clay, silt, sand, and gravel; 180-335 m evaporites in clay-carbonate matrix; 335-900 m shale, siltstone and sandstone. Below 900 m rocks are hydrothermally altered.	Altered shale, siltstone, and sandstone to 6100 m. Oldest sediments Late Miocene to Early Pliocene.	Hot water convection 135°-340°C. (Salton Sea is hottest).	• Dutcher, L.C., and others, 1972 • Elders, W.A., and others, 1972 • Rex, R.E., 1971 • Wilson, J.S. and others, 1974
Gulf Coast Geopressured Resource	Deep coastal sedimentary basin cut by E-W trending normal faults.	2400-3000 m.	Unconsolidated alluvium underlain by sandstone, shale, and siltstone of Late Tertiary and Quaternary age.	Undercompacted clay, shales and sandstones of Miocene age; reservoirs separated by regional gravity faults.	Geopressured hot water saturated with methane. 140°-160°C.	• White, D.E., and D.L. Williams, eds., 1975. USGS Circ. 726 • Gustavson, T.C. and C.W. Kreitler, 1977 • Kreitler, C.W., 1976
Geysers, CA	Folded and faulted sedimentary and volcanic rocks. Near volcanic field.	1000 m	Jurassic and Cretaceous graywacke, greenstone, shale, chert, and serpentine of Franciscan Assemblage.	Same as overburden but probably more fractured.	Vapor dominated ~240°C.	• Bacon, C.F. and others, 1976 • McLaughlin, R.J., 1974

I Caldera Structure - A caldera is a large, roughly circular, depression in volcanic terrain, typically caused by the explosion and subsequent collapse of a volcanic cone or vent. The depression is generally bounded by a series of arcuate faults known as "ring faults". Radial faults may also be present. The depression is typically filled with volcanic debris erupted after the collapse. Some alluvium may also be present in older calderas. Geothermal resources in caldera structures may be either hot water or vapor dominated, and springs often emerge along bounding faults.

Geothermal areas in this category include:

1. Lassen, California
2. Mono-Long Valley, California
3. Valles Caldera, New Mexico
4. Coso, H.S., California
5. W. Yellowstone, Montana

II Active Volcanoes - Geothermal resources in this category are associated with active volcanism, and are in areas of widespread and thick volcanic rocks, with little or no alluvium. Geothermal areas in this category include:

1. Baker, H.S., Washington
2. Mt. Hood, Oregon
3. Glass Mountain, California
4. Puna, Hawaii

III Block-Faulted Grabens of Basin and Range Province - Many geothermal resource areas are found in the basin and range geomorphic province, which includes Nevada, Southern New Mexico and parts of Oregon, California, Idaho, Utah, Arizona and Texas. This province is characterized by horst and graben structure. The many broad valleys of this province represent down-dropped fault blocks separated from each other by mountain ranges. The hot springs found in this region are commonly associated with range front faulting.

Geothermal areas in this category include:

1. Alvord, Oregon
2. Surprise Valley, California
3. Safford, Arizona
4. Chandler, Arizona
5. Steamboat Springs, Nevada
6. Leach, Nevada
7. Beowawe, Nevada
8. Brady, H.S., Nevada
9. Raft River, Idaho
10. Roosevelt H.S., Utah
11. Thermo, Utah
12. Fort Cove/Sulphurdale, Utah

IV Alluviated Valleys in Volcanic Terrain - Geothermal resources in this category are intermediate between the well developed basin and range structure of Category III and the volcanic terrain of Category I. Although some of the resource areas included may have a graben type structure, they are typically located in broad river valleys, where the volcanic rocks are overlain by alluvium.

Geothermal areas in this category include:

1. Bruneau-Grandview, Idaho
2. Weiser-Crane Creek, Idaho
3. Vale H.S., Oregon
4. Klamath Falls, Oregon

V Deep Sedimentary Basins - This category includes areas of thick accumulations of sedimentary rocks, which may range from unconsolidated alluvium at the surface to hard sandstone and shale at depth. Fluids contained in these basins are sometimes geopressured such as along the U.S. Gulf Coast. Geothermal areas in this category include:

1. Texas Gulf Coast
2. Louisiana Gulf Coast
3. Mexicali-Imperial Rift Valley

VI Folded and Faulted "Hard" Rocks, With Little or No Alluvial Cover - While associated with volcanic areas, these resources are not located in volcanic rocks, and may therefore have different subsidence characateristics. The only geothermal area in the western U.S. which fits into this category is the Geysers, California.

In summary, the geothermal areas examined fall into six different categories of geological settings. A brief review of the known subsidence areas suggests that most of the subsidence areas can also be accommodated within the six categories, so that a direct comparison between geothermal resources and subsidence cases is possible.

Summary of Information Available for Each Subsidence Area

The major subsidence sites caused by geofluid withdrawal were examined in terms of their physical characteristics and data availability. They were placed in geological categories, which are discussed above, and assess in terms of their relevance to geothermal sites. Data availability of each site was also assessed. The results of these subsidence site summaries are given in Table 3.

Subsidence Site Selection

Based upon the information presented in Tables 2 and 3, the project team prescreened eleven candidate subsidence sites for further evaluation. After more detailed review of the available literature on these eleven sites, and discussions with LBL personnel, four sites were ultimately selected for case histories. Table 4 gives a condensed summary of the selection rationale and results. Data availability and relevance to geothermal sites were the primary considerations, and both these considerations were to be evaluated as satisfactory in order for a site to be acceptable. The desire to cover as many geologic categories as possible was another important factor in the selection.

Table 3

General Characteristics and Data Availability for Subsidence Sites

State/Site	General Data: Withdrawn Fluid, Reservoir Depth (m), Maximum Subsidence (m)	Geologic Characteristics: Overburden	Geologic Characteristics: Reservoir	Category	Relevance to Geothermal Sites	Data Availability
ARIZONA Eloy-Picacho	Cold water 100-300 -1.1	Unconsolidated alluvial and lacustrine sediments	Same as overburden	III	Poor, too shallow	<u>In-house</u>. Only general data on subsidence and geology <u>Other</u>. Fair data on most categories being compiled by USGS
CALIFORNIA Santa Clara Valley	Cold water 50-300 -3.5	Unconsolidated bay and alluvial deposits of Pleistocene and Holocene age	Semi-consolidated alluvial and bay sediments of Pliocene and Pleistocene age	V	Poor, too shallow	<u>In-house</u>. Extensive reviews and well test data <u>Other</u>. Very good data of most types available
CALIFORNIA Wilmington	Petroleum 600-2300, most 600-1100 -9	Unconsolidated shale, sand, claystone and siltstone of Pliocene and Pleistocene age. Much local faulting	Unconsolidated to semi-consolidated sand with interbedded clay and shale	V	Quite good for shallow geothermal sites with local faults	Very good data of all types available in large quantities
CALIFORNIA The Geysers	Steam ≥ 1000, .13 in 4-1/2 yrs	Generally Metamorphic	Hydrothermally altered Franciscan greywacke with basalt interbedded metamorphic	VI	Relevant to metamorphic areas, but subsidence has been minimal	<u>In-house</u>. Mostly summary data on geology <u>Other</u>. Subsidence data limited to Lofgren (1978)

Table 3 -- Continued.

General Characteristics and Data Availability for Subsidence Sites

State/Site	General Data: Withdrawn Fluid / Reservoir Depth (m) / Maximum Subsidence (m)	Geologic Characteristics: Overburden	Geologic Characteristics: Reservoir	Category	Relevance to Geothermal Sites	Data Availability
CALIFORNIA San Jacinto Valley	Cold water Depth unknown ~.6	Alluvium and basin fill	Basin fill	V	Probably too shallow, but fault activation may be analogeous to deeper geothermal sites	In-house. Very little data Other. Good surface subsidence data in some areas, but little sub-surface data
CALIFORNIA San Joaquin: Los Banos-Keitleman City Area	Cold water 300-1000 ~7	Unconsolidated alluvial and lacustrine sediments of recent to Pliocene age	Same as overburden. Aquifers are generally confined	V	Fair for shallow geothermal sites with confined reservoirs	Excellent
CALIFORNIA San Joaquin: Tulare-Wasco Area	Cold water 150-320 ~3.7	Unconsolidated alluvial and lacustrine sediments of recent to Pliocene age	Same as overburden. Aquifers are semi-contained	V	Poor, too shallow	Excellent
CALIFORNIA San Joaquin: Arvin-Maricopa	Cold water 250-400 ~2	Unconsolidated alluvial and lacustrine sediments of recent to Pliocene age	Same as overburden, aquifers are semi-confined and confined	V	Poor, too shallow	Appears to be very good
CALIFORNIA Baldwin Hills	Petroleum 300-700 ~3	Unconsolidated alluvial and lacustrine sediments of recent to Pliocene age with much faulting	Sedimentary rocks of Pliocene and Miocene age	V	Fair, for shallow geothermal sites with much faulting. Subsidence probably due both to oil extraction and Tectonic activity	In-house. Only general information on subsidence and causes Other. Data appears to be limited and unavailable for some categories

Table 3 -- Continued.

General Characteristics and Data Availability for Subsidence Sites

State/Site	General Data: Withdrawn Fluid Reservoir Depth (m) Maximum Subsidence (m)	Geologic Characteristics Overburden	Reservoir	Category	Relevance to Geothermal Sites	Data Availability
COLORADO						
Denver	Cold water ≤ 900 ~.3	Alluvial sediments	Alluvium and Cretaceous sedimentary rocks	V	Fair, but somewhat shallow	In-house. Only general summary data Other. Probably quite limited
GEORGIA						
SAVANNAH	Cold water Depth unknown ~.2	Alluvial sediments and limestones	Limestone with beds of sand, and marl	V	Probably poor due to shallowness and overburden. Uncharacteristic of geothermal site	In-house. Only general summary data. Other. Probably quite limited
IDAHO						
Raft River Valley	Cold water ~20-120 ~.8	Unconsolidated alluvial gravel, sand and silt with some interbedded loess	Unconsolidated alluvial gravel, sand and silt with some permeable basalt	III	Poor, too shallow. However, it may be relevant to the Raft River Geothermal site (same location) depending on desired depth of geothermal resource	In-house. Only summary data Other. According to L34, quite limited
KANSAS						
Central Kansas	Cold water (salt solution) Depth unknown ~10			Probably V	Poor, subsidence process not the same	In-house. Only abstract information Other. Probably poor
Louisiana						
Baton Rouge	Cold water Probably shallow ~.5	Alluvial sediments	Alluvial sediments	V	Poor, too shallow	In-house. Only abstract information Other. Probably limited

Table 3 -- Continued.

General Characteristics and Data Availability for Subsidence Sites

State/Site	General Data: Withdrawn Fluid Reservoir Depth (m) Maximum Subsidence (m)	Geologic Characteristics Overburden	Reservoir	Category	Relevance to Geothermal Sites	Data Availability
LOUISIANA New Orleans	Cold water Probably shallow -.8	Alluvial sediments	Alluvial sediments	V	Poor, too shallow	In-house. Only abstract information Other. Probably limited
NEVADA Las Vegas	Cold water 60-215 -1.7	Alluvial and lacustrine sediments and clays of Quaternary age, set in a basin and range region	Alluvial sediments of late Tertiary and Quaternary age, set in a basin and range region	III	Poor, too shallow	In-house. Only summary information on subsidence Other. From Mindling, data base looks good.
TEXAS Goose Creek	Petroleum and water 220-1450 -1	Alluvium over Tertiary sandstone and shale	Sandstone and shale of Oligocene to Pliocene age. Deeper part is intensity faulted	V	Fair for "A" category geothermal sites, but too shallow for Gulf Coast geopressured sites	Fair, but data on subsidence is old and probably insufficient
TEXAS Saxet (Corpus Cristi)	Petroleum and gas Shallower than Chocolate Bayou	Alluvium over Cenogoic sandstone and shale	Sandstone and shale of late Tertiary age	V	Fair for "A" category geothermal sites, but too shallow for Gulf Coast geopressured sites	In-house. Very little data Other. Some good data Survey data old; unitized field may make subsurface data difficult to obtain

Table 3 -- Continued.

General Characteristics and Data Availability for Subsidence Sites

State/Site	General Data: Withdrawn Fluid, Reservoir Depth (m), Maximum Subsidence (m)	Geologic Characteristics: Overburden	Geologic Characteristics: Reservoir	Category	Relevance to Geothermal Sites	Data Availability
TEXAS Chocolate Bayou	Petroleum and methane gas 2500-4000 -.4	Unconsolidated sand, clay and silt of Oligocene to Pliocene age	Same as overburden. Deep portion of gas reservoir is geopressured	V	Due to depth and geopressured nature of reservoir, this site is uniquely analogous to Gulf Coast geothermal sites	In-house. A small amount of summary information. Other. Good data available at Texas Rail Comm., USGS and Phillips Oil
TEXAS Houston - Galveston	Cold water 50-600 -1.1	Unconsolidated sand and clay deposits of late Tertiary and Quaternary age	Same as overburden	V	Poor, too shallow	Excellent, data on subsidence, but because of the number of wells in the area, extraction information probably difficult to decipher
UTAH Milford	Cold water Depth unknown -1.8	Unconsolidated sedimentary deposits of Quaternary age in basin and range setting	Same as overburden	III	May have fair relevance to local geothermal sites such as Roosevelt hot springs, but generally too shallow	In-house. Only one survey paper on subsidence and geology. Other. Not known, probably many data voids

Table 3 -- Continued

General Characteristics and Data Availability for Subsidence Sites

Country/Site	General Data: Withdrawn Fluid / Reservoir Depth (m) / Maximum Subsidence (m)	Geologic Characteristics: Overburden	Geologic Characteristics: Reservoir	Category	Relevance to Geothermal Sites	Data Availability
ENGLAND Thames Estuary	Cold Water Probably < 100 ~.2	Alluvial sediments and London clay	London clay	V	Poor, too shallow	In-house. Only general summary data available. Other. Not known, probably poor
ENGLAND Cheshire	Salt brine ~700-1300	Alluvial sediments, sands, clays and marl	Same as overburden with salt beds	V	Poor, too shallow	In-house. Very little data. Other. Probably some good data in England on recent subsidence, but most subsidence occurred in the 19th century
ITALY Venice	Cold water Up to 300m At least .15	Alluvial sand and clay sediments	Alluvial sand and clay sediments	V	Poor, too shallow	In-house. Summary information and Gambolati model papers with associated data. Other. Unknown, but what data that is available would be difficult to obtain
ITALY Po Delta	Methane Gas ~600-1000 In the order of 2-4	Relatively unconsolidated. Quaternary marine deposits. Quite sandy but with some clay	Same as overburden	V	Good for very shallow "A" class geothermal site, but generally too shallow	In-house. Only summary information on subsidence and geology. Other. Unknown, but probably difficult to obtain

Table 3 — Continued.

General Characteristics and Data Availability for Subsidence Sites

State/Site	General Data: Withdrawn Fluid, Reservoir Depth (m), Maximum Subsidence (m)	Geologic Characteristics Overburden	Reservoir	Category	Relevance to Geothermal Sites	Data Availability
TEXAS Chocolate Bayou	Petroleum and methane gas 2500-4000 -.4	Unconsolidated sand, clay and silt of Oligocene to Pliocene age	Same as overburden. Deep portion of gas reservoir is geopressured	V	Due to depth and geopressured nature of reservoir, this site is uniquely analogous to Gulf Coast geothermal sites	<u>In-house</u>. A small amount of summary information. <u>Other</u>. Good data available at Texas Rail Comm., USGS and Phillips Oil
TEXAS Houston - Galveston	Cold water 50-600 -1.1	Unconsolidated sand and clay deposits of late Tertiary and Quaternary age	Same as overburden	V	Poor, too shallow	Excellent, data on subsidence, but because of the number of wells in the area, extraction information probably difficult to decipher
UTAH Milford	Cold water Depth unknown -1.8	Unconsolidated sedimentary deposits of Quaternary age in basin and range setting	Same as overburden	III	May have fair relevance to local geothermal sites such as Roosevelt hot springs, but generally too shallow	<u>In-house</u>. Only one survey paper on subsidence and geology. <u>Other</u>. Not known, probably many data voids

Table 3 -- Continued

General Characteristics and Data Availability for Subsidence Sites

Country/Site	General Data: Withdrawn Fluid, Reservoir Depth (m), Maximum Subsidence (m)	Geologic Characteristics: Overburden	Geologic Characteristics: Reservoir	Category	Relevance to Geothermal Sites	Data Availability
ENGLAND Thames Estuary	Cold Water Probably < 100 ~.2	Alluvial sediments and London clay	London clay	V	Poor, too shallow	In-house. Only general summary data available. Other. Not known, probably poor
ENGLAND Cheshire	Salt brine ~700-1300	Alluvial sediments, sands, clays and marl	Same as overburden with salt beds	V	Poor, too shallow	In-house. Very little data. Other. Probably some good data in England on recent subsidence, but most subsidence occurred in the 19th century
ITALY Venice	Cold water Up to 300m At least .15	Alluvial sand and clay sediments	Alluvial sand and clay sediments	V	Poor, too shallow	In-house. Summary information and Gambolati model papers with associated data. Other. Unknown, but what data that is available would be difficult to obtain
ITALY Po Delta	Methane Gas ~600-1000 In the order of 2-4	Relatively unconsolidated. Quaternary marine deposits. Quite sandy but with some clay	Same as overburden	V	Good for very shallow "A" class geothermal site, but generally too shallow	In-house. Only summary information on subsidence and geology. Other. Unknown, but probably difficult to obtain

Table 3 — Continued.

General Characteristics and Data Availability for Subsidence Sites

Country/Site	General Data: Withdrawn Fluid Reservoir Depth (m) Maximum Subsidence (m)	Geologic Characteristics		Category	Relevance to Geothermal Sites	Data Availability
		Overburden	Reservoir			
JAPAN Osaka	Mostly cold water 100-300, most ≤ 200 ~2.8	Alluvial and diluvial sands and clays of Quaternary age	Same as overburden	V	Poor, too shallow	In-house. Good summary information on subsidence and geology. Some detailed data. Other. Good data probably available in Japan. Likely difficult to obtain
JAPAN Tokyo	Cold water Probably similar to depths of Osaka wells ~4.6	Alluvial and diluvial sands and clays of Quaternary age	Same as overburden	V	Probably too shallow	In-house. Poor summary of subsidence and geology. Other. Unknown, but since most data is probably in Japan, difficult to obtain
JAPAN Niigata	Water and methane gas ≤ 1000 ~2.6	Unconsolidated sediments of sand, pebbles and sandstone	Relatively unconsolidated sediments of Cenogoic age. Some interbedded clay layers	V	Good for shallow "V" class geothermal sites, but generally too shallow	In-house. Only summary information on subsidence and geology. Other. Good data probably available in Japan, but difficult to obtain
JAPAN Other Japanese Plain Areas	Cold water Generally < 300 ~.5-2	Generally unconsolidated and alluvial and dilluvial sediments of Quaternary age	Same as overburden	V	Poor, too shallow	Generally poor and difficult to obtain

Table 3 -- Continued.

General Characteristics and Data Availability for Subsidence Sites

Country /Site	General Data: Withdrawn Fluid Reservoir Depth (m) Maximum Subsidence (m)	Geologic Characteristics Overburden	Reservoir	Category	Relevance to Geothermal Sites	Data Availability
MEXICO						
Mexico City	Cold water 50-300 -7.5	Bentonitic clay and cemented sand layers with some basalt flows	Sand and gravel with interbedded Bentonitic clays	IV	Poor, too shallow	In-house. Only summary information on subsidence and geology
NETHERLANDS						
Groningen	Methane gas -2900 -.05	Sandstone and clays probably young alluvial deposits	Primarily sandstone	V	Fair, except very little subsidence has occurred	In-house. Mostly modelling study data available. Other. It appears that an excellent data gathering program exists for this field, however most of the data is in the Netherlands
NEW ZEALAND						
Wairakei	Hot water 150-1360, primarily 180-300 -7	Pumice alluvium and tuffaceous mudstone and sandstone	Primarily pumice breccia with sandstone and some rhyolitic intrusion	IV and I	Very good, since it is a geothermal site. Its characteristics are generally representative of U.S. Category IV geothermal sites	In-house. Mostly summary data on geology and subsidence history. Other. Some detailed data may be available from NSF (or S^3). An excellent data base has been developed on this case

Table 3 -- Continued.

General Characteristics and Data Availability for Subsidence Sites

Country/Site	General Data: Withdrawn Fluid / Reservoir Depth (m) / Maximum Subsidence (m)	Geologic Characteristics: Overburden	Geologic Characteristics: Reservoir	Category	Relevance to Geothermal Sites	Data Availability
NEW ZEALAND						
Broadlands	Hot water Most 200-800 -.22	Pumice alluvium, lacustrine siltstone, and sandstone	Pumice and tuff breccias with sandstone and rhyolitic intrusion	IV and I	Very good, since it is a geothermal site	In-house. Mostly data on geology of the area Since subsidence is small, little subsidence information
VENEZUELA						
Lake Maracaibo	Petroleum Depth unknown -3.4	Unconsolidated, interbedded sands, hard clays and silts	Same as overburden	V	Fair, wells are over 500 meters deep	In-house. A brief summary of subsidence and very little other data. Other. Good data may be available, but very hard to obtain

Table 4

SELECTION OF SUBSIDENCE SITES BASED UPON RELEVANCE TO GEOTHERMAL SITES AND DATA AVAILABILITY

Sibsidence Sites	Geologic Category	Relevance To Geo-thermal Sites	Data Avail-ability	Acceptable	Case History Sites
1. Eloy-Picacho	III	Poor X	Poor X		
2. Santa Clara Valley	V	Poor X	Good ✓		
3. Wilmington	V	Good ✓	Good ✓	✓	
4. The Geysers	VI	Good ✓	Fair ✓	✓	✓ (circled)
5. San Jacinto Valley	V	Poor X	Fair ✓		
6. San Joaquin (Los Banos-Kettleman City Area)	V	Fair ✓	Good ✓	✓	
7. San Joaquin (Tulare-Wasco)	V	Poor X	Good ✓		
8. San Joaquin (Arvin-Maricopa)	V	Poor X	Good ✓		
9. Baldwin Hills	V	Fair ✓	Fair ✓	✓	
10. Denver	V	Fair ✓	Poor X		
11. Savannah	V	Poor X	Poor X		
12. Raft River Valley	III	Fair ✓	Fair ✓	✓	✓ (circled)
13. Central Kansas	V	Poor X	Poor X		
14. Baton Rouge	V	Poor X	Poor X		
15. New Orleans	V	Poor X	Poor X		
16. Las Vegas	III	Poor X	Good ✓		
17. Goose Creek	V	Fair ✓	Fair ✓	✓	
18. Saxet	V	Good ✓	Poor X		
19. Chocolate Bayou	V	Good ✓	Fair ✓	✓	✓ (circled)
20. Houston-Galveston	V	Poor X	Good ✓		
21. Milford	III	Fair ✓	?	✓	
22. Thames Estuary	V	Poor X	Poor X		
23. Cheshire	V	Poor X	Poor X		
24. Venice	V	Poor X	Fair ✓		
25. Po Delta	V	Good ✓	Poor X		
26. Osaka	V	Poor X	Fair ✓		
27. Tokyo	V	Poor X	Poor X		
28. Niigata	V	Fair ✓	Fair ✓	✓	
29. Other Japanese Areas	V	Poor X	Depends on area		
30. Mexico City	IV	Poor X	Poor X		
31. Groningen	V	Fair ✓	Good ✓	✓	
32. Wairakei	I & IV	Good ✓	Good ✓	✓	✓ (circled)
33. Broadlands	I & IV	Good ✓	Fair ✓	✓	
34. Lake Maracaibo	V	Fair ✓	Poor X		

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CHOCOLATE BAYOU

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1. INTRODUCTION

Chocolate Bayou is an oil and gas field approximately 30 miles south of Houston, Texas. The field lies in the deep sedimentary Gulf Coast zone (Category 5). Oil and gas production has occurred from both normally and geopressured zones (the geopressured area lies below a depth of about 10,000 feet). Chocolate Bayou has experienced land subsidence of nearly 2 feet. Due to its strong similarities with proposed Gulf Coast geothermal sites, and its fairly good data base on geology and subsidence, the Chocolate Bayou field was considered to be an ideal case study site.

2. NATURAL CONDITIONS

2.1 PHYSIOGRAPHY

The Chocolate Bayou oil and gas field is located about 25 miles south of Houston in northeastern Brazoria County, Texas. The field occupies approximately 25 square miles in Township 6 South, Ranges 38, 39 and 40 East, between 95°00' and 95°30' N latitude and 96°00' to 96"30' longitude (see Figure 1). The principal operator of the field is Phillips Petroleum Company, although Texaco, General Crude and several smaller operators also have wells in the field.

In the vicinity of the oil and gas field, the Gulf Coast plain dips very gently southeastward, and is traversed by many meandering streams and sloughs. Surface elevations at the field are approximately 10 to 40 feet above sea level. Surface soils are mainly slough and levee deposits consisting of mud and clays with some clayey sand and silt. Agriculture is the dominant land use.

2.2 REGIONAL GEOLOGY

2.2.1 Structure

The Texas and Louisiana Gulf Coast Region forms the northern flank of a major geosyncline, the axis of which trends approximately parallel to the continental margin as shown in Figure 2. This structural basin is filled with a sequence of sedimentary rocks, approximately five to nine miles thick and ranging in age from Late Paleozoic and Triassic to Quaternary (Wilhelm and Ewing, 1972). Approximately the uppermost 25,000 feet are sandstone and

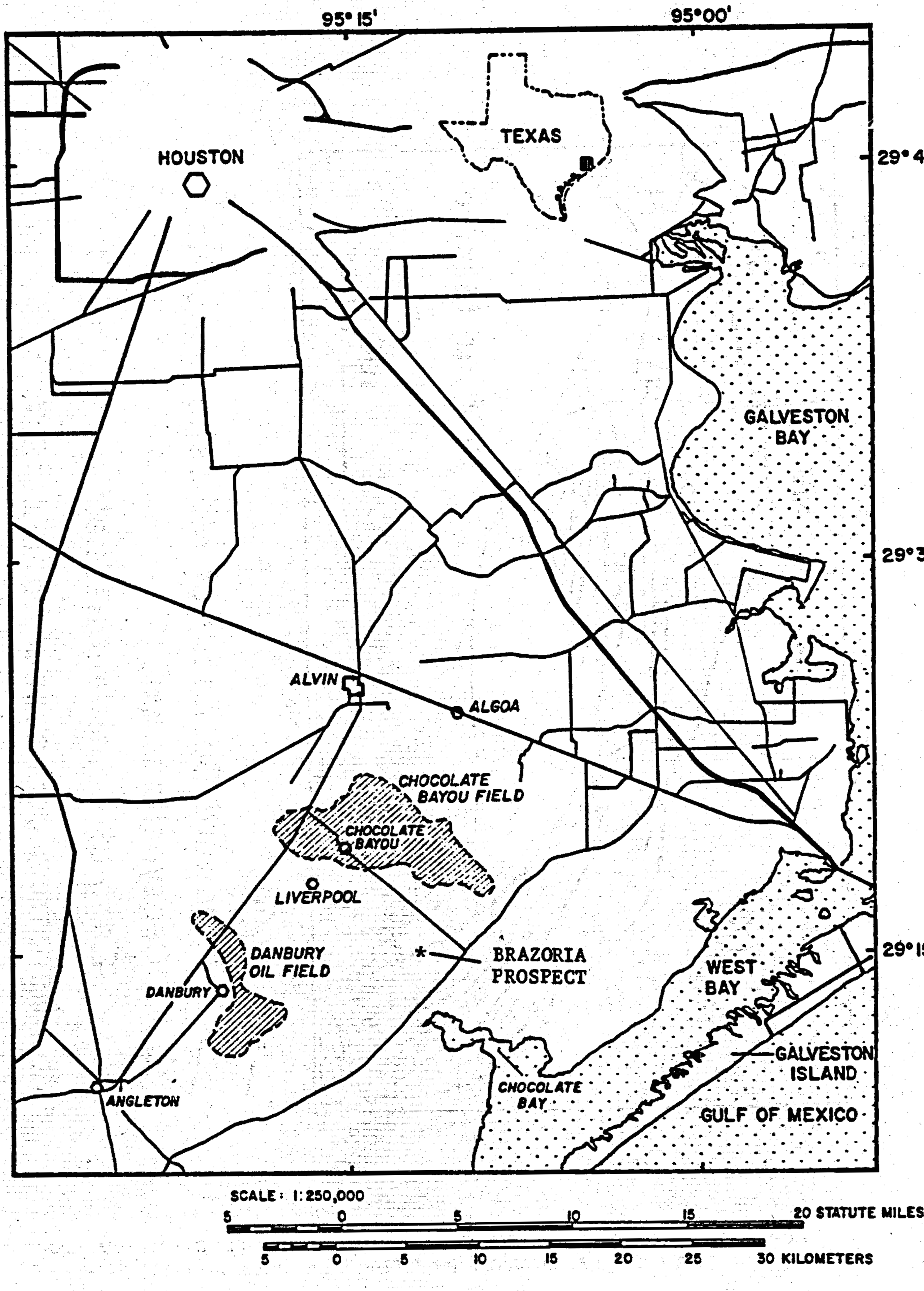

FIGURE 1 CHOCOLATE BAYOU LOCATION MAP

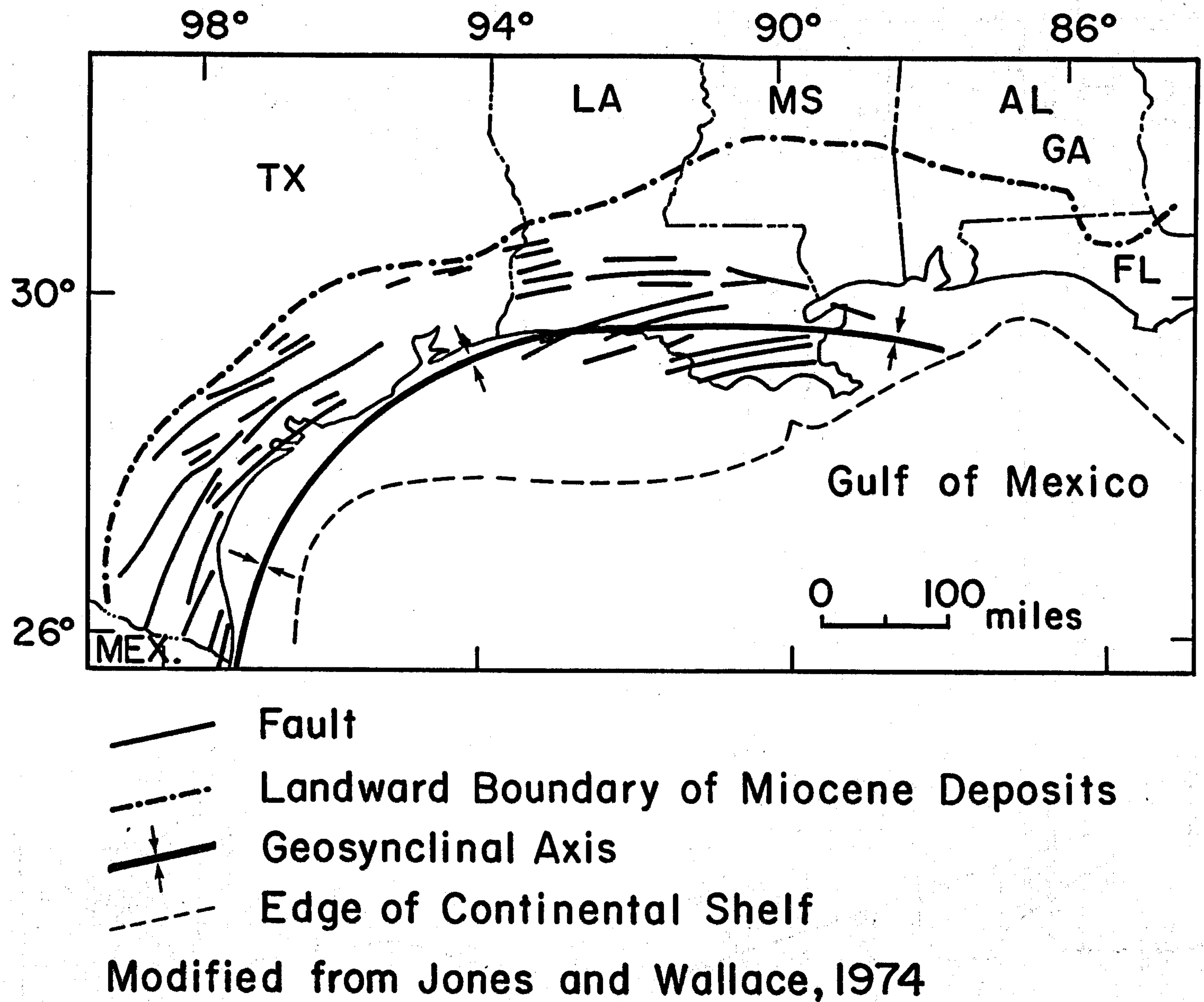

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FIGURE 2 MAJOR REGIONAL FAULT ZONES IN NEOGENE DEPOSITS, NORTHERN GULF OF MEXICO BASIN (modified from Murray, 1961) shale; the rocks below this depth are principally shale (Dorfman and Deller, 1976). Gravity faulting parallel to the geosynclinal axis has occurred contemporaneously with deposition, resulting in a basinward thickening of the stratigraphic section. Known as growth faults, these are faults whose dip is steep near the surface but flattens out with depth. Individual fault blocks strongly resemble giant landslide masses in cross section.

Although active faulting is common in the Gulf Coast Region, it is not generally accompanied by earthquakes. In fact, no earthquakes of Modified Mercalli Intensity V or greater have been reported for the Texas Gulf Coast Region (Coffman and von Hake, 1973).

The significance of growth faulting in the Gulf Coast Region is that it is the principal mechanism by which abnormally pressured sand and shale layers are created. Such layers are formed when loose and soft saturated sediments are down-faulted against less permeable materials, so that the normal migration of pore water lost during compaction and consolidation is halted or retarded. Migration of water is blocked down-dip by facies changes or other fault barriers. Because the trapped pore water is incompressible, it must support the weight of the overlying sediments. These abnormally pressured zones therefore, have pore pressures in excess of hydrostatic. Since the weight of a column of saline water is equivalent to a pressure gradient of approximately 0.465 psi per foot (0.429 psi/ft for fresh water) any subsurface layer having a fluid pressure gradient of greater than 0.465 psi/ft is considered to be geopressured. Some writers have reserved the term geopressured for fluid pressure gradients of 0.7 psi/ft or greater, but for the purposes of this report, all pressure gradients in excess of hydrostatic (0.465 psi/ft) will be considered geopressured.

The presence of abnormally pressured sediments in the Gulf Coast Region has been known for many years; the evidence was provided by the many deep oil and gas wells drilled. Downhole measurements indicate that depth to the top of the geopressured zone is typically 8000-10000 feet. Fluid pressures within the geopressured zone often vary from one strata to another. Even normally pressured layers may occur within the geopressured zone where fluids have been able to migrate along fault zones or into permeable zones of lower pressure.

2.2.2 Stratigraphy

Data sets from petroleum exploration have also been used for studies of Gulf Coast Tertiary stratigraphy (e.g., Baker, Jr., 1977; Houston Geological Society, 1954; Rainwater, 1964). Regional studies have shown that the subsurface Quaternary, Tertiary and Cretaceous sections consist of a series of off-lapping, basinward thickening sand and shale wedges underlain by thick Jurassic salt beds, and Triassic red beds. Delineation of the detailed stratigraphy is complicated by the facies changes typical of deposition in deltaic environments, and also by the down-dip thickening of units across growth faults. Stratigraphic correlation is facilitated by the use of micro paleontological methods.

Many regional cross sections of the Gulf Coast have been published, most of them showing only the Tertiary units which have been a major source of petroleum and natural gas since the beginning of this century. The stratigraphy of the Quaternary units has not been a subject of intensive study by petroleum geologists, but the overall relationships have been determined in connection with groundwater investigations. Such studies have shown that, as in the Tertiary units, facies changes are common in the Quaternary units and groundwater aquifers do not always correspond to formational units. Table 1 shows the generalized stratigraphy of the Upper Gulf Coast Region of Texas. The subsurface distribution of the units

Table 1. GENERALIZED STRATIGRAPHY OF EAST CENTRAL BRAZORIA COUNTY

ERA	SYSTEM	SERIES	GROUP OR FORMATION		PRINCIPAL HYDROGEOLOGIC UNITS
CENOZOIC	QUATERNARY	Holocene	Alluvium		Chicot Aquiter
		Pleistocene	Beaumont Clay		
			Montgomery Fm.		
			Bentley Fm.		
			Willis Sand		
	TERTIARY	Pliocene	Goliad Sand		Evangeline Aquiter
		Miocene	Fleming Fm.		Burkeville Confining System
			Oakville Sandstone		Jasper Aquiter
		? ?	Anahuac Fm. Frio Fm. (Catahoula in outcrop)		Catahoula Confining System(restricted)
		Oligocene	Vicksburg Group		
			Jackson Group		
		Eocene	Claiborne Group	Yegua Fm. Crockett-Cook Mtn Sparta Sand Weches Fm. Queen City Sand Reklaw Fm. Carrizo Sand	
			Wilcox		
		? ? Paleocene	Midway		
MESOZOIC	CRETACEOUS	Gulf Series	Navarro Taylor Austin Eagleford Woodbine		
		Comanchean	Washita Fredericksburg Trinity		
		Pre-Comanchean Undifferentiated			

Modified from: Porter and Chimene, 1953; Houston Geol. Soc., 1954; Sandeen and Wesselman, 1973; Baker, Jr., 1977 and Bebout, et al., 1976.

shown in Table 1 are illustrated in Figure 3, a down-dip regional geologic cross section reproduced from a recent Bureau of Economic Geology publication (Bebout, et al., 1976). From the location of the section, it can be seen that the down-dip (southern) part passes through the Chocolate Bayou field. Growth faults have been omitted from this section by the authors because the faults tend to obscure regional trends. Closely spaced wells were used for correlation, but many were omitted from the final section for the sake of clarity.

No discussion of regional stratigraphy would be complete without mention of the salt domes and diapirs which have intruded the Tertiary sediments in many parts of the Texas Gulf Coast. The Jurassic salt beds, mobilized by the weight of the tremendously thick Tertiary sediments have moved upward, doming and intruding the overlying rocks. Although the deepest wells in the Chocolate Bayou field have not penetrated any salt beds, it has been proposed (Allen and Allen, 1953) that the field is underlain by a buried salt dome. This hypothesis is supported by the very high salinities of water in the geopressured zones at the bottom of the reservoir. Furthermore, Chocolate Bayou is less than five miles northeast of the Danbury salt dome.

2.3 GEOLOGY OF THE SUBSIDENCE AREA

The geology of the Chocolate Bayou area is typical of the Gulf Coast Region, as described above; the subsurface structure is well known from oil and gas wells drilled in eastern Brazoria County. Gas fields discovered in the area have substantial reserves of natural gas along with some petroleum and, of these, the largest is Chocolate Bayou. Historically, the greatest production has been from East Chocolate Bayou, an anticlinal structure bounded by major growth faults on the southeast and northwest. These faults separate the main structure from two other areas of substantial hydrocarbon production known as West Chocolate and South Chocolate.

Figure 3 follows

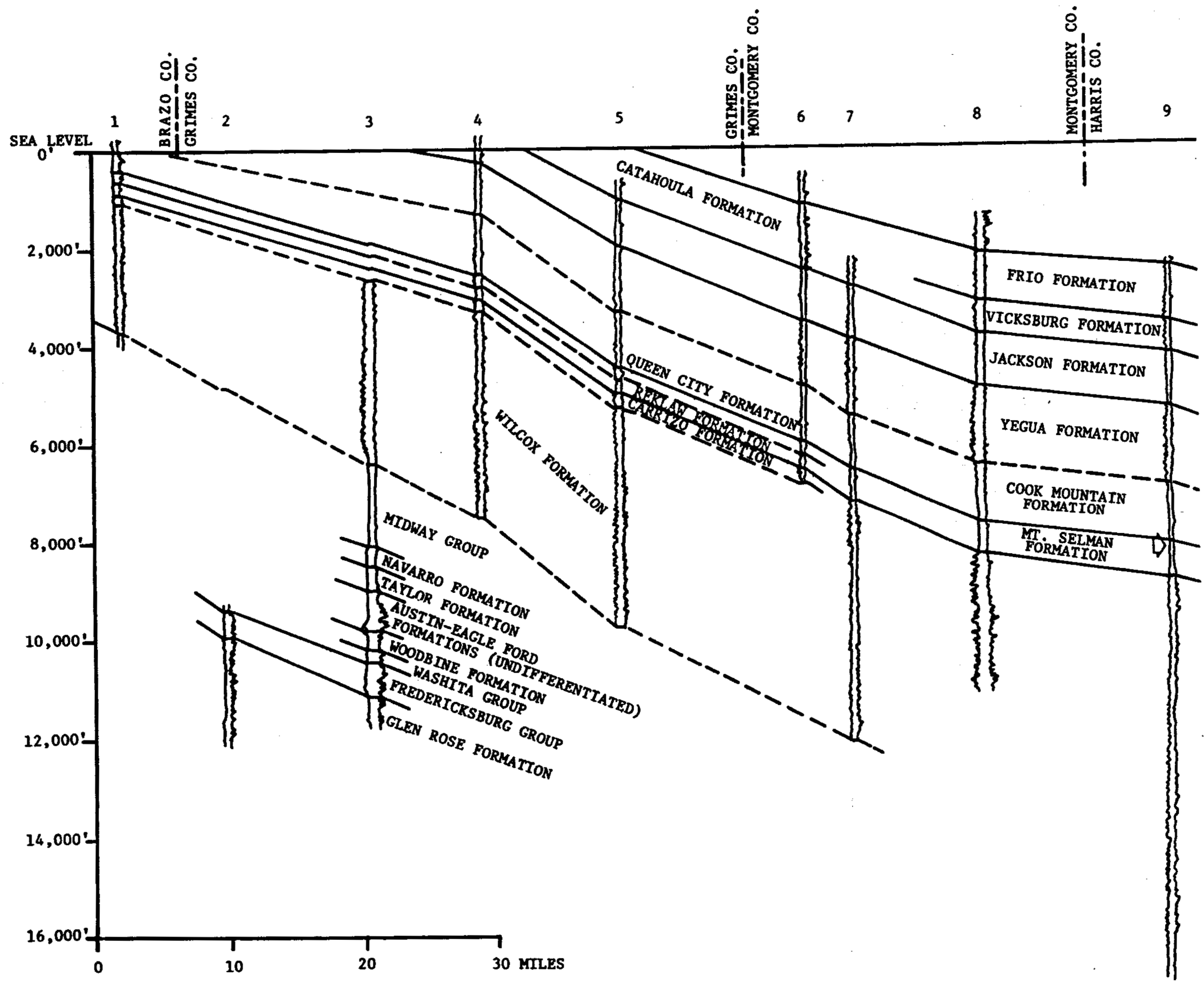


FIGURE 3 REGIONAL CROSS SECTION W-W'
(From Bebout, et al, 1976)

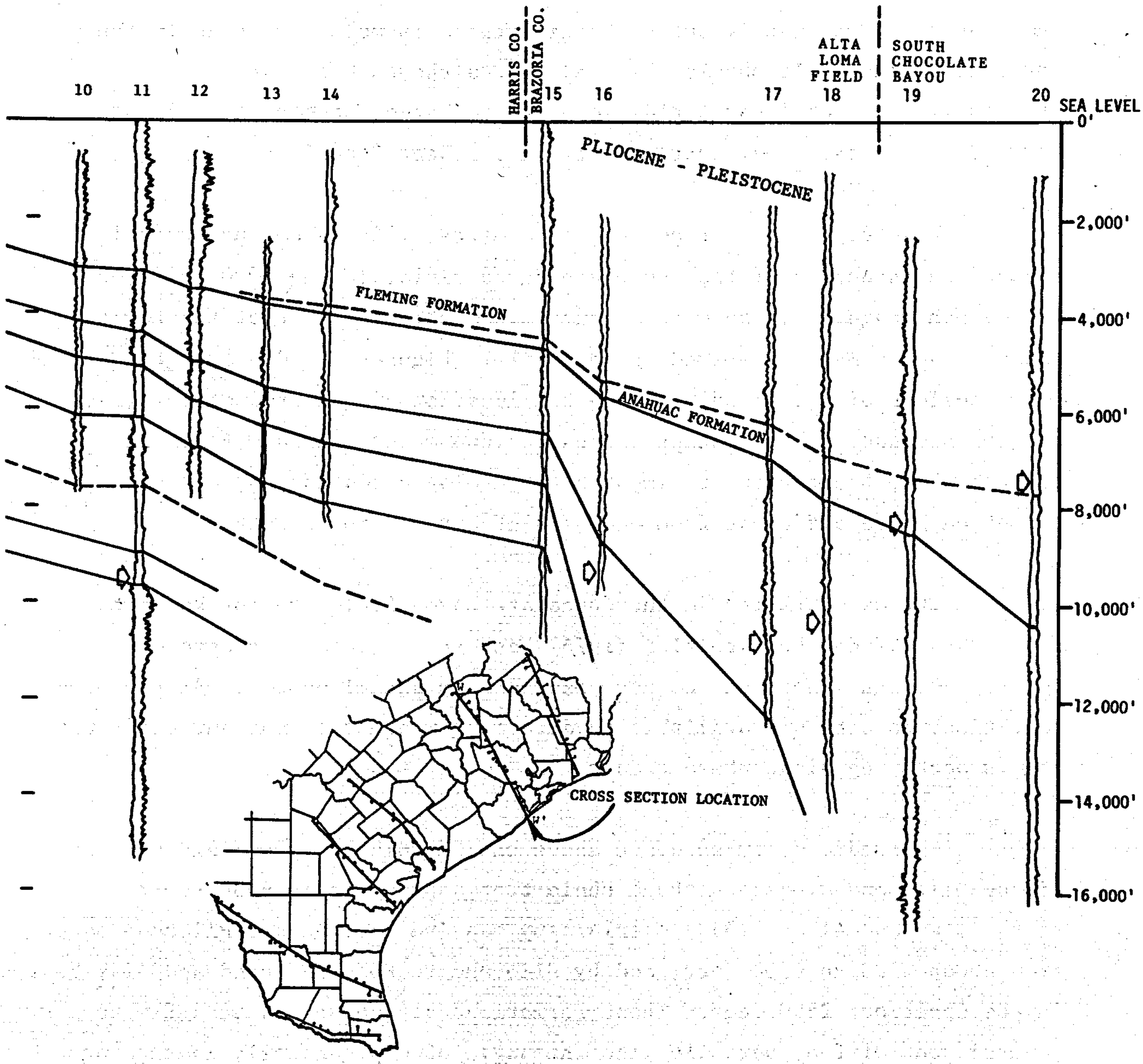


FIGURE 3 *(continued)*

Gas is also recovered from several other smaller blocks (such as North and Southeast Chocolate), but production there is much less than in the three main areas. It should be noted that although Chocolate Bayou is principally a natural gas field, moderate to large amounts of crude oil have also been produced, particularly in the West Chocolate Block.

Figures 4, 5 and 6 adapted from Myers, 1968, show the general subsurface structure of the Chocolate Bayou field, in the 8000 to 16,000 foot depth range. Figure 4 is a generalized structure map of the Lower Andrau Sand, a major gas sand in the field. Figures 5 and 6 are generalized cross sections of the field, showing the location of gas production zones and the pressure relationships across the two major faults. As these figures show, the faults are important hydrologic boundaries, and pressures are often quite different from one side of a fault to the other.

The major faults in the Chocolate Bayou field are not known to break the surface, but Kreitler (1976) has extrapolated them upward to correspond with lineaments he has mapped from aerial photos. At the present time, no data are available to determine whether or not surface faulting is occurring along these trends.

The sedimentary sequence above the Chocolate Bayou field consists of the Oligocene-Miocene Anahuac shale from approximately 6500 to 8700 feet (Allen and Allen, 1953) overlain by massive Miocene and Pliocene sands from about 2500 to 6500 feet, and by Pliocene to Holocene sand and clay beds in the uppermost 2500 feet. These formations dip coastward at a few to several tens of feet per mile with the angle of dip generally increasing with depth.

Detailed data on the engineering characteristics and mechanical properties of the Plio-Pleistocene materials at the site are not available,

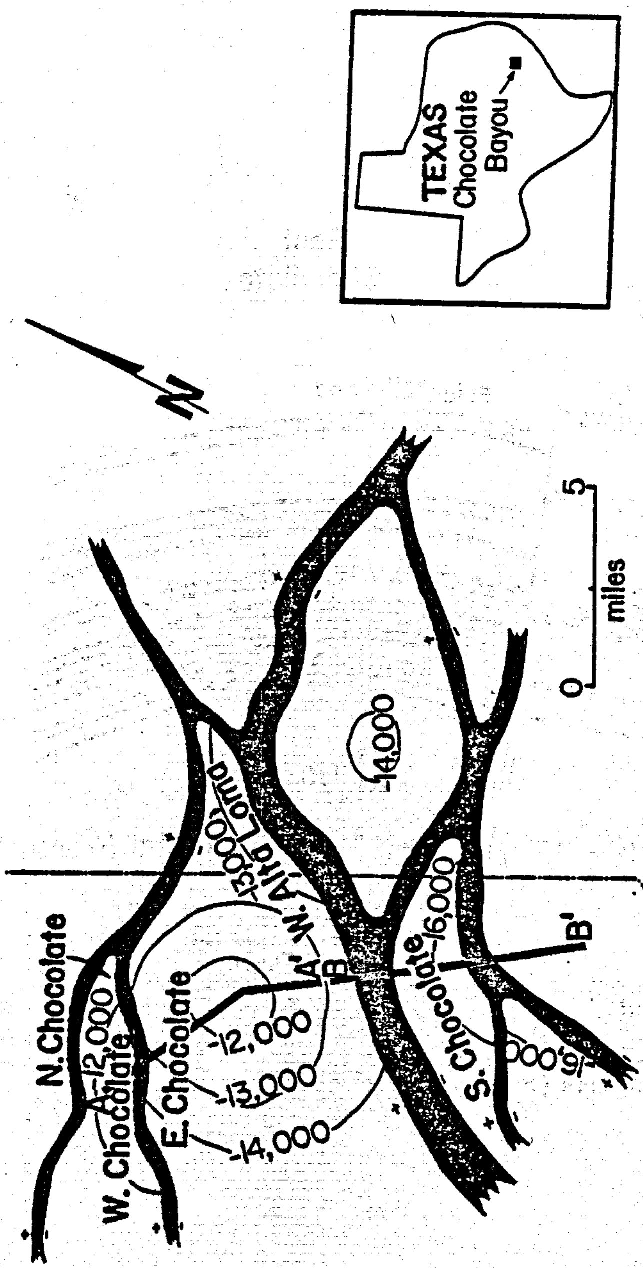


FIGURE 4 GENERALIZED STRUCTURE MAP LOWER ANDRAU SAND (from Myers, 1968)

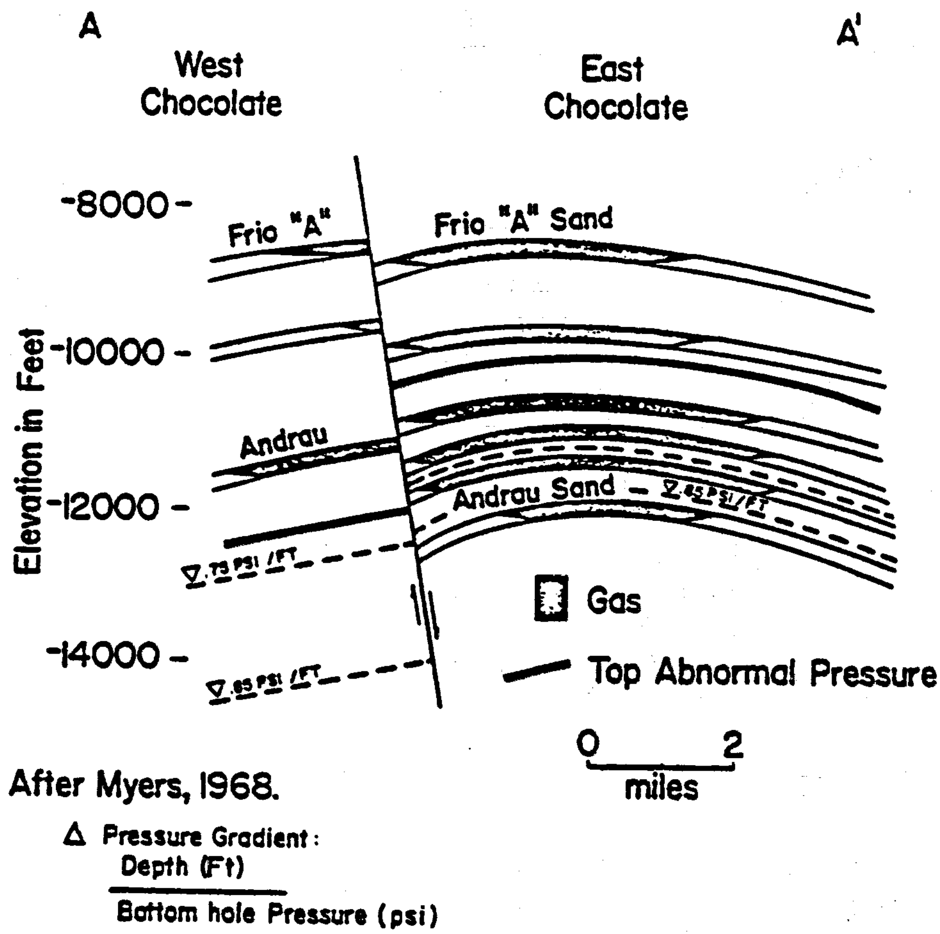


FIGURE 5 CROSS SECTION A-A' (See Figure 4 for location of section)

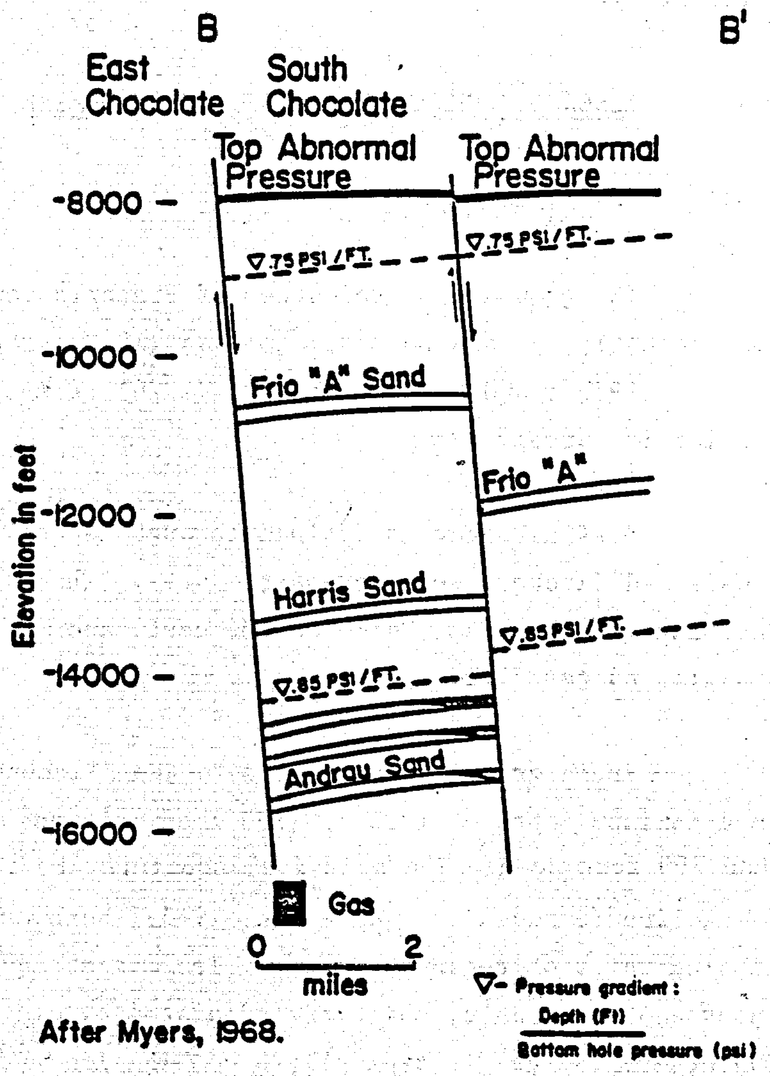


FIGURE 6 CROSS SECTION B-B' (See Figure 4 for location of section)

but the sediments present in the Chocolate Bayou area belong to the same geologic unit as the materials of the Houston area and probably have similar gross characteristics. Compaction in the compressible deposits has caused more than 7.5 feet of subsidence in the Houston area and is probably responsible for at least some of the observed subsidence in the Chocolate Bayou area. Subsidence will be discussed further in a later section

2.4 RESERVOIR CHARACTERISTICS - GROUNDWATER

2.4.1 Geology and Hydrology

The groundwater resources of Brazoria County have been studied most recently by Sandeen and Wesselman (1973); Baker, Jr. (1977); Kreitler, et al., (1977); and Naftel, et al., (1976) from which the following discussion is largely drawn.

Surface water is drained through several bayous and a series of canals and ditches, which cross the area. The principal bayous are Chocolate on the west, Halls on the east, and Mustang Bayou which crosses the oil and gas field.

Fresh ground water occurs in the Pliocene to Holocene sands to a maximum depth of 1000 to 1200 feet, although most wells are less than 700 feet deep. The principal aquifers are the Chicot and the Evangeline (Sandeen and Wesselman, 1973); both are alluvial, coastward dipping units of regional extent. The Chicot aquifer is divided into an upper and lower unit, which are separated by clay. The upper unit, Late Quaternary in age, is typically a combination water table and artesian aquifer consisting of interconnected shallow sands between the surface and 100 to 300 feet. The lower unit is Pliocene to Pleistocene in age, and is an artesian or leaky artesian aquifer. It includes the massive "Alta Loma" sand mapped in other parts of the Houston region. The base of the Upper Chicot in the Chocolate Bayou area is at an elevation of -50 to -200 feet, and the base of the Lower Chicot is at an elevation of -700 to -850 feet. (Due to the near sea level altitude of the Chocolate Bayou field, elevation and depth are roughly equivalent.) Sand thickness maps prepared by Sandeen and Wesselman (1973) show approximately 65 feet of sand in the upper unit and 90 to 250 feet of sand in the lower unit of the Chicot with the greatest sand thickness being to the southeast. Aquifer tests in east-central Brazoria County show that wells completed in the Chicot aquifer have coefficients of transmissibility of 50,000 to 75,000 gallons per day per foot; permeabilities are in the range of 400-650 gallons per day per square foot (Sandeen and Wesselman 1973). These data are based on the results of tests on three wells north of the Chocolate Bayou field. Wells at the field may have somewhat different hydraulic characteristics.

The Evangeline aquifer of Late Tertiary to Pleistocene Age is a sequence of alternating sands and clays with an aggregate thickness of over 1000 feet. In the sections of the aquifer which contain fresh to slightly saline water (only the upper few hundred feet of the aquifer in the Chocolate Bayou area) individual beds range in thickness from a few to about 100 feet. Published records of wells in east central Brazoria County (Naftel, et al., 1976; Sandeen and Wesselman, 1973) show that most wells are screened in the Chicot. No wells near the Chocolate Bayou field tap the Evangeline. Aquifer test data are not available for the Evangeline in Brazoria County, but maximum transmissibilities have been estimated at 100,000 gallons per day per foot by using 400 feet as the maximum thickness of fresh water sands (from interpretation of electric logs) and a permeability of 250 gallons per day per foot, which is the average permeability of the heavily pumped layer in the Houston District (Sandeen and Wesselman, 1973). Transmissibilities would be somewhat less in the Chocolate Bayou area because of a smaller thickness of fresh water sands.

Between the fresh aquifers of Pliocene to Holocene age and the oil and gas sands of Oligocene and Miocene age, are a series of thick predominantly-sand or predominantly-shale units. Below depths of 1000 to 1200 feet sands of the Evangeline and older aquifers contain saline water. Salt water produced with the oil and gas at Chocolate Bayou is pumped into saline aquifers below a depth of 2000 feet. The receiving aquifers are separated from the fresh water aquifers by thick shale sequences.

Since they were not readily available, details of the mineralogy and petrology of the geologic units overlying the Chocolate Bayou, oil and gas reservoirs have not been compiled. However, over five feet of subsidence has occurred in the Houston-Galveston region east of Brazoria County, indicating that clays in the Pliocene and younger units are susceptible to compaction, if they are subjected to increased effective stress. Gabrysch (1970) reports that the clay fraction of fine-grained deposits in the region typically has a mineral assemblage consisting of montmorillonite, illite, and kaolinite, with montmorillonite making up at least half of the material finer than two microns.

2.4.2 Chemical Character of Groundwater

Water from the Chicot aquifer is of the sodium bicarbonate type with moderate hardness and dissolved solids. Chloride levels are variable, but are typically in the range of 100-200 ppm (Sandeen and Wesselman, 1973, p. 190-191). In east-central Brazoria County, water in the Evangeline aquifer is of similar quality, but with higher chloride levels. Salt water intrusion of the fresh water aquifers could be a potential problem with continued overdraft, but this has not been reported to date. The trend toward increased use of surface supplies makes this possibility unlikely.

2.5 RESERVOIR CHARACTERISTICS - OIL AND GAS FIELD

2.5.1 Geology and Hydrology

As discussed above, the Chocolate Bayou field produces from a faulted anticline, divided into three principal producing areas by major growth faults on the northwest and southeast (see Figures 3, 4 and 5). Production is out of the Oligocene Frio Formation, from a series of sands interbedded with shales. The producing zones range in depth from 8600 feet to more than 13,000 feet as shown in Figure 8, and are underlain and overlain by thick shales. The Frio becomes progressively thicker and more shaly down-dip across the major growth faults. This relationship is apparent from Figures 4 and 5, which show that the interval between the Frio A Sand, near the top of the Frio Formation, and Andrau Sand in the lower part of the producing zone, is approximately 2600 feet in the West Chocolate block, increasing to about 3300 feet in the East Chocolate block and 5000 feet in the South Chocolate block. According to Allen and Allen (1953), the pay sands to a depth of about 10,200 feet produce mainly 40 degree oil (equivalent to a specific gravity of 0.8251), and reservoirs below this depth produce mainly gas and condensate. Most of the oil sands have gas caps.

The general shape of the Chocolate Bayou field is shown by Figure 3, a structural map of the Lower Andrau Sand. Within the reservoir, production is from more than 20 different pay zones, ranging from less than ten to more than 200 feet in thickness (See Figure 7).

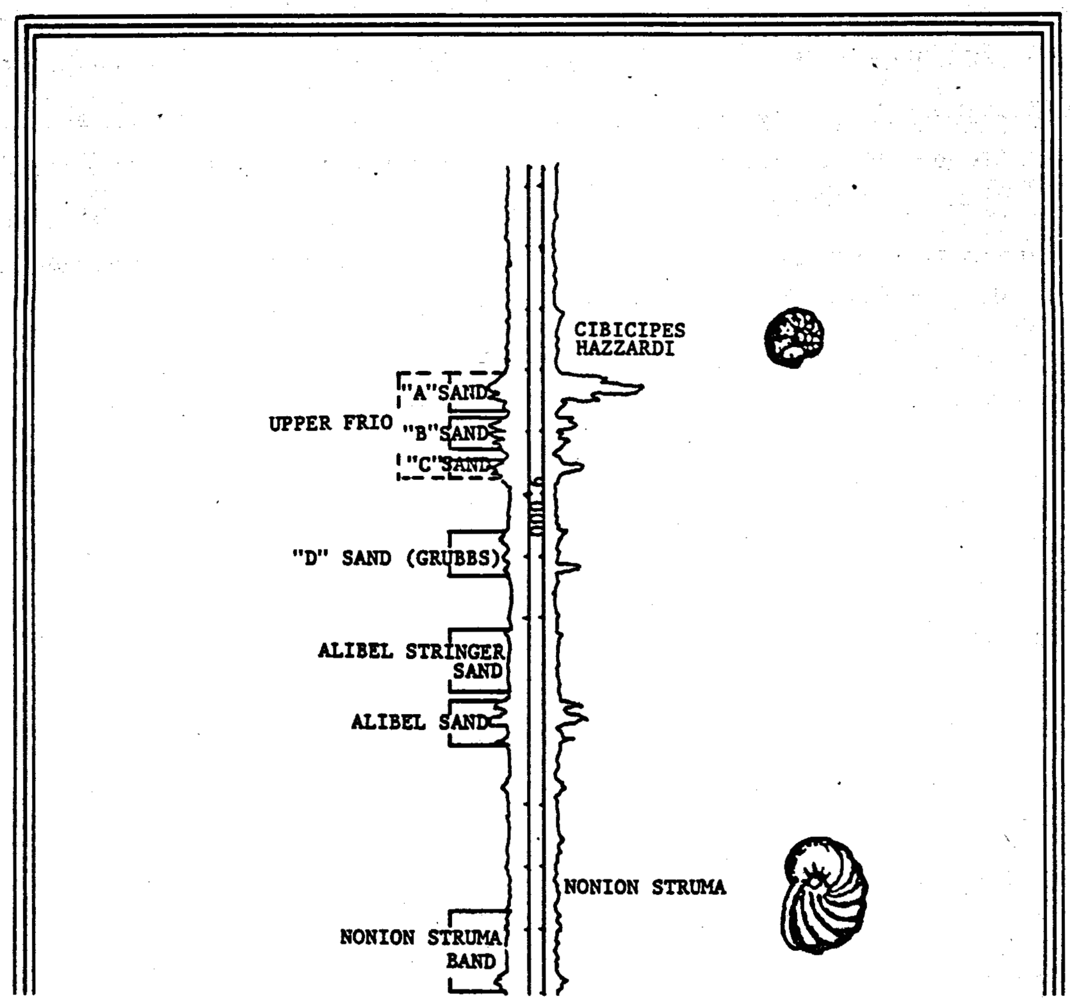


FIGURE 7A TYPE LOG CHOCOLATE BAYOU FIELD BRAZORIA CO., TEXAS

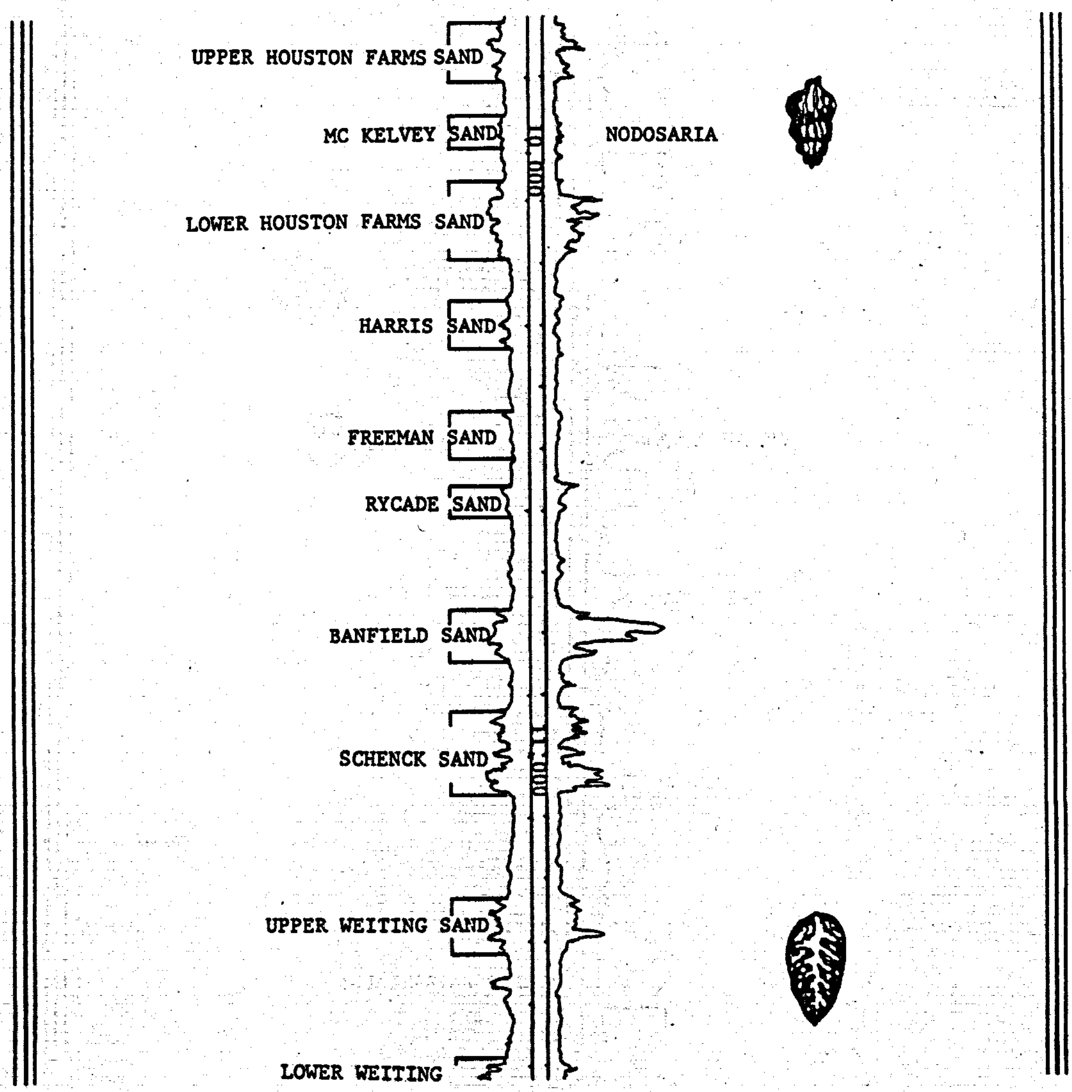


FIGURE 7B TYPE LOG CHOCOLATE BAYOU FIELD BRAZORIA CO., TEXAS

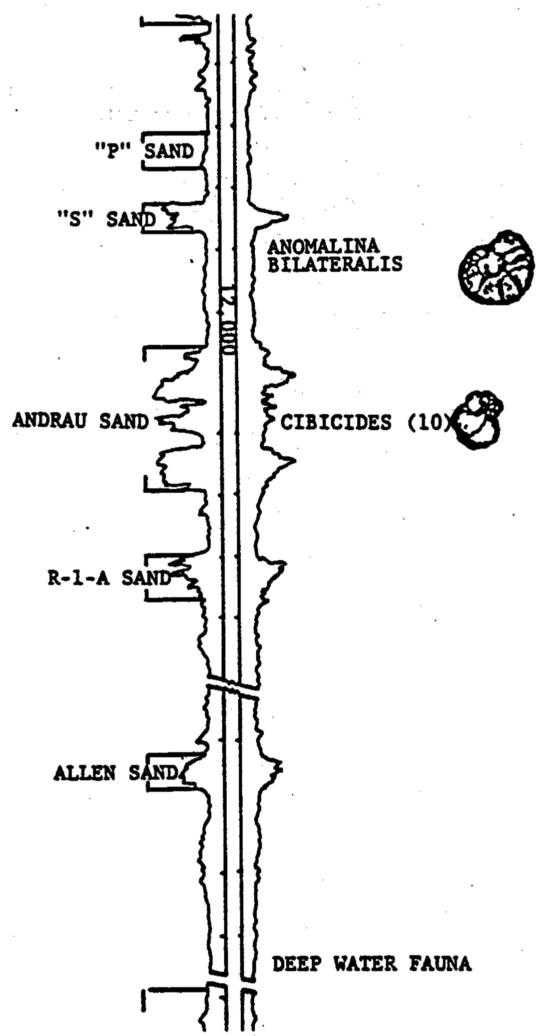


FIGURE 7C TYPE LOG CHOCOLATE BAYOU FIELD BRAZORIA CO., TEXAS

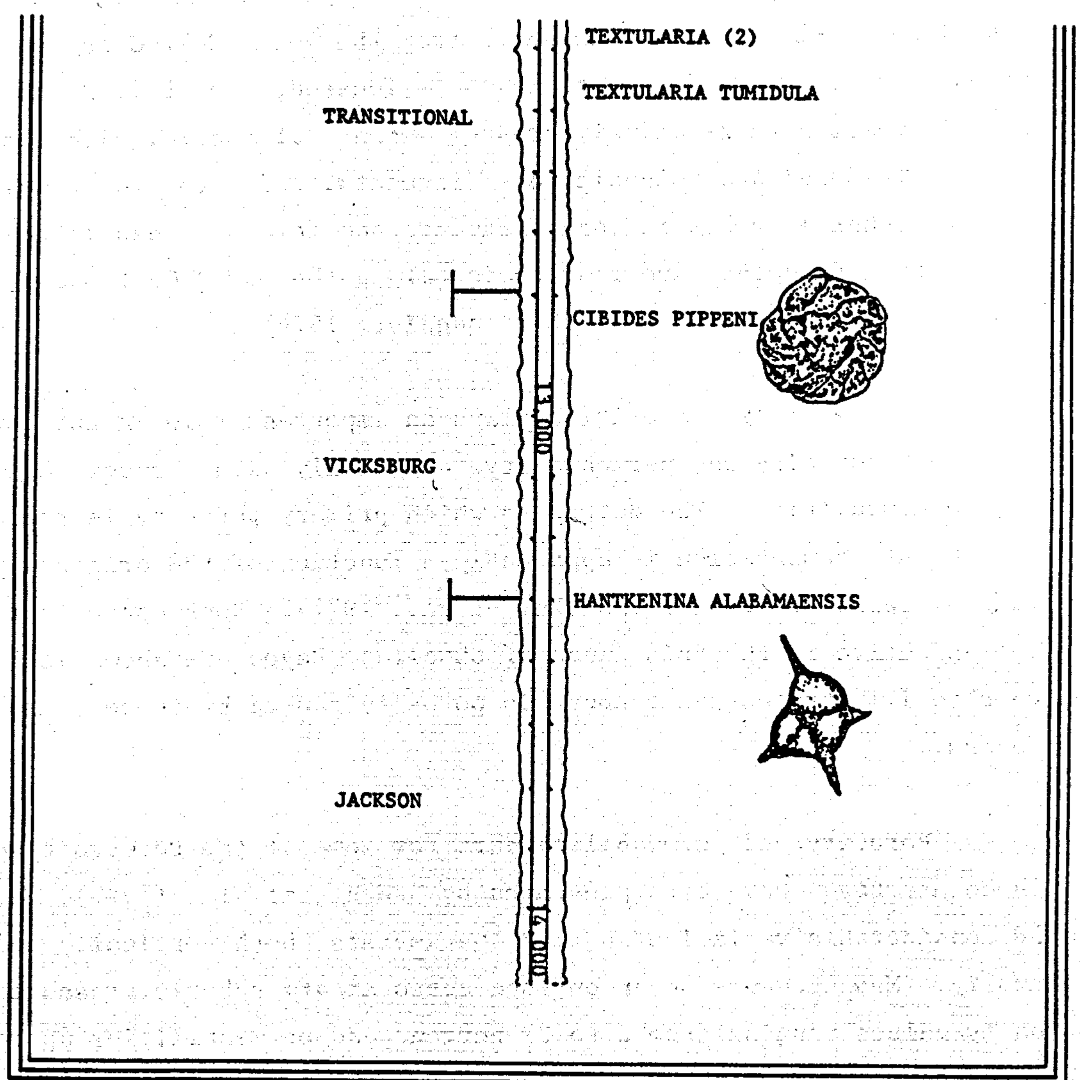


FIGURE 7D TYPE LOG CHOCOLATE BAYOU FIELD BRAZORIA CO., TEXAS

2.5.2 Reservoir Material Properties

The porosity and permeability of Frio Sands have been the subject of a recent study by Loucks, et al. (1977). Figure 8 illustrates the compositional variation of these sands from the lower Gulf Coast to the upper Gulf Coast, where Chocolate Bayou is located. The Frio Sands of the upper Gulf Coast have relatively greater amounts of quartz, with lesser amounts of feldspar and volcanic rock fragments, while the lower Gulf Coast sands are higher in volcanic rock fragments and feldspar than in quartz. Carbonate rock fragments are most common along the lower Gulf Coast, decreasing in abundance to the north (Lindquist, 1976).

Initial rock composition plays an important role in the control of reservoir porosity and permeability, especially with respect to late carbonate cementation. The degree to which primary porosity is reduced by late carbonate cementation is apparently a function of the original percentage of carbonate grains (Loucks, et al., 1977). Rock consolidation processes active in the Frio Sands of Chocolate Bayou are shown in Figure 9, which also illustrates the changes in porosity caused by these consolidation processes.

Porosity and permeability data for some of the reservoir sands at Chocolate Bayou have been presented by Bebout, et al., (1978), who found considerable variation in these parameters, both vertically and laterally. Measurements on unconfined cores at atmospheric pressure gave porosity values ranging from 2 to 27 percent and permeabilities up to thousands of millidarcys. When correlated with logs of the formation, the porosity and permeability values appear to vary with the depositional environment (see Figure 10), being highest at the top of deltaic cycles in the distributary channel-fill and distributary-mouth bar deposits (Bebout, et al., 1978, p. 80).

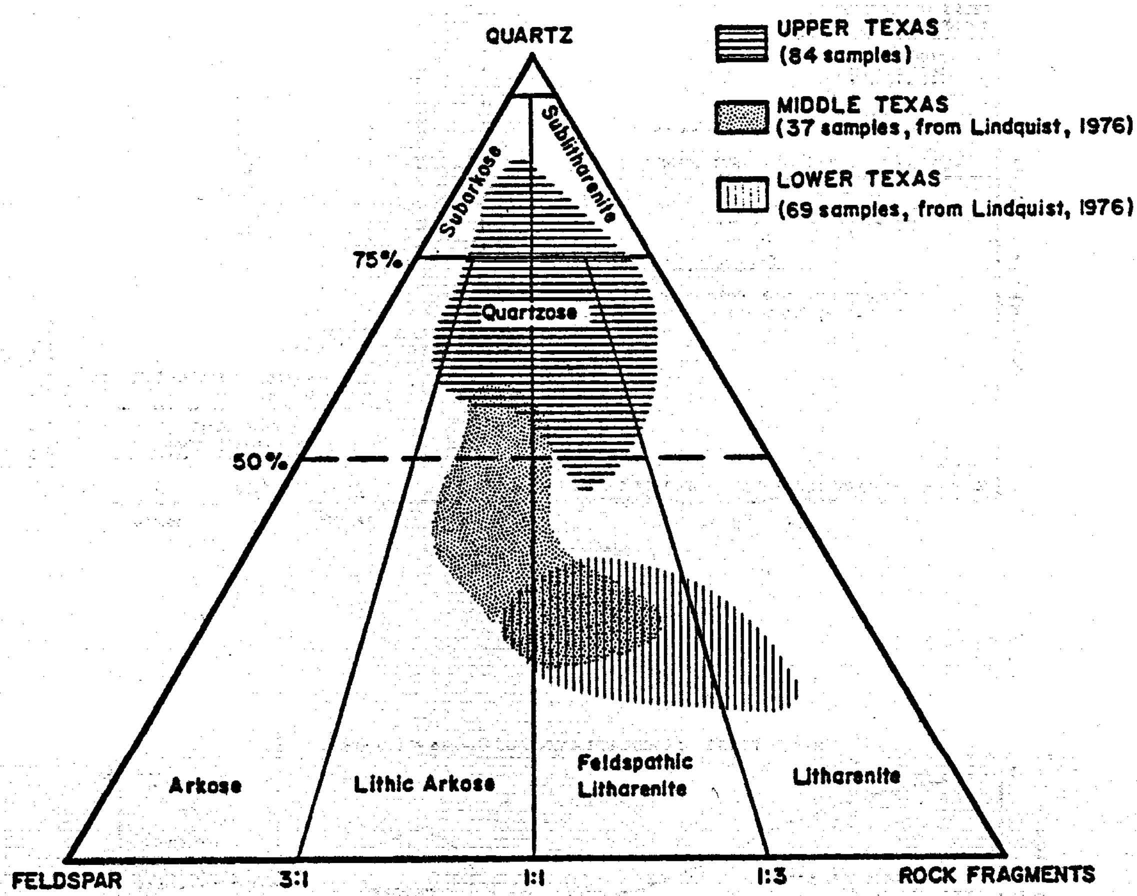
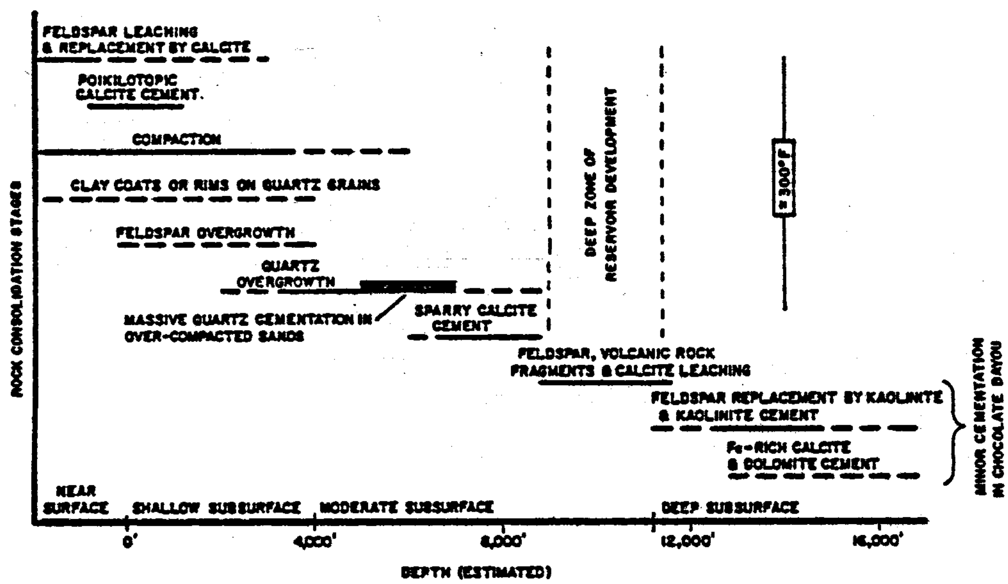


FIGURE 8 SANDSTONE COMPOSITION OF THE FRIO FORMATION ALONG THE TEXAS GULF COAST. SANDSTONE CLASSIFICATION (from Loucks et al, 1977)



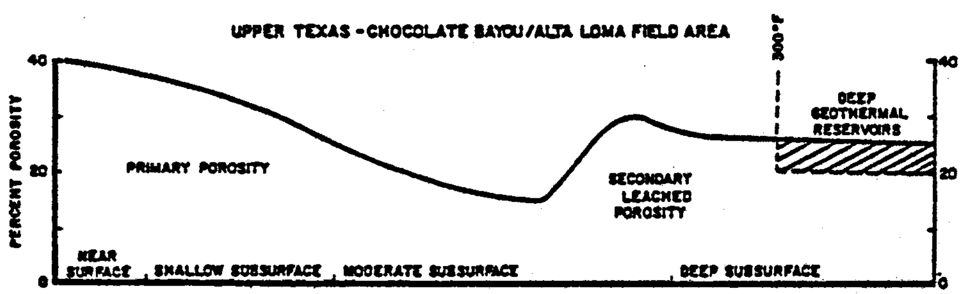


FIGURE 9 ROCK CONSOLIDATION STAGES WITH INCREASING DEPTH (from Loucks et al, 1977)

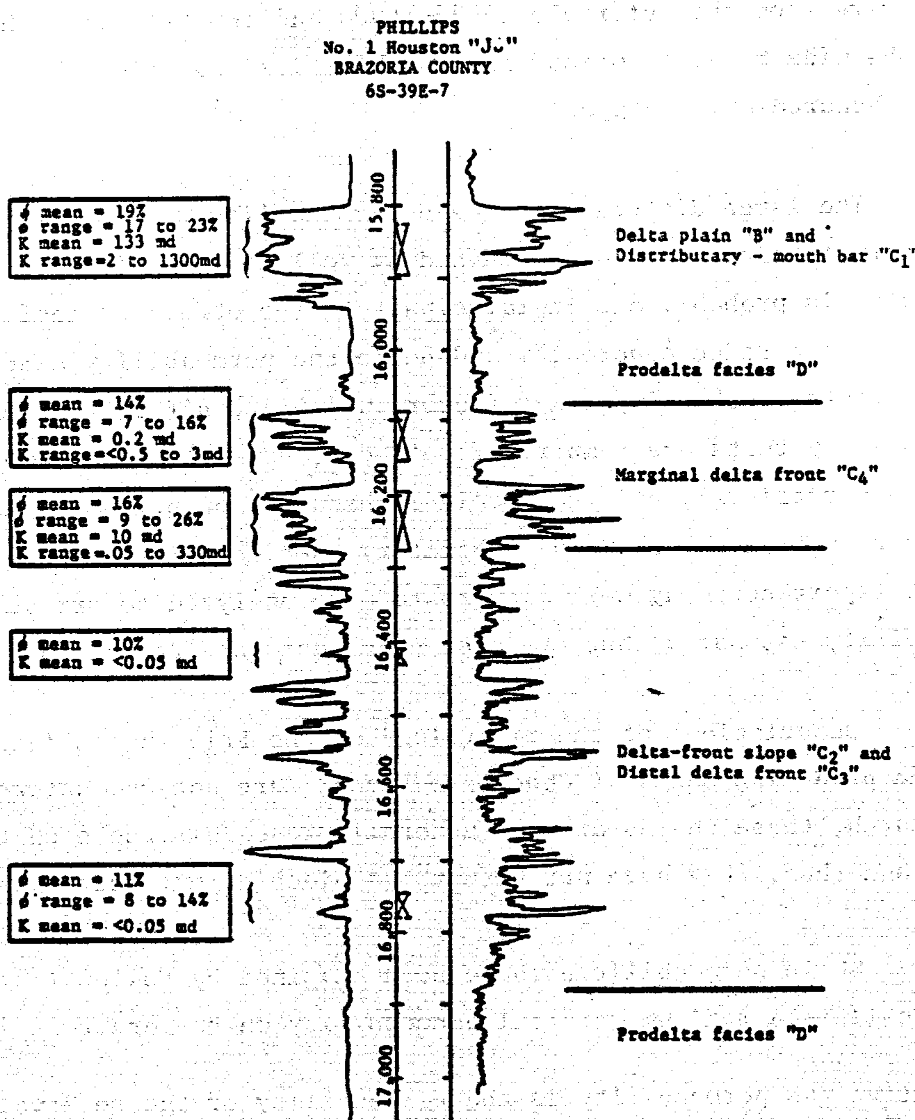


FIGURE 10 ELECTRICAL LOG DATA FROM THE PHILLIPS NO. 1 HOUSTON "JJ"
(from Bebout et al, 1978)

Effective permeabilities of thin (10-30 feet) relatively tight gas sands at Chocolate Bayou have been determined from production flow tests and are estimated at 1 to 6 millidarcys (Bebout et al, 1978)*. Absolute permeabilities were estimated to about 2 to 10 millidarcys. Figure 11 is a plot of permeability vs. porosity from core measurements made at atmospheric pressure for a well in South Chocolate Bayou. Samples tested were from the intervals 15826-15900 and 16035-16885. This figure shows the wide range of measured permeabilities from less than 0.1 to several hundred millidarcys.

The large difference between permeability values determined by laboratory testing and those obtained by well tests on in-situ reservoir materials, is probably due in large part to the effect of confining pressure which reduces porosity and hence the permeability measured by in-situ tests. Other important factors which can affect the reliability of laboratory tests are temperature effects, damage to the sample during coring and retrieval, and the chemical character of brine present in the reservoir, but absent from the laboratory specimen. Bebout et al., 1978 did not report how many well flow tests were analyzed to arrive at their permeability estimates, but at least nine tests are described.

Descriptions of the mineralogy of the Frio shales interbedded with the producing sands of Chocolate Bayou, were not encountered in our data search; these shales are not generally reservoir rocks on the Gulf Coast, and thus, they have not been the subject of extensive research.

Shale permeabilities have been examined by Fowler (1970, p. 423) who calculated a maximum vertical permeability on the order of 7.1×10^{-7}

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* Effective gas permeability is the permeability of the reservoir to gas in the presence of other fluids, typically oil and/or water.

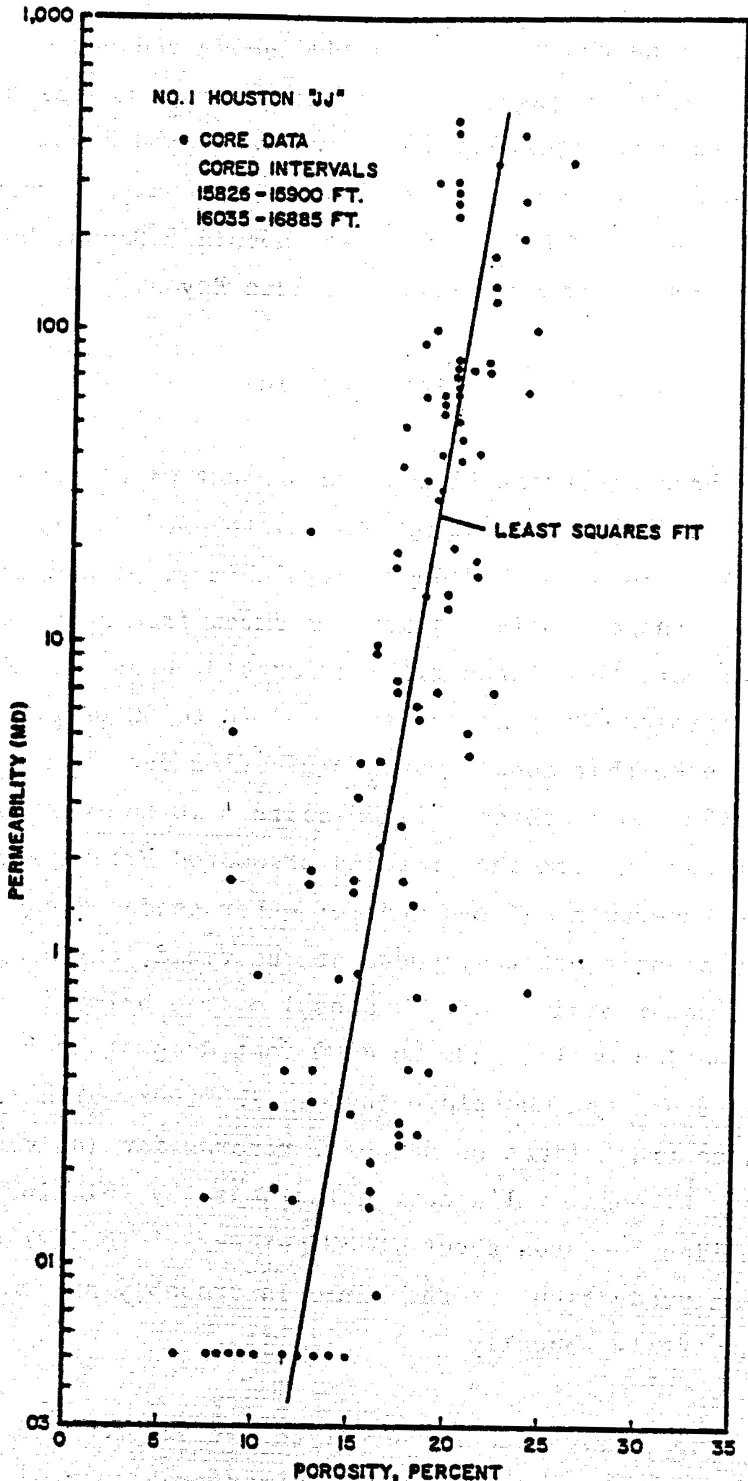


FIGURE 11 POROSITY-PERMEABILITY RELATIONSHIP FROM CORE MEASUREMENTS MADE AT ATMOSPHERIC PRESSURE FOR PHILLIPS NO. 1 HOUSTON "JJ," CHOCOLATE BAYOU FIELD, BRAZORIA COUNTY, TEXAS (from Bebout et al, 1978)

millidarcys. The reservoir is bounded above and below by thick shale wedges. Within the reservoir interbedded shale sections may be as think as five to ten feet, but are more typically 50 to 100 feet with occasional thicker sections (see Figure 7). The percentage of shale in the reservoir is probably on the order of 60 percent in East and West Chocolate Bayou, but it increases down-dip in South and Southeast Chocolate Bayou.

2.5.3 Reservoir Fluid Characteristics

Three different fluids are present within the Chocolate Bayou reservoir - oil, gas (including condensate) and water. The crude oil has API gravity of 30.4 to 50.0 degrees, with most production being in the 40.0 to 50.0 range. Brine is also produced from many wells, currently at the rate of more than three million barrels annually. Data obtained from Phillips Petroleum Company, operator of 70 to 80 percent of the wells at the field, show that annual water production from their wells has been approximately two to three million barrels in the past several years, with about half coming from the normally pressured Frio A and B Sands near the top of the reservoir. The amount of water produced can also be measured by records of salt water disposal at the field, which agree fairly well with records of water production. Disposal of the brine is accomplished through 4 to 5 injection wells, 2000 to 4000 feet deep, four in the main producing area and one in Southeast Chocolate Bayou. The four wells in the main area are connected to trunk lines so disposal records for individual wells are not available. Disposal wells currently in use by Phillips are shown in Figure 12. Since Phillips operates about 70-80 percent of the wells at Chocolate Bayou, total brine production for the field is probably on the order of 3 to 5 million barrels annually.

The chemical character of the water produced at Chocolate Bayou has been discussed by Fowler (1970), by Kharaka, et al., (1977) and Bebout, et al., (1978). Figure 13 illustrates the salinity and temperature of water

Figure 12 follows

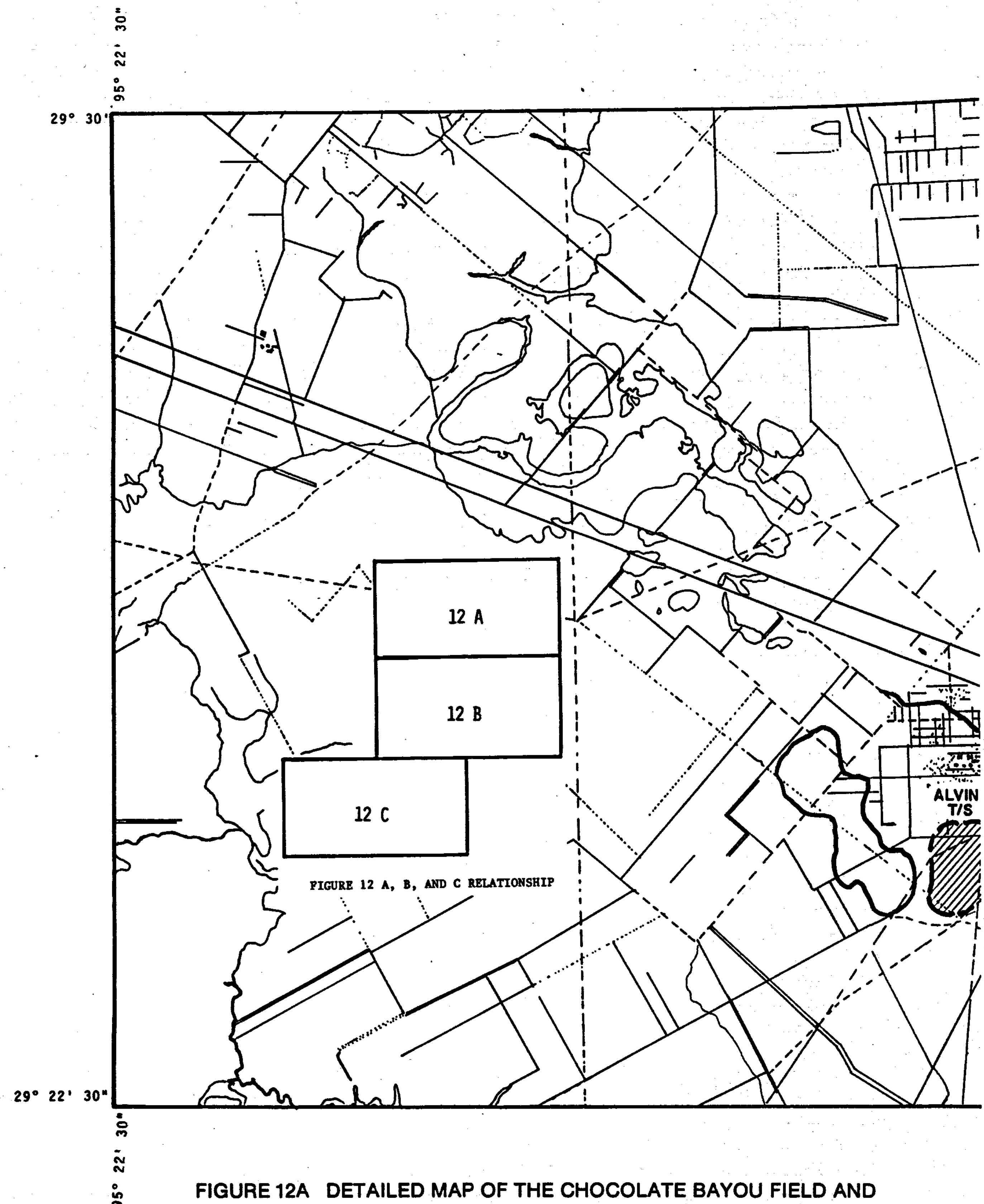


FIGURE 12A DETAILED MAP OF THE CHOCOLATE BAYOU FIELD AND SALT WATER DISPOSAL WELLS

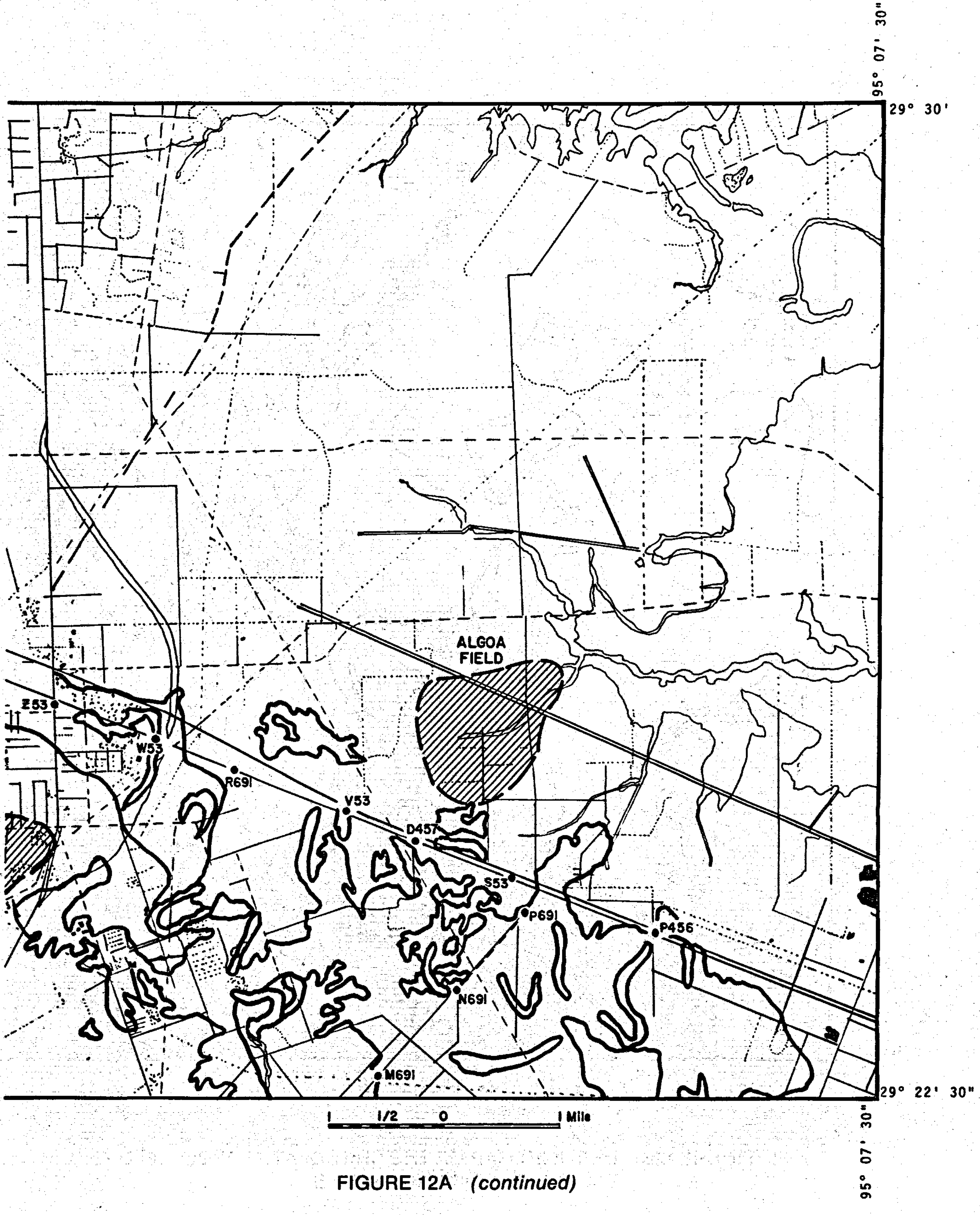


FIGURE 12A (continued)

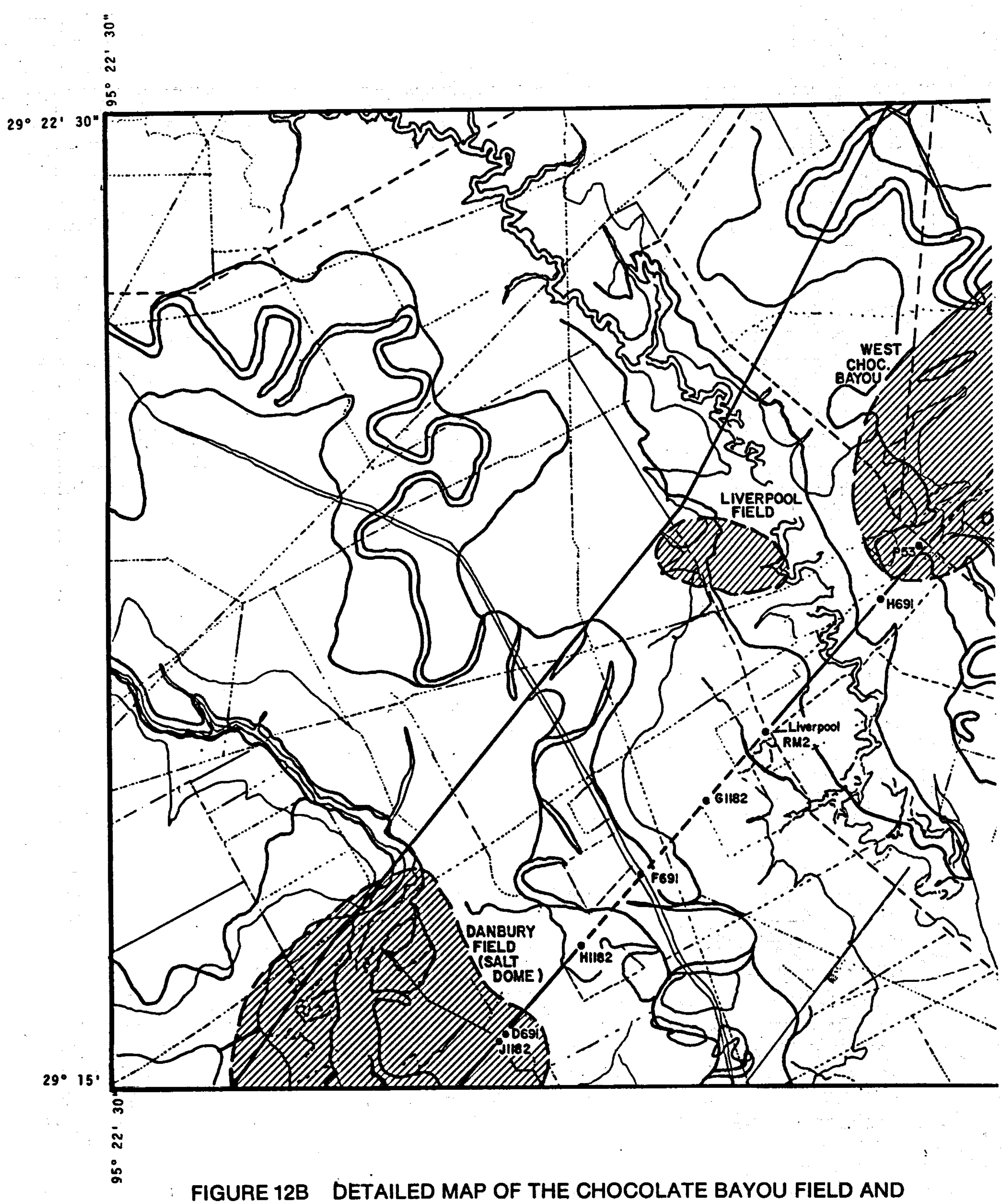


FIGURE 12B DETAILED MAP OF THE CHOCOLATE BAYOU FIELD AND SALT WATER DISPOSAL WELLS

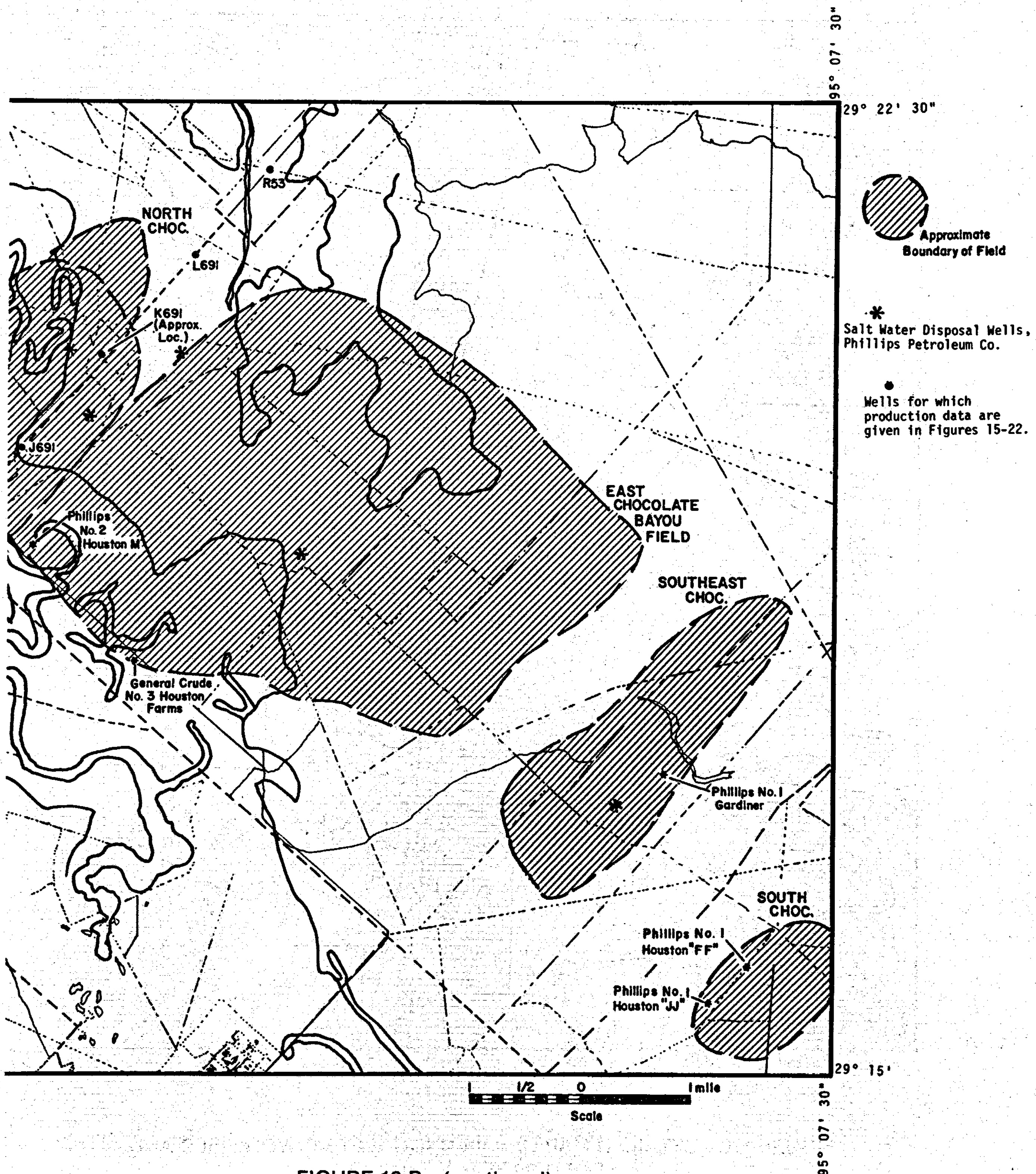


FIGURE 12 B *(continued)*

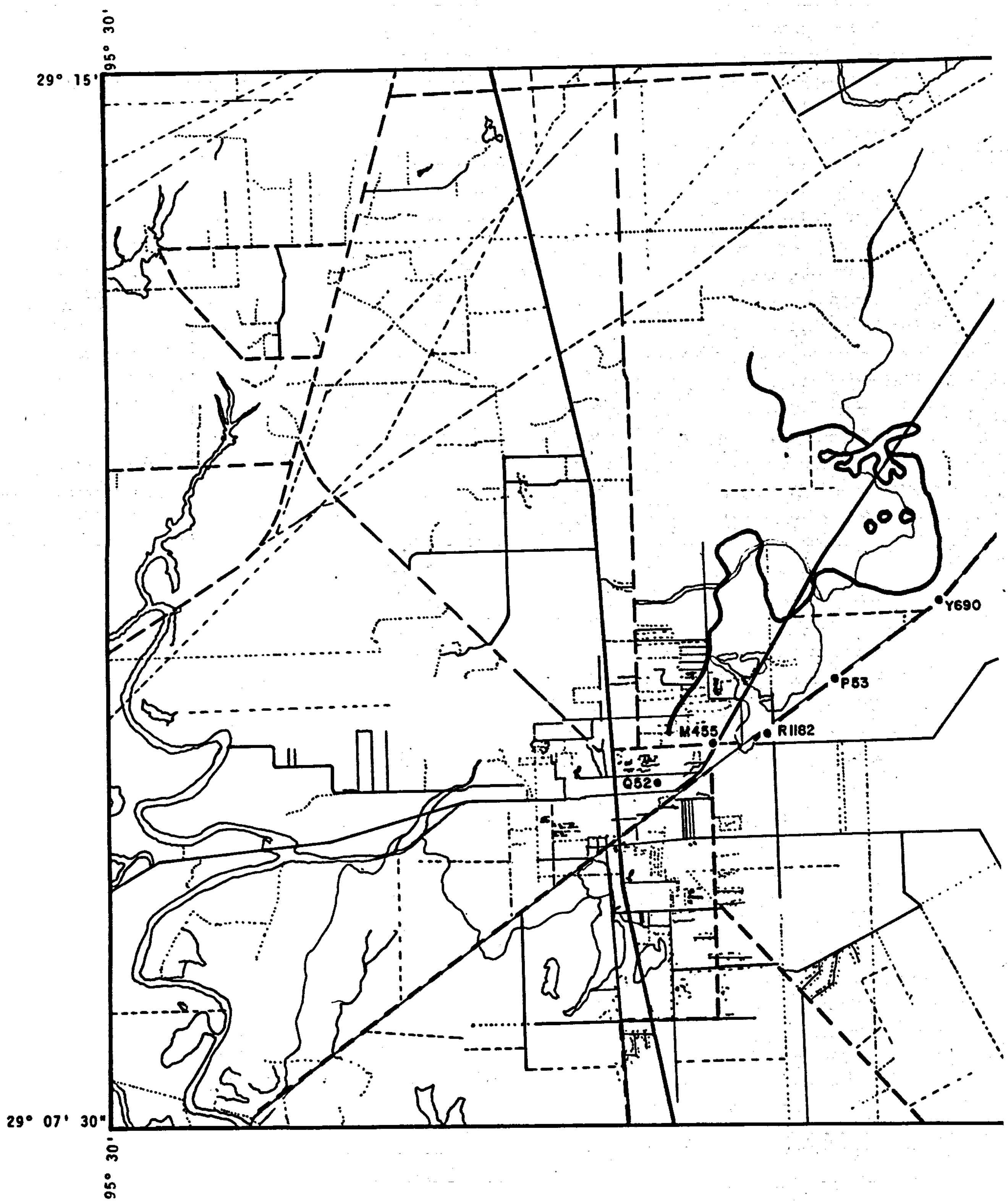


FIGURE 12C DETAILED MAP OF THE CHOCOLATE BAYOU FIELD AND SALT WATER DISPOSAL WELLS

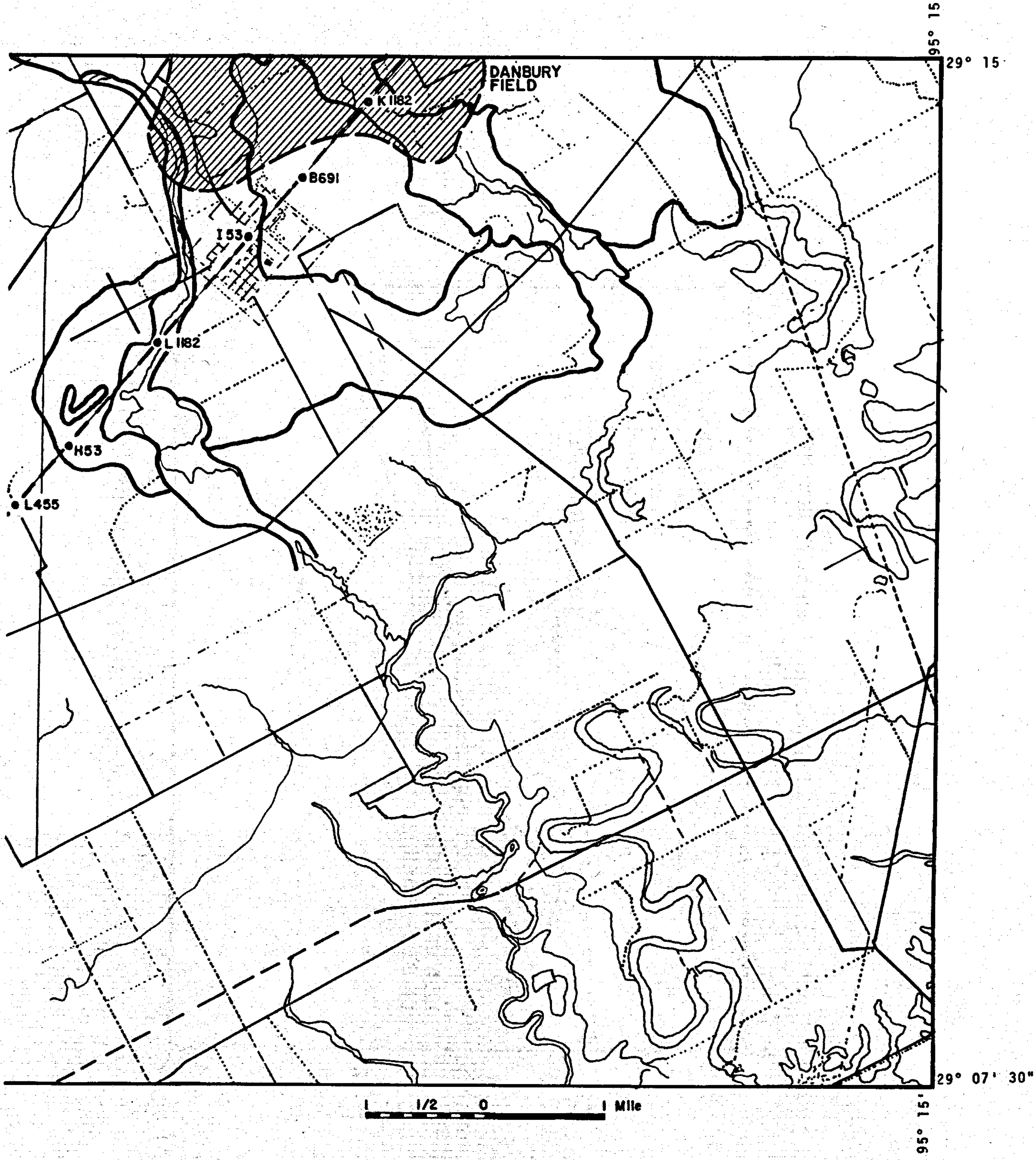


FIGURE 12C *(continued)*

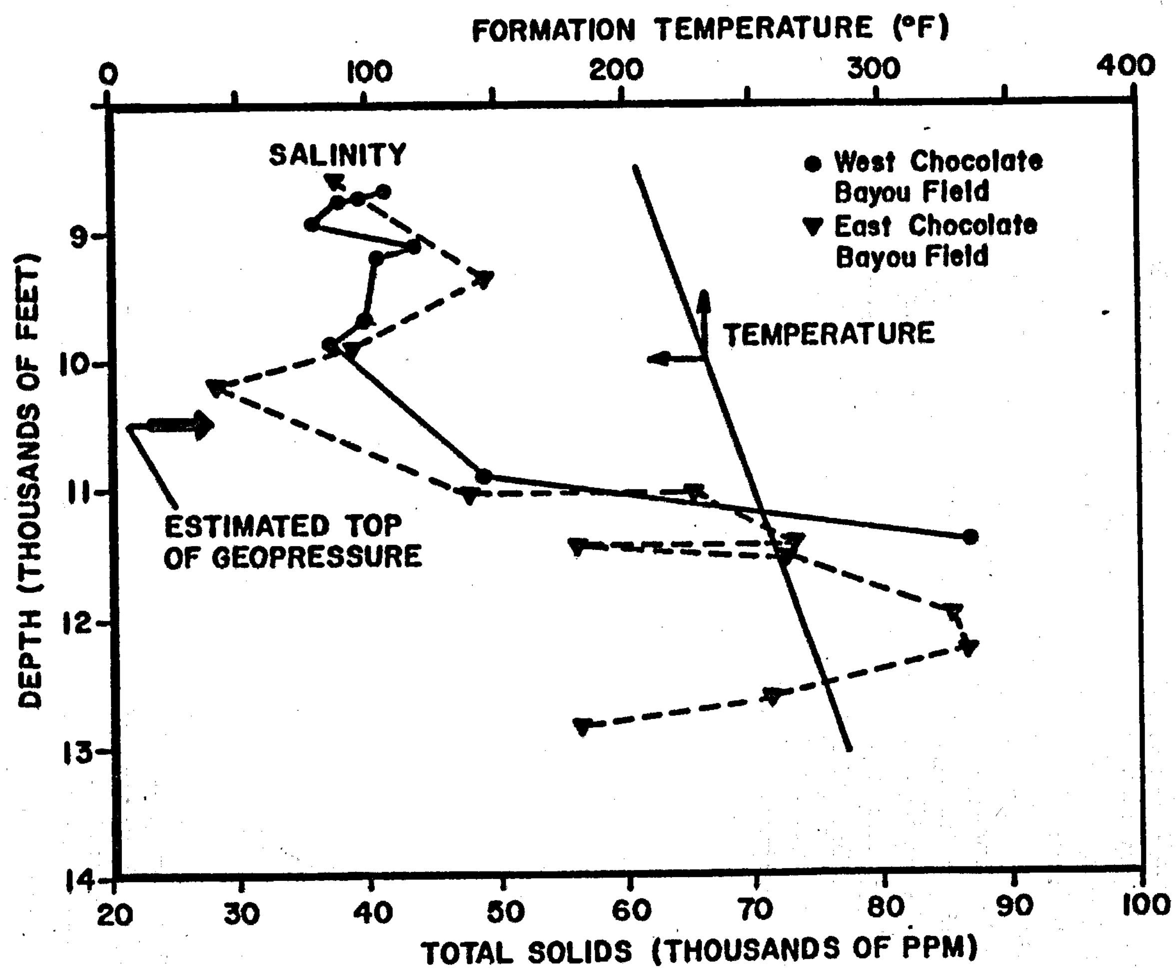


FIGURE 13 SALINITY AND TEMPERATURE OF WATERS FROM CHOCOLATE BAYOU FIELD (from Bebout et al, 1978)

from wells in the Chocolate Bayou field. The rapid increase in total dissolved solids below the normally pressured zone is apparent. Since water in the geopressured zone of other fields is often found to be less saline than waters of the normally pressured zone (Jones, 1975) the rapid increase is suggestive of a buried salt structure below the Chocolate Bayou field.

Kharaka, et al., (1977) have presented more detailed analyses of water from three wells, as shown in Table 2. The authors propose that the data set for the Cozby Number 2 well is indicative of mainly condensed water vapor rather than formation water. This conclusion is based principally on the much lower temperature calculated from the Na-k-Ca ratio. A more complete discussion of the methodology is available in Kharaka, et al., (1977). Additional data will be available later this year, when proceedings of the 3rd Geopressured Geothermal Energy Conference are published.

Table 2 Analyses of Water in Wells Near the Chocolate Bayou Field, With Additional Data on Production Depth, Temperature and Pressure*

Well Number	Kitchen No. 1	Cozby No. 2	Gardiner No. 1
Production Zone	Frio "B"	Schenk	Lower Weiting
Perf. Interval (ft.)	8688-86 97	10,905-11,037	11,772-11,785
Temperature, °C Measured	100	114	129
Calculated from Na-k-Ca geothemembers	112	86	124
Bottom Hole Pressure (original), psi	4,000	6,770	7,589
Chemical Composition (mg/1)			
Tds	42,000	3,100	68,500
Na	16,500	1,075	24,000
K	130	8.5	300
Rb	0.35	<0.2	0.80
NH_3	9.8	8.8	26
Mg	60	3.0	235
Ca	290	100	2,000
Sr	22	5.8	380
Fe	0.15	11.0	8.0
Mn	0.52	-	2.7
Cl	23,200	1,740	40,500
HCO_3	1,660	90	520
SO_4	39	12	0.6
H_2S	1.6	0.85	0.32
SiO_2	70	1.5	87
B	42	1.8	30
pH	7.0	5.2	6.3

*After Kharaka, et al., 1977)

3. PRODUCTION HISTORY

3.1 OIL AND GAS DEVELOPMENT

Discovered in 1941, the Chocolate Bayou field has produced a total of over 16 x 10^{12} standard cubic feet of natural gas and over 35 million barrels of oil. Liquid hydrocarbons from gas wells have contributed an additional 41 million barrels. Annual production figures published by the Texas Railroad Commission have been compiled for the field and are shown graphically in Figure 14. This figure shows that production of oil and liquid hydrocarbons was greatest during the late 1940's to early 1960's, while production of natural gas peaked in 1962. By far the greatest petroleum producers have been the Upper Frio (includes Frio A, B and C Sands) and the Alibel Sands. As shown in Figure 7, these sands are near the top of the Frio Formation. Together these horizons account for 50 to 80 percent of annual oil production from the field. Other important producers are the Grubbs, Houston Farms and since 1974, the 9020 Sand. Casinghead gas extracted from oil wells at Chocolate Bayou has averaged 1 x 10^9 standard cubic feet annually since 1970, when the Texas Railroad Commission began requiring that operators report casinghead gas. Although this is small compared to peak production from gas wells (in excess of 100 x 10^9 scf annually) it is 10 to 20 percent of the current gas production.

There are many natural gas reservoirs at Chocolate Bayou, both in Upper and Lower Frio Sands, but the production has been greatest from the Andrau and Eanfield Sands, which have each yielded over 35x10^{10} scf since the early 1950's. Other major gas sands are the Rycade, Upper Weiting, and the 12,000 foot sand. In South Chocolate Bayou, production

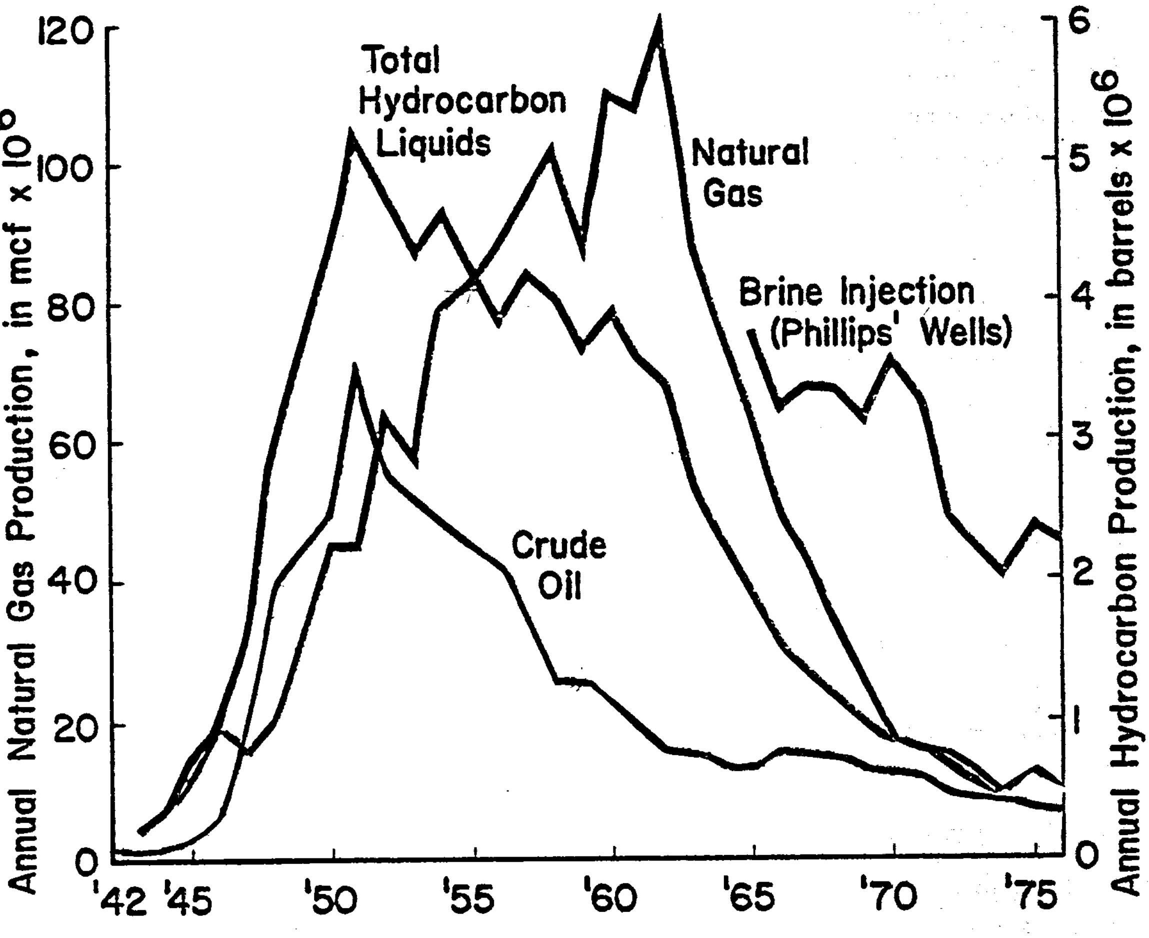


FIGURE 14 PRODUCTION HISTORY OF CHOCOLATE BAYOU FIELD (Hydrocarbon production from Texas Railroad Commission; Salt water disposal from Phillips Petroleum Company)

is generally from the deeper sands such as Frio P, "S" Sand, Andrau, Schenek and Lower Weiting (see Figures 5 and 7), with wells commonly deeper than 15,000 feet.

Along with hydrocarbons, wells at Chocolate Bayou produce brine. Since operators are not required to file water production records with the Texas Railroad Commission, these data are not readily obtainable. However, Phillips Petroleum Company provided recent water production and salt disposal records for their leases at Chocolate Bayou. Since Phillips operates some 70 to 80 percent of the wells at the field, this data is probably representative of the general volume of water produced at the field as a whole. Records of brine disposed of by injection have been kept only since 1965 (during earlier years of the field's operation, disposal was to surface evaporation ponds), and are believed to be representative within about 10% of brine produced.

Available data on brine disposal are shown in Figure 14. Although water production data are not available prior to 1965, it is clear that the annual volume of brine produced during the period 1965-1973, is about the same as the annual volume of oil produced during peak years, expecially if it is taken into account that the water records shown are only for 70-80 percent of the wells at the field. Since 1965, brine has been the predominant liquid recovered from the reservoirs. This is not surprising, since water production from a particular well often increases as the hydrocarbon yield diminishes.

3.2 CHANGES IN RESERVOIR CHARACTERISTICS

The watering-out of wells is closely related to pressure changes within the reservoir as a result of production. Fowler, of Phillips Petroleum

Company, has made detailed studies of Chocolate Bayou (1964, 1970) and summarizes the overall pressure relationships in the field as follows (1970, p. 412):

> Within a major fault block, each aquifer usually contains a single fluid system. The variation of pressures with depth within each fault block is generally similar. A normally pressured section extends down from the surface, showing little change in pressure gradient throughout except for a possible very slight increase at great depths. Below this normally pressured section is a section where pressure gradients increase from values close to hydrostatic to gradients approaching geostatic over a comparatively short vertical distance. Underlying this section is a long interval, commonly extending to the limits of subsurface control, where pressure gradients are approaching geostatic. Although pressure gradients may show little increase with depth in the lower part of the section, pressures are still increasing with depth at a rate well above hydrostatic, and the fluids will still tend to flow upward toward the lower-energy environments in the shallower beds.
>
> An analogous pattern of pressure variation is observed along a dip section of each correlative horizon. A considerable area of normally pressured sediments extends downdip from the outcrop, showing little variation in pressure gradient. Then, across one or two fault blocks, pressures increase downdip from values close to hydrostatic to pressures approaching geostatic. These radical pressure changes usually

occur across major growth faults. Basinward from this interval, pressure gradients may increase slightly, if at all, to the downdip limits of subsurface control in the correlative section. Again, although gradients may not increase much downdip, pressures are increasing with depth at a gradient far in excess of hydrostatic, and the potential energy of the fluids, or potentiometric surface will increase downdip. Hence, any flow will tend to be updip.

As shown in Figures 4 and 5, the producing zones in West Chocolate Bayou are all normally pressured; in East Chocolate Bayou, both normally and abnormally pressured zones are present; and in South Chocolate Bayou, all pays are abnormally pressured. Fowler (1970, p. 413) mentions the presence of at least one abnormally pressured shale, in the West Chocolate fault block. His explanation for this anomaly is that although the normally pressured sand underlying the higher pressured shale is faulted against abnormally pressured shales on both the northwest and southeast, it does adjoin normally pressured sediments to the southwest, which has allowed excess fluid pressures to dissipate. Lower permeability in the shale has prevented dissipation of abnormal pressures.

Bebout, et al., (1978) have compiled detailed data on geopressured gas production history and pressure/temperature declines for several wells perforated in different pay zones within the Chocolate Bayou field, as shown in Figures 15 through 22 (see Figure 12 for location of these wells). From these figures, it is apparent that initially, production is high, but typically drops off rapidly as fluid pressure declines, stabilizing at some lower level. Temperature declines over time appear to be relatively small.

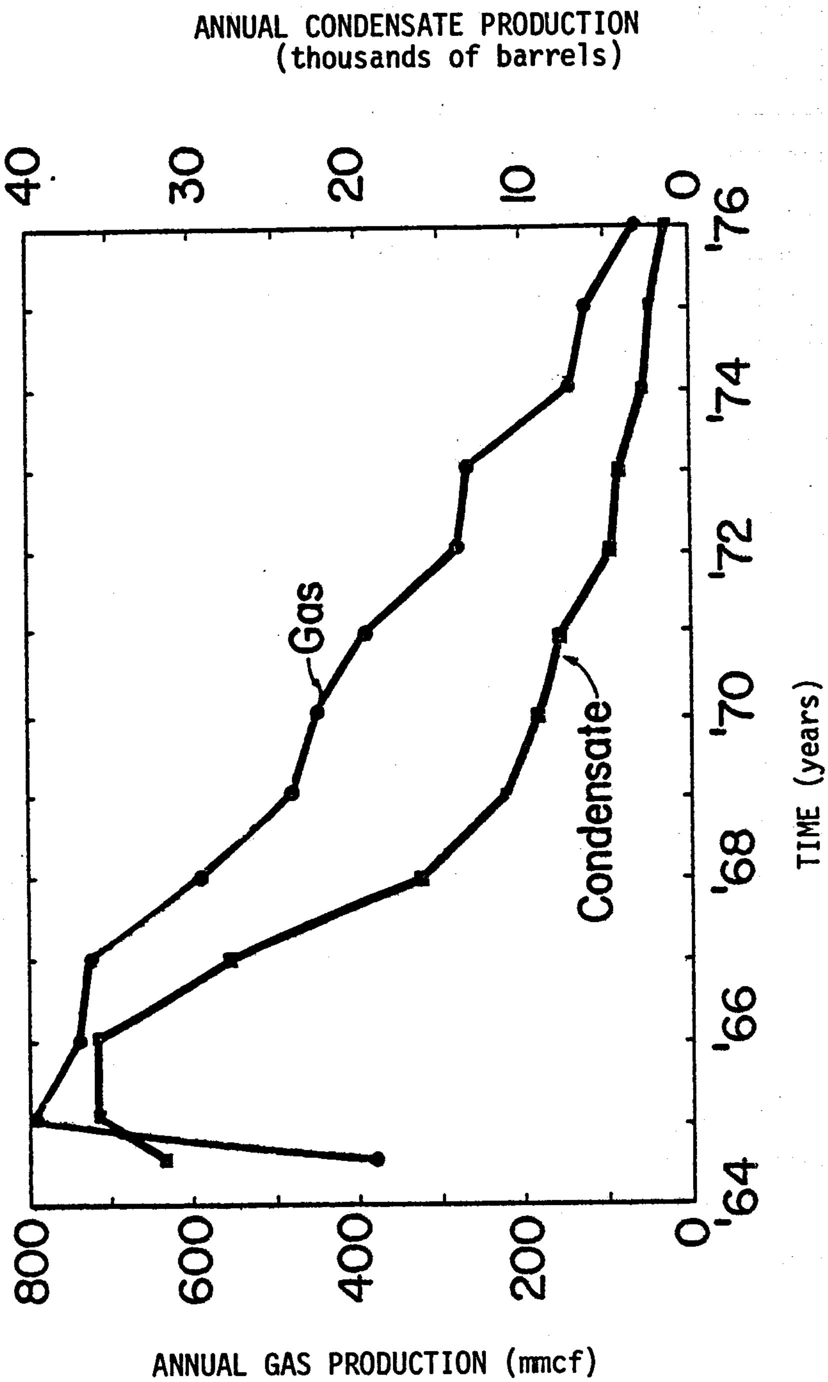


FIGURE 15 PRODUCTION HISTORY OF GENERAL CRUDE NO. 3 HOUSTON FARMS DEVELOPMENT COMPANY, CHOCOLATE BAYOU FIELD (from Bebout et al , 1978) (See Figure 12 for well location)

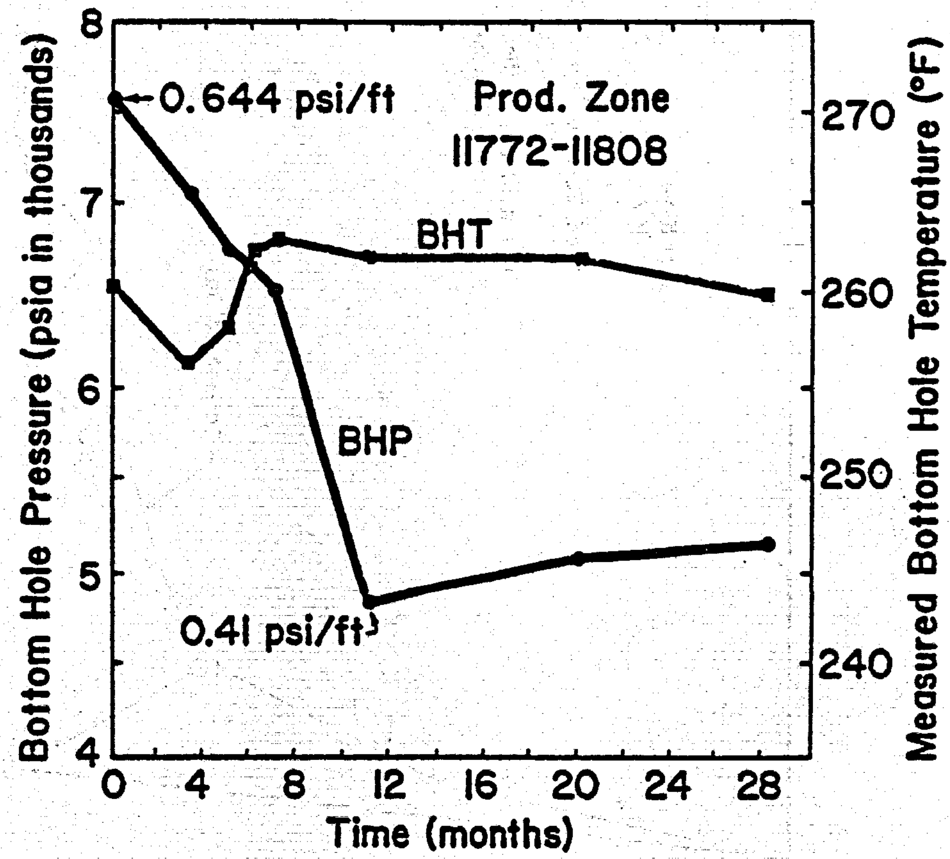


FIGURE 16 EARLY HISTORY OF BOTTOM-HOLE PRESSURES AND TEMPERATURES IN PHILLIPS NO. 1 GARDINER, SOUTH CHOCOLATE BAYOU FIELD (from Bebout et al , 1978) (See Figure 12 for well location)

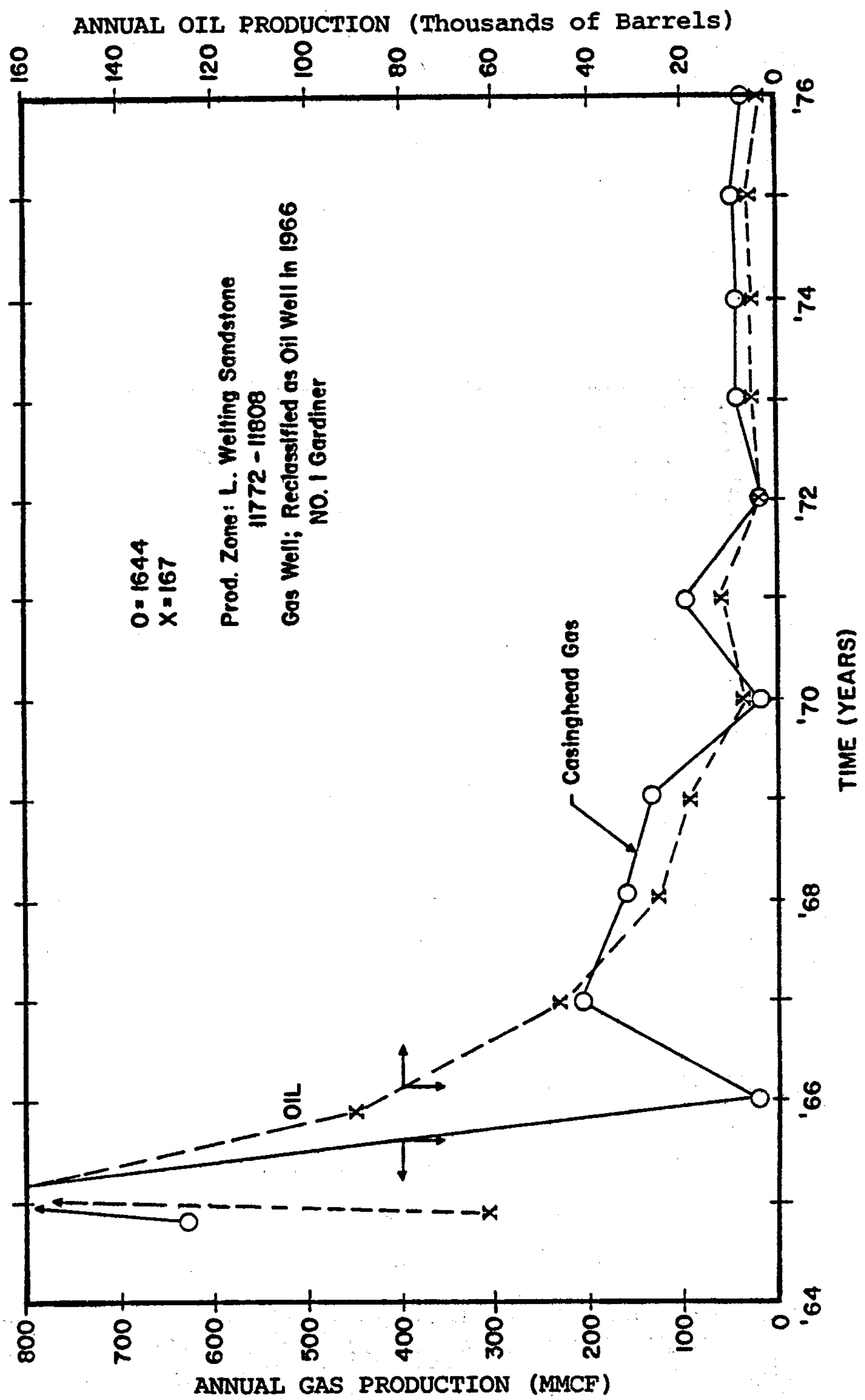


FIGURE 17 PRODUCTION HISTORY OF PHILLIPS NO. 1 GARDINER, SOUTH CHOCOLATE BAYOU FIELD (from Bebout et al , 1978) (See Figure 12 for well location)

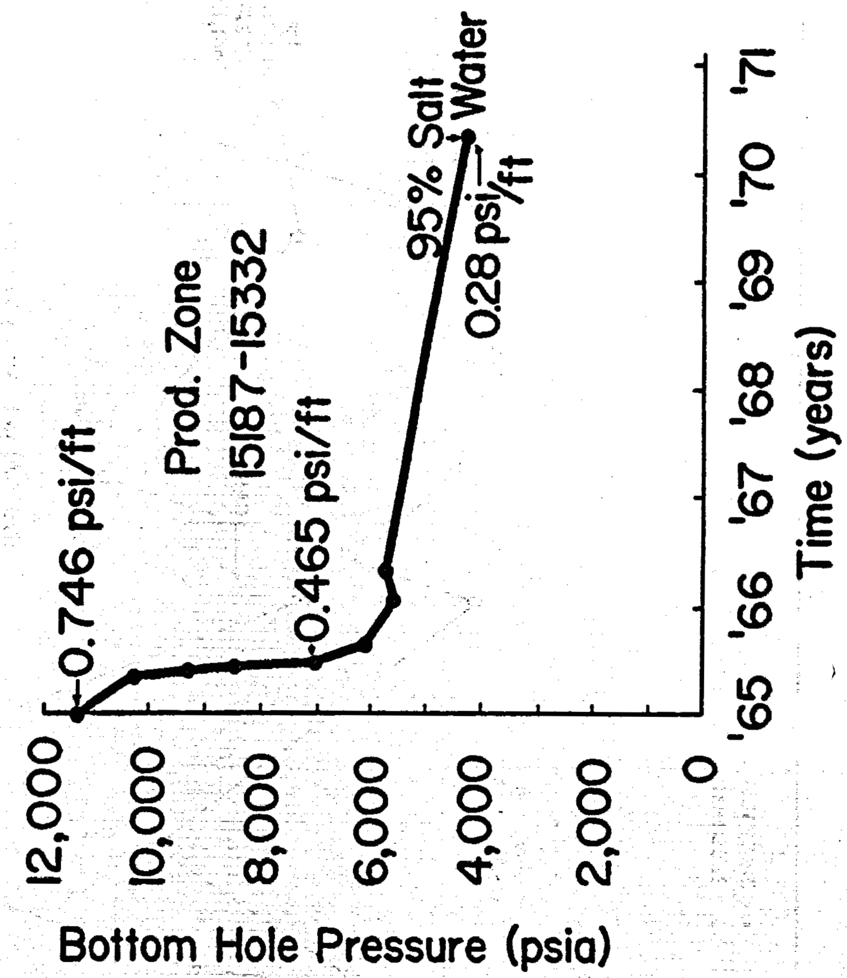


FIGURE 18 HISTORY OF DECLINE IN BOTTOM-HOLE PRESSURE FOR PHILLIPS NO 1 HOUSTON "JJ," SOUTH CHOCOLATE BAYOU FIELD (from Bebout et al , 1978) (See Figure 12 for well location)

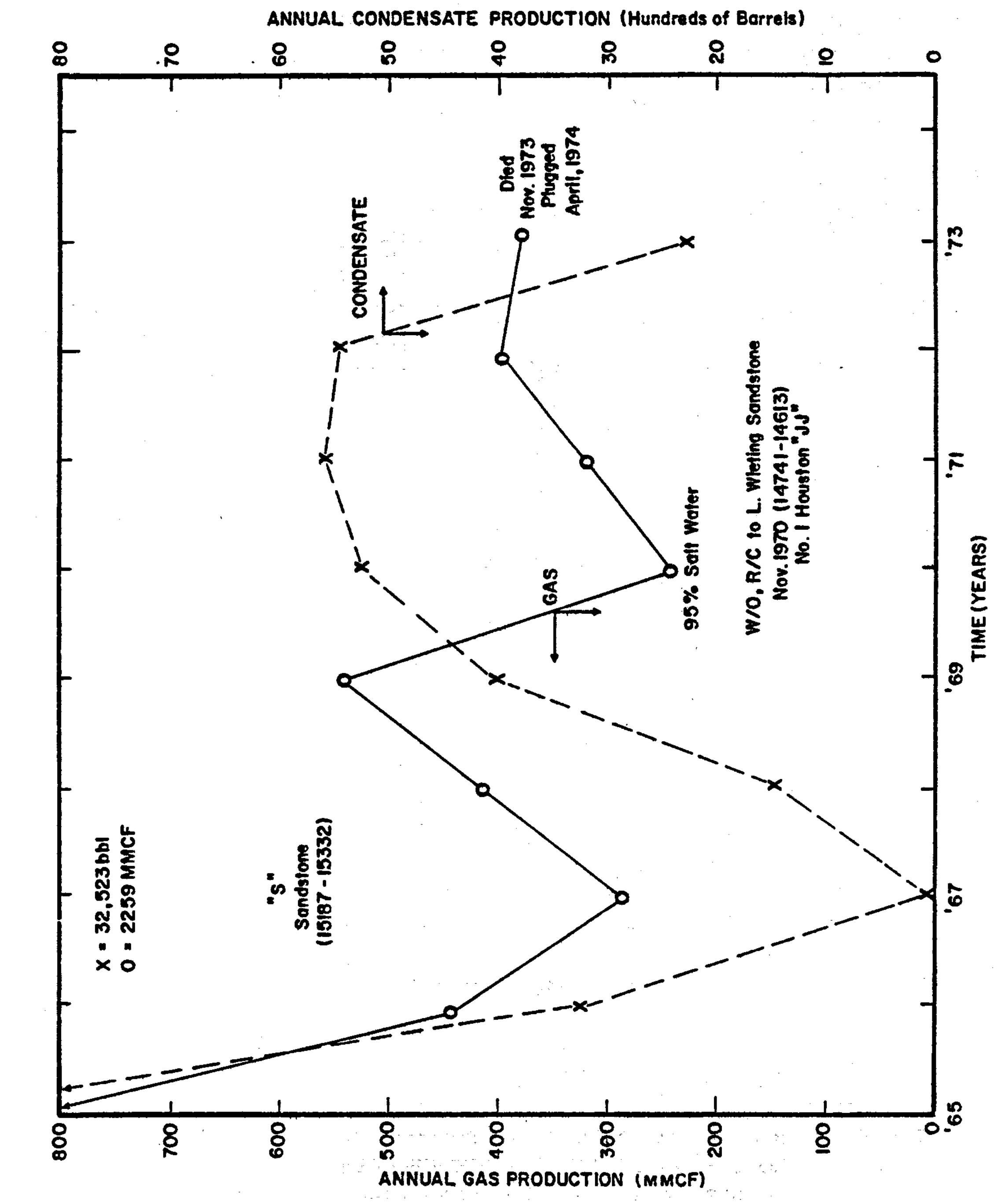


FIGURE 19 PRODUCTION HISTORY OF PHILLIPS NO. 1 HOUSTON "JJ," SOUTH CHOCOLATE BAYOU FIELD (from Bebout et al , 1978) (See Figure 12 for well location)

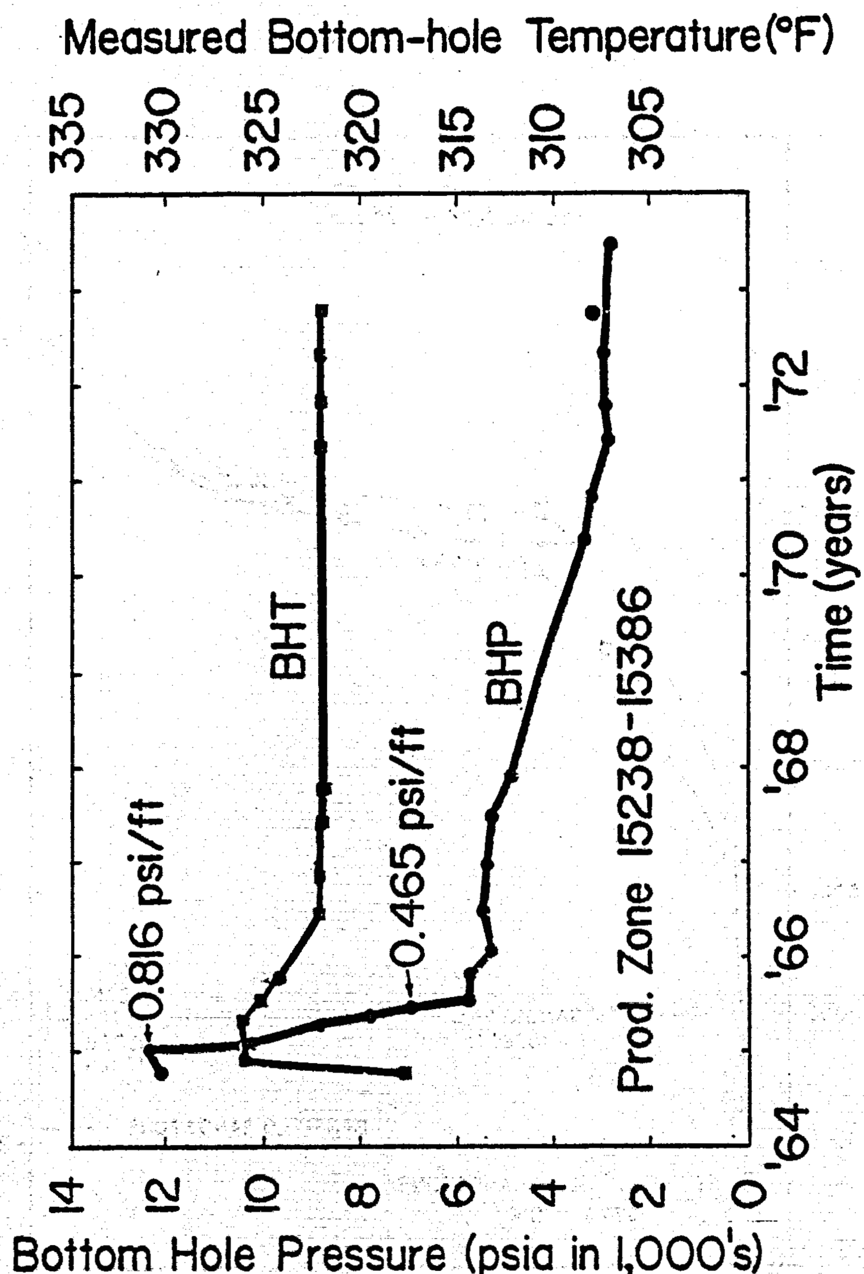


FIGURE 20 HISTORY OF DECLINE IN BOTTOM-HOLE PRESSURE AND TEMPERATURE FOR PHILLIPS NO. 1 HOUSTON "FF," SOUTH CHOCOLATE BAYOU FIELD (from Bebout et al , 1978) (See Figure 12 for well location)

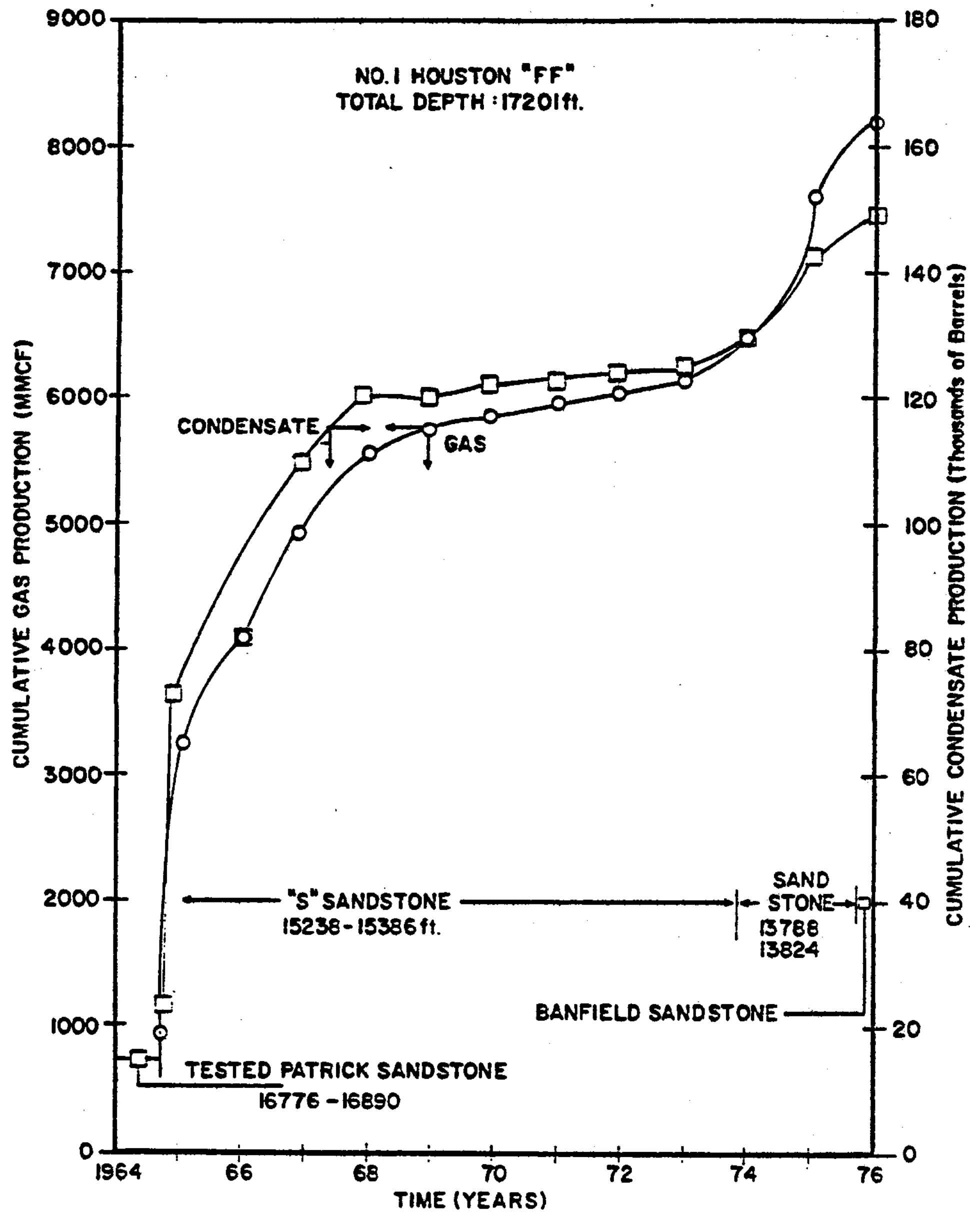


FIGURE 21 PRODUCTION HISTORY OF PHILLIPS NO. 1 HOUSTON "FF," SOUTH CHOCOLATE BAYOU FIELD (from Bebout et al , 1978) (See Figure 12 for well location)

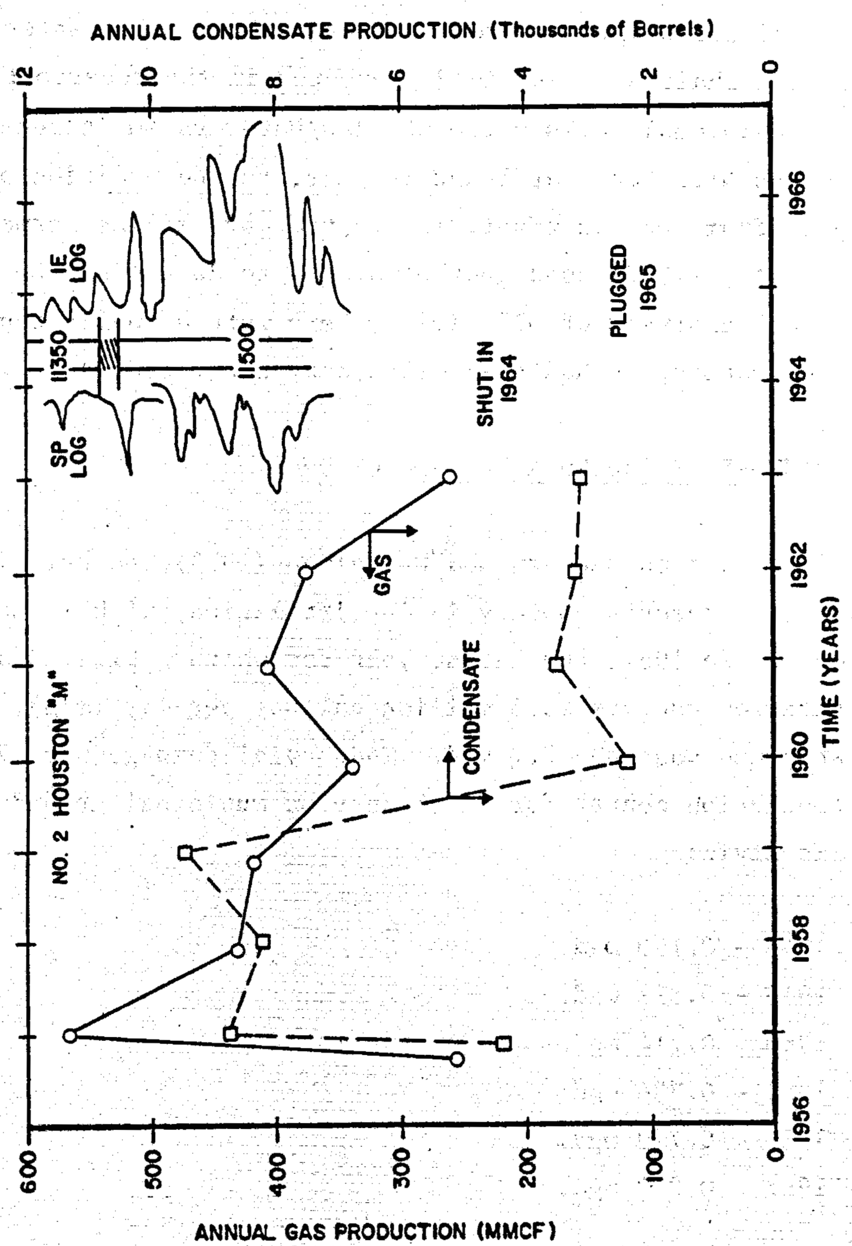


FIGURE 22 PRODUCTION HISTORY OF PHILLIPS NO. 2 HOUSTON "M," CHOCOLATE BAYOU FIELD (from Bebout et al , 1978) (See Figure 12 for well location)

Changes in the chemical character of water produced with oil and gas may provide a clue as to whether shale compaction is occurring in the reservoir. Fowler (1970) noted a general trend toward decreasing salinity with time in the water produced in Chocolate Bayou. He attributed this to dilution of the original formation waters by fresher water released by the compacting shale beds as fluid pressures in the reservoir were drawn down. For individual wells where the gas/water ratio increased with time, freshening was attributed at least in part, to the addition of condensed water vapor (from the gas reservoir) to the more saline formation waters. Kharaka, et al., (1977) used geothermometry to determine the degree to which chemical analyses of oil field waters were actually representative of formation waters, or had been diluted by condensed water vapor.

3.3 HISTORY OF GROUNDWATER PRODUCTION

According to Sandeen and Wesselman (1973) the principal use of groundwater in Brazoria County is for irrigation, with industrial use being second. In 1967, the latest year for which published data are available, irrigation use was 22.6 million gallons per day (mgd), while municipal and domestic use was only 7.7 mgd. Industrial pumpage was 12.7 mgd. The nearest population center for which data on municipal groundwater use are reported is Alvin:

1945 - 0.150 mgd.
1955 - 0.517 mgd.
1960 - 0.714 mgd.
1965 - 0.736 mgd.
1966 - 0.719 mgd.
1967 - 0.852 mgd.

Angleton, about 15 miles southwest of Chocolate Bayou has a similar groundwater consumption history:

1945 - 0.100 mgd.
1955 - 0.459 mgd.
1960 - 0.566 mgd.
1965 - 0.957 mgd.
1966 - 0.901 mgd.
1967 - 0.917 mgd.

Use of groundwater in the county since the early 1900's has resulted in considerable pressure decline in the two principal aquifers, the Chicot and Evangeline (see discussion above). In the Chocolate Bayou area, production has been mainly from the Chicot, probably partly because the lower sands of the Evangeline are saline. Figure 6 shows that the amount of head decline in the Chicot between 1943 and 1973 was approximately 50 feet in the Chocolate Bayou area.

Table 3 shows representative water levels for wells in the Chocolate Bayou area. The aquifers tapped by the wells in Table 3 are as follows:

BH-65-46-601 - Upper Chicot
BH-65-46-801 - Upper Chicot
BH-65-47-201 - Lower Chicot
BH-65-47-401 - Chicot

Also shown in Table 3 is a hydrograph (1946-1968) for well BH-65-47-401, located in the Chocolate Bayou field. This hydrograph shows a decline in water levels of over 63 feet, through 1968, and the water level records suggest an additional decline of several feet from 1969-1974. A comparison

Table 3 Water Levels in Wells Near the Chocolate Bayou Field (In Feet Below Land Surface)*

Well A: BH-65-46-601
Stanolind Oil & Gas Co.
Elevation: 23
Depth: 226 Feet

Well B: BH-65-46-801
Exxon Company
Elevation: 26
Depth: 311 Feet

Date	Level	Date	Level
July 19, 1946	7.98	July 29, 1946	1.89
Jan. 3, 1949	7.20	Jan. 4, 1949	12.13
Aug. 19, 1949	6.72	Aug. 29, 1949	8.38
Jan. 16, 1950	6.55	Jan. 17, 1950	3.52
Aug. 21, 1950	6.85	Aug. 30, 1950	4.63
Jan. 12, 1951	7.20	Jan. 15, 1951	4.50
Aug. 23, 1951	8.10	Jan. 11, 1952	9.79
Jan. 11, 1952	8.27	Aug. 14, 1952	6.52
Aug. 14, 1952	7.80	Jan. 15, 1953	7.73
Jan. 15, 1953	7.89	July 23, 1953	7.60
July 23, 1953	8.41	Jan. 29, 1954	4.71
Jan. 29, 1954	7.17	Aug. 4, 1954	10.48
Aug. 4, 1954	8.71	Aug. 19, 1955	10.84
Aug. 19, 1955	10.24	Jan. 20, 1956	8.87
Jan. 20, 1956	10.23	Aug. 3, 1956	9.70
Aug. 3, 1956	13.96	Jan. 25, 1957	13.28
Jan. 25, 1957	14.61	Aug. 9, 1957	8.95
Aug. 12, 1957	15.28	Jan. 22, 1958	7.57
Jan. 22, 1958	14.55	Aug. 8, 1958	8.15
Aug. 8, 1958	12.84	Aug. 26, 1960	5.01
Aug. 13, 1959	9.94	Jan. 23, 1961	4.15
Aug. 3, 1960	13.27	Aug. 18, 1961	4.03
Jan. 23, 1961	8.53	Jan. 22, 1962	3.95
Jan. 22, 1962	10.07	Aug. 15, 1962	4.49
Aug. 15, 1962	10.14	Feb. 1, 1963	5.05
Jan. 31, 1963	11.72	Aug. 27, 1963	7.58
Aug. 27, 1963	9.54	Feb. 3, 1964	5.98
Aug. 12, 1964	9.43	Aug. 12, 1964	6.30
Jan. 28, 1965	9.10	Jan. 21, 1965	6.41
Aug. 11, 1965	10.00	Aug. 11, 1965	6.89
Jan. 20, 1966	8.97	Jan. 20, 1966	7.38
Jan. 25, 1967	8.58	Jan. 25, 1967	5.59
Aug. 11, 1967	10.27	Aug. 11, 1967	6.21
Jan. 22, 1968	8.72	Jan. 26, 1968	5.98
Jan. 28, 1970	9.79	Aug. 6, 1968	5.39
Aug. 12, 1971	10.07	Jan. 29, 1969	5.68
Aug. 15, 1972	8.27	Aug. 14, 1969	5.97
		Jan. 22, 1970	6.27
		Aug. 11, 1970	5.21
		Jan. 13, 1971	4.77

*Data from Sandeen and Wesselman, 1973 and Naftel, et al., 1976.

Table 3 -- Continued.

Well C: BH-65-47-201
Texaco, Inc.
Elevation: 26
Depth: 691 Feet

Well D: BH-65-47-401
Phillips Petroleum Co.
Elevation: 23
Depth: 400 Feet

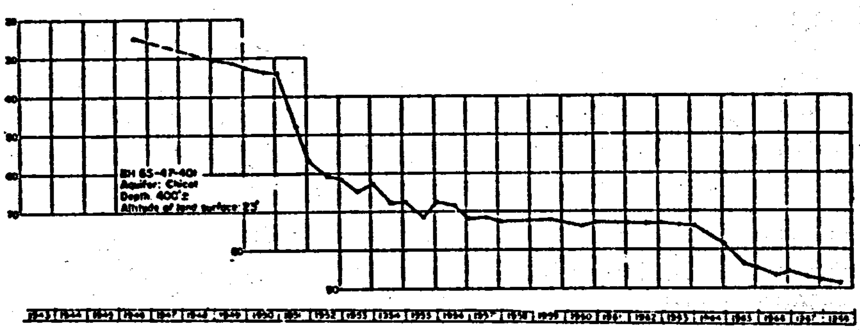
Date	Level	Date	Level
Jan. 12, 1951	77.04	July 25, 1946	24.80
Jan. 11, 1952	80.22	Jan. 3, 1949	30.87
July 23, 1953	84.80	Aug. 19, 1949	31.55
Jan. 20, 1956	87.57	Jan. 16, 1950	32.29
Aug. 3, 1956	91.80	Aug. 21, 1950	33.46
Jan. 25, 1957	91.03	Jan. 12, 1951	33.76
Aug. 12, 1957	93.55	Aug. 23, 1951	47.44
Jan. 22, 1958	90.33	Jan. 11, 1952	56.57
Aug. 8, 1958	94.07	Aug. 14, 1952	60.72
Aug. 13, 1959	94.62	Jan. 15, 1953	61.39
July 22, 1960	97.62	July 23, 1953	64.72
Jan. 23, 1961	93.55	Jan. 29, 1954	62.83
Jan. 22, 1962	94.71	Aug. 4, 1954	67.81
Aug. 15, 1962	97.86	Jan. 31, 1955	67.40
Feb. 1, 1963	95.85	Aug. 19, 1955	71.33
Aug. 27, 1963	100.16	Jan. 20, 1956	67.34
Feb. 3, 1964	97.62	Aug. 3, 1956	68.19
Jan. 21, 1965	99.40	Jan. 25, 1957	71.70
Aug. 11, 1965	103.48	Aug. 12, 1957	71.26
Jan. 20, 1966	100.55	Jan. 22, 1958	72.31
Aug. 15, 1966	103.82	Aug. 13, 1959	71.92
Jan. 25, 1967	102.72	Aug. 26, 1960	73.49
Aug. 11, 1967	106.94	Jan. 23, 1961	72.50
Jan. 26, 1968	105.04	Jan. 22, 1962	72.99
Aug. 12 1968	107.57	Aug. 15, 1962	73.01
Jan. 29, 1969	109.30	Jan. 31, 1963	72.78
Aug. 14 1969	111.47	Aug. 27, 1963	73.02
Jan. 28, 1970	113.74	Feb. 3, 1964	73.32
Jan. 22. 1971	114.36	Jan. 21, 1965	78.30
Jan. 19, 1972	116.96	Aug. 11, 1965	83.80
Aug. 15 1972	120.78	Jan. 20, 1966	84.71
Jan. 29, 1973	119.58	Aug. 15, 1966	86.40
Jan. 22, 1974	121.87	Jan. 25, 1967	85.61

*Data from Sandeen and Wesselman, 1973 and Naftel, et al., 1976.

Table 3 -- Continued.

Well D - Continued: BH-65-47-401

Date	Level
Aug. 11, 1967	86.96
Jan. 22, 1968	87.76
Aug. 5, 1968	88.49
Jan. 27, 1969	89.10
Aug. 14, 1969	90.64
Jan. 22, 1970	92.23
Aug. 12, 1970	92.77
Jan. 18, 1971	94.10
Aug. 12, 1971	94.67
Jan. 19, 1972	95.47
Aug. 15, 1972	96.57
Jan. 29, 1973	97.20
Aug. 7, 1973	95.91
Jan. 22, 1974	86.13
Aug. 9, 1974	87.18



Hydrograph of Well No. BH-65-47-401

of this well with other wells in Table 3 shows that the two shallower wells (screened in the unconfined Upper Chicot), have not had substantial water level declines, whereas the other deep well, which taps the Lower Chicot, has had a head decline of nearly 45 feet over the 23 year period, 1951 to 1974.

Detailed data on groundwater production are not consistently available for the Chocolate Bayou area. Published data on extractions are either for Brazoria County as a whole, or for specific municipalities. Some data have been assembled in grid format by the U.S. Geological Survey for use in hydrological modeling of the Houston-Galveston area. These data, made available by Robert Gabrysch at the U.S. Geological Survey in Houston show that the only areas near Chocolate Bayou where average groundwater consumption in recent years has exceeded one million gallons per day (mgd), are at Marvel and Alvin. These areas are also among the few where groundwater consumption is still increasing. The general trend over the past few years has been to stabilized or decreased pumpage from groundwater aquifers.

The available data for the Chocolate Bayou field show that since 1961, groundwater usage has been less than about .02 mgd per square mile, which is lower than most other areas in the vicinity. This number is probably a minimum, however, because it is an estimate based on the power consumption and efficiencies of the larger wells in the Chocolate Bayou area. Despite low extraction rates, the Chocolate Bayou area has almost certainly been affected by pumping from the Chicot aquifer in adjacent Galveston County.

4. SUBSIDENCE

4.1 LOCATION AND AMOUNT

Land surface subsidence in the Houston-Galveston region has been well documented (Gabrysch, 1970 and 1977; Gabrysch and Bonnet, 1975; Kreitler, 1976 and 1977). The primary cause of subsidence in this area has been groundwater overdraft to meet spiraling municipal, industrial, and agricultural water needs. Between 1943 and 1974, over seven feet of subsidence occurred near Houston, in Harris County. During the same period fewer than two feet of subsidence occurred in east-central Brazoria County as shown in Figure 23.

The national Geodetic Survey has several lines of benchmarks for vertical control in the Chocolate Bayou area, which have been surveyed to first order precision.* These lines are shown diagrammatically in Figure 24, and are described below:

1. Line 101 along the Missouri Pacific Railroad between Angleton and Algoa;
2. Line 101 from Algoa to northwest of Alvin along the Atchison, Topeka and Santa Fe Railroad;
3. Line 108 from Algoa to Hitchcock along the Atchison, Topeka and Santa Fe Railroad; and
4. Line 107 south and west of Alta Loma.

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*First order precision is defined as the maximum difference between forward and backward sights of (4mm) x $\sqrt{\text{distance in km}}$.

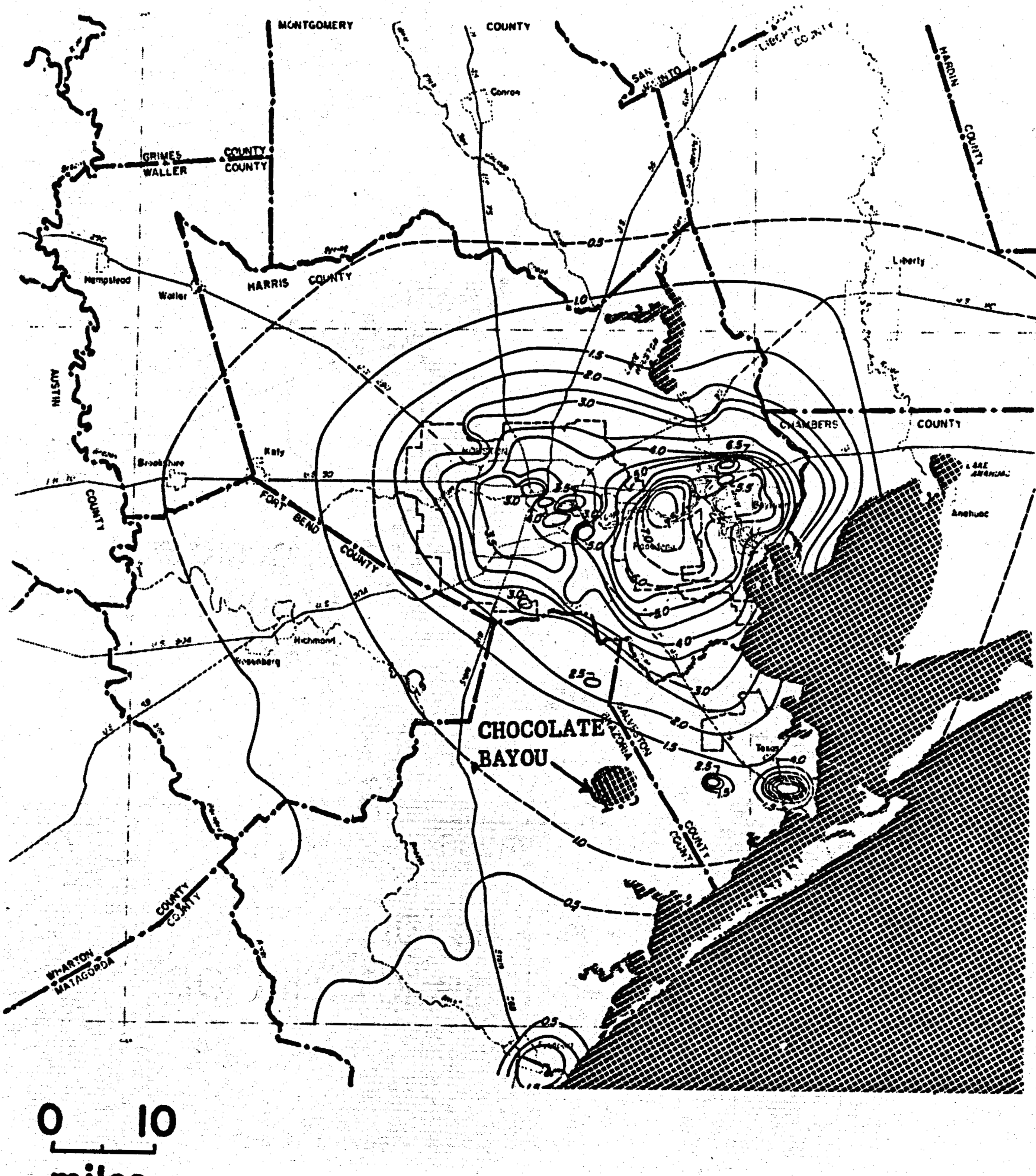

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FIGURE 23 SUBSIDENCE OF THE LAND SURFACE IN THE HOUSTON-GALVESTON REGION, 1943-1978 (from Gabrysch and Bonnet, 1975)

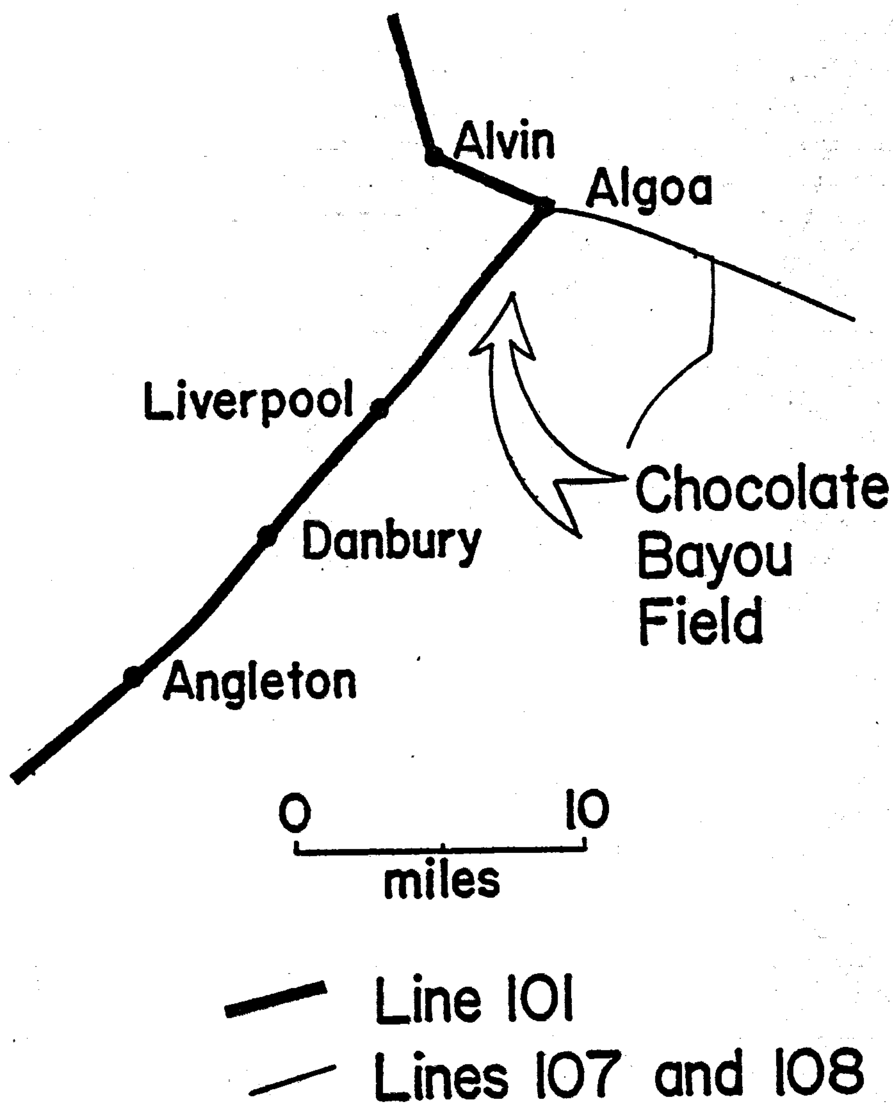

FIGURE 24 FIRST ORDER LEVELING

Second order leveling (maximum difference between forward and backward sights of 8 mm x $\sqrt{\text{distance in km}}$), has also been done along lines south from Liverpool and southeast and west of Danbury. However, second order leveling is not considered to be sufficiently precise for use in subsidence studies of this type.

Of the first order lines available, only line 101 has been re-leveled frequently enough for use in a detailed subsidence analysis. The original benchmarks were surveyed in 1918, and the most recent releveling was done in 1973. Line 108 was leveled to first order precision in 1951, 1954 (only a few points), 1959, 1964 and 1973, but is several miles from the main Chocolate Bayou field.

An examination of elevation changes along line 108 between the years 1951 and 1973 shows that the benchmarks have subsided 0.987 to 1.273 feet. Subsidence on all the benchmarks surveyed in both 1951 and 1973 is 1.13 ± 0.15 feet as shown below.

Hitchock ↑

Benchmark	Subsidence 1951-73 (In Feet)
N 456	1.024
R 305	0.087
B 901	1.273
S 305	1.119
C 753 Reset 1951	1.227
Alta Loma, Rm 1	1.250
Alta Loma, Rm 2	1.263
V 305	1.073
P 456	0.991

↓ Algoa

A subsidence profile for Line 101 between Angleton and Algoa has been prepared by Lofgren (1977) as shown in Figure 25. The year 1943 was chosen as the base line for this profile because the majority of the benchmarks were surveyed in that year. (See Figure 12 for location of benchmarks.) Maximum subsidence on this line, between 1943 and 1973, was 1.8 feet for benchmark K 691, which is in good agreement with the 1.5 feet shown on the regional map, Figure 23.

The year 1950 was used as a baseline for a profile of Line 101 from Algoa to Alvin, as shown in Figure 26. Where available, earlier data has also been shown for comparison. Maximum subsidence on this line for the period 1950 to 1973 was 1.256 feet at benchmark W53. From 1918 to 1973, this benchmark subsided a total of 1.899 feet (see Figure 12 for location of benchmarks used in Figure 26). It is interesting to note that subsidence has not been appreciably greater at Alvin, where groundwater use is relatively high, than at other points along the profile.

4.2 INSTRUMENTATION

Unfortunately, no instruments for measuring subsidence (such as compaction recorders or tiltmeters) are presently installed in the Chocolate Bayou area, so that measurements of vertical distribution of compaction, or horizontal movements are not available. No damage to the wells at Chocolate Bayou has been reported (Bill Fowler, Phillips Petroleum Company and Frank Wellborn, Jr., Texaco, oral communication) nor has any other surface effect of subsidence been noted.

4.3 SUBSIDENCE CHARACTERISTICS

4.3.1 Subsidence Rates

Table 4 shows how average subsidence rates have increased since initial leveling of Line 101 by the Geodetic Survey in 1918. It is notable

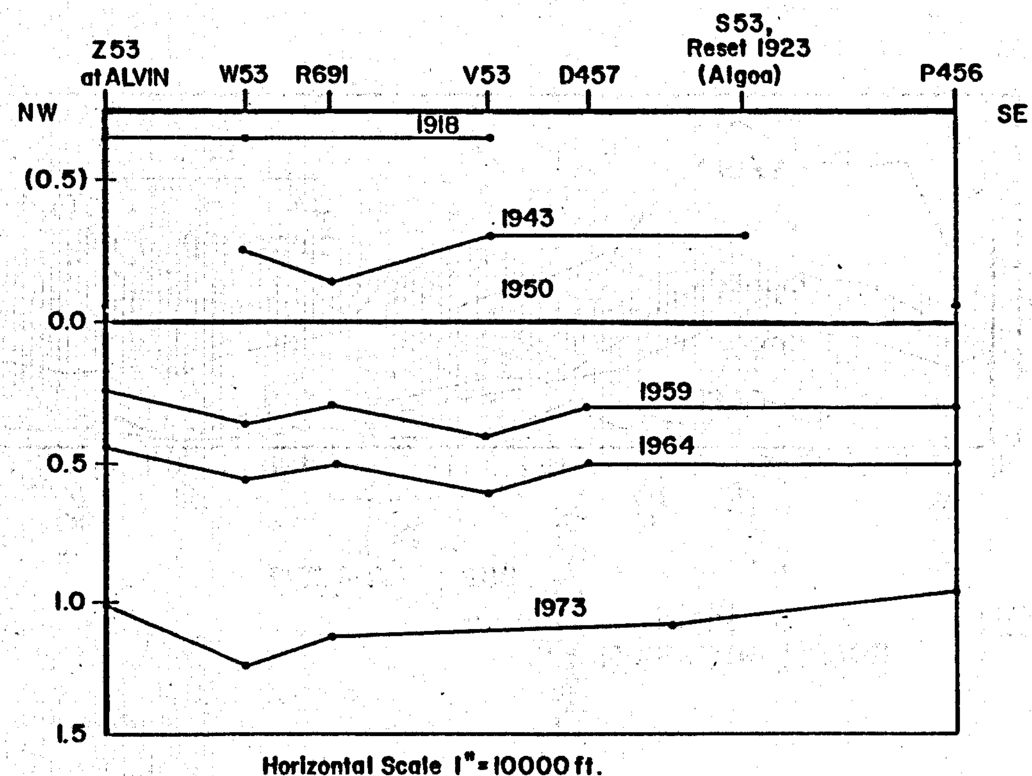

FIGURE 25 SUBSIDENCE PROFILES FROM ANGELTON TO ALGOA ACROSS THE CHOCOLATE BAYOU FIELD, 1943 to 1973 (from Lofgren, 1977)

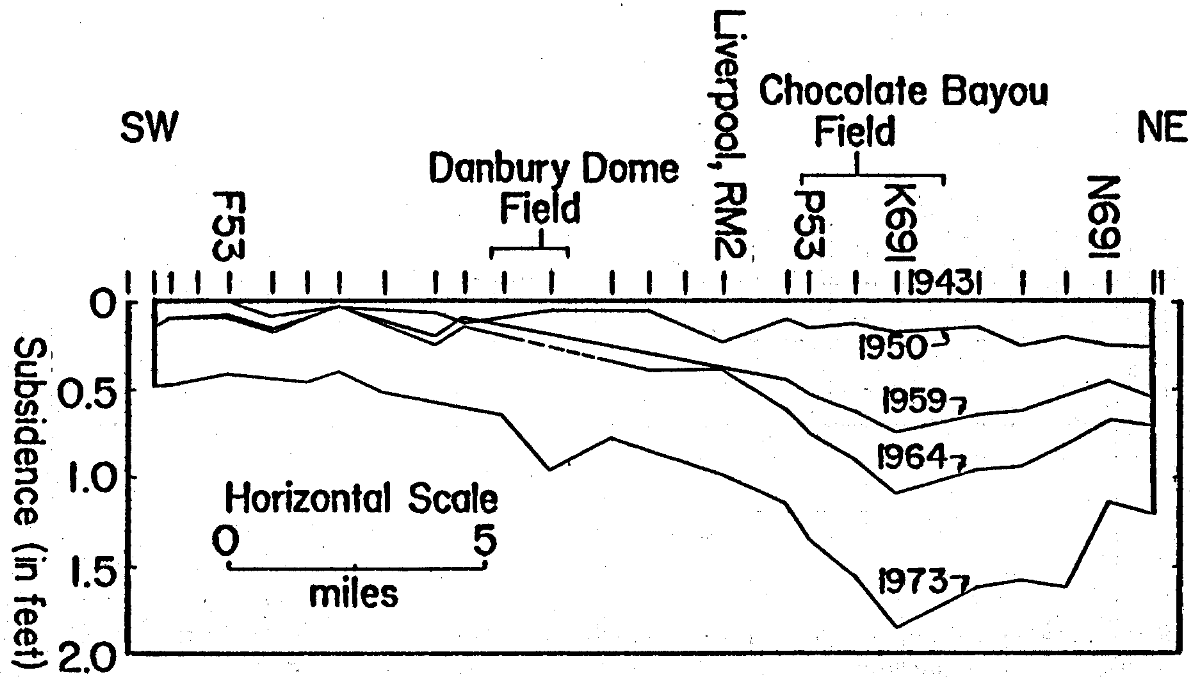

FIGURE 26 SUBSIDENCE PROFILE FROM ALVIN TO SOUTHEAST OF ALGOA

Table 4 Comparison of Average Subsidence Rates From 1918-1943 and From 1964-1973 for Benchmarks Leveled in 1918 Survey (First-Order)

Benchmark	Average Subsidence Rate 1918-1943	Average Subsidence Rate 1964-1973	Approximate Amount Increase in Rate
Angleton to Algoa:			
F 53	.00708 Ft/Yr	.03611 Ft/Yr	~ 5X
H 53	0.0 Ft/Yr	.04011 Ft/Yr	-
I 53	.00604 Ft/Yr	Not Recovered in 1973	-
P 53	.00328 Ft/Yr	.06489 Ft/Yr	~20X
R 53	.00564 Ft/Yr	.07211 Ft/Yr	~13X
Algoa to Alvin:			
V 53	.01508 Ft/Yr	Destroyed After 1964	-
W 53	.01732 Ft/Yr	.08266 Ft/Yr	~ 5X
Z 53	.01968* Ft/Yr	.07111 Ft/Yr	~3½X

*1918-1950 Average

that in the early 1900's, subsidence rates were about twice as high near Alvin and Algoa as at Angleton. It is also apparent that subsidence rates have increased dramatically in the Chocolate Bayou area (benchmarks P53 and R33) since the early surveys. Rates in the area surrounding the field have also increased, but to a much lesser extent. Figure 27 illustrates these relationships graphically. The subsidence history of each benchmark which was repeatedly releveled is shown individually.

An examination of Figure 27 shows several interesting relationships. First, the rate of subsidence (equivalent to the slope of the lines) has not changed greatly since the 1950 releveling for benchmarks northeast of H691, while benchmarks southwest of H691 show a rapid increase in subsidence rate after the 1964 releveling. Factors which could have contributed to these differences are that at Angleton, average ground water consumation nearly doubled between 1960 and 1965, to reach its current level of about 1 mgd. Benchmarks near the Chocolate Bayou field may have been affected by the onset of major oil production, beginning in the late 1940's. In both cases, there is probably some lag time between fluid extraction and surface expression of compaction at depth.

Another significant pattern shown by Figure 27 is that although hydrocarbon production at the Chocolate Bayou field has been decreasing since 1964, the average rate of subsidence from 1964 to 1973 was greater than from 1959 to 1964 for all benchmarks, especially those from H691 to the northwest, across the field. If extraction of oil, gas and brine from the field has contributed to subsidence, then the fact that subsidence rates are still increasing suggests that there is probably a lag time of at least several years between extraction of deep fluids and the appearance of subsidence effects at the surface. The groundwater extraction data compiled by the U.S. Geological Survey indicates that pumpage in the east-central part of Brazoria County has generally not increased rapidly since

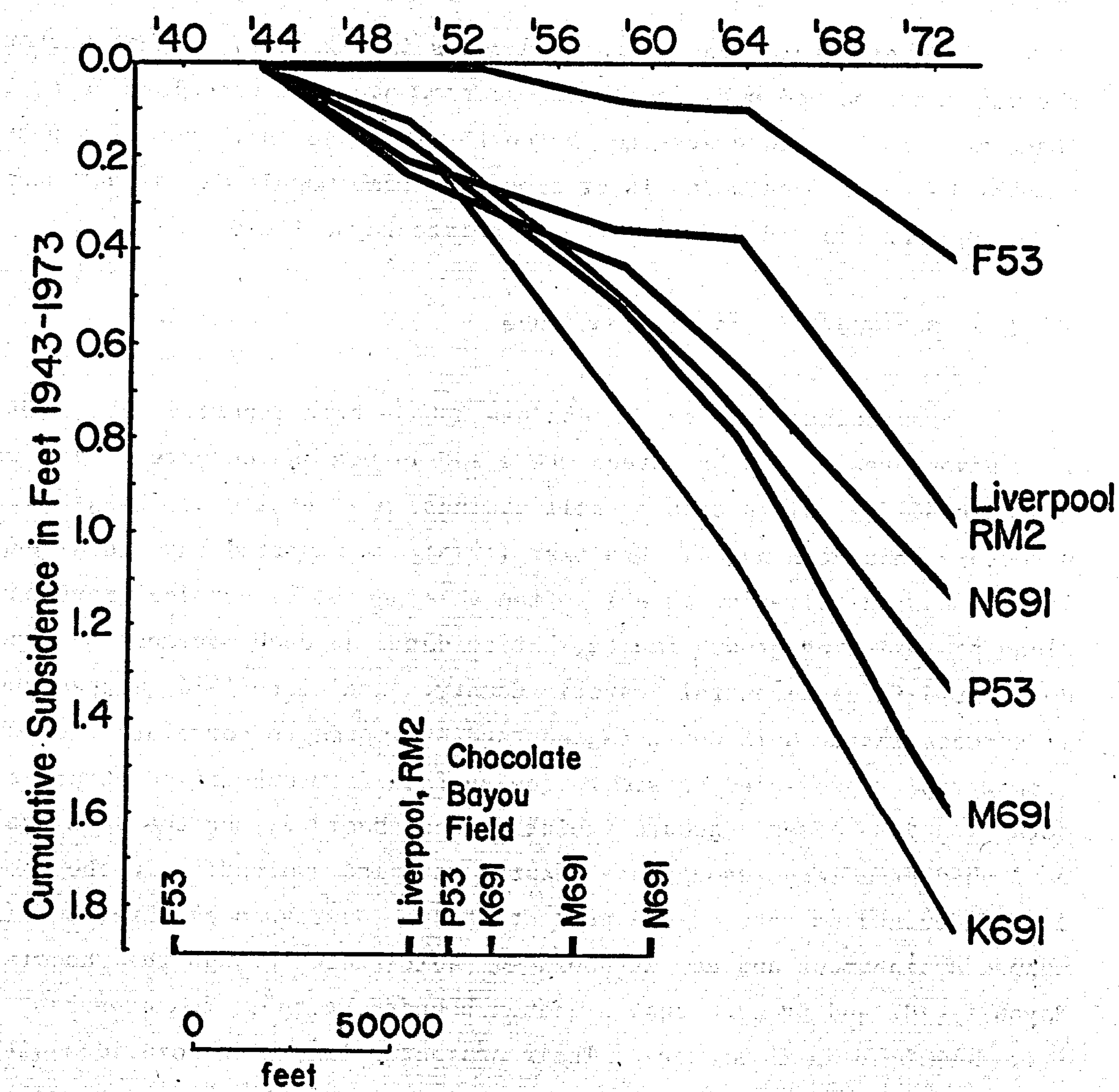

FIGURE 27 SUBSIDENCE OF INDIVIDUAL BENCH MARKS IN THE CHOCOLATE BAYOU AREA

the 1960's, so that the steepening of curves on Figure 27 should not be directly attributable to increasing groundwater use, except perhaps at Angleton.

A third relationship which appears in Figure 27 is that although the maximum observed subsidence has occurred over the Chocolate Bayou field (benchmark K691), benchmarks to the north (W53) and northwest also show cumulative subsidence which is of about the same magnitude as that shown by benchmarks P53 and J691, in the Chocolate Bayou field.

4.3.2 Surface Effects of Subsidence

No surface effects of subsidence have been reported in the Chocolate Bayou area. In other areas where subsidence has occurred, faulting, ground cracking, disruption of well casings, and settlement damage to structures has been noted. Kreitler (1976) has reported that subsidence in the Houston-Galveston area is often accompanied by vertical movement along pre-existing growth faults, but to date, no such movement has been documented in east-central Brazoria County. Kreitler (1976) mapped photo lineaments in the Gulf Coast region, and attempted to correlate them with growth faults projected upward to the surface from subsurface structural data. In some cases a good correlation was observed, but the data are not published at a large enough scale for a detailed evaluation in the Chocolate Bayou and as part of the present study. Gustavson and Kreitler (1976) mapped a lineament and an extrapolated fault trace through the Chocolate Bayou field, and proposed that a graben bounded by these features has been developed in this area. Their projected lineament coincides with benchmark P53 on Figure 25, and the extrapolated fault trace intersects the profile between benchmarks M691 and N691. It is not known whether these features can be traced across the Alvin to Algoa profile, Figure 26.

Although it is certainly possible that subsidence at Chocolate Bayou has been controlled by existing faults, further study, including surface mapping or perhaps trenching of the linear features would be necessary before a definite relationship between subsidence and existing fault traces can be established.

4.4 CAUSES OF SUBSIDENCE

Major factors which could contribute to the observed subsidence at Chocolate Bayou are tectonic movements, groundwater production, and deep oil-and-gas production. Tectonic movements are known to be occurring on the Gulf Coast, but would probably not be a primary factor within a restricted area such as Chocolate Bayou particularly over a time period of only 30 years. For this reason, the principal causes are believed to be production of groundwater, oil and gas.

In order to determine the maximum amount of subsidence which would be possible from groundwater production an empirical relationship between subsidence, head decline, and percent clay in the production zone has been used. This correlation was developed for the Houston-Galveston area by Gabrysch in 1970 (see Figure 28). In a previous section of this report, it was reported that nearly all pumpage was from the Chicot aquifer, with a total sand thickness of 155 to 310 feet, which extends to elevation -810, a depth of approximately 785 feet beneath the Chocolate Bayou field. Since clay content is highly variable within the aquifer, percent of clay has been computed based on the estimated sand thickness in the vicinity of benchmark K691. From Sandeen and Wesselman (1973), these sand thicknesses are approximately 65 feet for the Upper Chicot and 120 feet for the Lower Chicot, or a total of 185 feet of sand. Thus, percent clay is computed as follows:

$$\frac{785 - 185}{785} = 76.4 \text{ percent}$$

Using a head decline of 50 feet, the graph in Figure 28 gives an estimated 1.05 to 1.3 feet of subsidence which could be attributed to groundwater production near benchmark K691. This value is believed to be conservative, based on the somewhat higher sand percents given by Kreitler, et al., (1977), (30 to 40 percent sand in the upper 1000 feet). If accumulative sand thickness is taken at 40% of the total thickness, estimated subsidence (using Figure 28) would be less than one foot.

Another estimate of subsidence as a result of head decline was made by Sandeen and Wesselman (1973, p. 49) who compared subsidence at four benchmarks with water-level measurements in a nearby well. The well, completed in the Upper Chicot was located in Freeport about 25 miles south of the Chocolate Bayou field. Their comparison showed a subsidence to head decline ratio of 1 to 100 for this location. This would suggest that less than 1 foot of the subsidence of Chocolate Bayou is due to groundwater withdrawal.

The form of the leveling profiles, Figures 25 and 26, suggests that some of the observed subsidence southwest of Algoa is due to hydrocarbon production from the Chocolate Bayou field. The Missouri-Pacific Railroad, along which the benchmarks of the Angleton to Algoa leveling line are located, crosses the southeast edge of the West Chocolate Bayou block of the field. Gustavson and Kreitler (1976) compared the average rates of subsidence with hydrocarbon production and concluded that the maximum subsidence rates were coincident with periods of maximum gas production from the geopressured zone.

Other evidence, some of which was not available to Gustavson and Kreitler, suggests that the principal cause of subsidence from development of the field is the extraction of oil and brine. The benchmarks along the Missouri-Pacific Railroad are located on the West Chocolate block of the

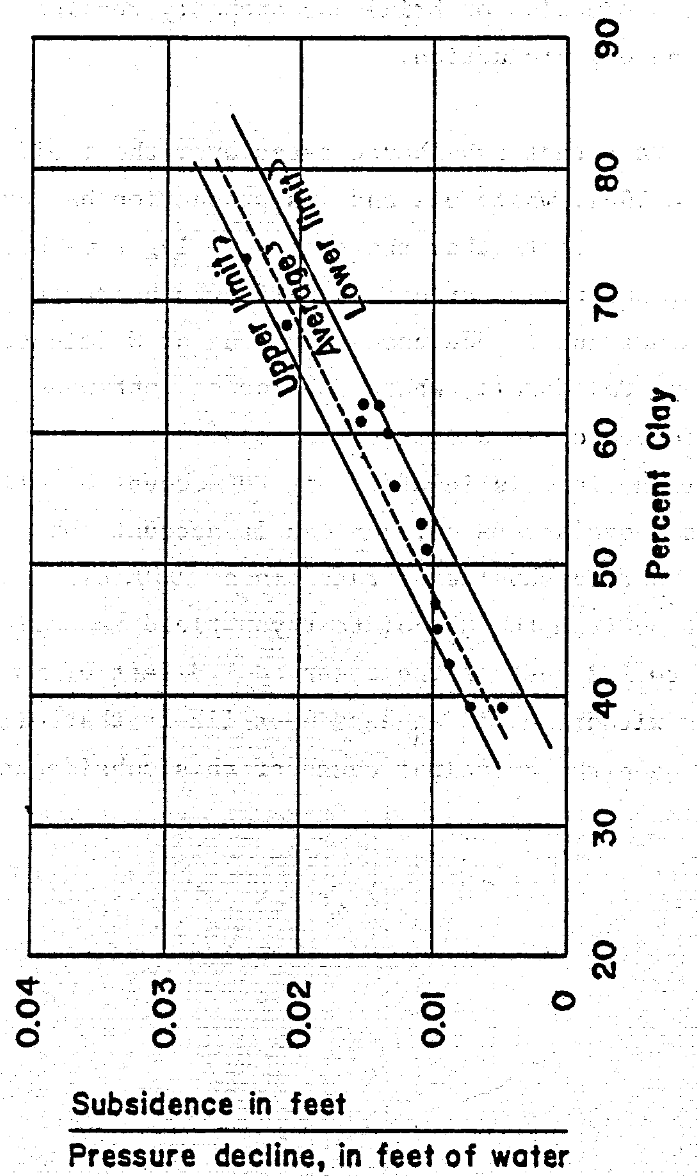

FIGURE 28 RELATION BETWEEN PERCENT CLAY AND SUBSIDENCE DUE TO PRESSURE DECLINE IN HOUSTON AREA (from Gabrysch 1970)

field, which produces mainly oil and brine from an average depth of about 9500 feet (see Figure 11). Maximum rate of oil production also corresponds to the marked increase in the subsidence rate after 1950, as shown in Figure 22. Although oil production has declined significantly since the early 1960's, production of brine has probably remained steady or increased with decreasing oil production.

The fact that subsidence rates over the field have continued to increase since 1964, while oil and gas production has dropped to a fraction of peak values, suggests that there is some lag time between fluid extraction at depth, and the occurence of surface subsidence. This fact has been observed in other subsidence cases, such as at Wilmington and in the San Joaquin Valley, California, where subsidence continued after fluid extractions were stopped or stabilized. In conclusion, it appears that groundwater extraction alone is insufficient to account of all of the observed subsidence at Chocolate Bayou, nor can it account for the continuing increase in observed subsidence rate since 1950. Oil and gas with associated brine production from the Chocolate Bayou field is believed to have caused at least 0.5 to 1.2 feet of the observed 1.8 feet of maximum subsidence. Of the fluids withdrawn, it appears most likely that oil and brine extraction has been the principal cause of this subsidence.

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RAFT RIVER VALLEY

TABLE OF CONTENTS

1. INTRODUCTION

Raft River Valley, Idaho has had up to 2.6 feet of subsidence due to ground water overdraft. This subsidence, which has occurred in the northern part of the valley, probably began in the early 1950's and has been documented by releveling a line of bench marks established in 1934 and 1958. After a maximum head decline of more than 50 feet in fifteen years, water levels have stabilized since 1970. The effect of rising water levels on total subsidence and subsidence rate is not yet known, but may be analyzed after the scheduled 1978 releveling.

Subsidence in the Raft River Valley is of particular interest because of geothermal development in the southern part of the valley. The existing geologic and hydrologic data suggest that some communication probably occurs between shallow ground water and deeper geothermal reservoirs, so that a study of subsidence due to shallow ground water extraction may be useful in assessing potential for subsidence resulting from geothermal development.

Chemical analyses of water samples suggest that all ground waters in the valley, including thermal waters, are meteroric in origin. Since the Raft River drainage basin does not receive surface water or ground water flows from other basins, both the ground water and geothermal reservoirs are probably recharged by infiltration of the annual precipitation - approximately 15 inches per year. Thus, it is possible that extraction from geothermal reservoirs could affect ground water levels over the long term, causing additional subsidence. Proposed reinjection of geothermal waste water would help mitigate this possibility.

Potential subsidence due to decreased pore pressure and resultant compaction of sediments within and immediately above geothermal reservoirs cannot be definitely analyzed without additional data on stratigraphy of the basin and physical properties of individual sedimentary horizons.

2. NATURAL CONDITIONS

2.1 PHYSIOGRAPHY

Raft River Valley lies in Cassia County in south-central Idaho (Figure 1). The 15 by 40 mile valley includes parts or all of T10S to T16S and R26E to R28E. Highways 81, 30S and 80N traverse the valley and connect all the small rural communities of Idahome, Malta, Bridge, and Strevell.

The Raft River rises at the drainage divide adjacent to the Great Basin geomorphic province, flows through a series of north-trending Basin and Range valleys, and empties onto the Snake River Plain slightly above Lake Walcott (Figure 1). From its headwaters, southwest of Raft River Valley, the river flows through Junction Valley, through a constriction known as the Upper Narrows and into Upper Raft River Valley. The stream then flows through another constriction, the Narrows, and into Raft River Valley, and thence northward through the flat-floored valley and into Snake River (Figure 2).

Mountain ranges of differing character surround the Raft River Valley on three sides. The Malta, or Cotterel, Range lies to the west and rises about 2500 feet above the valley floor. This is a tilted volcanic capped block having a gentle western slope and a steep eastern slope. Cassia Creek divides the range near its midpoint into the Cassia Mountains to the north and the Jim Sage Mountains to the south. The Raft River Mountains comprise an east-west-trending domal range that rises about 4500 feet above the valley floor, and forms the southern limit of Raft River Valley. To the east and southeast, the valley is bounded by the Black Pine and Sublett Ranges (Figure 1) which rise some 3000 to 3500 feet above the valley floor.

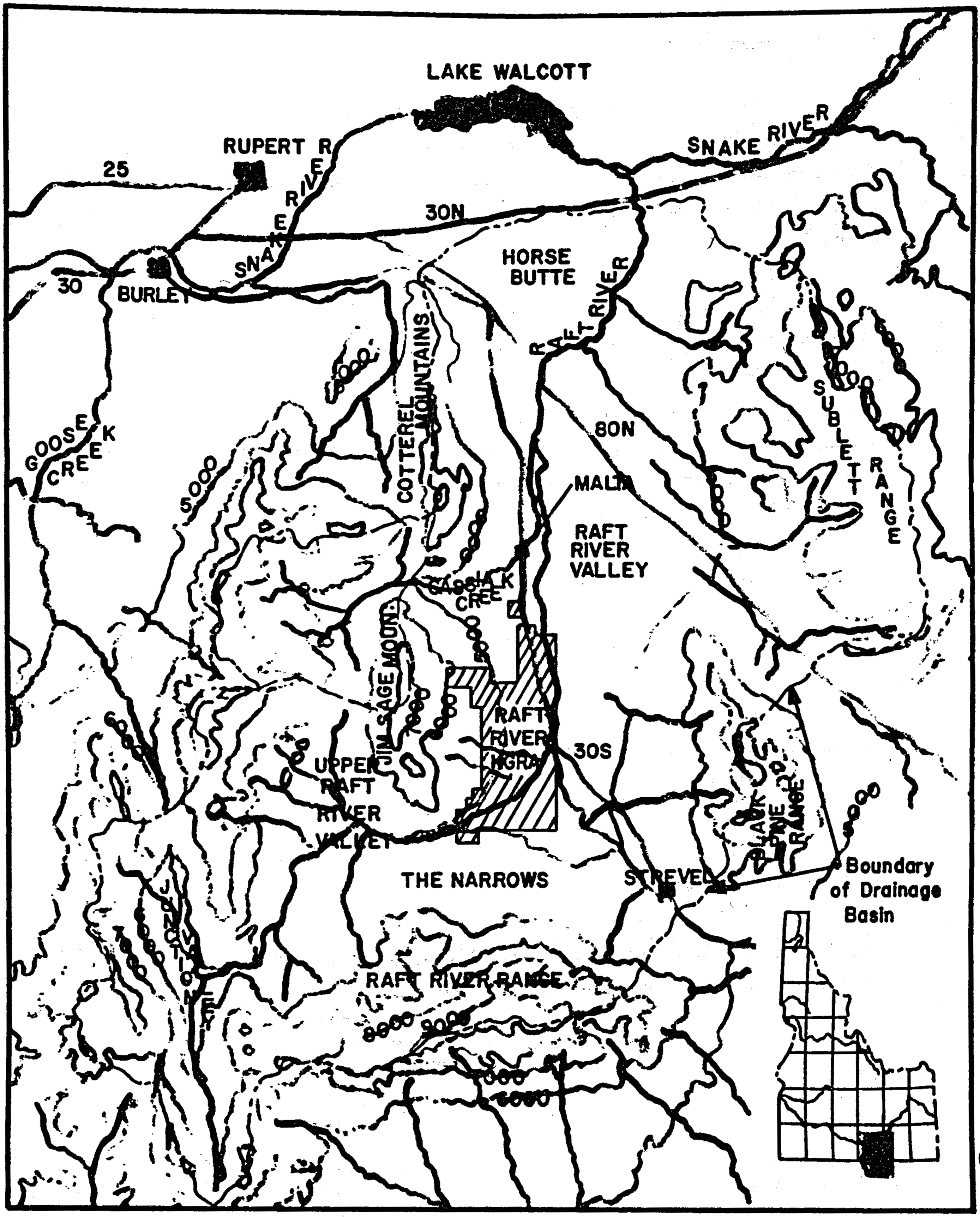

LAKE WALCOTT
RUPERT
25
SNAKE RIVER
30N
HORSE BUTTE
30
BURLEY
RAFT RIVER
GOOSE CREEK
5000
COTTEREL MOUNTAINS
80N
MALTA
SUBLETT RANGE
RAFT RIVER VALLEY
CASSIA CREEK
JIM SAGE MOUN.
RAFT RIVER KGRA
30S
UPPER RAFT RIVER VALLEY
BLACK PINE RANGE
THE NARROWS
STREVELL
Boundary of Drainage Basin
JUNCTION VALLEY
RAFT RIVER RANGE
8000
9000
6000

FIGURE 1

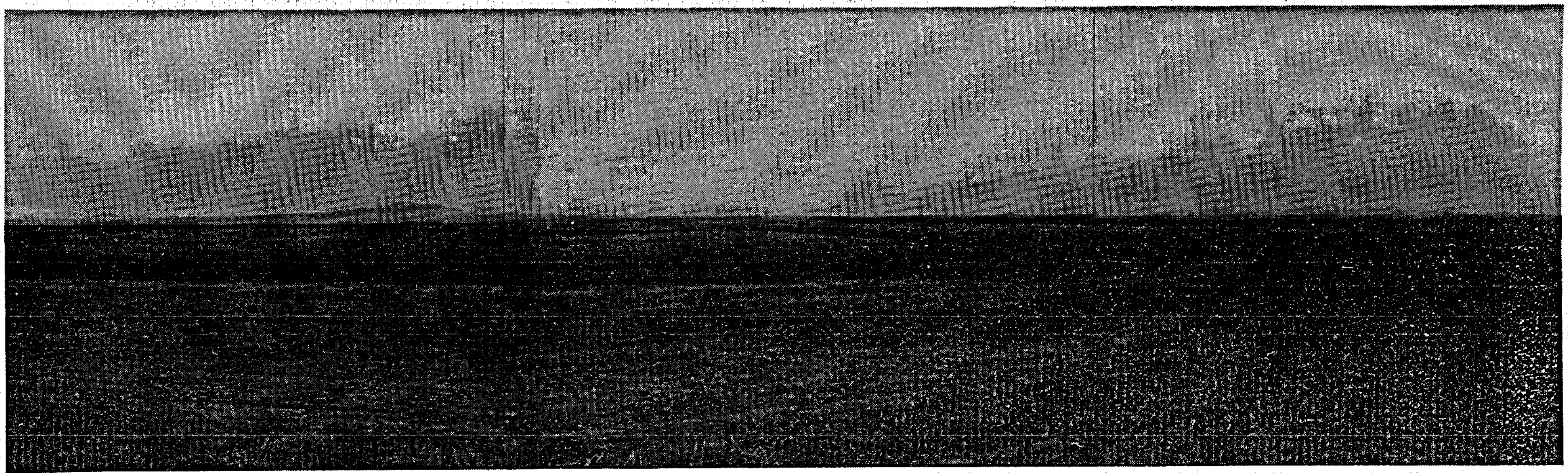


FIGURE 2 PANORAMIC VIEW OF THE RAFT RIVER VALLEY

The arid climate of this part of Idaho supports a grass-sage-brush-greasewood plant association on the valley floor, while juniper, lodge pole pine, douglas fir, and spruce grow on the higher slopes and mountains. Agriculture supports the local economy, where wheat, alfalfa, potatoes, seed crops, sugar beets, sheep, and cattle are the main produce.

2.2 GEOLOGY

The earliest geologic investigations of the Raft River area were reconnaissance studies of eastern Cassia County, begun in 1928 and published by Anderson in 1931. This work, as later modified by Walker et al., (1970), is still the most detailed published investigation available for most of the Raft River Valley. The U.S. Geological Survey and others have an on-going project in the Raft River geothermal area in the southwestern portion of the valley. Data from this project are being released as open-file reports and include gravity measurements (Mabey and Wilson, 1974); aeromagnetic data (USGS, 1974); seismic refraction measurements (Ackermann, 1975); audiomagneto-telluric soundings (Hoover); Schlumberger sounding (Zohdy et al., 1975); geologic mapping (Williams et al., 1974, 1976); and bore hole data (Crosthwaite, 1974, 1976; Covington, 1977, 1978). Others currently studying the area include the Idaho Department of Water Resources, Energy Resources Development Administration, Idaho National Engineering Laboratory, and E.G. & G.-Idaho, Inc.

2.2.1 Stratigraphy

The geologic map of Raft River Valley (Figure 3) shows the areal distribution of rock units. Table 1 summarizes the stratigraphy of Raft River Valley and provides data on lithology and water bearing characteristics.

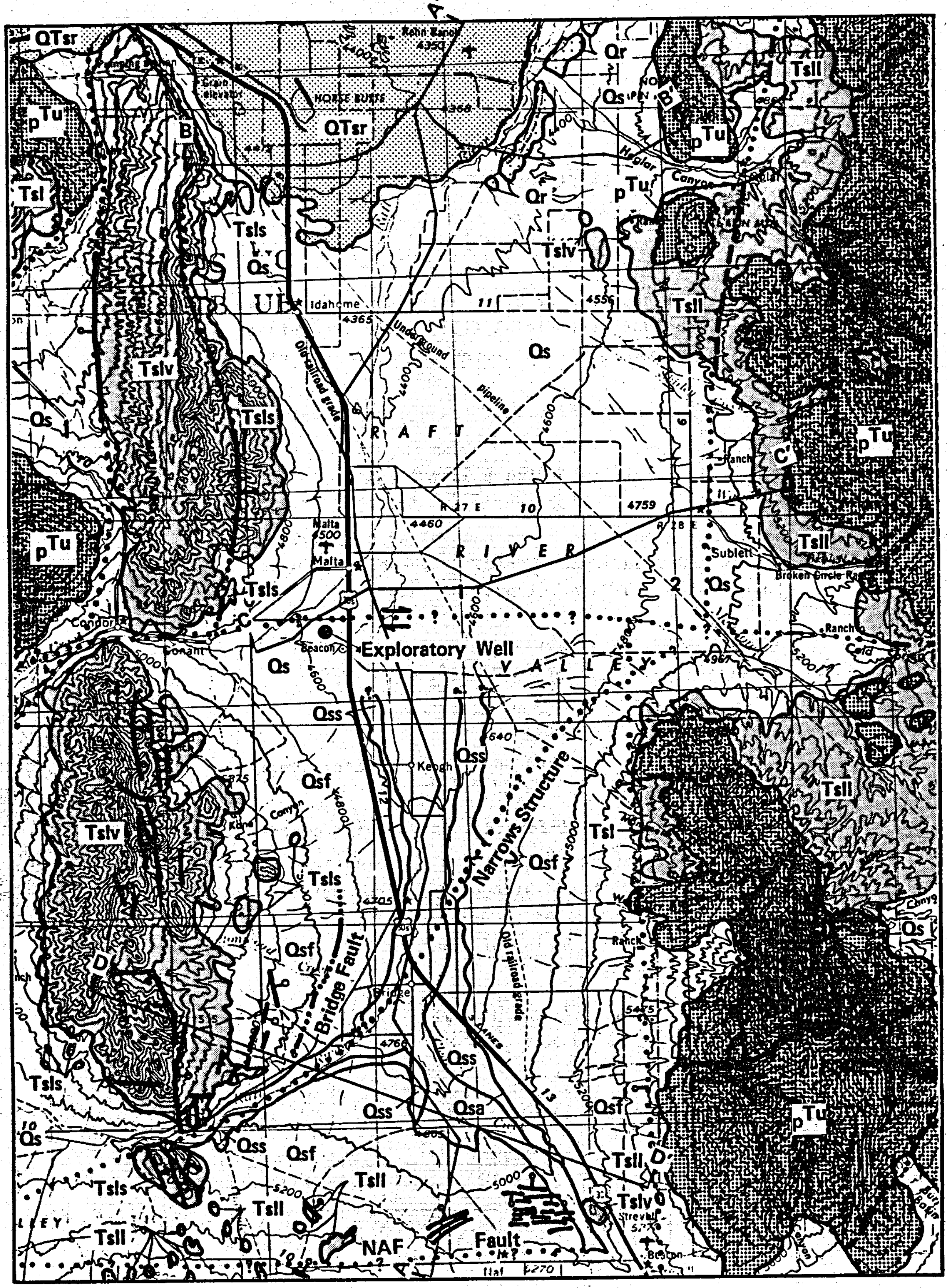
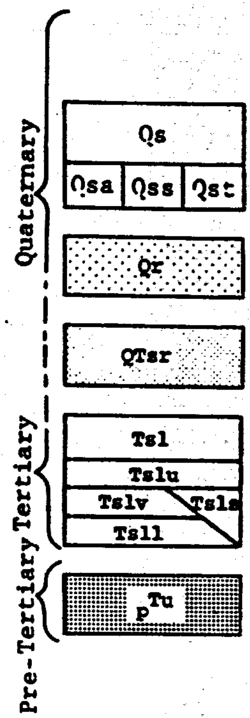


FIGURE 3 GEOLOGIC MAP OF RAFT RIVER VALLEY AREA; SEE EXPLANATION ON FOLLOWING PAGE.

EXPLANATION

Geologic Units



Sedimentary deposits of clay, silt, sand and gravel; locally includes artificial fill; where subdivided Qsa = alluvium Qss = silt, and Qsf = fan gravels

Raft formation; chiefly silt, sand, and gravel

Snake River basalt; olivine basalt flows

Salt Lake group; sediments and volcanic deposits; where subdivided Tslu = upper unit, Tslv = volcanic unit, Tsll = Lower unit, and Tsls - landslide unit

Pre-Tertiary rocks; includes Phosphoria (?), Wells, and Brazer formations, Harrison series, and other undifferentiated rocks

Map Symbols

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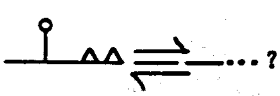
Geologic contact; dashed where approximate, queried where uncertain



Fault; dashed where inferred, dotted where concealed by younger deposits, and queried where uncertain; bar and ball on downthrown side of normal or reverse fault; barbs on upper plate of thrust fault; arrows indicate direction of movement of strike-slip fault

NOTES:

1) Topographic base from portion of U.S. Geological Survey 1:250,000 map, Pocatello, Idaho

2) Geology modified from Anderson, 1931; Nace and others, 1961; Walker, et.al., 1970; and William, et.al., 1976.

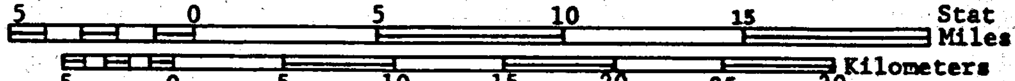


Figure 3
Geologic Map of Raft River Valley area

Table 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; unconsolidated; 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 mouth 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 in transmitting water from catchment area to lowlands

Source: Walker, et al. (1970), Mundorff, Crosthwaite, and Kilburn (1964) and Crosthwaite (1957)

• Pre-Tertiary Rocks. The oldest rocks of the area (>65 million years) are a diverse group of metamorphic rocks - quartzite, marble, schist - consolidated sedimentary rocks such as limestone, sandstone, shale, and chert, and igneous granitic rocks. Included in the pre-tertiary group are rocks of the Cassia batholith, Phosphoria and Wells Formation, Harrison series, and undifferentiated rocks of Mississippian and Cambrain age. These rocks are generally impermeable, and ground water occurs in them chiefly in open joints or solutions cavities in the limestones. The pre-tertiary rock crop out in the mountains surrounding the valley and are found at considerable depth beneath the valley. They form the "basement" rock of the area and tend to divert surface runoff to the valleys, lowland areas, and aquifers.

• Salt Lake Group. The Salt Lake group, a term suggested by Crosthwaite (personal communication, 1978) for those Pliocene and Miocene sedimentary and volcanic rocks mapped by others as Payette or Salt Lake Formation (Anderson, 1931; Nace and others, 1961; Walker et al., 1974, 1976), quartz latite (Anderson, 1931), and volcanic domes and welded tuff (Williams et al., 1974, 1976). The unit is at least 2500 feet thick where it is exposed in the Malta Range and more than 4000 feet thick beneath the southern end of Raft River Valley (Prestwich, personal communication, 1978). Thinner sections blanket parts of the Sublett and Black Pine Ranges.

For the purpose of this report, the Salt Lake group is divided, where known, into four members (after Walker et al., 1970): 1) the upper member consist of welded tuff, glassy latite or rhyolite, and some interbedded sand and tuff; 2) a volcanic member chiefly of flow rocks; 3) a sedimentary member of landslide debris, sand, silt, conglomerate, and some fresh-water limestone; 4) and a lower member predominantly of welded tuff.

Most of the wells that produce water from the Salt Lake group penetrate only beds of sandstone, conglomerate, and occasional layers of clayey silt and volcanic flow rocks. The upper member is the principal ground water aquifer of the group. Medium yield of water to wells in the Salt Lake group is about 1600 gpm (Walker et al., 1970).

- Raft Formation. The Raft Formation is a sedimentary deposit of middle or late Pleistocene age that underlies much of the Raft River Valley lowlands but crops out only at the north end of the valley. It was first identified by Stearns et al., (1938) as the Raft Lake Beds, but the name has since been changed to Raft Formation to reflect the alluvial and possibly fluvioglacial facies in the unit. The formation consists of thin bedded and interlensed, unconsolidated and semiconsolidated clay, silt, sand, and gravel with the proportion of coarse grained material increasing to the south. The lacustrine beds have low permeability, but good ground water production has been obtained from the alluvial portions of the formation.

Thickness of the Raft Formation is difficult to determine because the contact with underlying Salt Lake group is often poorly defined, but it is believed to be less than 1000 feet thick (Prestwich, personal communication, 1978).

- Snake River Basalt. A small area of olivine basalt flows covers the northwestern part of the Raft River Valley, similar to the more extensive flows that form the Snake River Plain to the north. The flow here is contemporaneous with the Raft Formation (Pleistocene and Holocene) and probably was instrumental in the accumulation of the Raft sediments by damming the ancestral Raft River. Individual flows tend to be relatively impermeable except where columnar jointing is found. The rubble zones between flows, however, have high permeability and transmissivity.

• Quaternary Sedimentary Deposits. Geologically recent, unconsolidated silt, sand, and gravel blanket much of the present landscape of the Raft River area. Mapped only in those areas were thickly accumulated, this unit consists of alluvial, fan, landslide, glacial, and wind-blown deposits. Where the deposits have been transported long distances, they are well sorted and stratified; where transportation has not been great, they are poorly sorted, jumbled, and coarser grained. Only in the vicinity of the KGRA has sufficiently detailed mapping allowed subdivision of the unit.

• Soils. The various soil types developed in Raft River Valley and their general characteristics are listed on Table 2; their distribution is indicated on Figure 4. All soils in the Raft River Valley are classified as loams, meaning a mixture of clay, silt, sand, and organic matter; all are moderate to well drained; and most are more saline-alkaline than normal. The texture varies with distance from parent material. The greatest concentration of clay loam and likewise the lowest permeability, is in the narrow Cassia Creek valley, along the Raft River flood plain, and in the central portion of Raft River Valley.

2.2.2 Structure

The overall structure of the Raft River Valley is believed to be that of a graben, downdropped along a series of steeply dipping, north-trending normal faults, as shown in the cross sections of Figure 5. Downwarping of the Tertiary and Quaternary sediments within the basin has also occurred over the course of geologic time.

With the exception of the Jim Sage Mountains, where detailed mapping has been done, only reconnaissance geologic mapping has been completed. Consequently, the fault pattern shown on Figure 3 (especially in the mountain ranges), reflects mainly the level of effort of original

Table 2. CHARACTERISTICS OF SOILS IN THE RAFT RIVER VALLEY (From Chugg, 1967)

Soil Association	Surface Texture & Modifiers	Subsoil Texture & Modifiers	Permeability (inches/hr)	Depth (inches)	Restrictive Layers	Underlying material (40-96")	Available Water holding Capacity (inches) to 48"	Remarks
A	loam, silt loam	loam, clay loam, silt loam	0.2-2.5	<20 to 40+	none to clay layer below 40"	silty clay, loam, gravel	<3 & >6	moderate saline-alkali; substratum somewhat restrictive to water
B	gravelly loam, silt loam	very gravelly loam, silt loam	0.8-5.0	<20 to 40	none	gravel	<3 to 4.5, >6	moderate saline to alkali, well-drained
D	silt loam, silty clay loam	silty clay loam, silt loam	0.05-2.5	40+	none	silt loam, silty clay loam, gravel	>6	none to severe saline-alkali, poorly to moderately well-drained
E	silt loam, loam	loam, silt loam, gravelly loam	0.8-5.0	40+	none	gravel	4.5 to >6	none to moderate saline-alkali, well-drained
F	silt loam, loam	silt loam, loam	0.05-2.5	<20 & 40+	none	gravel	<3 & >6	moderate to severe saline-alkali, moderately well to well-drained

Table 2. Continued

Soil Association	Surface Texture & Modifiers	Subsoil Texture & Modifiers	Permeability (inches/hr)	Depth (inches)	Restrictive Layers	Underlying material (40-96")	Available Water holding Capacity (inches) to 48"	Remarks
H	loam, very cobbly silty clay	loam, clay loam, very cobbly silty clay	.05-2.5	20-40+	none to clay layer or indurated caliche below 40"	silty clay, loam, gravel, cobble	4.5 to >6	moderate saline-alkali, restricted permeability, well drained
I	loam, silty clay loam, silty laom	loam, clay loam, silt loam	0.2-2.5	20-40+	none to clay layer below 40"	silty clay, loam, gravel, cobble	4.5 to >6	high water table, moderate saline-alkali, poor to well drained
J	loam, rocky loam	clay loam, gritty loam	0.2-2.5	<40	none to bedrock	gravel, bedrock	<3 & 4.5-6	well drained
K	loam, silt loam	silt loam, clay loam, gravelly loam	0.8-5.0	40+	none to compacted lime at 20-40"	bedrock, loess, gravel	>4.5	well drained
O	silt loam	silt loam	0.2-2.5	40+	none to slightly compacted lime layer	loess	>6	well drained
P	silt loam, rocky silt loam	silt loam	0.2-2.5	<20 to 40+	basalt, indurated caliche, slightly compacted lime layer	bedrock, loess	<3 & >4.5	well drained

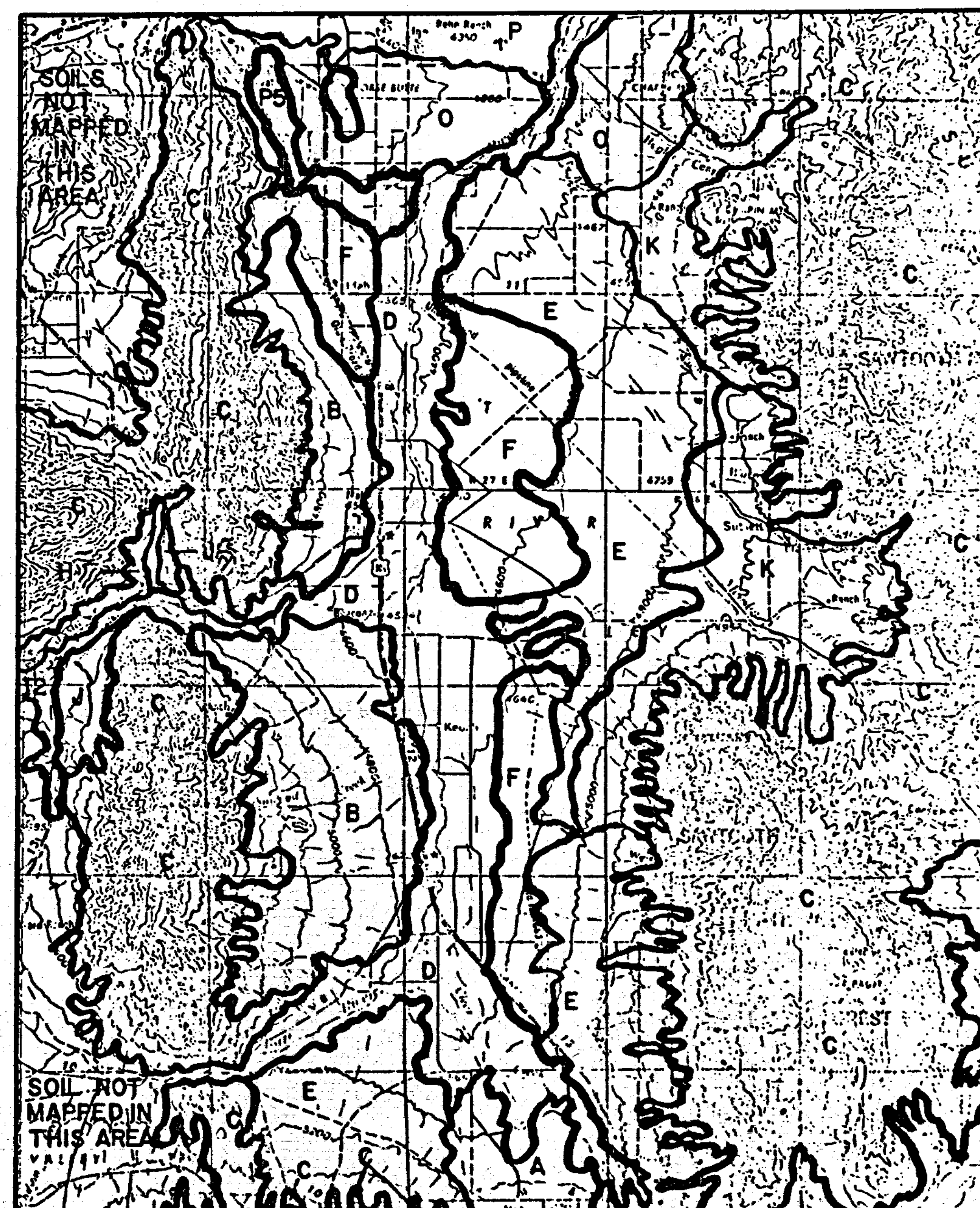


FIGURE 4 GENERALIZED SOIL ASSOCIATION MAP OF RAFT RIVER VALLEY AREA
SEE EXPLANATION ON FOLLOWING PAGE

VI-15

EXPLANATION

Soil Association	Physiographic unit	Slope
A	Alluvial plains and fans	0-4%
B	Alluvial fans or pediments	0-12%
D	Bottoms and Terraces	0-4%
E	Alluvial fans	0-12%
F	Alluvial fans and terraces	0-4%
H	Alluvial fans and plains	0-4%
I	Bottoms, alluvial fans, and terraces	0-4%
J	Alluvial fans	4-12%
K	Toe slopes and alluvial fans	4-20%
O	Loess sheet	0-20%
P	Loess sheet	0-12%
C	Hills and mountains	

Notes

1) Topographic base from a portion of U.S. Geological Survey 1:250,000 map, Pocatello, Idaho

2) From Chugg et. al. (1967)

Figure 4
Generalized Soil Association
Map of Raft River Valley area

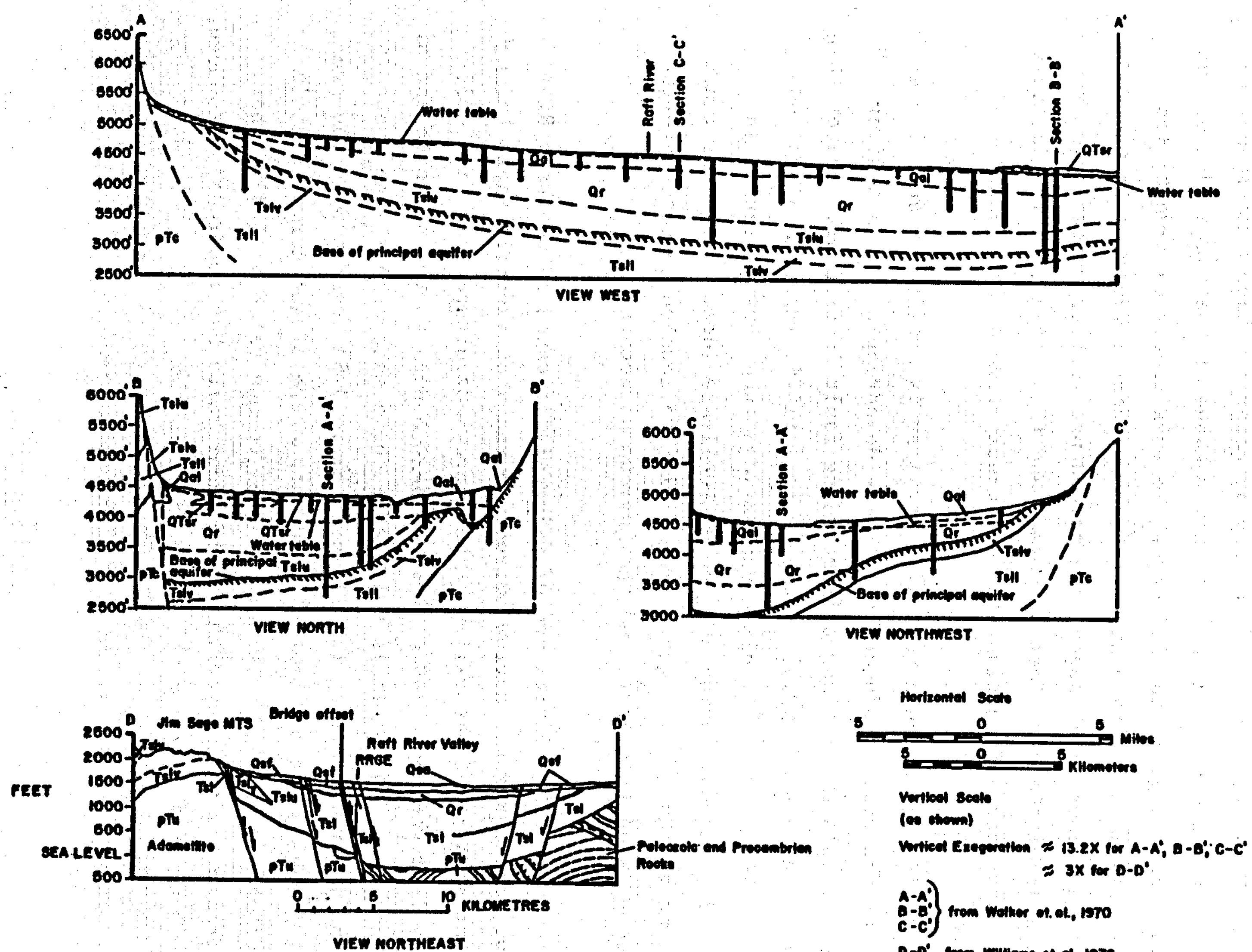


FIGURE 5 GEOLOGIC CROSS-SECTION THROUGH THE RAFT RIVER VALLEY

mapping. Pre-tertiary rocks are probably more extensively faulted than shown, but because these rocks do not form important aquifers, mapping has delineated only the major faults. The many faults shown in the Jim Sage Mountains are the result of detailed geologic mapping in that area and do not necessarily reflect a greater degree of tectonic activity.

Folds and faults in the region generally have a northeast to northwest trend except in the Raft River Range at the south edge of the valley. This range is an antiform whose axis trends east-west; its northern flank is cut by east-west-trending normal faults. In the Sublett and Black Pine Ranges, the folded pre-Tertiary rocks have been offset several thousand feet by normal and thrust faults. The Tertiary strata show less deformation, and dip gently towards the valley.

The Malta Range west of the valley is a tilted block with a steep eastern scarp produced by relative downdropping of Raft River Valley. Displacement along this bounding fault is probably greater than 3000 feet (Anderson, 1931). Kunze et al., (1975) report a dip of 60 degrees east on the fault plane near Bridge (the "Bridge fault" in Figure 3). One hot spring and one hot well are located near the fault here, and the Raft River geothermal wells are located to penetrate the intersection of this fault and the Narrows structure.

Two other faults are of major significance in the Raft River Valley. These are the Narrows Structure and a strike-slip fault through the central part of the valley. The Narrows Structure (see Figure 3) extends from the south end of the Jim Sage Mountains to the north end of the Black Pine Range. It is believed to be a major shear zone probably of right-lateral faulting (Williams et al., 1975), confined to the pre-tertiary rocks. It may be the source structure of geothermal heat in the Raft River KGRA (Prestwich, personal communication, 1978). The strike-slip fault crossing the valley near Malta has apparently produced the right-lateral shift of the Cotterel Mountains and Sublett Range with respect to the Jim Sage Mountains and Black Pine Range. This fault was mapped by Williams et al., (1976); its precise location and nature are not presently known.

Normal faulting with similar orientation to that which has displaced the tertiary rocks has continued through middle to late pleistocene time and displaced quaternary sediments and basalt. The Snake River downwarp has tilted these rocks 5 to 8 degrees to the north near the mouth of the valley.

The present-day structure, as depicted on the geologic cross sections, Figure 5, is basically that of a downdropped and downwarped block surrounded by normal faults on three sides. Over the course of geologic time, thick deposits of permeable material have accumulated in the basin and form the present-day source of ground water.

2.2.3 Tectonic History

The earliest indications of tectonic stress on the Raft River area are recorded in the pre-tertiary rocks. The folding and faulting in these strata indicate an episode of strong compression with maximum stress from the west and southwest. These forces were probably active during the Laramide revolution about 65 million years ago. This period was ended by a tensional phase that broke the strata with large normal faults. Magma was intruded toward the close of this crustal disturbance. The end result of these stresses was an uplifted region with mountains that were higher and probably more rugged than those of today.

In Pleistocene and possibly Pliocene time, downwarping and filling with basaltic lava occurred to the north in the Snake River Plains area. Some of this lava dammed the mouth of Raft River Valley to create a higher base level for the accumulation of sediments in the valley.

Evidence of alpine Pleistocene glaciation is vaguely seen in the Black Pine Range (Anderson, 1931), but the valley was probably not covered by ice.

Tensional faulting, volcanic activity, erosion, and deposition has continued through latest Pleistocene. The Holocene seems to be a seismically stable period with little abnormal geologic stress being manifested in the valley, although Zoback and Thompson (1978) indicate the Basin and Range Province as a whole is presently undergoing extension along a N65°W-S65($\pm$20°) trend.

2.2.4 Holocene Tectonism

The Raft River Valley is located within the Basin and Range Province, an area generally associated with current tectonic activity, and adjacent to both the Intermountain Seismic Belt, a broad area of intense historic tectonism and macroseismicity, and the generally aseismic Snake River Plain. This information, together with the basic geologic framework, suggests that the area has a high rate of Holocene (>11,000 years before present) tectonism.

Detailed studies have shown that several faults have offset Pleistocene (2,000,000-11,000 years before present) alluvial fans in the southern end of the valley (see Figure 3). The most recent movement on these faults was several hundred thousand years ago (Williams et al., 1976). It is likely that similar faulting occurs in the northern valley, but lack of detailed geologic mapping has not yet permitted its identification.

The only case of apparent Holocene tectonic deformation was reported by Lofgren (1975). By studying vertical elevation changes along precisely leveled lines, he has discovered as much as 0.21 foot of uplift in the forty year period between 1934 and 1974. This movement is confined to the Cassia Creek area between the Cotterel and Jim Sage Mountains. The pattern of this deformation is not clearly understood, but a strike-slip fault is shown in that area by Williams et al., (1976), and some indications of faulting have been observed in the bedrock of that area by recent investigators (Crosthwaite, personal communication, 1978).

No historic macroseismic activity has occurred within the Raft River Valley (Kumamoto, 1976). The nearest (and only) events recorded in Cassia County are listed below:

DATE	COORDINATES	RICHTER MAGNITUDE (M)
March 12, 1934	42.0°N/114.0°W	5.1
November 19, 1937	42.1°N/113.9°W	5.4
December 1973	42.2°N/113.75°W	1.5-2.5

These epicenters are accurate to within 0.1°, or approximately ±10 km, at best. No focal depths could be determined, because the events were recorded on only a few, distant seismographs.

A microseismic survey of the Raft River Geothermal Prospect was conducted between July 26 and October 29, 1974 by L.H. Kumamoto (1976). His array consisted of two single component seismographs located on bedrock and one three component seismograph located on alluvium. The detection threshold throughout the valley as far north as Horse Butte was less than M 0.3 and as low as M -0.5 in the area between Malta and Bridge. During the ninety days of field operations, only seven local events were detected (within 17 km of the network), although two to four distant events were recorded daily. These events ranged in magnitude from -0.45 M to +0.17 M and included one swarm of four events. Kumamoto (1976, p. 34) concludes "The seismicity rate of the Raft River Prospect, less than 0.2 events per day (M greater than 0.0), is extremely low and categorizes the area as being seismically more akin to the Snake River Plain than to the Intermountain Seismic Belt."

The Idaho National Engineering Laboratory and EG&G-Idaho, Inc. have operated a microseismic network for the past four years in conjunction with their work on the Raft River KGRA. Within this time, only one event has been detected with M greater than 1.6 (Spencer, personal communication, 1978). The system currently consists of three Sprengnether 1 Hz. vertical geophones, although only two were operating as of March 1978. The system will be expanded to four stations set in bedrock by spring 1978, and attempts are being made to convert to a tri-axis system.

2.3 RESERVOIR CHARACTERISTICS

2.3.1 Regional Geohydrology

The Raft River drainage basin encompasses about 1560 square miles. About 715 square miles of this is in the Raft River Valley sub-basin, about 740 square miles in upstream and bordering tributary areas, and about 175 square miles in the Snake River Plain (see Figure 1). The climate ranges from humid to subhumid in the higher mountains and to semiarid on the valley floor.

All the water entering in the Raft River basin originates as snow or rain falling within the basin. A part of this precipitation is returned directly to the atmosphere as evaporation and transpiration; a part replaces depleted soil moisture; a part goes into ground water storage; and the remainder leaves the basin as streamflow and ground water outflow. Water yield is the total average annual input minus evaporation and transpiration. The most recent estimate of water yield for the entire Raft River basin (Walker et al., 1970) is 140,000 acre-feet and for the Raft River Valley subarea 27,700 acre-feet. The average annual precipitation ranges from less than 10 inches on the central part of the valley floor to more than 30 inches near the summits of the highest mountains where it occurs mainly as snow. The seasonal distribution of precipitation is indicated on Figure 6. Average annual precipitation over the entire basin is 15.0 inches or 1,280,000 acre-feet of water (Walker et al., 1970).

Although in its natural condition the Raft River maintained flow throughout its entire reach, diversions for irrigation and a lowered water table have caused flow to cease in summer and fall near Bridge. At the present time, the river remains dry nearly to its mouth. Under natural conditions, about one-third of the water yield (47,000 acre-feet) moves into the central valleys as surface flow (Walker et al., 1970). Most of the remaining two-thirds (93,000 acre-feet) moves into and through the valleys as ground water. The Raft River Valley therefore receives water directly as precipitation, as runoff from peripheral mountains, from surface flow of the Raft River and its tributaries, and as underflow from the Upper Raft River basin. Most of the ground water then flows through the generally permeable valley-fill deposits, from which it is pumped in increasing amounts for irrigation and domestic use.

The Raft River geothermal system is probably the result of deep circulation of ground water along major faults. Williams et al., (1976) propose a model in which meteoric water collects in the deep Cenozoic fill (primarily Salt Lake Formation Rocks) in the Upper Raft River basin west of the Narrows and in the southernmost Raft River Valley. Some of this water descends along faults to the depths sufficient

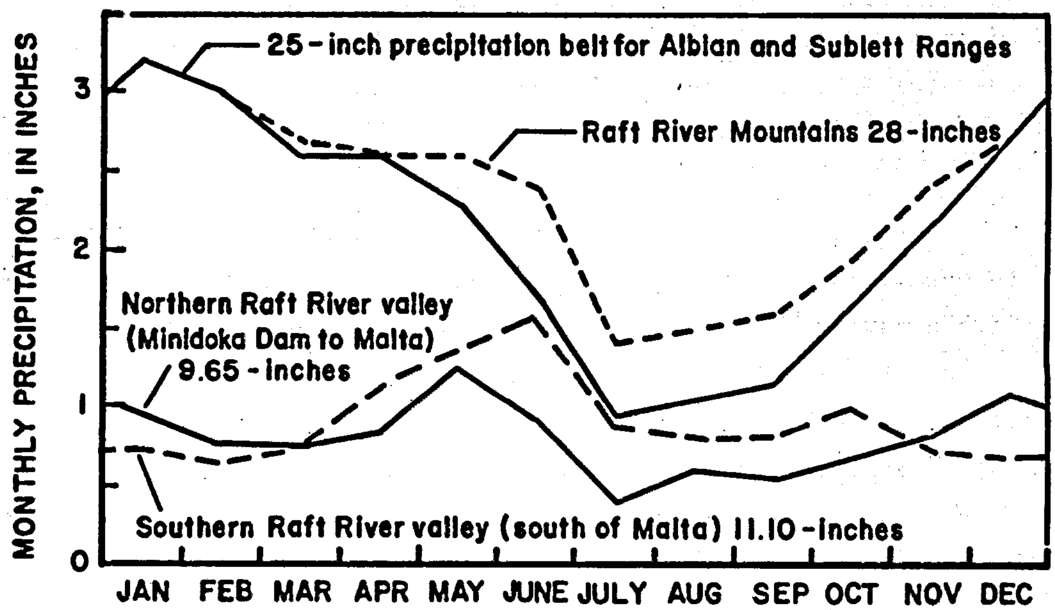


FIGURE 6 GENERALIZED SEASONAL PRECIPITATION DISTRIBUTION FOR DIFFERENT PARTS OF THE RAFT RIVER BASIN (from Walker, et al, 1970)

to heat it to 145°C. The heated water then migrates upward along the Narrows structure and along north-trending faults. Wells intersecting these structures or springs aligned along them provide an outlet for these heated water. The conduit system includes not only these faults, but also permeable aquifers in the Salt Lake Formation, fractured zones in the Precambrain rocks, and perhaps thrust faults in the pre-tertiary rocks. The time required for circulation of the water is unknown, but tritium analysis indicates all thermal water is pre-1952 in origin (Stoker et al., 1977).

The hydraulic continuity between geothermal and cool, near surface water is unconfirmed, but both waters originate as precipitation within the basin. The occurrence of warm water in springs and shallow wells scattered throughout the Raft River area and 70°C water leaking from a deep petroleum exploration well near Malta (Williams et al., 1976) suggests that the geothermal resource is not confined to the Bridge area. It is likely therefore that the geothermal and cool waters are in hydraulic continuity, but that free mixing of the two occurs only in zones of high permeability.

2.3.2 Reservoir Geometry

Although that Raft River drainage includes several ground water basins, subsidence from ground water withdrawal has occurred only in the Raft River Valley, which has a surface area of about 50 square miles. The ground water reservoir of this valley includes the permeable formations of Cenzoic age - alluvium, Snake River basalt, Raft Formation, and Salt Lake group - which extend to a depth of more than 5000 feet at the south end of the valley, and probably more than 7000 feet at the north end (see Figure 5). The lateral boundaries of the basin are the faults forming the eastern front of the Malta Range at the west, the Naf fault at the south; pre-tertiary rocks at the east; and the Snake River at the north.

Total capacity of the near surface (domestic and irrigation) aquifer is about 12 million acre-feet; the capacity below the near surface, but above the geothermal aquifer, is about 50 million acre-feet; and the inferred capacity of the geothermal aquifer is about 288,000 acre-feet (Stoker et al., 1977).

The extent and shape of the geothermal reservoir in the Raft River area have not yet been fully determined. Stoker et al., (1977) describe the geothermal "reservoir" as having a thickness ranging from 900 feet to 1750 feet, averaging 1200 feet. This includes mostly the lower part of the Salt Lake Formation and some "basement" rocks. The effective permeable producing thickness is about 600 feet. The apparent extent of the geothermal reservoir is about 5 square miles.

Contour maps showing the general shape of the water table in Raft River Valley have been published since 1936. The most recent of these maps is for 1966 and is shown on Figure 7, along with the boundary of the Raft River Valley basin. Geologic cross sections A-A', B-B', and C-C' on Figure 5 show the 1966 water table relative to geologic conditions. Figure 23 indicates in part the depth of the water table along Highway 30S.

The depth to ground water ranges from 0 feet near parts of the Raft River to more than 400 feet, but is generally less than 150 feet. Ground water is deepest in three areas: 1) beneath the alluvial apron east of Jim Sage Mountains where the depth to water increases toward the west from 150 feet to more than 400 feet; 2) a long, narrow strip beneath the alluvial fans along the eastern margin of the valley where the water table depth ranges from 150 to 300 feet; and 3) at the north end of the valley beneath the Snake River basalt where the water depth is more than 250 feet. The slope of the water table is much flatter than the slope of the land surface, and varying depths to ground water reflect the

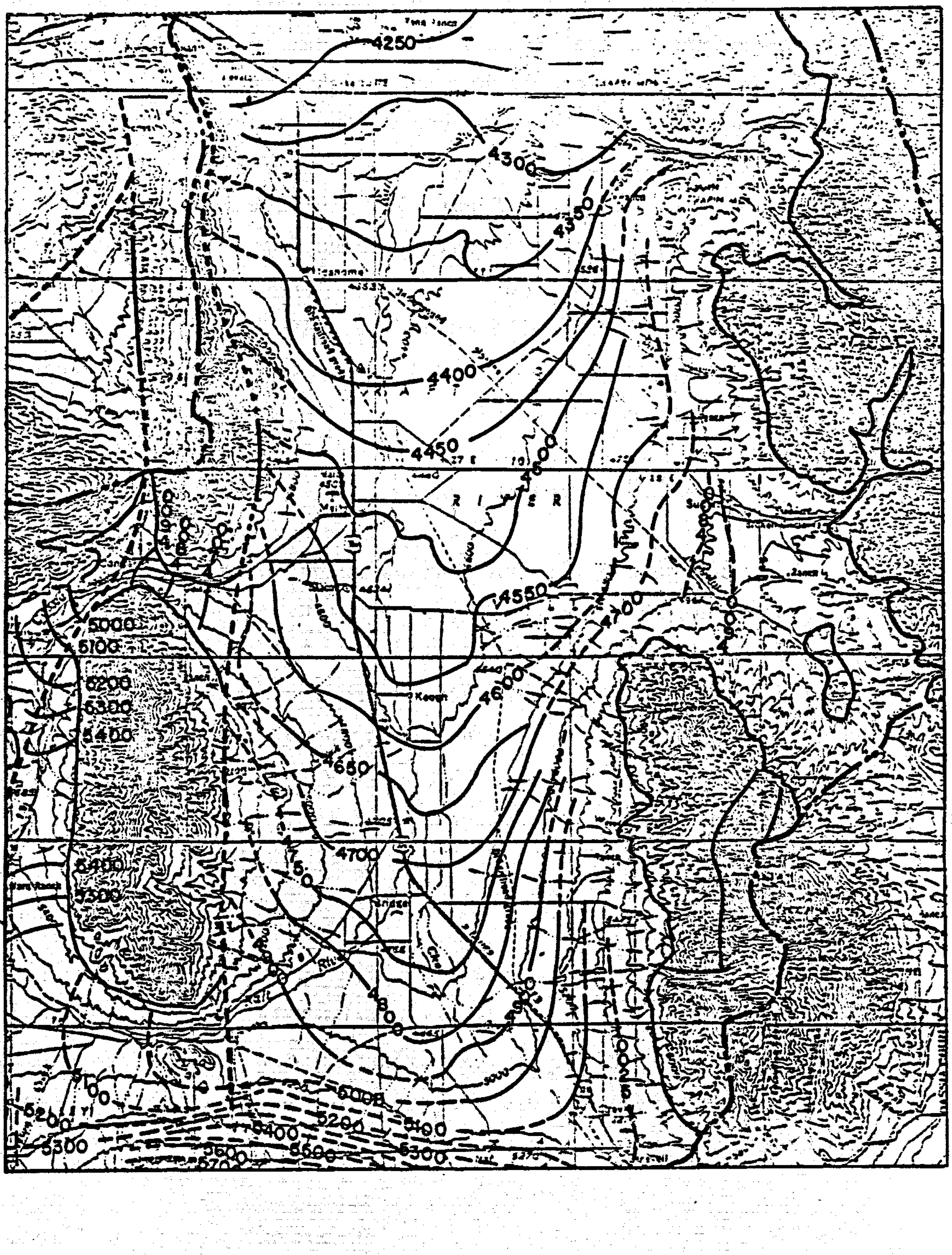


FIGURE 7 SPRING 1966 WATER LEVEL IN THE RAFT RIVER VALLEY

difference in these slopes rather than different ground water bodies. The overall northward gradient of the water table is about 15 feet per mile.

Depth to the base of the ground water reservoir is known only at a few points in the central valley area. Geothermal tests wells RRGE-1, 2, and 3 penetrated basement rock (quartz schist) at depths of 4595 to 5400 feet at the south end of the valley. These intercepts along with geophysical data were used by Williams et al., (1976) to draw their cross section (D-D', Figure 5). This section was drawn near the head of the valley, so an overall average depth at valley centerline may be on the order of 6500 feet. One petroleum exploration well was drilled about 2 miles south of Malta (see Figure 16 for location) and probably reached basement rock, but the details of this boring are unknown (Stoker, personal communication, 1978).

2.3.3 Overburden Properties

Overburden for the shallow ground water basin may include soil, alluvium, Raft Formation, or Snake River basalt. The geothermal reservoir is overlain by soil, alluvium, Raft Formation, and the upper sections of the Salt Lake group. These overburden materials, with the exception of soils, also compose the ground water reservoir; they have been described previously in the Geology section and will be discussed in further detail in the following section.

2.3.4 Groundwater Reservoir Material Properties

Alluvium, Snake River basalt, Raft Formation, and the upper unit of the Salt Lake Formation constitute the main water-bearing units in the Raft River Valley. The volcanic (middle) and lower units of the Salt Lake Formation are probably relatively impermeable (Walker, 1970) and generally are not penetrated by most irrigation wells. These units have recently been exploited as sources of geothermal water. A general description of the geologic and water-bearing properties of these units has been given in the section on stratigraphy. Unfortunately, little additional detail exists on the sedimentologic, consolidation, alteration, and deformation properties of these units.

The most detailed lithologic description of the main water-bearing units is from the southern part of Raft River Valley, near the geothermal development. Here a detailed stratigraphic column of alluvium, Raft Formation, and upper Salt Lake Formation (Table 3) can be pieced together from the work of Crosthwaite (1976). Because of the interlensing and facies changes of these units, this section will not be duplicated elsewhere in the basin, but should serve as the best approximation to date.

By studying drillers' logs of water wells, approximate contacts between geologic units may be determined and their thickness estimated. Walker et al., (1970) has used these data to produce isopachous (equal thickness) maps of the principal water-bearing units. These maps are duplicated as Figures 8 to 11. Alluvium, basalt, and Raft Formation tend to be thickest beneath the present course of the Raft River except at the north end of the valley, where the thick sediments follow the original river course before it was deflected by flows of the Snake River. The Salt Lake Formation thickens westward to the Malta Range front fault.

The only quantitative data on ground water reservoir materials deal with water-bearing properties; these in turn are related to shape, packing, size distribution, and cementation of the constituent particles. The water yield and specific capacity (yield per foot of drawdown) of wells penetrating the various formations in the Raft River Valley are listed on Table 4. The specific yield (the ratio of the volume of water

Table 3 COMPOSITE STRATIGRAPHIC COLUMN FROM INTERMEDIATE DEPTH CORE HOLES IN THE RAFT RIVER GEOTHERMAL AREA (Data from Crosthwaite, 1976)

Cumulative Depth to base of unit (feet)	Description
20	Loess with 30-40% rhyolite, angular to subrounded 3/8-4 inches (1-10 cm) size range.
170	Angular gravel. Pebbles and cobbles of rhyolite with minor amounts of tuff, dolomite, limestone, and quartzite; mixing probably indicates inter-bedded fan gravels and Raft River gravels. Matrix is tan silt to sandy silt, non-calcareous.
243	RAFT(?)FORMATION Clay. Tan, sandy, non-calcareous. Scattered pebbles of tuff, quartzite, and rhyolite below 170 ft. (52cm). Pebbles are angular to sub-rounded and up to 0.8 in (2cm) in size. Thin, grayish-white, ash beds locally.
513	Sandstone, tan to gray-brown, coarse to fine; minor silt, clay, and gravel bed a few cm thick. Scat-tered pebbles of rhyolite and tuff throughout. Particles mostly rhyolite both glassy and devitri-fied, quartz, feldspar, tuff and glass shards.
908	Sandstone, conglomerate, silt, and clay, inter-bedded; tan to gray-brown, minor carbonate cement, and traces of carbonized plant remains. Clasts are primarily rhyolite and tuff. Smaller particles are mostly rhyolite, both glassy and devitrified, quartz, feldspar, tuff, and glass shards.
980	SALT LAKE FORMATION, UPPER PART Conglomerate, gray, well cemented, subangular to subrounded peb-bles of rhyolite, quartzite, tuff, and limestone, up to 2 in. (5cm). Few thin sandstone beds, gray, medium to fine grain.. containing limestone pebles to 3/4 in. (2cm.). Non-calcareous.
1040	Siltstone, gray to gray-green, slightly calcareous. Thin very fine sandstone with abundant biotite throughout.
1101	Sandstone, gray, subrounded to angular medium to coarse grains. Scattered rounded pebbles of rhy-olite up to 2-1/2 in. (6cm) and calcareous clay balls up to 1-1/2 in. (4cm). Pyrite and calcite throughout.
1197	Siltstone interbedded with fine sandstone, green to gray-green, non-calcareous. Many small, high angle faults cemented with calcite and silica.
1232	Conglomerate, gray-green, rhyolite, tuff, quartzite, angular to subrounded, up to 2 in. (5cm), non-calcareous. Minor amounts of pyrite.
1350	Siltstone, green to gray-green, slightly calcareous to non-calcareous, thin interbeds of calcareous claystone and fine sandstone. 3 m. conglomerate bed of subrounded pebbles up to 5cm. Rhyolite 25%; quartzite, 25%; limestone, 10%; calcareous clay, 35%; tuff, 5%. Many high angle faults and open fractures containing calcite and silica. Minor amounts of pyrite and carbonaceous material.
1436	Sandstone, gray-green, medium grained, subangular to subrounded, clear to frosted. Light gray non-calcareous clayey matrix. Abundant pyrite. Many open fractures containing calcite and silica. Average total porosity = 36.5%; average effective porosity = 32.4%.
1518	Siltstone-sandstone interbedded, light gray-green siltstone, siliceous cement. Sandstone, medium grained, frosted, subangular to subrounded, slight-ly calcareous to non-calcareous. Abundant pyrite. Many open fractures with calcite and silica. Abun-dant carbonaceous material. Average total porosity = 44.1%; average effective porosity = 40.5%.
1562	Sandstone-siltstone-claystone interbedded, gray in color. Sand is medium to fine grained and cal-careous. Abundant carbonaceous material. Average total porosity = 35.3%; average effective porosity = 31.5%.
>1706	Conglomerate, poorly consolidated and coarse sand. Slightly calcareous subangular to subrounded peb-bles and cobbles up to 4 in. (10cm). Rhyolite, 10-20%; quartzite, 30%; black limestone, 30-60%. 10% biotite in the sand. Some carbonaceous mater-ial. Average total porosity = 33.6%; average ef-fective porosity = 29.4%.

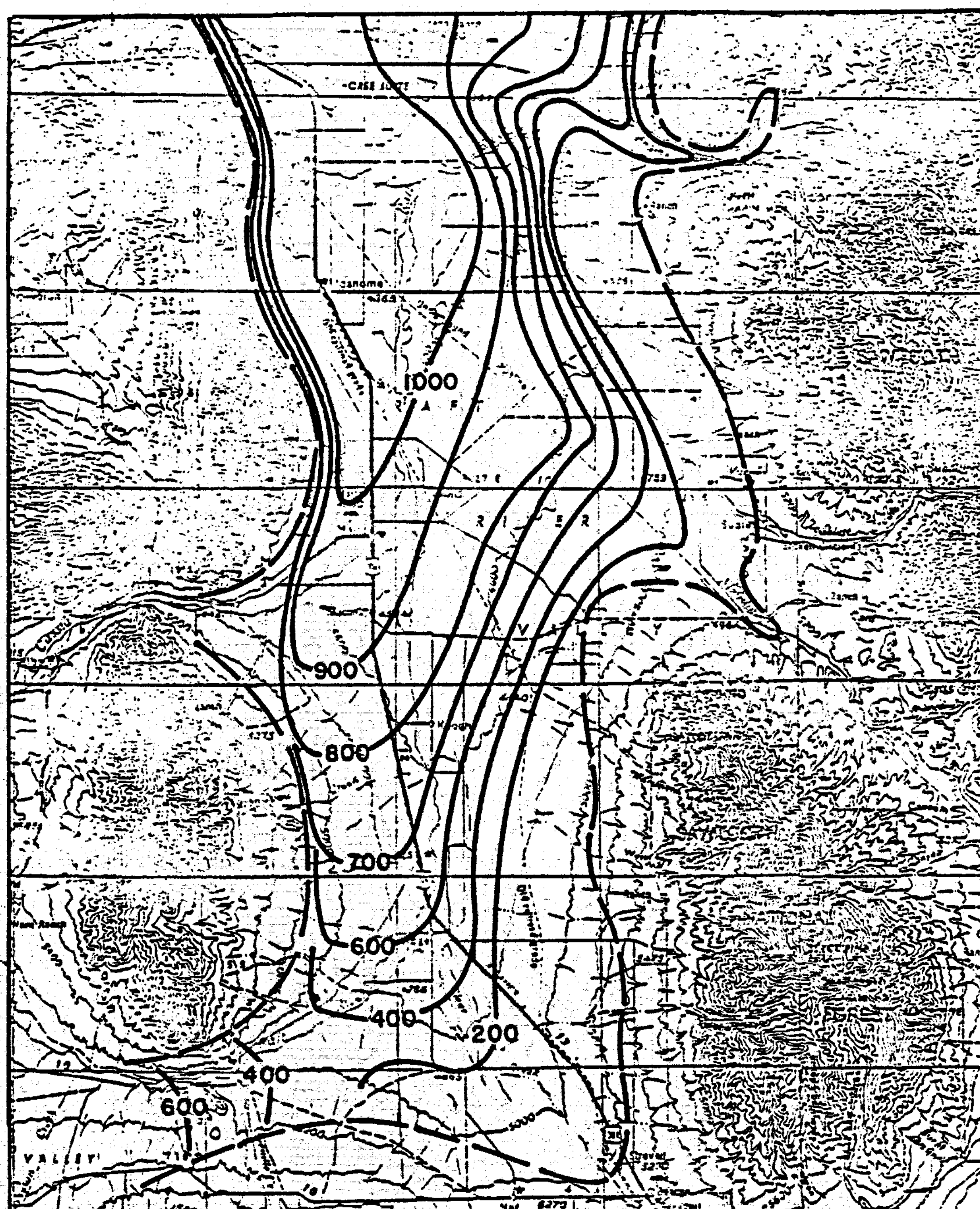


FIGURE 8 APPROXIMATE THICKNESS OF COMBINED ALLUVIUM, BASALT, AND RAFT FORMATION WHERE THESE CONSTITUTE PRINCIPAL AQUIFIERS (from Walker, et al, 1970)

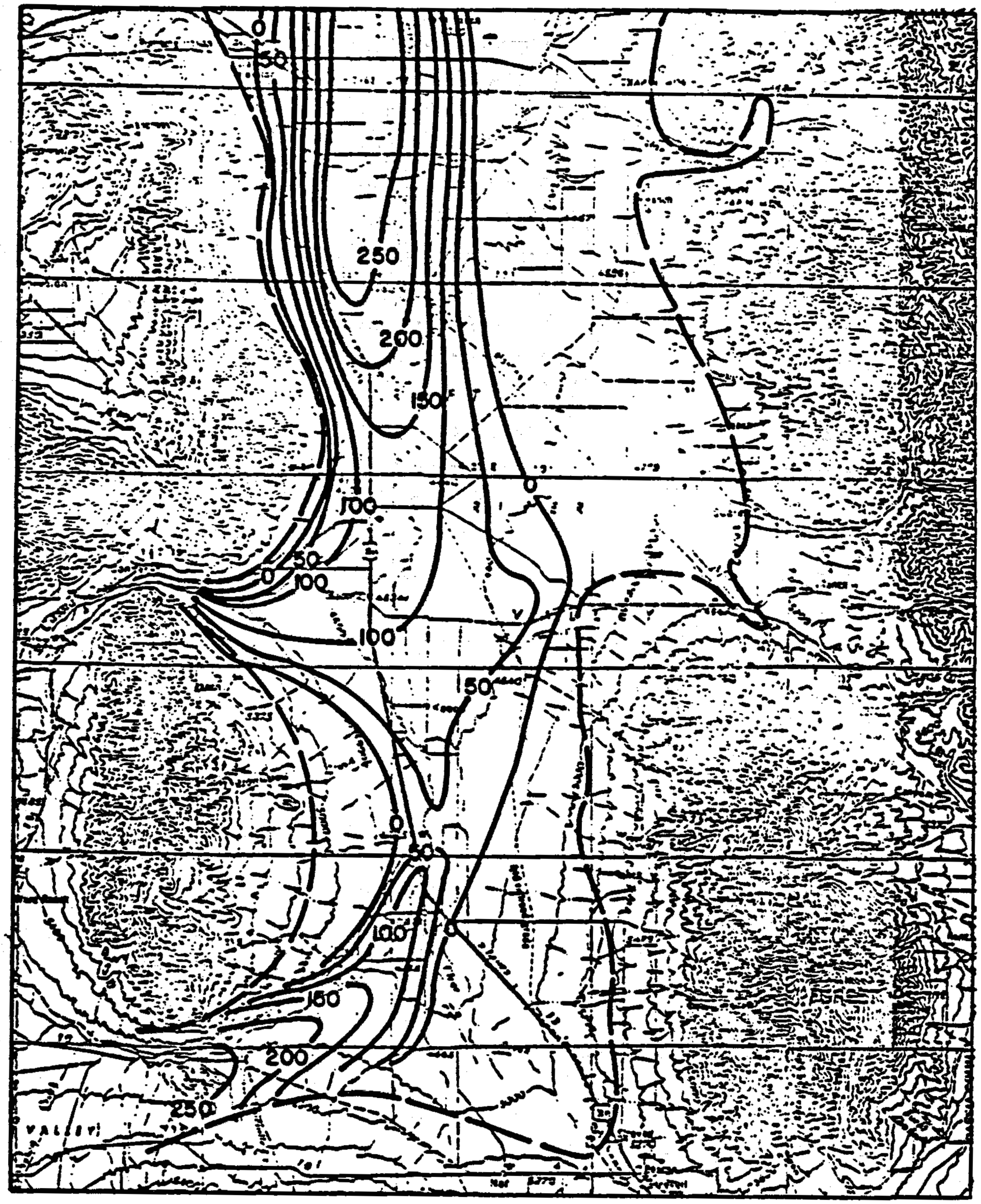


FIGURE 9 APPROXIMATE THICKNESS OF MOST PERMEABLE DEPOSITS IN THE COMBINED ALLUVIUM, BASALT, AND RAFT FORMATION (from Walker, et al, 1970)

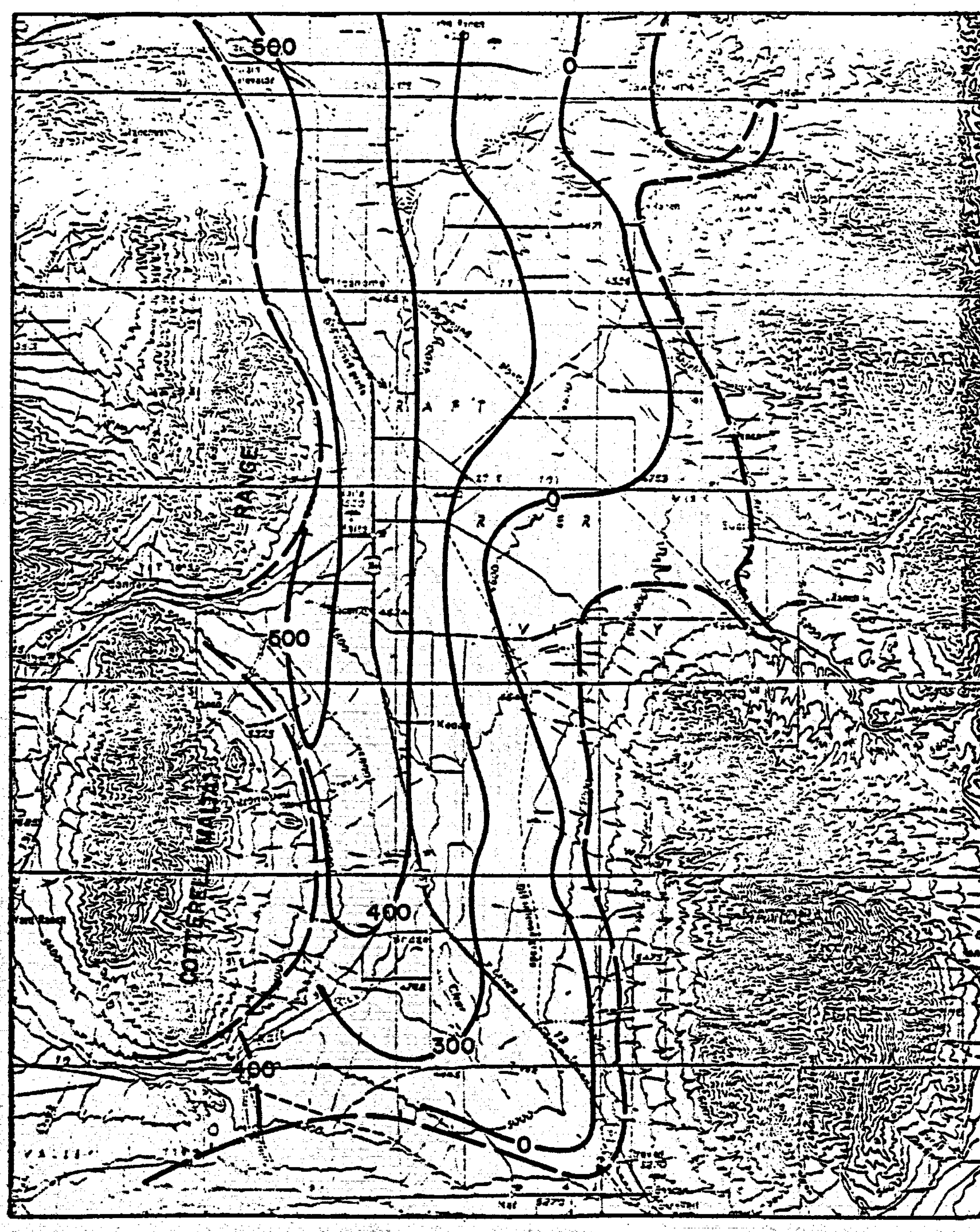


FIGURE 10 APPROXIMATE THICKNESS OF THE UPPER UNIT OF THE SALT LAKE FORMATION (from Walker, et al, 1970)

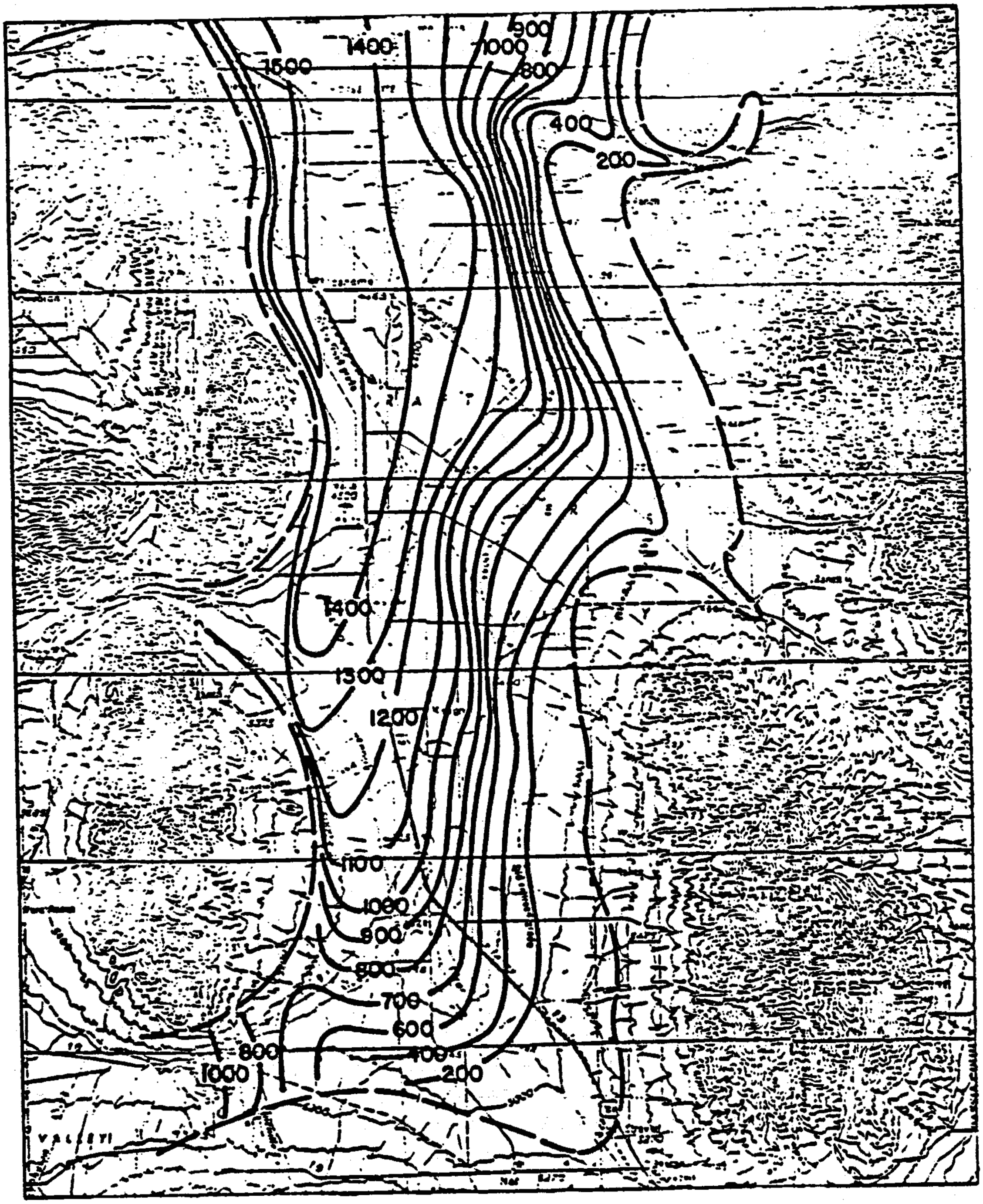


FIGURE 11 APPROXIMATE THICKNESS OF ALL PRINCIPAL WATER-BEARING DEPOSITS IN THE RAFT RIVER SUBBASIN (from Walker, et al, 1970)

Table 4. YIELDS AND SPECIFIC CAPACITIES OF WATER WELLS IN THE RAFT RIVER BASIN

Formation	Yield (gpm)			Specific capacity		
	No. of tests	Average	Median	No. of tests	Average	Median
Limestone of pre-Tertiary age	2	1,485	-	2	22.5	-
Upper unit of the Salt Lake Formation	18	1.520	1,600	9	27	19
Raft Formation	96	1,350	1,200	64	32	25
Basalt of Snake River Group	6	2,700	-	4	250	-
Alluvium	21	984	900	13	72	68

From Walker et al. (1970).

which a deposit will yield by gravity, after being saturated, to the volume of the deposits drained) for various materials in the Raft River basin is listed in Table 5. A map showing the distribution and average specific yield of water-bearing deposits in the Raft River Valley is shown on Figure 12.

Permeability, bulk density, grain density, porosity, and effective water porosity for some of the deep materials in the Raft River KGRA are listed on Tables 6 and 7. Locations of these samples are shown on Figure 13.

2.3.5 Water Characteristics

Several chemically distinct types of ground water are pumped from wells in the Raft River Valley. These differences are due to variations in the water's history since its meteoric origin. Some variations are man-made, such as the change in irrigation water returned to the water table. The chemical quality of water from selected stream, spring, and well locations is shown diagrammatically on Figure 14. Also indicated are the boundaries of some of the distinct ground water types.

One large body of ground water extends through the lowlands the full length of the valley. This water appears to be closely related chemically to surface water in the Raft River. Its dissolved-solids concentration ranges from 600 to 1000 mg/l, the salinity hazard for agricultural uses is high, and the silica (SiO_2) content ranges from 30 to 70 mg/l.

The most extensive body of characteristic ground water is beneath and within the alluvial fans on the east side of the valley. The distinguishing characteristic of this water is that it has a total dissolved solids concentration ranging from about 320 to 500 mg/l (medium

Table 5. ESTIMATED SPECIFIC YIELD OF WATER-BEARING SEDIMENTS IN RAFT RIVER BASIN

Material	Range %	Average %
Clay	1- 5	2
Silt	3-12	8
Sandy Clay	3-12	7
Fine Sand	10-32	21
Medium Sand	15-32	26
Coarse Sand	20-35	27
Gravelly Sand	20-35	25
Fine Gravel	17-35	25
Medium Gravel	13-26	23
Coarse Gravel	12-26	22

From Walker et al. (1970).

EXPLANATION

Raft River basin boundary

Boundary of Raft River valley subbasin ground-water storage unit

Specific yield of thin saturated alluvium about 10 percent

Specific yield of the shallow deposits about 20 percent and of the desposits deeper than about 25 feet below the 1966 water table about 10 percent.

Specific yield of the alluvium and Raft Formation about 20 percent to a depth of about 50 feet below the 1966 water table; about 15 percent for deeper deposits.

Specific yield of the most permeable deposits in the alluvium and Raft Formation about 20 percent to a depth of about 100 feet below the 1966 water table; about 15 percent for deposits 100-200 feet below the 1966 water table.

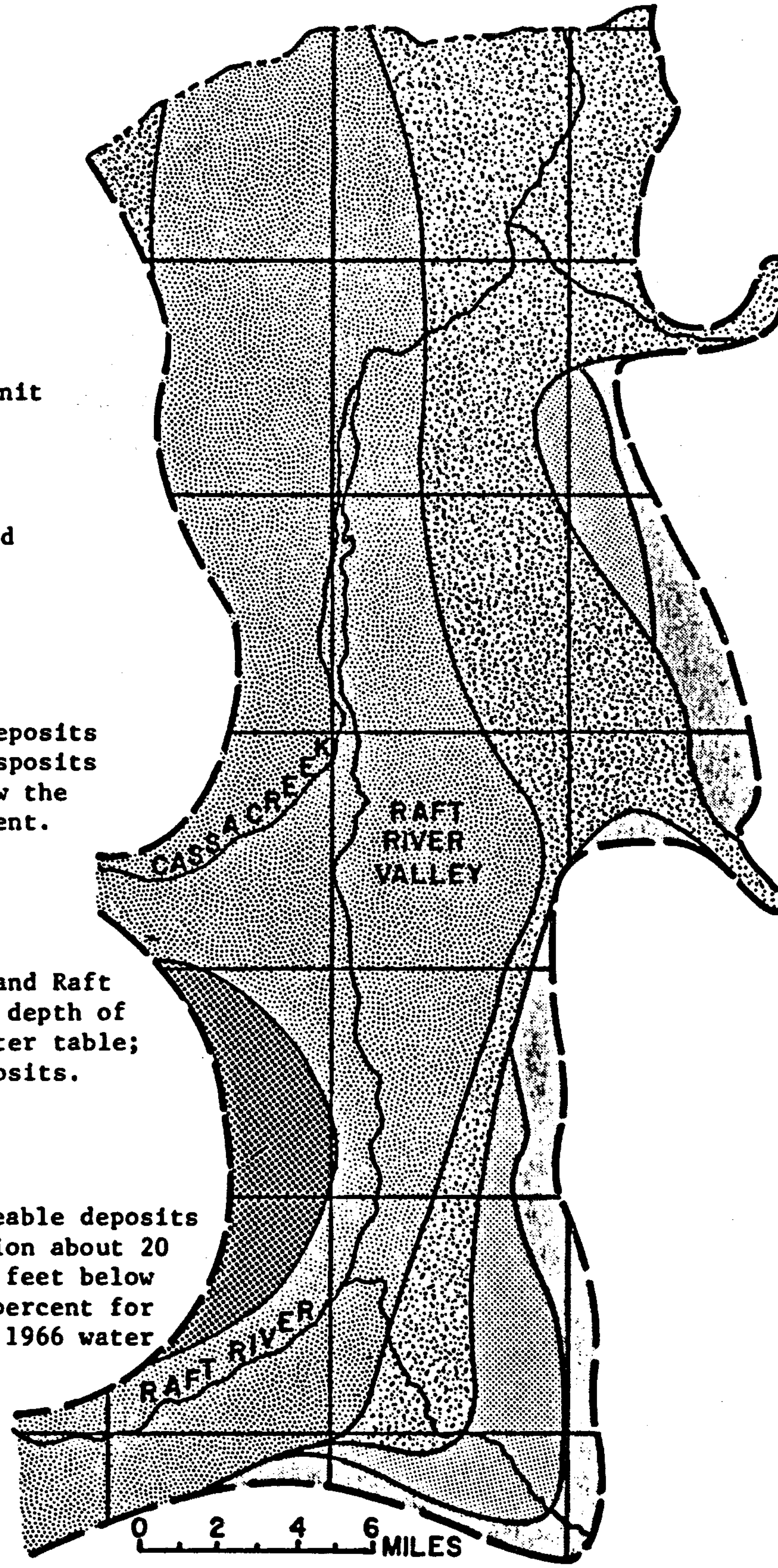


FIGURE 12 ESTIMATED AVERAGE SPECIFIC YIELD OF WATER-BEARING DEPOSITS IN RAFT RIVER VALLEY (from Walker, et al, 1970)

Table 6 RAFT RIVER GEOTHERMAL EXPLORATORY WELL CORE PERMEABILITIES

Well	Depth, KB	Permeability (Millidarcies)	Rock Type
RRGE-1	4,227 ft	.003 - .04 (cap)	Siltstone
RRGE-1	4,506 ft	5.0	Tuffaceous Siltstone
RRGE-2	4,372 ft	0.0022 (cap)	Shale
RRGE-3A	2,807 ft	.25	Sandstone
RRGE-3A	3,365 ft lower	.04	Tuffaceous Siltstone
	3,365 ft upper	>35. (∿100)	Tuffaceous Siltstone
RRGE-3 (A,B, & C)	4,985 ft	.035	Tuffaceous Siltstone
RRGE-3 (A,B, & C)	4,994 ft	.001	Tuffaceous Sandstone
RRGE-3 (A,B, & C)	5,273 ft	.117	Siltstone

from Stoker, et al. (1977).

Table 7 PHYSICAL PROPERTIES OF RAFT RIVER GEOTHERMAL WELL CORES (from Stoker et al, 1977)

SAMPLE	WET BULK DENSITY (GM/CC)	WET BULK DENSITY (GM/CC)	GRAIN DENSITY (GM/CC)	TOTAL POROSITY (%)	EFF. WATER POROSITY (%)
RRGE-1 4500.5'	--	1.88	2.62	28.8	28.8
4518.0'	--	2.20	2.67	17.6	14.3
4687.0'	--	2.73	2.79	2.2	0.8
RRGE-2 3728.4'	--	2.16	2.66	18.8	13.2
4223.8'	--	2.07	2.66	22.2	15.0
4227.0'	2.29	2.20	2.72	19.3	17.4
4373.0'	--	2.28	2.67	14.5	13.6
6560.0'	--	2.57	2.64	2.7	0.8
RRGE-3A (L) 3365.0'	--	1.74	2.60	33.1	11.3
3365.0'	--	1.53	2.48	38.3	34.7
RRGE-3C 4994.0'	--	2.31	2.70	14.4	9.1
5273.0'	--	1.97	2.66	25.9	23.0
5550.5'	--	2.64	2.70	2.2	1.2

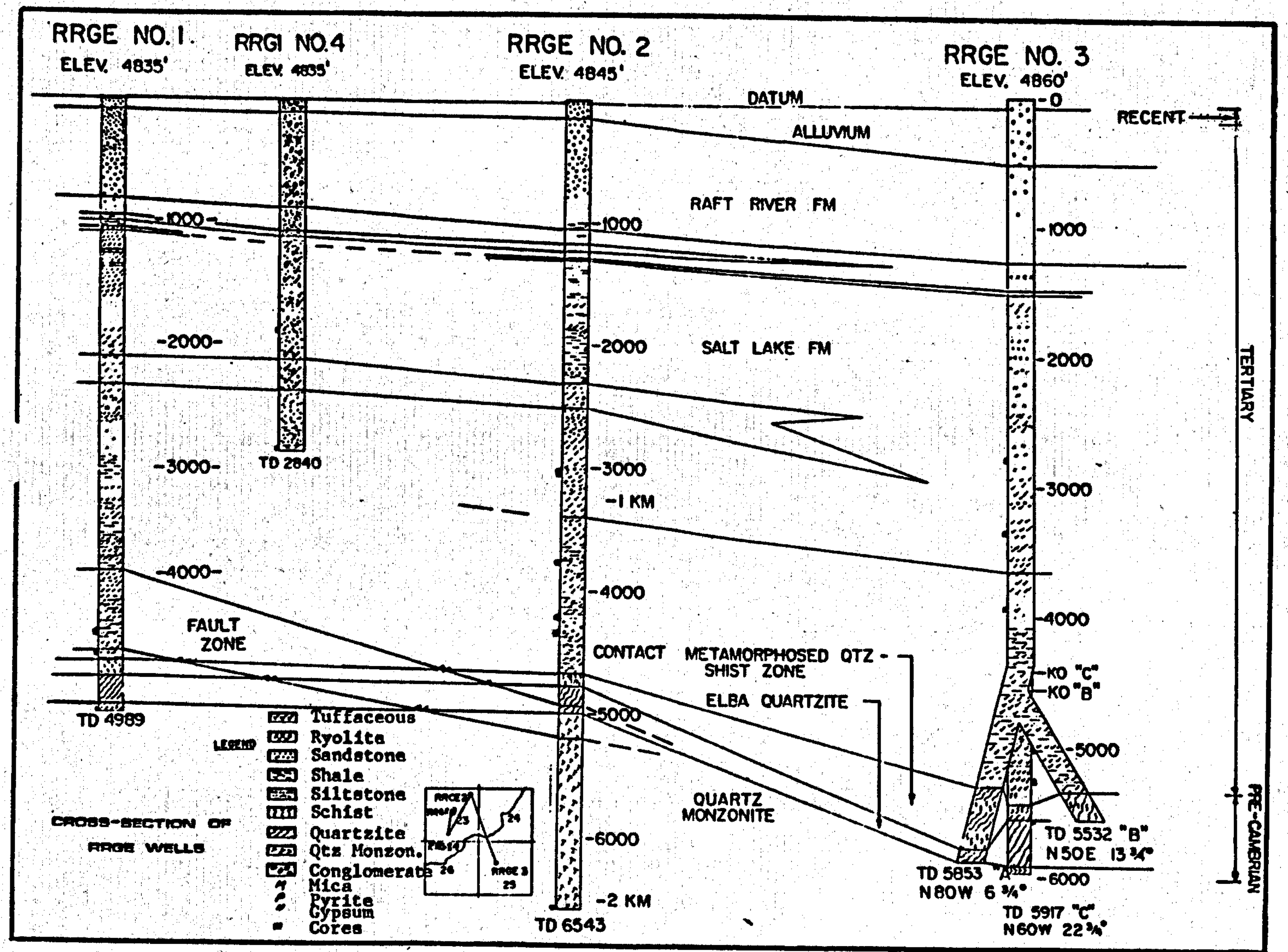


FIGURE 13 DIAGRAMATIC CROSS-SECTION OF RAFT RIVER GEOTHERMAL TEST WELLS (from Prestwich, written commun., 1978)

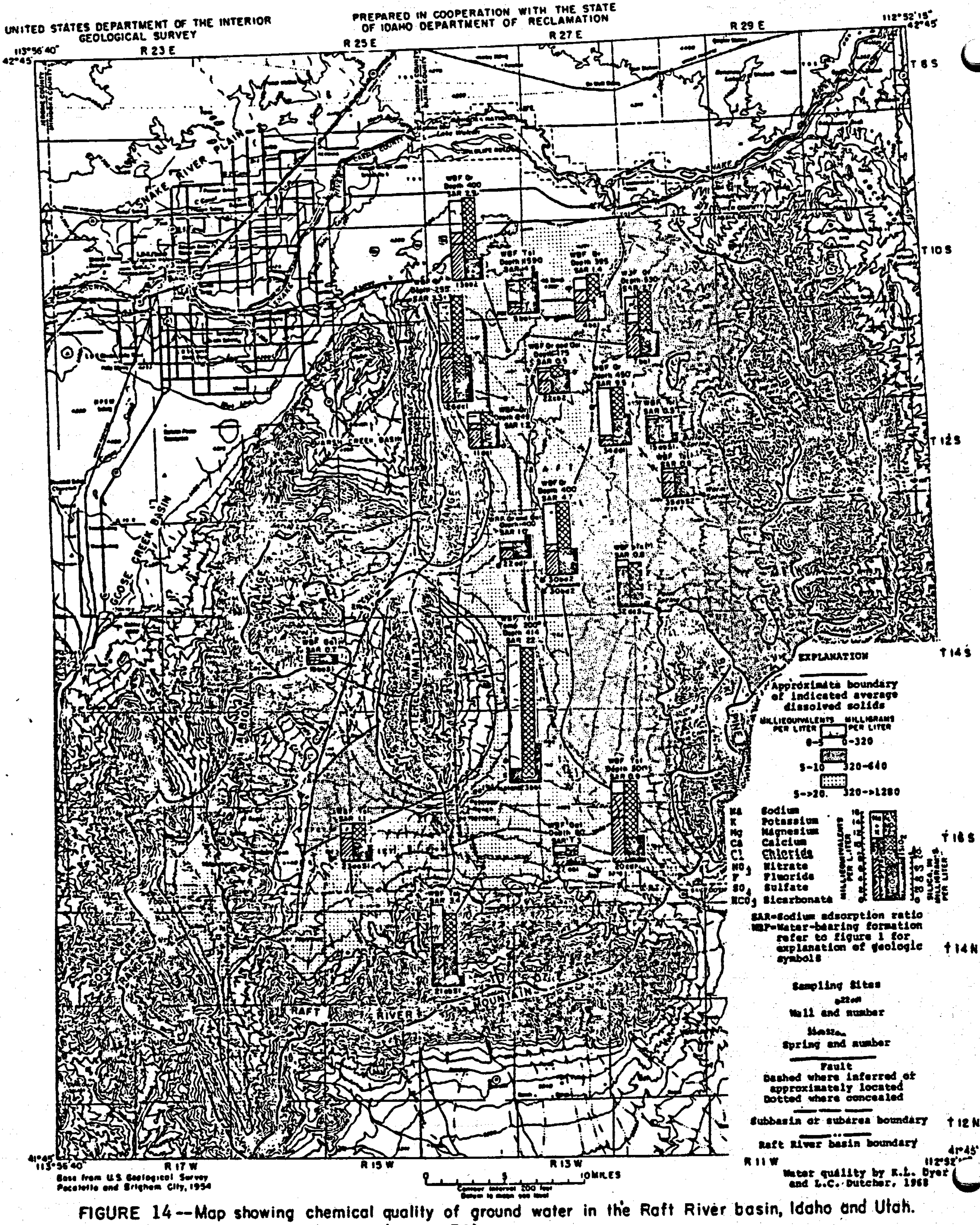


FIGURE 14--Map showing chemical quality of ground water in the Raft River basin, Idaho and Utah. (from Walker, et al, 1970)

salinity hazard). The quality of the water found in the various springs of the area and in spring-fed Sublett Creek is almost identical to the underlying ground water. Similar ground water occurs along the base of the Raft River Mountains and along the east flank of the Malta Range. Most of the water is very hard. Silica content ranges from about 15 to 80 mg/l.

The ground water pumped from beneath the Cassia Creek fan is similar to the water of Cassia Creek. The shallow water generally has a dissolved solids concentration of about 320 mg/l, or less, and so has only a medium salinity hazard.

A local body of moderately mineralized ground water occurs in the northern part of the Raft River Valley. Calcium is the predominant cation in this water, pumped from a few wells north of Idahome, so the sodium hazard for irrigation is low, and the hardness is exceedingly high. The dissolved-solids concentration ranges from 1500 to 3400 mg/l so the salinity hazard is very high. The source of the mineralization in this area is unknown, but it probably is from recirculated irrigation water. Water temperature is normal for the ground water of the area. The dissolved-solids concentration is about the same as that in thermal flowing wells; however, the sodium percentage is much lower.

Geothermal water flows under artesian pressure from several wells and at least one spring southwest of Bridge. The water temperature in shallow wells ranges from 85° F (29.5° C) to 211° F (99° C) (Nace and others, 1961). A comparison of the chemical analyses of water from two of these wells with water from three cold-water wells in the valley is indicated on Table 8. Fraizer Hot Spring (near Bridge) flows at 120 gpm, and the 204° F (95° C) water is used for irrigation (Waring, 1965). Three wells 5000 to 6500 feet deep drilled in 1975-1976 for the Raft River geothermal project produce 297-301° F (147-149° C) water at 350 to

Table 8 CHEMICAL ANALYSES OF WATER FROM SELECT WELLS IN THE RAFT RIVER VALLEY (from Nace and others, 1961)

[Chemical constituents in parts per million. Analyses by Geological Survey and Idaho Department of Public Health]

Well no.	10S-25E-10ba1	11S-26E-14ab1	13S-27E-23bb1	15S-26E-23bb1	15S-26E-23dd1
Depth of well (feet)	[1]175	[1]157	[1]28	[2]414	[2]540
Date of collection	4-8-49	6-9-49	6-25-47	6-8-49	6-9-49
Temperature (°F)	57	54	49	199	211
Silica (SiO_2)	44	54	--	82	84
Iron (Fe)	--	--	.14	--	--
Calcium (Ca)	60	59	59	52	125
Magnesium (Mg)	40	11	18	1.7	3.3
Sodium (Na) and Potassium (K)	39	49	240	530	1,070
Bicarbonate (HCO_3)	242	151	220	58	45
Sulfate (SO_4)	56	26	54	59	64
Chloride (Cl)	98	105	360	820	1,800
Flouride (F)	--	.4	.1	8.9	6.0
Nitrate (NO_3)	3.5	.3	--	.0	1.0
Boron (B)	.02	.0	--	.05	.04
Dissolved solids:					
Parts per million	460	379	618	1,580	3,180
Tons per acre-foot	.63	.52	.84	2.2	4.32
Hardness as $CaCO_3$:					
Total	314	192	221	136	326
Noncarbonate	116	68	41	89	288
Percent Sodium	21	36	70	90	88
Sodium-adsorption ratio	1.0	1.5	7.0	20	26
Residual sodium carbonate	.00	.00	.00	.00	.00
Specific conductance (micromhos at 25°C)	780	658	--	2,920	6,010
pH	--	--	7.7	--	--

[1]Water-table well.
[2]Artesian well.

400 gpm under artesian pressure (Kunze and Miller, 1977). The general characteristics of these three wells are indicated on Table 9, and a comparison of the chemical analyses of the water produced by each well with that from the Raft River and from two shallow thermal wells are shown on Table 10.

In general, the thermal water is high in Chloride, Fluoride, and Sodium and Potassium relative to most other Raft River Valley water. Dissolved solids range from 1500 to 4600 mg/l. Its use as irrigation water would involve a very high salinity hazard and a very high sodium hazard (Walker et al., 1970).

As ground and surface water outflow from the Raft River Valley decreases, ground water will increase in dissolved solids due to recirculation of irrigation water. This could cause and adverse salt-balance to develop and locally make the shallowest ground water too mineralized for reuse in irrigation (Walker et al., 1970).

Table 9 PERTINENT CHARACTERISTICS OF RAFT RIVER GEOTHERMAL EXPLORATION WELLS (from Kunze and Miller, 1977)

RRGE #1 - Completed in March 1975, 5000 ft deep

Solids in water:	1700 mg/liter
Artesian Pressure:	50 psig cold 175 psig hot
Reservoir Temperature:	297°F (147°C)
Flow Experience:	400 gallons per minute for many days with artesian pressure only 870 gallons per minute for 4 days with a pump, drawing down 375 ft below ground level
Predicted after 10 years of operation:	1100 gallons per minute with 900 ft drawdown below ground level

RRGE #2 - Completed in June 1975, 6500 ft deep

Solids in water:	1800 mg/liter
Artesian Pressure:	60 psig cold 165 psig hot
Reservoir Temperature:	298°F (148°C)
Flow Experience:	400 gallons per minute for several days with artesian pressure only
Predicted after 10 years of operation:	800 gallons per minute with 900 ft drawdown below ground level

RRGE #3 - Completed in June 1976, 5917 ft deep

Solids in water:	4600 mg/liter
Artesian Pressure:	40 psig cold 140 psig hot
Reservoir Temperature:	301°F (149°C)
Flow Experience:	350 gallons per minute for a day under artesian pressure (291°F at surface)
Predicted after 10 years of operation:	500 gallons per minute with 1000 ft of drawdown below ground level

Table 10 COMPARISON OF CHEMICAL ANALYSES OF THERMAL WELLS AND THE RAFT RIVER (Deviations in µg/mL)

	RRGE-1		RRGE-2		RRGE-3		RAFT RIVER		BLM WELL		CRANK WELL	
Chemical Species	$\overline{X}$	S_x	$\overline{X}$	S_x	$\overline{X}$	S_x	$\overline{X}$	S_x	$\overline{X}$	S_x	$\overline{X}$	S_x
Cl^-	776	184	708	70	2170	302	153	70	1139			
F^-	6.32	1.47	8.25	1.06	4.55	0.25	0.65	0.21	5.6		4.11	
Br^-	<1.5		<1.5		<1.5		<1.5		<0.15		<0.15	
I^-	0.036	0.003	0.028	0.019			0.066	0.016	<0.040		<0.040	
*HCO_3^-	63.9	20.8	41.3	11.2	44.4	11.1	172.5	45.0	83			
SO_4^-	60.2	6.7	54.1	5.1	53.3	14.6	55.2	28.0	54		54	
NO_3^-	<0.2		<0.2		<0.2		3.8	<0.2				
Total NH_3	1.56	1.19	0.60	0.41			1.0		0.59			
Total P	0.023	0.014	0.020	0.011			0.038	0.028	0.27			
S^-			0.256									
$Si(OH)_4$	182	33	201	40	242	21	40.4	21.0	132		142	
Si	56.6	16.7	61.2	14.5	74.0	8.0	18.7	1.5	46		49	
Na	445	99	416	44	1185	52	77	26	550		1074	
K	31.3	7.0	33.4	5.3	97.2	7.3	7.7	0.7	20		34	
Sr	1.56	0.35	1.03	0.32	6.7	0.7	0.52	0.16	1.35		0.36	
Li	1.48	0.40	1.21	0.57	3.1	0.2	0.04	0.01	1.4			
Ca	53.5	9.5	35.3	8.7	193	15	85.3	29.6	55		130	
Mg	2.35	2.09	0.58	0.80	0.60	0.16	23.9	9.8	0.2		0.5	
pH							7.94	0.15				
Total Dissolved Solids	1560		1267		4130	36			1640		3720	
X_m	.898		1		0				.870		.143	
Conductivity	3373		2742		9530	1546						
*Total Gas	33.4	21.9	35.4	22.1					12.9			
H_2	0.10	0.14	0.67	0.69					0.11			
He	0.03	0.01	0.01	0.01					N.D.			
N_2	30.6	20.8	18.8	7.1					12.4			
O_2	0.13	0.17	0.27	0.56					0.05			
Ar	0.49	0.21	0.35	0.12					0.16			
CO_2	1.91	2.48	1.01	0.63					0.15			

*HCO_3^- concentrations are recorded in µg/mL as $CaCO_3$

*Conductivity is recorded in µmho/cm

*Gas volumes are in Standard cc/liter

$\overline{X}$--Average Value

S_x--Standard Deviation of a single value

from: McAtee & Allen (1972).

3. PRODUCTION HISTORY AND SUBSIDENCE

3.1 HISTORY OF DEVELOPMENT AND USE

Probably the first permanent settlers in what is now Cassia County were those settling in the Raft River Valley (Idaho Water Resource Board, 1973). It was the "lush grass of the Raft River Valley" that attracted cattlemen. The first cattle arrived in spring 1868, and by 1883 the area had gained such prominence that it was granted a post office.

Beginning in the 1870's, large tracts were irrigated by diversion of surface flow from the Raft River and its tributaries (Shanklin, 1977). Stearns et al., (1938, p. 211) have described this process in their report on ground water of the Snake River plain.

> "During the irrigation season the whole river is diverted in the vicinity of Malta, and hence for a short distance the channel is dry. However, within a few miles sufficient water collects from irrigation waste and ground water inflow to make it profitable to divert the river again for irrigation. This procedure is repeated several times before the river finally empties into Lake Walcott."

Another early method of obtaining irrigation water was through the use of collector ditches (Stearns et al., 1938). These were dug radially on alluvial fans at a grade slightly less than the slope of the land. The trenches were dug 1000 to 2000 feet long, or until they intersected the water table, lined with tile, and backfilled. These drains had considerable discharge in the Spring, but were inaffective during periods of low ground water levels.

Over the years, virtually all divertable surface flow during the growing season has been exploited, and by 1928 the total consumptive use of surface water is estimated to have been 47,000 to 48,000 acre-feet (Walker et al., 1970). As pumping of ground water increased, this value decreased so that by 1960 only about 20,000 acre-feet of surface water was used.

Pumping ground water for irrigation in the valley began in the 1920's. In 1938 Stearns et al., show 114 wells on their map of the Raft River Valley area. These wells extended a few feet below the water table and were generally of poor construction. It was not until about 1950 that large scale pumping began to supplement irrigation by surface diversion and to irrigate large tracts remote from surface supplies. The increase in number of irrigation wells, cumulative percent of total pumpage, and ground water pumpage as computed from electricity used for the period 1948 to 1966 are shown on Figure 15. Figure 16 indicates the location of water wells in the valley as of 1966.

Increased use of ground water in early 1960's caused the Idaho State Reclamation Engineer to declare on July 23, 1963 the Raft River Valley a Critical Ground Water Area, to cease to approve new permits to appropriate ground water, and to study and re-examine the ground water situation (Haight, 1964). The action was challenged by local interests, and litigation followed. The area between the Narrows and the Yale-Cotterel Road, north of Horse Butte, presently retains a Critical Ground Water Area designation (Crosthwaite, personal communication, 1978), with new wells being drilled only under old permits.

Increasing water consumption is expected to continue in the future; the greatest portion will be for irrigation. Shanklin (1977) presents data that indicates water applied for irrigation will increase at about 423 acre-feet/year during 1976-1981 and about 1196 acre-feet/year during 1981-1986. Flood irrigation should decrease, while the

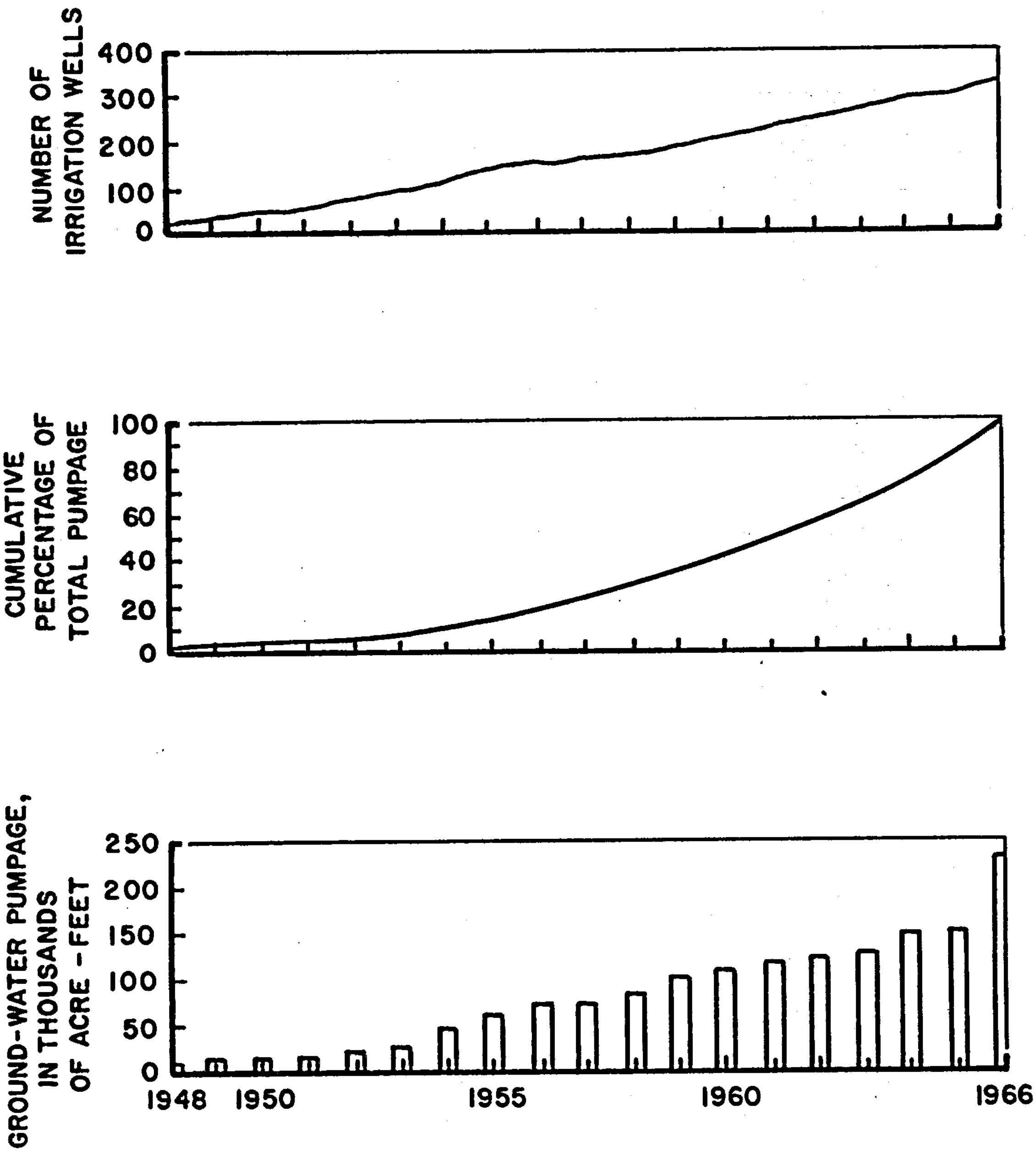


FIGURE 15 GRAPHS SHOWING PUMPAGE AND NUMBER OF IRRIGATION WELLS IN THE RAFT RIVER BASIN (from Walker, et al, 1970 and Chapman & Sisco 1973)

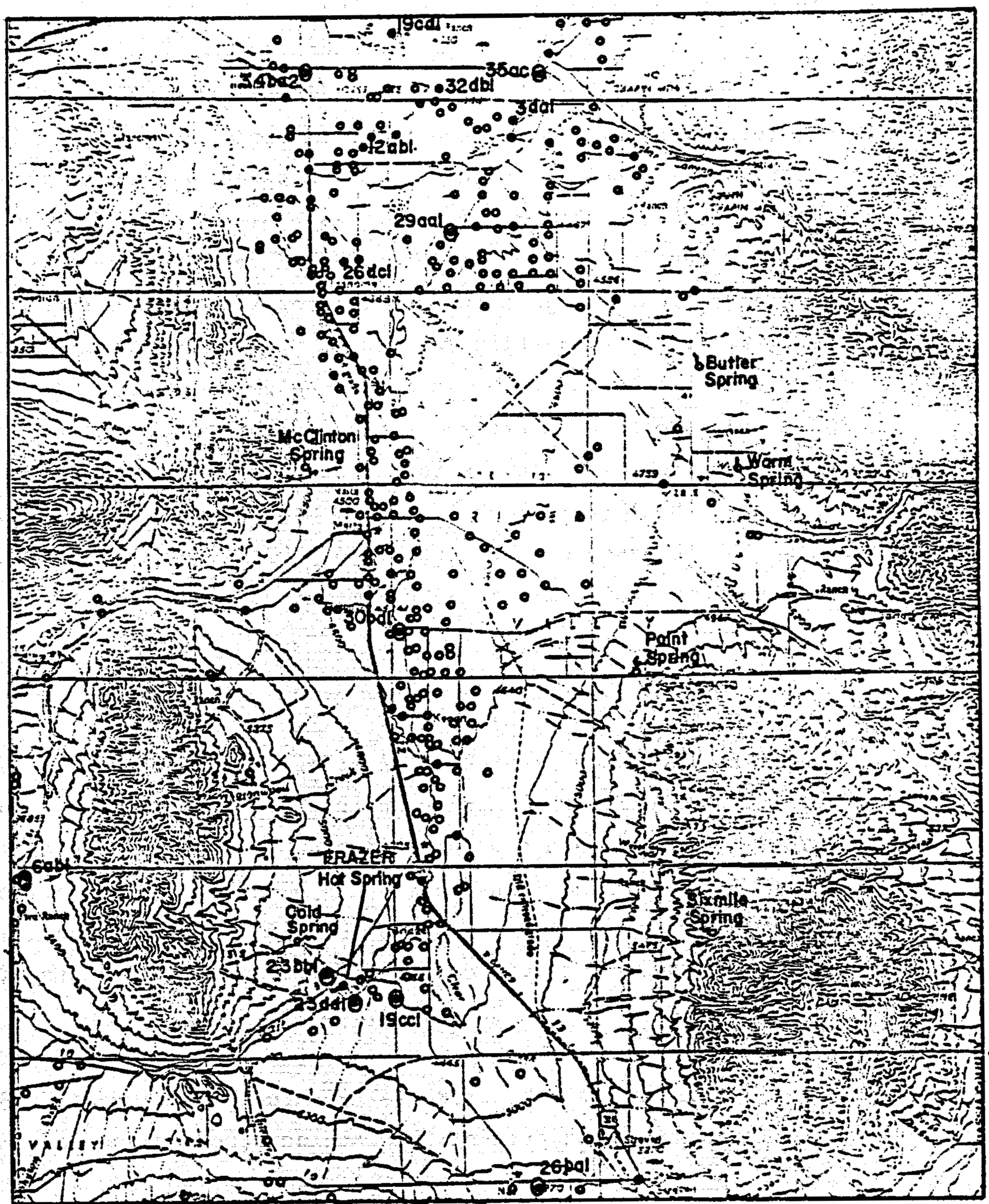


FIGURE 16 WELL LOCATION MAP OF RAFT RIVER VALLEY, 1966
(from Walker et al, 1970)

more efficient sprinkler irrigation increases. Domestic water consumption should remain near its present low level.

The first Raft River geothermal well began production early in 1975. Total monthly flow of the three currently producing wells through December 1977 is shown on Figure 17. The spent geothermal fluids presently percolate back into the ground water reservoir from surface ponds. Some reinjection testing has been done on RRGE-2, but because of decreased production following injection, the testing was stopped (Kunze and Miller, 1977). A reinjection well (RRGI-4) will eventually be used to inject spent geothermal water at depths below the near surface aquifer (600 feet). Tests have proven it can easily accept a flow of 600 gpm, but 1200 gpm flows for many years are necessary for an economical geothermal injection well (EG&G-Idaho, 1978). Geothermal water use should continue to increase, but reinjection of this water back into the ground water reservoir should minimize the amount of water consumed.

3.2 CHANGES IN RESERVOIR PROPERTIES AS A FUNCTION OF USE

As mentioned previously, little is known about the physical properties of the material making up the Raft River Valley ground water reservoir, and nothing has been published on how these properties may be changing with use. The main concern has been how use has affected water levels rather than how the withdrawal has affected the reservoir. Nearly fifty years of record exists on at least some aspects of this topic. Stearns et al., (1938, p. 217) write...

> "From the few measurements made in the spring of 1928 and from the fact that much of the land adjacent to the Raft River is submerged in the spring by floodwater, which causes the water to rise to the surface, the average annual rise of this water table in the area enclosed by the contour showing 10 foot

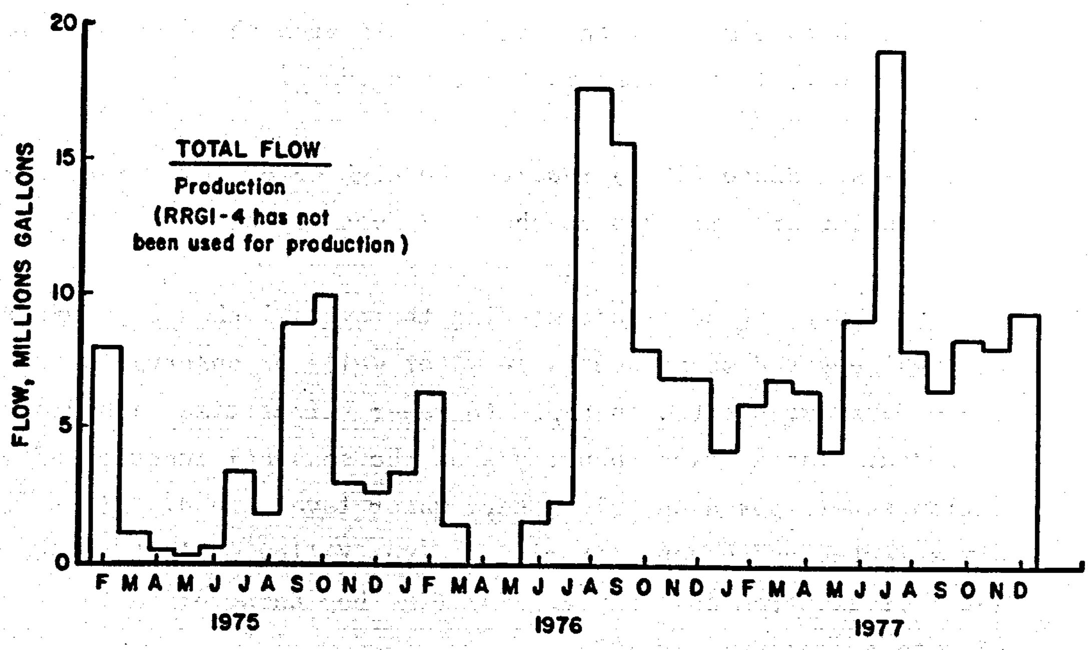


FIGURE 17 MONTHLY TOTAL FLOW PRODUCTION OF RAFT RIVER GEOTHERMAL WELLS RRGE-1,-2,and -3 (from EG&G - Idaho, Inc. 1978)

depth to water is estimated at about 4 feet. Thus, the 10 foot line in the fall would approximate the position of the 6 foot line in the spring. During the spring in the middle part of this area, ground water has been observed on several thousand acres standing practically at the surface. Also numerous borrow pits and natural depressions only a few feet deep were kept supplied by ground water, even in the late fall, and hence the line of 10 foot depth to water was controlled by many observations of natural depressions and swampy tracts. Within much of the land of this area the depth to water is only 1 to 3 feet in the spring."

By contrast, Sisco (1976) reports the high water level for observation wells in the area in 1975 at about 12 feet depth.

One method of documenting the overall change in water level is through repeated measurements in water wells or observation wells. When these data are plotted as depth to water versus time, a hydrograph is produced. These graphs usually show the seasonal function of water inflow superimposed on a long term water level trend. Figure 18 shows six selected hydrographs from Raft River Valley wells that document water levels from as early as 1947 (the beginning of heavy ground water use) to as recently as 1975.

The hydrograph of well 16S-27E-26bal, located near Naf, where irrigation has not affected the water level, is included in Figure 18 to show the natural fluctuation of the water level. Water levels begin to rise in late winter or early spring as a result of precipitation and runoff, peak in summer and decline to a seasonal low in late winter. This hydrograph also shows periods of below average precipitation, such as 1954-55, 1959-60, and 1966, and intervening normal or high rainfall periods.

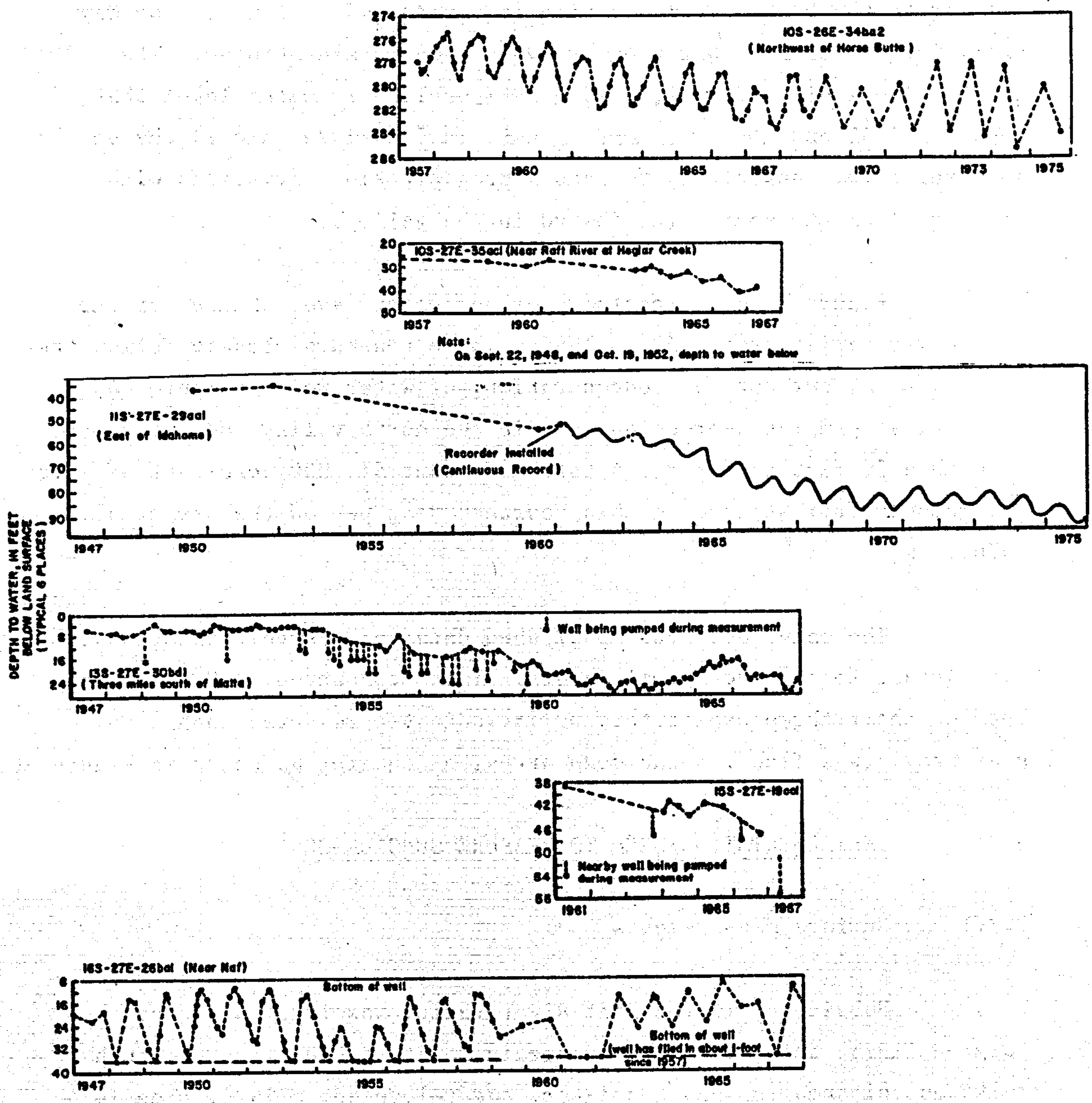


FIGURE 18 HYDROGRAPHS OF SELECTED WELLS IN THE RAFT RIVER VALLEY

Note:
1) Location of wells shown on Fig 16
2) Hydrographs are arranged in order from S (at bottom) to N (at top)
3) From Walker, et al (1970) & Sisco (1974,1975,1976)

The additional hydrographs on Figure 18 indicate water level fluctuation in areas of the Raft River Valley where irrigation has affected water levels. These show a seasonal change in water level similar to the Naf well with a high in spring and declining from May until October or November when irrigation wells are pumping. The hydrographs also indicate: 1) the long term decline in water level that began in 1952 and somewhat stabilized in 1969-1970, and 2) the decrease in water level sensitivity to annual precipitation variations with distance from the source (northward in the valley).

Figure 19 shows contours of net water level change for the Raft River Valley from 1952 to 1966. These contours closely follow the distribution, but not the concentration, of water wells (Figure 16). The largest pumping depressions are in the north valley and amount to more than 50 feet in depth. A total of about 513,000 acre-feet of water was removed from storage in this fourteen year period (Walker et al., 1970).

The only additional published data on reservoir changes with use pertain to the geothermal waters. Tests conducted by EG&G-Idaho, Inc. on their three exploratory wells indicate projected change in pressure versus flow for the deep artesian acquifer as shown in Figure 20.

3.3 INSTRUMENTATION USED TO MEASURE SUBSIDENCE

3.3.1 Surface Measurements

Subsidence in the Raft River Valley was first detected when Lofgren (1975) determined the change in relative elevation of bench marks established in 1934 and later, and releveled in 1974. The 1974 releveling was done to investigate possible ground movement prior to geothermal development and was to include only bench marks south of

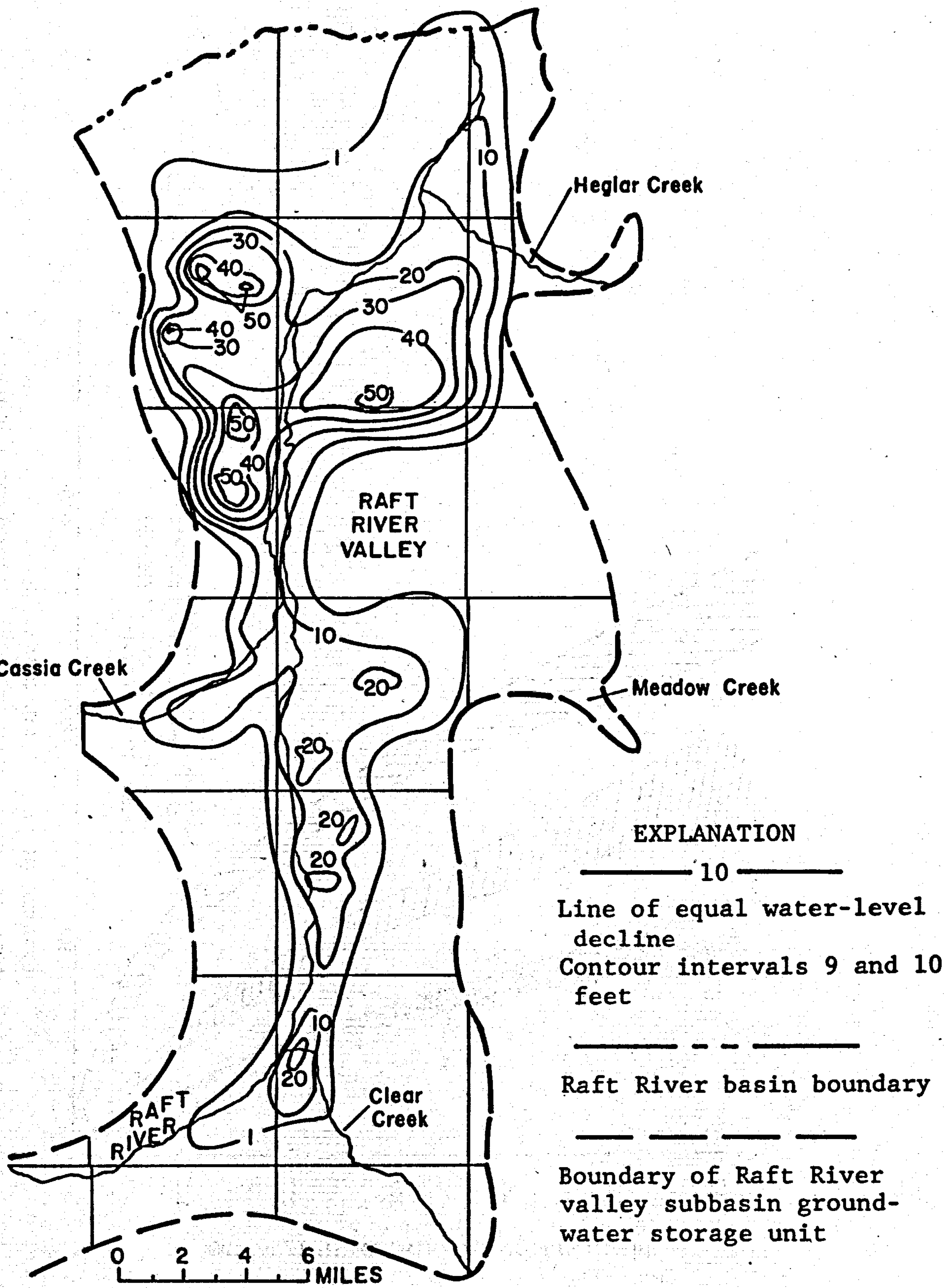


FIGURE 19 NET WATER-LEVEL CHANGE IN RAFT RIVER VALLEY, SPRING 1952 TO SPRING 1966 (from Walker, et al, 1970)

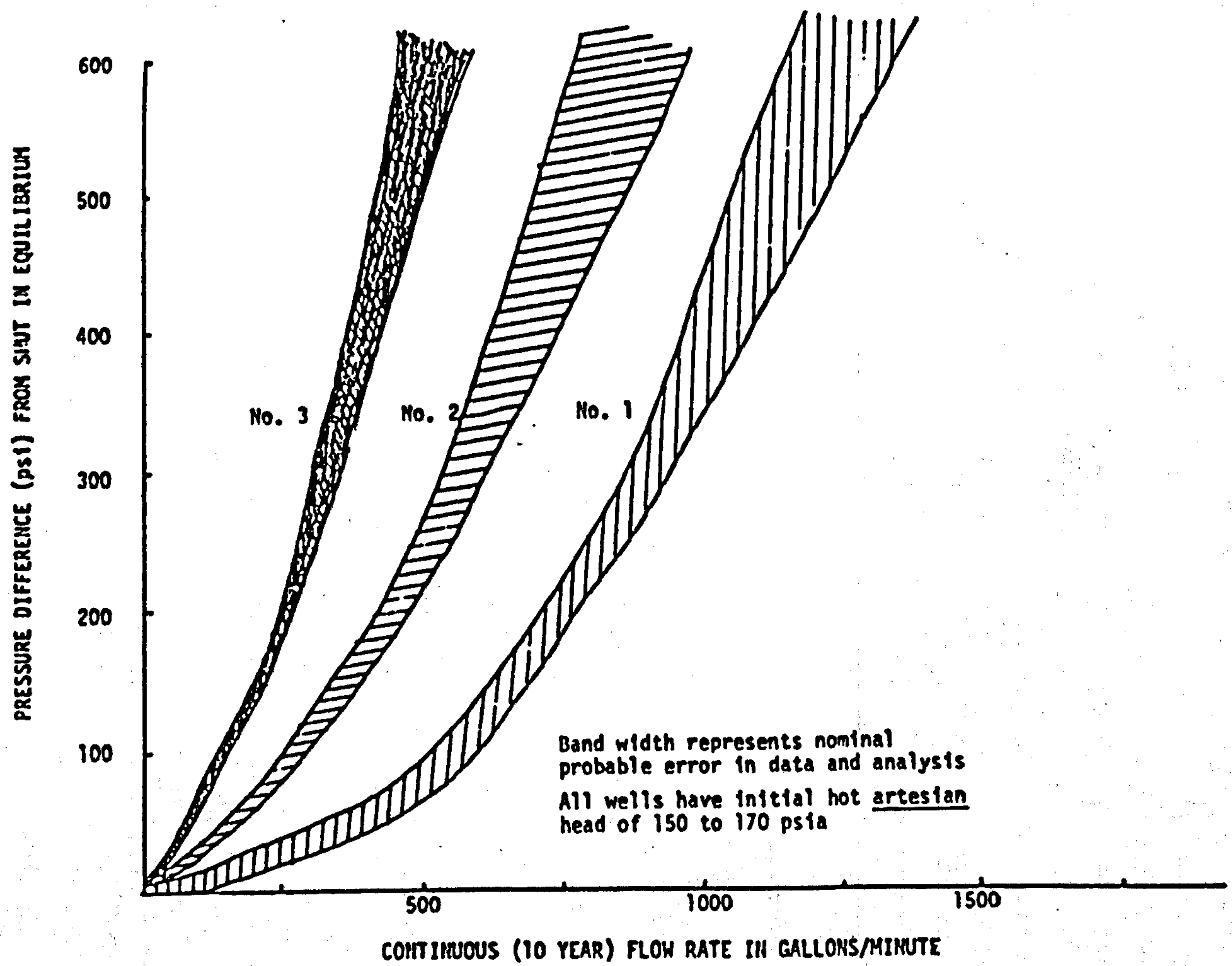


FIGURE 20 RAFT RIVER GEOTHERMAL WELLS PRODUCTIVITY CURVES AS EXTRAPOLATED TO 10 YEARS OF CONTINUOUS FLOW (from Kunze & Miller, 1977); SEE TABLE 9 FOR DESCRIPTION OF WELLS.

Malta. The program was expanded north to Horse Butte and east along Cassia Creek after recognition of an earth fissure in the Idahome area probably related to ground water drawdown. The location of bench marks used in this comparison, as well as bench marks set in 1974, are shown on Figure 21.

The U.S. Coast and Geodetic Survey established most of the original bench marks in the Raft River Valley. The survey line following Highway 30S down the middle of the valley was originally leveled in September 1934. A portion of the line, from near Horse Butte to Malta, was releveled, and additional bench marks established in July 1958. The line along Cassia Creek, west of Malta, follows the Oakley Road, and was originally surveyed in July 1935. Additional lines that have been established but not releveled include: a September 1960 line following a gravel and dirt road southeast from Horse Butte to east of Malta (probably abandoned due to construction of Highway 80N); a line east from Malta along a gravel road surveyed in August and September 1960; a line along the east side of the valley running south to Sublett Creek, surveyed in 1935 and releveled in 1938; and a 1934 line along the south foothills, west from Strevell. All of these lines have second-order accuracy (closure within 3 mm x $\sqrt{\text{distance in km}}$).

The U.S. Geological Survey's first leveling in the valley was in 1967 along a gravel road southwest through the Narrows. During their releveling surveys in 1974, additional bench marks were established along the Highway 80S line, on bedrock on either side of the Narrows, on the north and south side of Cassia Creek where it passes through the Malta Range, and on the Snake River basalt east of Interstate 80N. They also established a new line running east from Highway 80S near Bridge to the edge of the valley.

EXPLANATION

-2.61
L122

Bench mark, number, and elevation change for period shown. HLS bench marks set in 1967. DOR bench marks and those with no change set in 1974. All others set in 1934-35.

— — — 1.0
Tentative line of equal subsidence. Interval 0.5 feet.

Raft River Geothermal Subsidence Grid

Line of horizontal control established 1974-75

Earth fissures of Lofgren (1975)

Earth fissures pictured in this report (Figs 24 & 25).

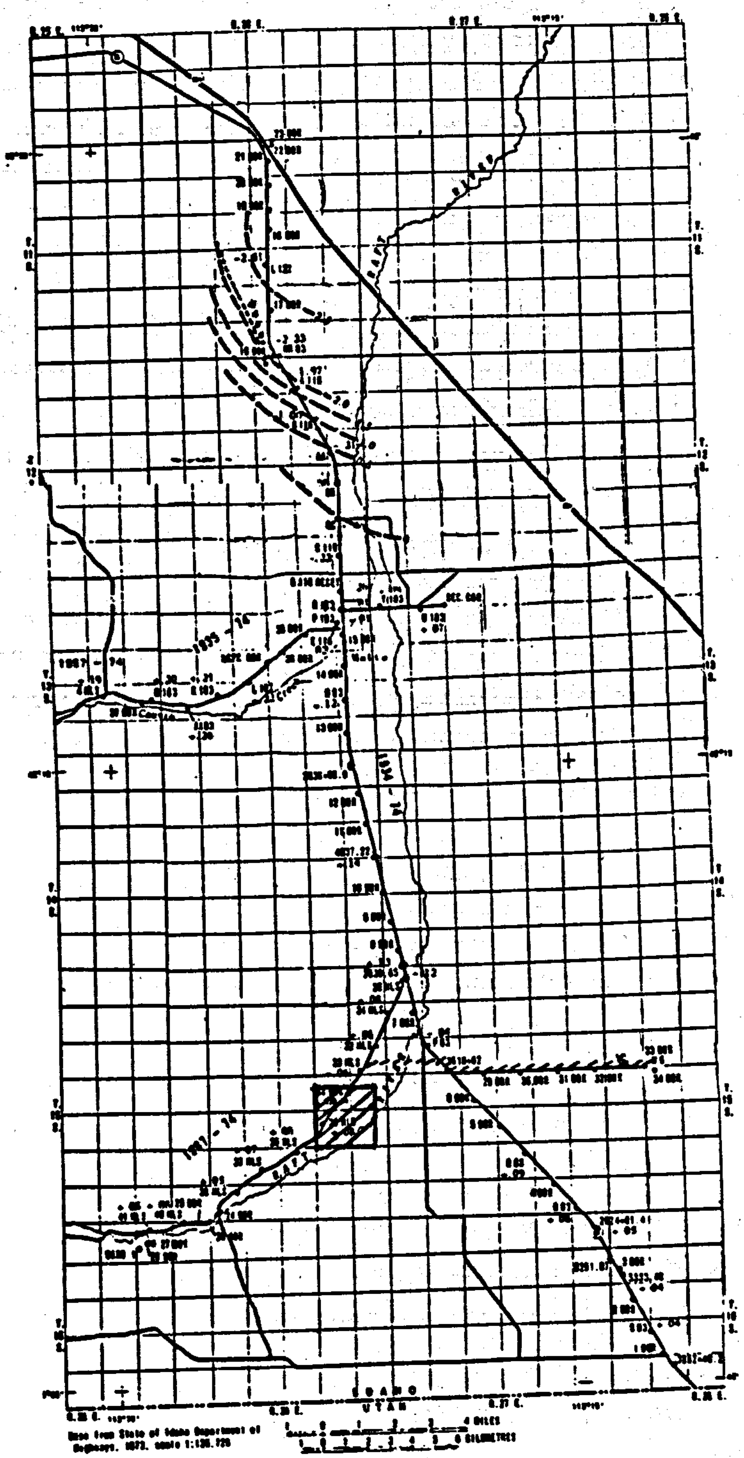
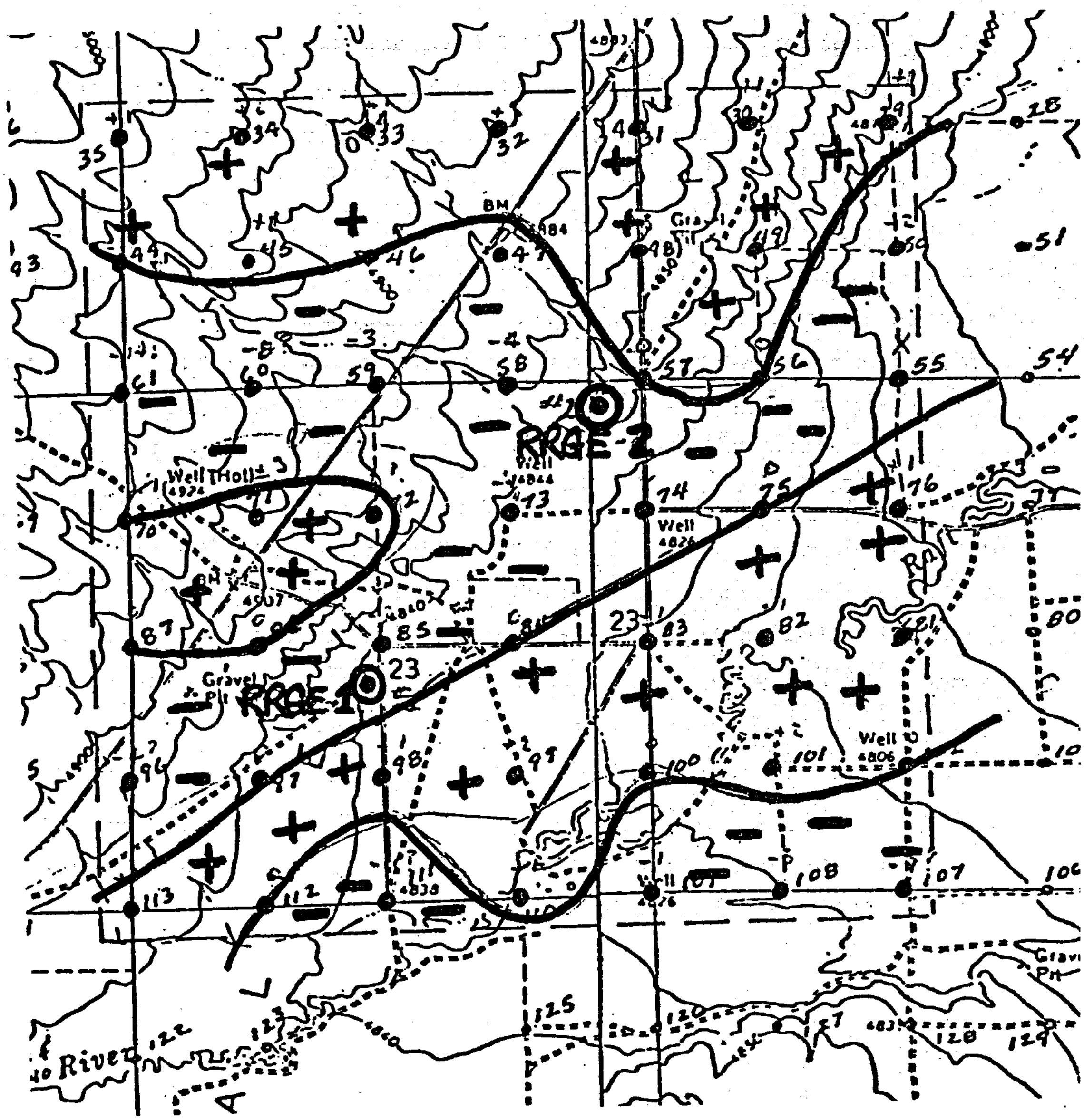


FIGURE 21 MEASURED CHANGE IN ELEVATION OF BENCH MARKS, RAFT RIVER VALLEY, Idaho (from Lofgren, 1975)

Spencer and Depot (1976) have described the grid establihsed by EG&G-Idaho, Inc. to check subsidence in the area of Geothermal wells RRGE-1 and 2. This grid covers a 9 square mile area with elevation points established on one-quarter mile centers (see Figure 21). The horizontal position of each point was originally set out with second-order accuracy and its elevation measured to third-order accuracy ($6 \text{ mm} \times \sqrt{\text{distance in km}}$), tying in to four established U.S.G.S. bench marks within the grid (Stoker, personal communication, 1978). The original elevation points were leveled in June 1975, but were not verified by closures. The grid was narrowed to those points within 1-1/2 mile square in November 1975, leveled, and the lines closed in segments. This smaller grid is surveyed semi-annually and was due for releveling in April 1978. The future surveys will include additional U.S.G.S. bench marks for at least 10 miles to the northeast (Spencer, written communication, 1978). The accuracy of this system is such that only relatively large changes in land surface elevation could be detected. In comparing the three level runs between June 1975 and September 1976, Spencer and Depot (1976) found no indication of any settlement within the grid. Figure 22 is a contour map of these data. It shows a definite pattern of change, but the meaning is unclear.

Second and third order horizontal control monuments have been established in the valley and bordering mountains by the U.S.G.S and the National Geodetic Survey (formerly Coast and Geodetic Survey). These monuments are too far apart and too inaccurately located to give useful data relative to subsidence. Lofgren, (1975) established several lines of horizontal control in 1974 that have been reshot and extended annually. One line consists of closely spaced monuments along dirt roads running east-west through Bridge and extending to the valley margins. About thirty additional points are shot radially from a monument in the vicinity of the geothermal wells. No indication of horizontal change has been identified to date (Lofgren, personal communication, 1978).



◉ Geothermal Well

•73 Survey Points

+ Area of tentative rise in elevation

— Area of tentative drop in elevation

——— Zero change contour

FIGURE 22 ELEVATION CHANGE MAP OF PART OF THE RAFT RIVER GEOTHERMAL AREA JUNE 1975 THROUGH SEPT 1976

3.3.2 Subsurface Measurements

Gravity studies have been done by the U.S.G.S. in the southern Raft River area (Mabey and Wilson, 1974). These could be used to establish baseline conditions from which subsidence could be calculated from the change in gravity due to ground water withdrawal.

Installation of at least two extensometers is planned for spring 1978 in the geothermal area (Spencer, personal communication, 1978). These will be placed in shallow (500 feet) and intermediate depth (1500 feet) monitor wells.

3.4 SUBSIDENCE CHARACTERISTICS

Of the level lines previously described that have been repeatedly surveyed, only the Highway 30S lines shows a consistent drop in elevation. The major subsidence begins about 3.5 miles north of Malta and increases northward to a maximum measured drop of 2.61 feet over a distance of 7.2 miles. Although the greatest subsidence was measured at the end point of the survey, subsidence probably does not increase greatly north of the last point, as this point is close to the center of the northernmost pumping depression shown in Figure 19. One area near Bridge and another immediately north of Malta may be experiencing minor subsidence of about 0.2 foot; this is based on only a couple data points, so is very speculative.

Tenative subsidence contour lines have been drawn by Lofgren (1975) and are indicated on Figure 21 along with net change at individual bench marks. The configuration of these lines has been influenced by: 1) the pattern of water level declines, 2) the configuration of the volcanic unit in the Salt Lake group, and 3) the trend of the earth fissure (Lofgren, 1975). Many more data points would be necessary to adequately contour this depression. The subsidence contours are arranged as subconcentric arcs about a center located near the point where the Raft River is first deflected by the Snake River basalt flow. Maximum rate of movement averaged over the forty year interval of releveling is 0.065 foot per year at bench mark L122. If subsidence began in the early 1950's with increased ground water pumpage, the maximum subsidence rate would be about 0.13 foot per year.

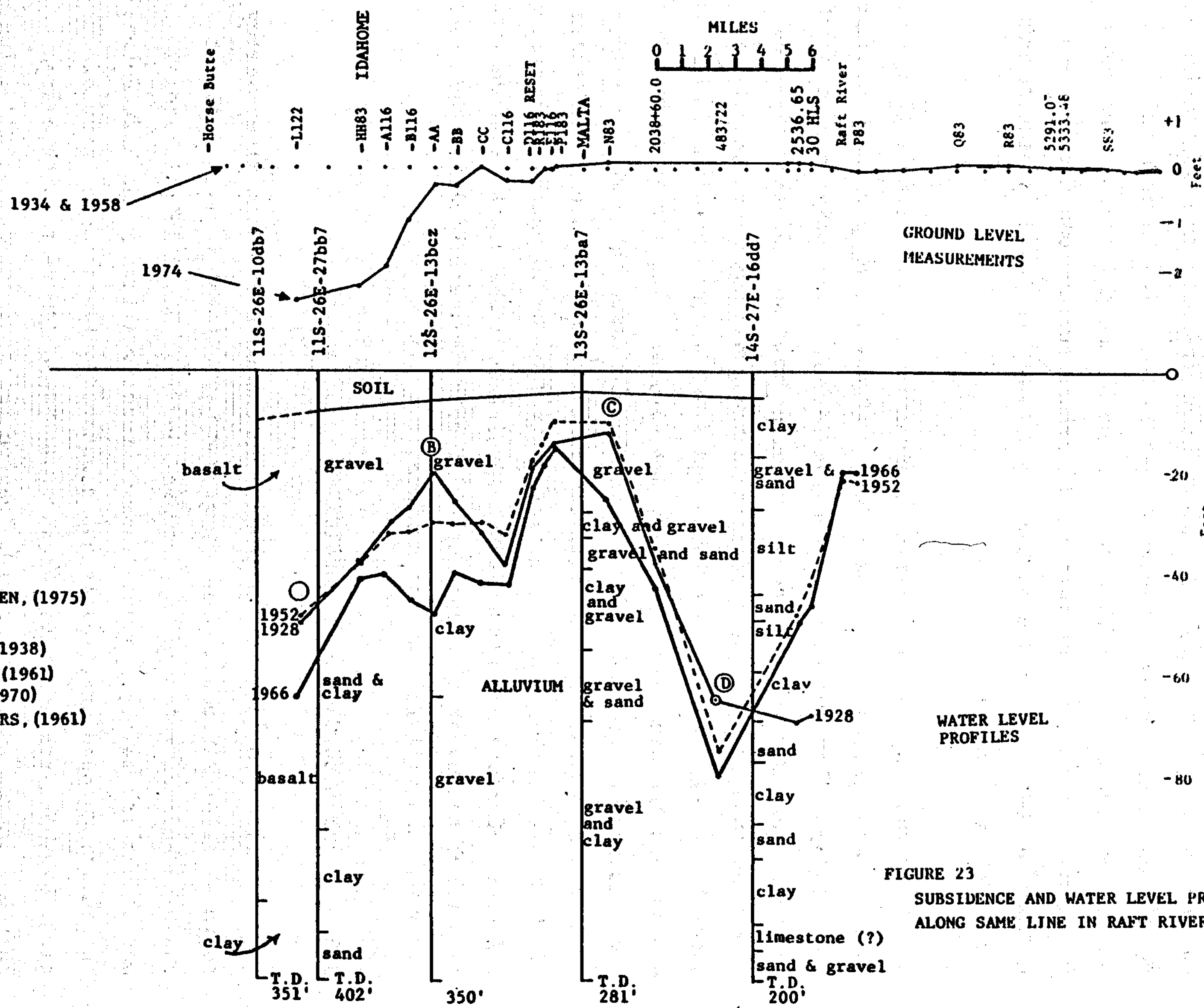
A profile along Highway 30S depicting subsidence, depth to water table, and subsurface geology is shown on Figure 23. Historic water levels, derived from water level contour diagrams, tend to be subparallel with the more recent levels lower than the previous ones by amounts ranging from 1 to 28 feet. Less change in water level configuration occurred in the 24 year interval between 1928 and 1952 than in the 14 year interval between 1952 and 1966.

The four areas of greatest water level decline are labeled (in Fig.23) "A"(-16'), "B"(-28'), "C"(-15'), and "D"(-15'). "A" corresponds to the area of maximum measured subsidence; "B" is at the edge of the subsidence bowl; "C" and "D" are located in areas where no subsidence has occurred. The correspondence between declines in water level and subsidence of the ground surface probably depends on the type of material dewatered. Where the dewatered section was predominately sand and gravel as at "C" and "D", no subsidence occurred; where thick clay units were detwatered, as at "A" and "B", subsidence did occur. The drillers' logs are not detailed enough to permit correlation between amount of subsidence and amount of clay.

The only observed surface manifestations of subsidence in the Raft River Valley are the earth fissures in the northwestern part of the valley about 1 mile nothwest of Idahome (Figure 21). Lofgren (1975) describes this feature as being a single, N24°W trending fissure 3.3

• DATA POINT

⊙ EXTRAPOLATED POINT



SOURCES OF DATA

1) SUBSIDENCE DATA FROM LOFGREN, (1975)
2) WATER-LEVEL DATA FROM:
   1928(?) - STEARNS ET AL., (1938)
   1952 - NACE AND OTHERS, (1961)
   1966 - WALKER ET AL., (1970)
3) WELL LOGS FROM NACE & OTHERS, (1961)

FIGURE 23
SUBSIDENCE AND WATER LEVEL PROFILES ALONG SAME LINE IN RAFT RIVER VALLEY

miles long. A site visit by representatives of Earth Sciences Associates and SCI in March 1978 revealed a N20°W to north-south-trending series of an echelon cracks greater than 1500 feet in total length near this location. Figures 24 and 25 show how some of these fissures appeared at that time. Individual openings in the ground surface measured as much as 3 by 10 feet. The fissures tapered downward as far as 8 feet before surficial fill was encountered.

The fissures were first observed in the early 1960's (Lofgren, 1975) after a period of intense rainfall (Crosthwaite, personal communication, 1978). They appear to be tension features that originate at depth on the western margin of a cone of pumping drawdown. Similar fissures have been observed along the edges of other ground water basins where water level declines have been observed (such as the Phoenix area in Arizona and the San Joaquin Valley, California). The mechanism by which such fissures are formed is not clear and, in fact, there may be several contributing factors. Such fissures typically develop along the margins of the basin, probably at a location controlled by an unknown subsurface features. Surface and ground water running down the cracks enlarge them by piping; the eventual accumulation of coarse material causes the crack to bridge and fill in near the surface.

3.5 IMPLIED CAUSES OF SUBSIDENCE

The proximity of subsidence in the northern Raft River Valley to the area of maximum decline of ground water level implies a direct cause-and-effect relationship between the two. Water in this area is unconfined and mainly produced from Quaternary alluvium and Raft Formation. The fall in groundwater levels has dewatered only the upper part of alluvium which ranges in thickness from 150 to 300 feet in this area. This has increased the effective load on the soil particles, resulting in compaction of the dewatered alluvium. If the maximum subsidence is

FIGURE 24 NORTH-NORTHWESTERN VIEW OF FISSURED GROUND. CRACKS TREND FROM CENTER FOREGROUND TO THE RIGHT AS SHOWN.

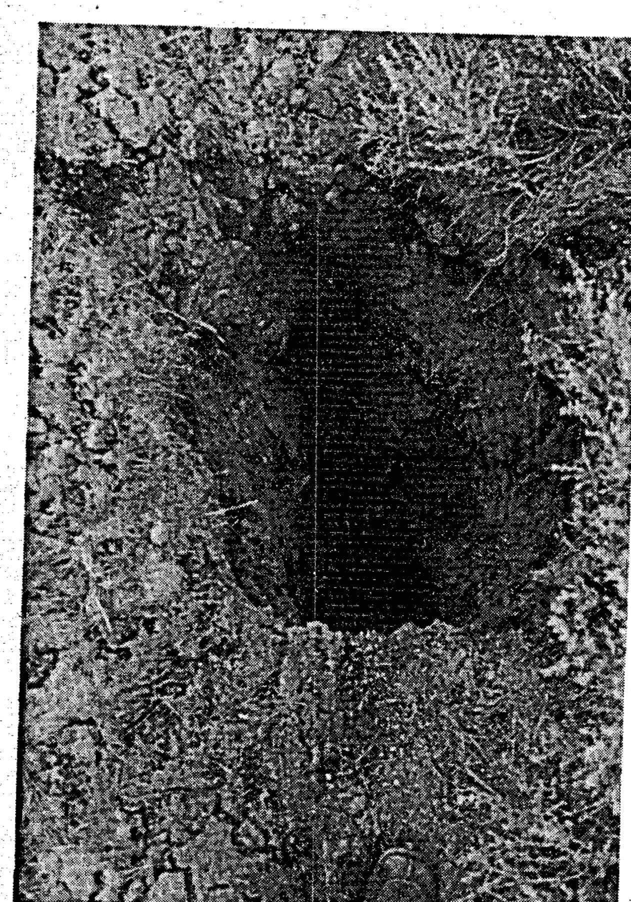


FIGURE 25 CLOSEUP VIEW OF TYPICAL FISSURE. THIS ONE IS ABOUT 0.5 M BY 1.5 M AT THE TOP OPENING AND TAPERS TO ABOUT 5 CM WIDE AT 2 M DEPTH. NOTICE HOW FISSURE EXTENDS BENEATH UNBROKEN SURFICIAL MATERIAL.

2.6 feet from 1934 to 1974 and the water level dropped from a depth of 34 feet to a depth of 85.7 feet during this period, the ratio of subsidence to water level decline is 0.050 foot per foot.

Lowering of ground surface elevation may occur from other causes such as active faulting, continued downwarping of the Snake River Plain, and loading by the Snake River basalt; however, none of these causes are consistent with the local and regional geologic framework. The possible influence of these factors may be demonstrated when the Highway 30S line with the recently established 1974 bench marks is releveled.

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WAIRAKEI

TABLE OF CONTENTS

1. INTRODUCTION

Wairakei is a geothermal field lying on the New Zealand North Island. Of all the subsidence sites reviewed in the project, Wairakei has one of the best overall subsidence data bases. Modeling studies already accomplished (Pritchett, 1976 and 1978, Mercer, 1975) have brought much of the available data base to the U.S., and have added to our knowledge of the Wairakei system. Wairakei is quite analogeous to many of the U.S. geothermal sites in geologic categories I and IV, and therefore should prove to be a valuable case study.

Production at Wairakei started in the early 1950; however, a major increase in production began in 1958 when power generation was started. In the early years of production, prior to 1963, recharge to the reservoir was much less than production volume (∿10%), thus causing large pressure drops in the reservoir (in the order of 250 psig in the western production area and over 300 psig in the eastern production area). After 1963 pressure decline in the reservoir leveled off to less than 10 psig per year. First and second order leveling since 1956 has shown that ground subsidence was relatively slow prior to 1960, and then increased to a sustained maximum subsidence rate from 1962 through 1971. By 1974, the maximum subsidence of the Wairakei area reached over 15 feet. Through 1974 the rate of subsidence continued to be high, even though reservoir pressures have remained nearly constant since 1968.

Maximum subsidence at Wairakei occurs away from the main production area, in the eastern part of the field. There are a number of possible explanations for this unusual phenomenon. Probably the most important explanation is the much greater thickness of the Waiora Formation reservoir under the eastern area. In addition, the groundwater pressure gradient falls strongly from west to east in the Waiora aquifer. As a result, pressure drops due to production would tend to be greater in the east.

2. NATURAL CONDITIONS

2.1 PHYSIOGRAPHY

2.1.1 Location

The Wairakei geothermal field lies in an active volcanic belt on the North Island of New Zealand (Figure 1). The field boundaries can be approximately defined by the Wairakei stream in the north and northeast, the Waikato River in the southeast, the Waipouwerawera stream in the south, and Poihipi road in the west.

2.1.2 Topography

The topography of the Wairakei field area consists of hills of Wairakei Breccia rising to between 300 and 500 feet above relatively flat valleys floored with Taupo Pumice Alluvium. The hill slopes are mantled with ash showers and windblown pumice alluvium, and outcrops are scarce except in steep bluffs where pumice breccia has been silicified by hydrothermal activity. Prior to development, the hydrothermal area was covered by native scrub with small clumps of self-sown pine trees; the latter have since colonised much of the Waiora Valley. In the last few years most of the accessible flat land has been cleared for drilling sites, steam lines, roads, and other purposes connected with geothermal development operations. The steep hill slopes are still, however, largely unaffected, although the pine trees are slowly being killed by deposition of silica from discharging wells.

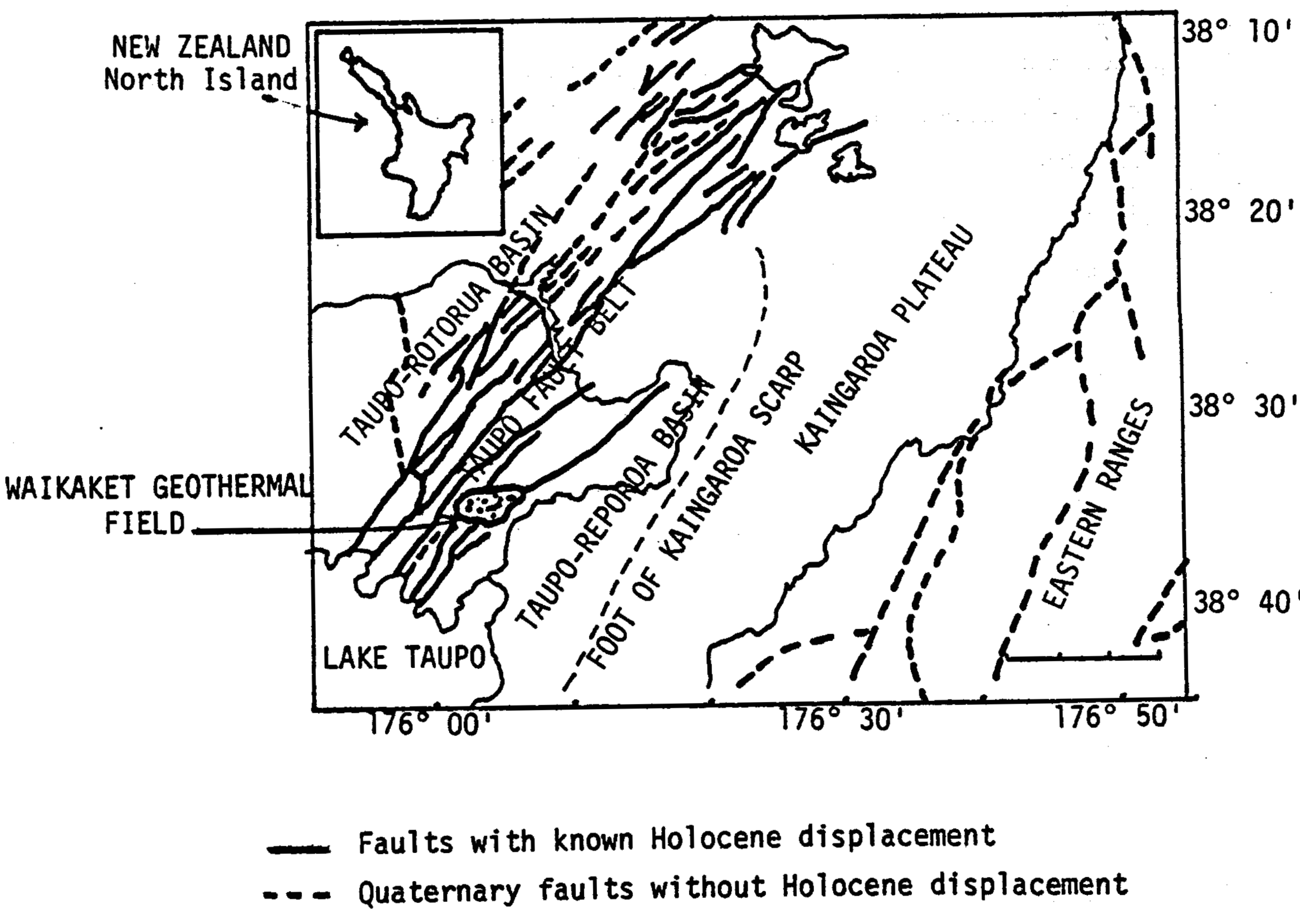


FIGURE 1 MAP SHOWING LOCATION OF THE WAIRAKEI FIELD AND REGIONAL STRUCTURE OF CENTRAL NORTH ISLAND, NEW ZEALAND (modified from Evison et al, 1976, p. 626)

2.2 GEOLOGY OF AREA

2.2.1 Structure and Stratigraphy

The regional geologic setting of the Wairakei geothermal field has been concisely described in a report by Systems Control, Inc. (1976, v2 p. 2-97) from which the following discussion is adapted.

The Wairakei geothermal area of New Zealand is situated in the North Island's central volcanic district, which has been active from early Pleistocene to historic time. The present and latest prehistoric activity has been concentrated in an elongate structural trough (10 to 20 miles wide) which extend approximately 150 miles south of Lake Taupo, to White Island in the Bay of Plenty (Grindly, 1965, p. 13). This trough, known as the Taupo Volcanic Zone, is the landward extension of a magmatic arc associated with the Tonga-Kermadec trend, a boundary between major crustal plates, and it parallels the regional Alpine fault zone, located to the southeast (see Figure 2).

The Taupo volcanic zone is subdivided structually into up and down-thrown blocks by a system of northwest and northeast-trending faults with dominantly normal displacement. The horst and graben structure is indicative of regional stresses which are tensional in nature. Contemporaneous faulting and sedimention has results in the formation and disruption of several sedimentary basins and, therefore, in large lateral changes in the thickness of major sediment units. Active andesitic volcanoes dominate the ends of the Taupo depression. However, the wider central part, in which the thermal areas occur, is covered by a thick sequence of rhyolitic ignimbrites, tuffs, and tuffaceous sediments which have been pierced by shallow rhyolitic intrusions.

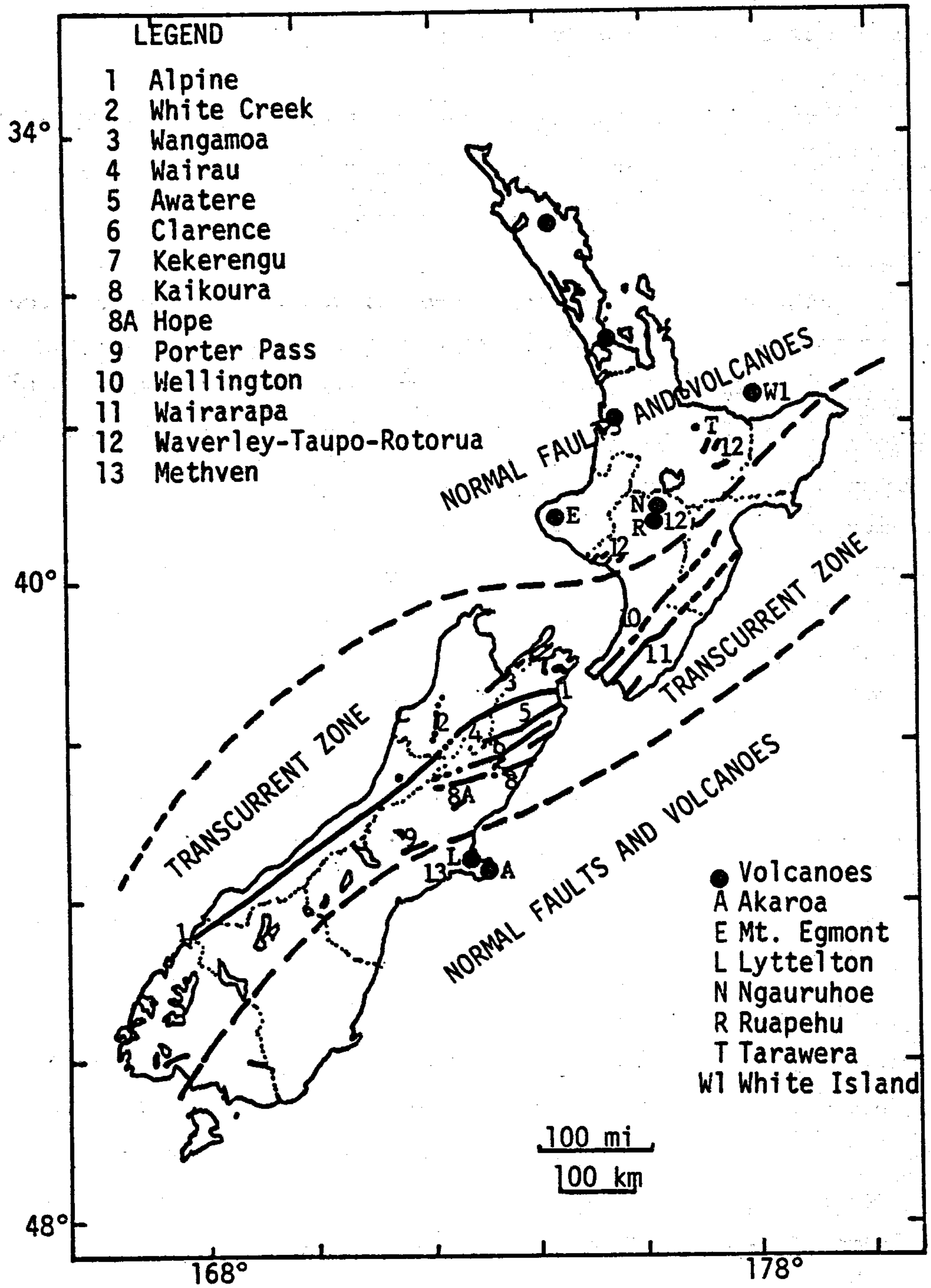


FIGURE 2 LOCATION OF MAJOR ACTIVE FAULTS AND VOLCANOES ACTIVE SINCE THE PLEISTOCENE (from Richter, 1958)

Basement rocks in the central North Island are interbedded graywacke and argillite of Permian to Cretaceous age. These rocks are well exposed in the mountain ranges east and west of the Taupo Volcanic Zone, and have been inferred to extend beneath the Volcanic Zone on the basis of geophysical data (Modriniak and Studt, 1959; Hochstein and Hunt, 1970). Evison, et al., (1976) in an interpretation of regional stress patterns, have proposed that the sedimentary basement rocks are not continuous beneath the Taupo Volcanic Zone, but instead, that the molten or semi-molten material which supplies heat to the geothermal areas extends to within about 2-4 miles (3-6 km) of the surface in this area.

In the central volcanic region, sedimentary basement rocks are overlain by a series of volcanic rocks and tuffaceous sedimentary deposits of Miocene to Holocene age. The volcanic rocks are mainly pyroclastic and include ignimbrites, pumice breccias and tuffs. Flow rocks of basaltic to rhyolitic composition are also present locally.

The straitigraphy of the Wairakei area is summarized in Table 1 which briefly describes the geologic units found in this area. A diagrammatic cross section of the Wairakei area, given in Figure 3, shows the inferred structure, stratigraphy and hydrothermal system. The geologic units shown in Table 1 and Figure 3 will be described in greater detail in subsequent sections of this report.

In the vicinity of Wairakei, the Taupo Fault Zone is subdivided by faulting into two northeast-trending basins separated by a central elevated block. This structure is postulated on the basis of gravity and magnetic measurements (Modriniak and Studt, 1959) and drilling information (Grindley, 1965). The general structure is delineated by

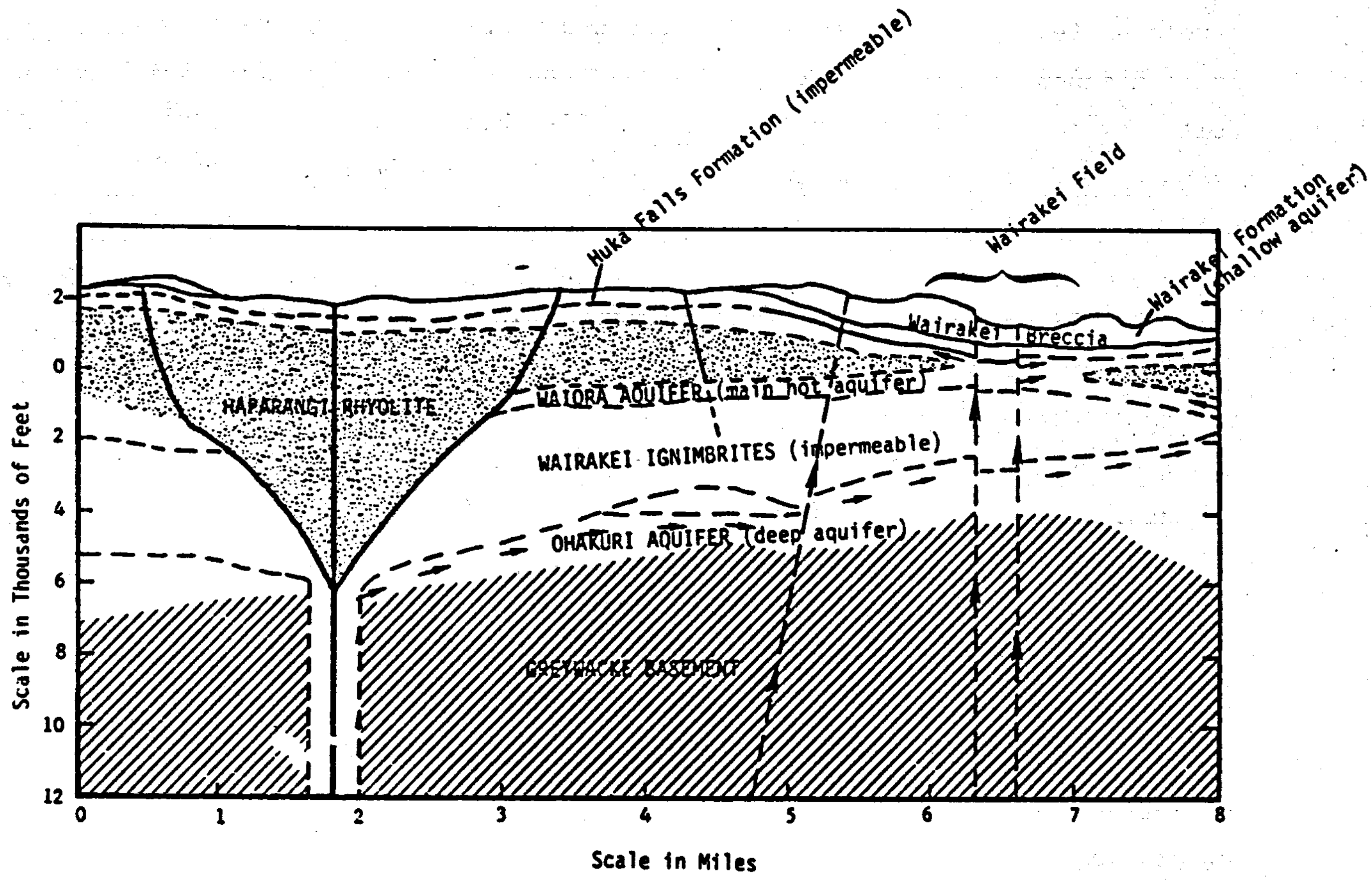


FIGURE 3 DIAGRAMMATIC SOUTHWEST-NORTHEAST CROSS SECTION SHOWING POSSIBLE RELATIONSHIP OF WAIRAKEI FIELD TO DEEP STRUCTURE AND TO RHYOLITIC VOLCANIC CENTER. ARROWS SHOW DIRECTION OF PRESUMED GROUNDWATER MOVEMENT. (from Grindley, 1965)

TABLE 1 STRATIGRAPHY AT WAIRAKEI GEOTHERMAL FIELD

	AGE	NAME	LITHOLOGY	THICKNESS
Penetrated by Drilling	Recent (youngest, A.D. 121)	Taupo Pumice Alluvium	Pumice alluvium, wind-blown pumice ash	Usually less than 100 feet
	---UNCONFORMITY---			
	Upper Pleistocene	Wairakei Breccia	Mostly vitric lapilli tuff, with chalazoidite tuff and tuffaceous sandstone	Maximum preserved 550 feet
	Middle Pleistocene	Huka Falls Formation (Formerly Hula	Tuffaceous mudstone and sandstone with interbedded vitric tuff, conglomerate, and diatomite	200 - 1000 feet
		Waiora Formation	Mostly pumice breccia and sandstone with minor interbedded siltstone and rhyolite breccia. Ignimbrite at base and top. Lower part includes the Waiora Valley Andesite, a buried volcanic flow up to 600 feet thick	1500 - 3000 feet
	---UNCONFORMITY---			
Inferred From Regional and Geophysical Data	Lower Pleistocene	Wairakei Ignimbrites	Ignimbrite, dense, hydrothermally altered at upper surface	400 to more than 1700 feet (based not drilled)
	---UNCONFORMITY---			
		Ohakuri Group	Tuffaceous sandstone and siltstone with interbedded pumice breccia	At least 600 feet
	---UNCONFORMITY---			
	Permain-Mesozic	"Graywacke Basement"	Altered graywacke, argillite	At estimated depth of 6000 feet, thickness unknown

Sources: Healy (1965), Grindley (1965)

thickness variations in the Huka Falls and Waiora Formations, (see Table 1) which are relatively thin on the upthrust block and thicken substantially in the surrounding basins. Though the main structural blocks are bounded by faults of relatively large displacement, they are not internally simple, but are themselves cut by faults of relatively small offset.

The Wairakei block is an area of anomalous high gravity measurements (Modriniak and Studt, 1959) which reflects the presence of intrusive rhyolite in the sedimentary sequence and possible basement uplift in the vicinity of the Wairakei field. The area is underlain by relatively thin sequences of Huka Falls and Waiora sediments, respectively less than 100 feet (30 m) and roughly 1420 feet (430 m) thick (Grindley, 1965). Basement rocks have not been encountered by drilling to depths of over 3000 feet (900 m).

Grindley (1965) has estimated depth to basement rocks at about 6000 feet (1800 m).

The Taupo-Reporoa basin is a northeast-trending, complex depression which is located on the southeastern side of the Wairakei block. Basement is postulated at least 8500 feet (2,600 m) below sea level in the deepest part of the basin east of Wairakei and is 4000 feet (1,200 m) lower than on the crest of the Wairakei block (Modriniak and Studt, 1959). The basin is filled with pumice pyroclastics and sediments of the Huka Falls Formation, probably underlain by the Wairakei Ignimbrites.

Because drillholes have penetrated the Wairakei Ignimbrite only at the northeast edge of the Taupo-Reporoa Basin, the thickness of the Waiora formation and depth to Wairakei Ignimbrites are not well known. Drillholes on the southeast side of the Wairakei high show an increase in thickness of both the Huka Falls Formation and the Waiora Formation, but the direction and rate of thickening of the Waiora Formation can only be inferred from the observed thickening of younger units and from geophysical data.

To the northwest of the Wairakei block is the Taupo-Rotorua basin, a large depression which is subdivided by faulting into several horst and graben blocks. The Te Mihi basin, that part of the Taupo-Rotorua basin which is adjacent to the Wairakei field, appears to have been produced by tectonic subsidence and modified by later faulting. The Huka Falls Formation and the Waiora Formation both thicken basinward from the Wairakei block, but as in the Taupo-Repora basin, the absence of holes drilled through to the underlying Wairakei Ignimbrite means that the direction and rate of thickening are poorly known for the Wairora Formation.

2.2.2 Faulting and Seismicity

Faulting in the sediments of the Taupo Volcanic Zone began in lower Pleistocene time, after deposition of the Ohakuri Group (see Table 1), and has continued at intervals to the present. All of the faults are considered active, as numerous ground surface traces are visible on aerial photographs and one fault has a relatively uneroded surface scarp, 100 feet (30 m) to 150 feet (45 m) high. With the exception of this fault, displacements in the near-surface sediments are usually small. However, the amount of displacement on each fault generally is presumed to increase downward with increasing age of the offset formations, as is required for recurrent faulting. Where displacements are known, the facts support this assumption. For example, in the

Wairakei field, the Waiora fault displaces the base of the Huka Falls Formation 10 feet (3 m) to nearly 100 feet (30 m) while displacement of the base of the Waiora Formation is 140 feet (42 m) to 400 feet (122 m) (Grindley, 1965). For many faults, the amount of vertical displacement at various depths is unknown. The amount of horizontal offset is also unknown, but is considered to be small and right-lateral in orientation (Grindley, 1965).

The northeast-trending faults, by far the most numerous, are mostly normal faults, but some have a significant proportion of rotational or hinge displacement. They slope both east and west with dips, where known, ranging from 65 degrees to 88 degrees. The northwest-trending fault which transects the production area is downthrown on the north side, but the dip of the fault plane, and, therefore, the extensional or compressional nature of the faulting, is unknown (Grindley, 1965).

Despite the closely-spaced faulting and rotational movement of some fault blocks, the strata in the Wairakei area are essentially flat-lying. Some portions of the sequence display small initial dips of a few degrees acquired during sediment accumulation on previously eroded topography. An angular discordance of 15 degrees between strata of the Ohakuri Group and the overlying Wairakei Ignimbrites is interpreted to result from rotation during an intervening period of erosion (Grindley, 1965).

The sediment sequence has been pierced and intruded by feeder dikes, domes, and sills associated with rhyolitic centers a few kilometers south and northwest of Wairakei. Beneath the southern part of the geothermal field, a rhyolite sill up to 1500 feet (460 m) thick has intruded the medial part of the Wairoa Formation. The sediments and basement rock below the sill have subsided by an amount equal to its thickness (Grindley, 1965).

The Wairakei geothermal field is located in the central volcanic district, an area of moderately high seismicity., characterized by deep-focus earthquakes of small to moderate magnitude along the western edge, and numerous shallow-docus earthquakes in a narrower zone along the Taupo-Fault belt. These shallower earthquakes are often associated with volcanic activity. Some, like the Taupo earthquakes of 1922, have been accompanied by faulting, with the formation of low scarps (Richter, 1958, p. 457).

In a recent study of seismicity in the Central North Island (Evison, et al., 1976), it was found that both microearthquakes and macro-earthquakes were many times more frequent in the Taupo Fault Belt than in either the adjoining basins or on the Kaingaroa Plateau to the east (see Figure 1). The assertion (Richter, 1958) that the seismicity of the region is dominated by earthquake swarms, is borne out by the results of the study by Evison et al., (1976). During a limited period of observation (less than one month) they obtained origins for 29 micro-earthquakes, of which 18 were contributed by three separate swarms. The pattern of macroseismicity in the same region during a three year period (1971-1973) was similar. Out of 28 earthquakes of magnitude 3.0 or greater, six events occurred as a swarm. All swarms were located in the Taupo Fault Belt rather than in adjacent basins, and individual events in this area were all shallower than nine miles (15 km). Deeper focus earthquakes were located to the east, on the Kaingaroa Plateau.

2.2.3 Tectonic Environment

New Zealand tectonics are dominated by transcurrent (strike-slip) faulting along a northwest trend, as shown in Figure 2. The right-lateral Alpine fault extends northeastward along the South Island, branching into several splays in the southeast part of the North Island. Displacement on this fault could be as much as 200 miles (35 km) (Richter, 1958). Grindley, (1965) indicates that the principal horizontal stress for the zone at Quaternary transcurrent faulting and folding is in an east-west direction.

In contrast, he postulates an east-north-east direction of compression for the Wairakei area, where fault trends are northeast and northwest and movement is in a normal sense. Based on their seismicity investigations, Evison, et al., (1976) have proposed a crustal model for the Central North Island, as shown in Figure 4. This model was developed to explain the occurrence of deep-focus earthquakes east of the Reporoa Basin, the low observed seismicity in the basin itself and the predominantly shallow-focus earthquakes in the Taupo Fault Belt. The authors maintain that this crustal model is consistent with the gravity data presented by Modriniak and Studt, (1959). They also feel that the high level of semi-molten material beneath the Taupo Fault Belt and Taupo-Reporoa Basin helps to explain the presence of geothermal resources in this region. Since drillholes at Wairakei have not reached basement rocks (at a maximum depth to date of 7200 feet (2200 m), this model remains to be verified.

2.3 CHARACTER OF OVERBURDEN MATERIALS

The bulk of the steam production at the Wairakei geothermal field is obtained from pumice breccias of the Waiora Formation. Overburden materials (from oldest to youngest) are the Haparangi Rhyolite, Huka Falls Formation, Wairakei Breccia and Recent Pumice Alluvium, all principally of volcanic origin. A second pumice breccia aquifer, the

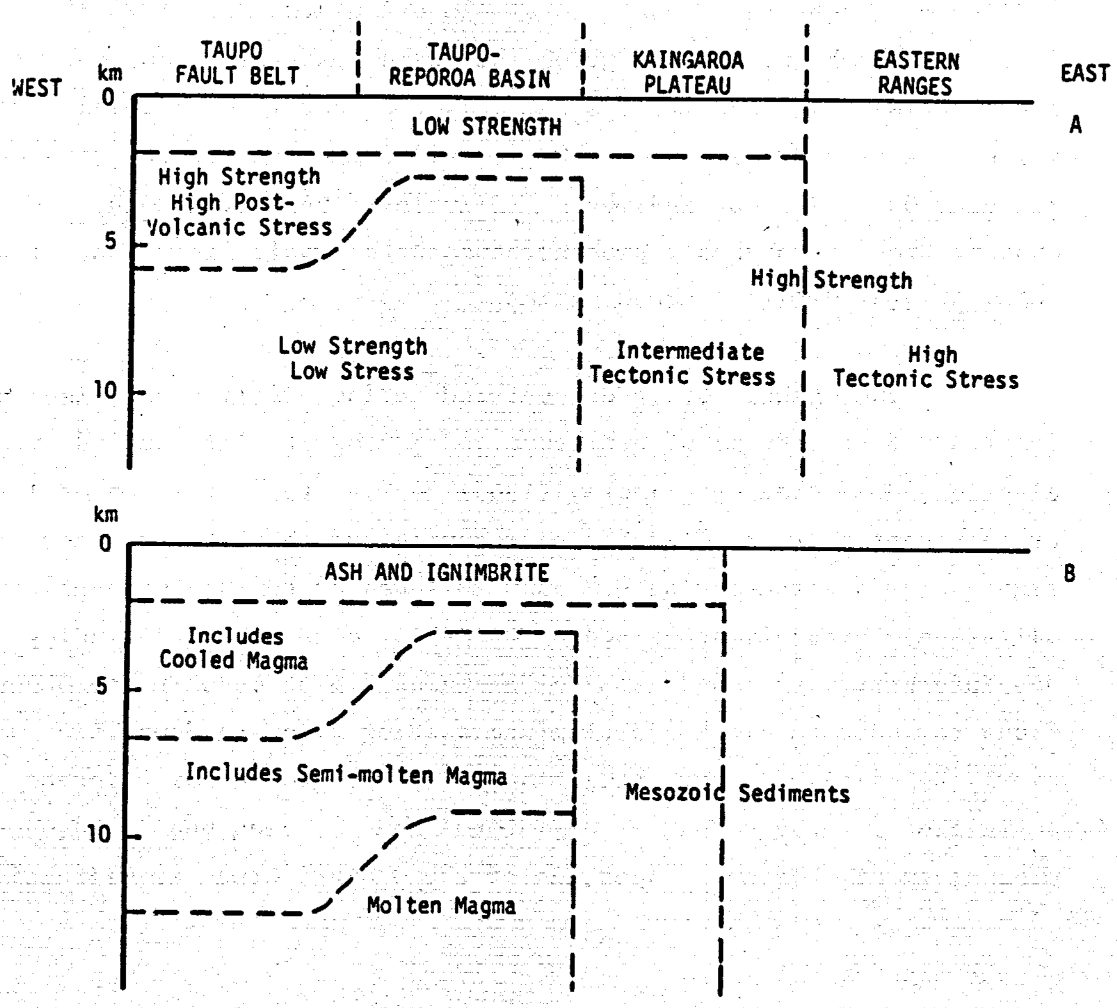


FIGURE 4 SCHEMATIC CROSS SECTIONS SHOWING (A) DYNAMICAL AND (B) STRUCTURAL MODELS OF THE EARTHS CRUST IN THE WAIRAKEI AREA (proposed by Evison et al, 1976)

Ohakuri Group, is separated from the principal aquifer by a thick section of ignimbrites, known as the Wairakei Ignimbrites. Geologic cross-sections showing these units in the Wairakei area are given in Figure 5-8.

2.3.1 Ohakuri Group

The oldest unit drilled at the geothermal field is the Ohakuri Group, composed of pumice breccias and interbedded freshwater pumiceous sediments, which are encountered at elevation 3200 feet (920 m) in a drillhole at the northern edge of the field. At this location, the overlying Wairakei Ignimbrites are only 800 feet (240 m) thick. Other wells have been drilled over 1500 feet into the Ignimbrites without reaching Ohakuri Group sediments. Grindley (1965) states that the Ohakuri Group is probably present beneath the whole field, but at depths below present drilling capabilities.

The Ohakuri Group encountered during drilling comprises at least 600 feet (180 m) of pumiceous sediments with interbedded pyroclastics, described by Grindley (1965) as "... relatively compact tuff-breccia containing small subangular pumice and rhyolite fragments in a fine-grained tuffaceous base," and "well bedded tuffaceous sandstone and siltstone - probably deposited on the floor of a lake." Grindley (1965) has interpreted the 30 degree to 35 degree dip of beds in the Ohakuri Group to indicate block faulting and tilting prior to deposition of the overlying Wairakei Ignimbrites. An early Pleistocene or Pliocene age is postulated for these rocks. No information has been published on the mineralogy or physical properties of the Ohakuri Group at Wairakei.

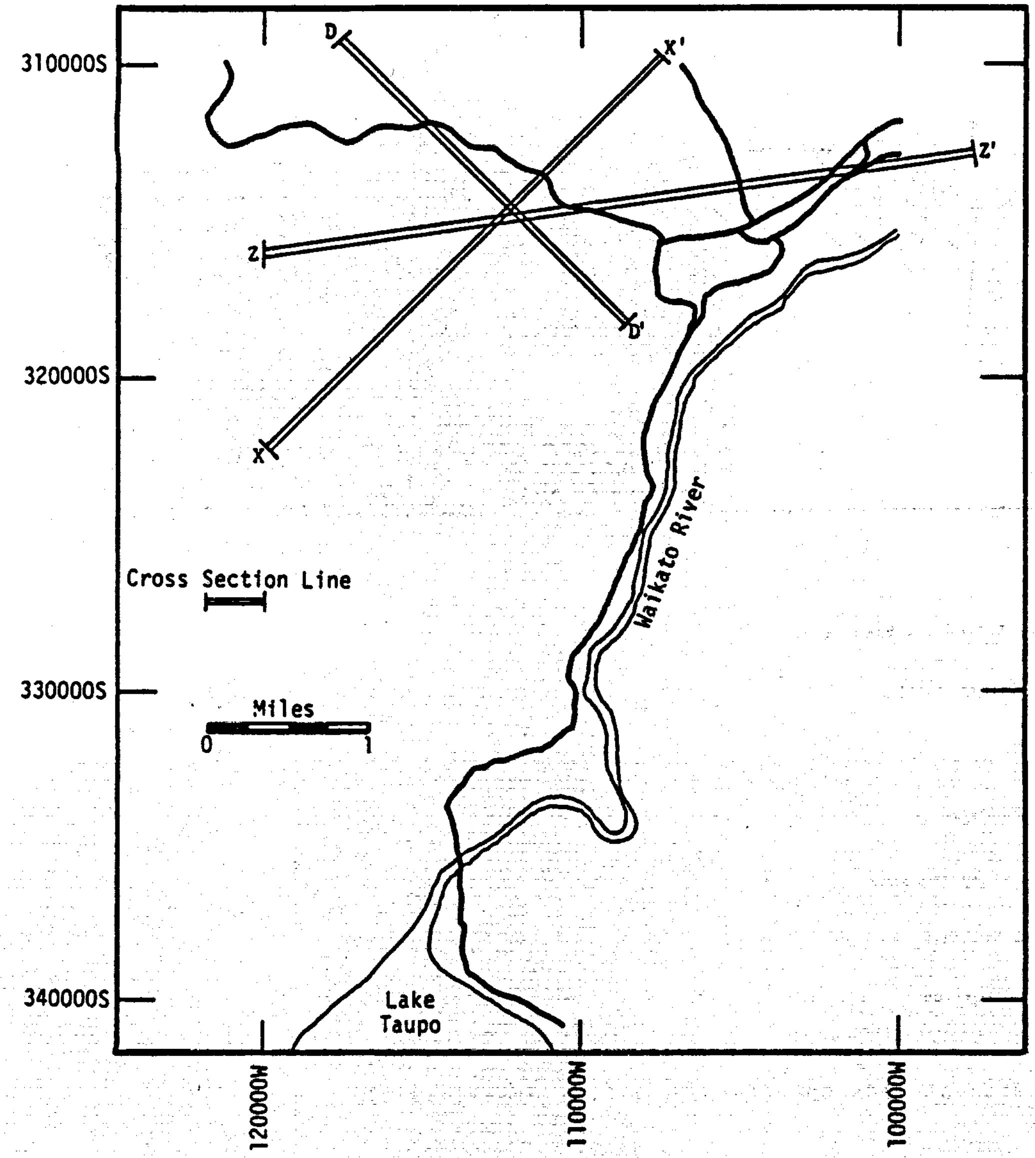


FIGURE 5 LOCATIONS OF CROSS SECTIONS SHOWN IN FIGURES 6 THROUGH 8 (from Pritchett et al, 1978)

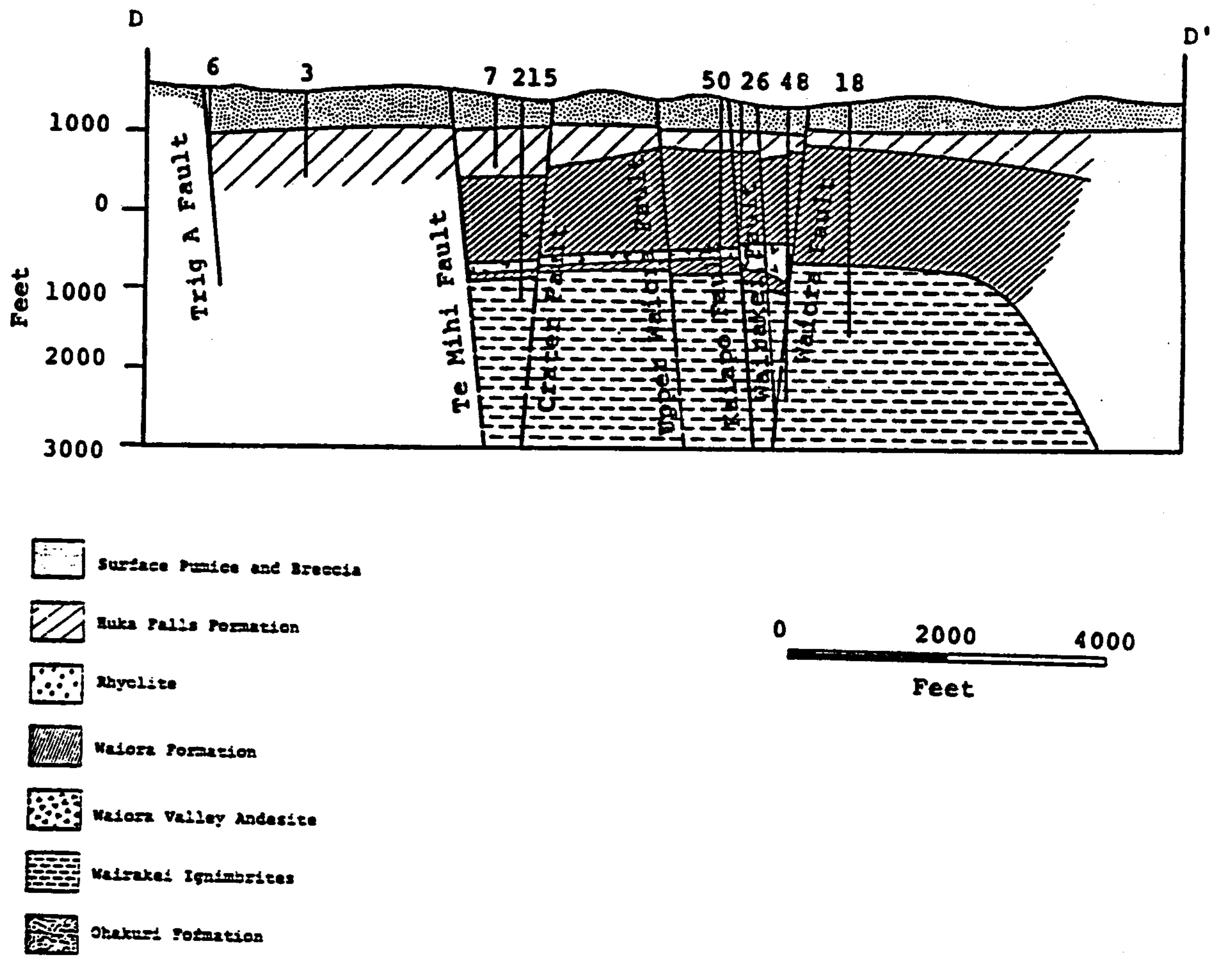


FIGURE 6 SECTION DD' (from Pritchett et al, 1978)

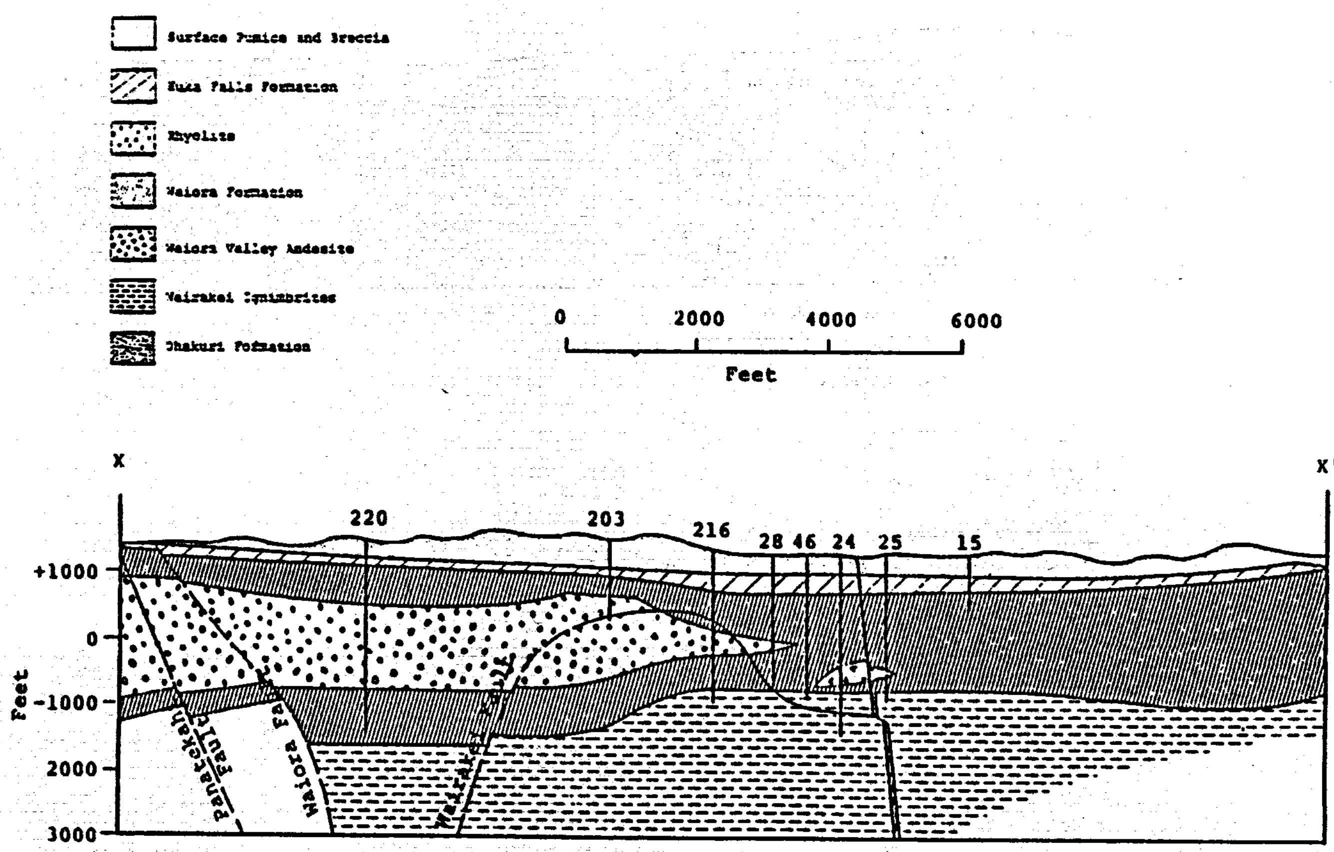


FIGURE 7 SECTION XX' (from Pritchett et al, 1978)

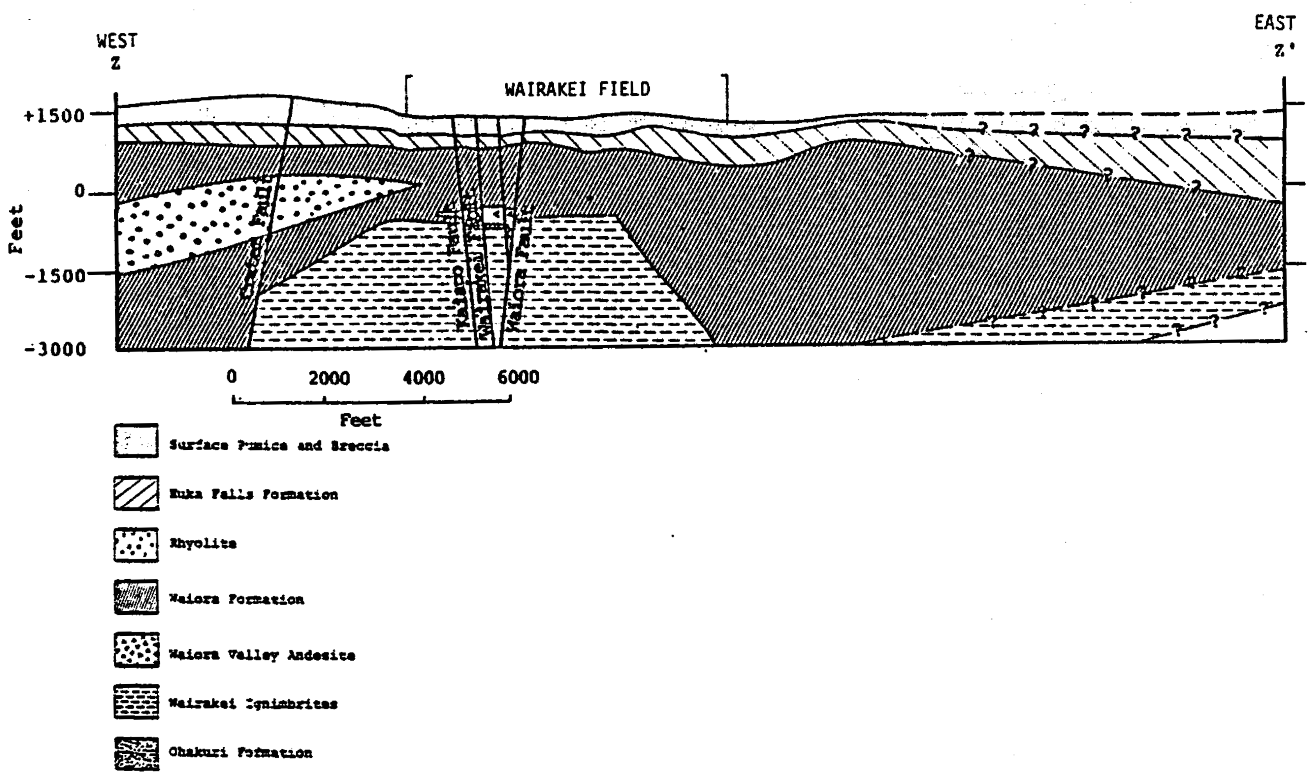


FIGURE 8 SECTION ZZ' (from Pritchett et al, 1978)

2.3.2 Wairakei Ignimbrite

Healy (1965, p. 218:4) described the Wairakei Ignimbrite as " ... a dense quartz-bearing rock containing also abundant plagioclase with minor hypersthene and biotite. In the production area, it lies approximately 2000 feet (610 m) beneath the surface ... Where encountered in the drillholes, the upper surface is usually highly altered and silicified, but the degree of alteration decreases downwards."

Thickness of the Wairakei Ignimbrite varies from about 400 feet (120 m) on the northwest of the field to more than 1700 feet (520 m) on the southeast, which may be a result of deposition on an irregular topographic surface. The Wairakei Ignimbrites are interpreted as a series of high temperature hypersthene-biotite, quartz-plagioclase, crystal rich ignimbrite flows, possibly originating in the Lake Taupo area during early Pleistocene time (Grindley (1965). Basaltic and rhyolitic flow rocks are present in the top ignimbrite sheet for many localities. Subsequent hydrothermal alteration has altered the ferromagnesian minerals to chlorite, calcite, clinozoisite and other secondary minerals, resulting in a typically green-grey to pale green color. Mineralogy of a typical core specimen from the Wairakei ignimbrite is given by Hendrickson (1976):

Composition	Percent by Volume
Fine-grain matrix (glass dust)	50
Feldspar	32
Sericite	9
Quartz	5
Calcite	2
Fiberous zeolites and chlorites	2
Opaques	Trace

2.3.3 Waiora Formation

Unconformably overlying the Wairakei Ignimbrite is a thick series of pyroclastic rocks, ignimbrites and interbedded sediments, collectively known as the Waiora Formation, of middle Pleistocene age. These rocks have been encountered in all but the shallowest drillholes at Wairakei and are believed to be widespread in the subsurface, despite the scarcity of outcrops. The total thickness of the Formation ranges from about 1300 feet (400 m) on the crest of the Wairakei Block, to over 2500 feet (760 m) in the adjoining basins, where the base of the Waiora has not been drilled. The Waiora Formation is the geothermal reservoir tapped at Wairakei, and is discussed in detail on Section 3 of this report.

2.3.4 Waiora Valley Andesite

A buried andesite flow in the lower part of the Waiora Formation has been drilled at Wairakei in the western part of the production area. The andesite is closely associated with the major faults in the field (especially the Waiora, Wairakei and Upper Waiora Faults) and is believed to have been extruded along fissures at the fault intersections. This mode of emplacement has been inferred from the rapid thinning away from fault planes and the steeply dipping flow banding observed in hand specimens. The andesites show a high degree of hydrothermal alteration, and thin sections typically show fresh andesine phenocrysts in a glassy matrix with chlorite, calcite wairakite, magnetite and leucoxene. Andesite breccias suggestive of blecky flows have also been encountered in some drillholes (Grindley, 1965).

The maximum observed thickness of andesite is nearly 60 feet (183 m) which occurs near fault intersections. It is the same age as Member 2 of the Waiora Formation, and in some locations replaces it in the stratigraphic sequence.

2.3.5 Huka Falls Formation

Overlying the Waiora Formation and the Waiora Valley Andesite, are a series of sedimentary and pyroclastic rocks known as the Huka Falls Formation. These relatively fine-grained rocks act as the cap-rock over the Waiora aquifer (see Figure 3). The Huka Falls Formation is widely distributed throughout the Central Volcanic Region and has been an important stratigraphic marker because of the pollen flora present in the sedimentary members.

As shown in Figure 9, the Huka Falls Formation is thinnest southwest of the main production area (less than 100 feet (30 m), thickening basinward to the northwest and southeast. The typical stratigraphic sequence is bedded mudstone in the lower part, overlain by coarse tuffaceous sandstone and vitric tuff, grading back into mudstone or diatomaceous shale. In the Te Mihi Basin, the basal unit is a thick tenticular conglomerate. The age of the Huka Falls Formation is believed to be Middle to Late Pleistocene (Grindley, 1965).

The mudstones of the Huka Falls Formation are composed principally of clay minerals with small amounts of detrital plagioclase and quartz. Carbonaceous material is usually present. The argillaceous locks do not show hydrothermal alteration as do the tuffaceous and arenaceous rocks (Steiner, 1953). The most common hydrothermal alteration is the conversion of glass into clay minerals of the montmonhanite

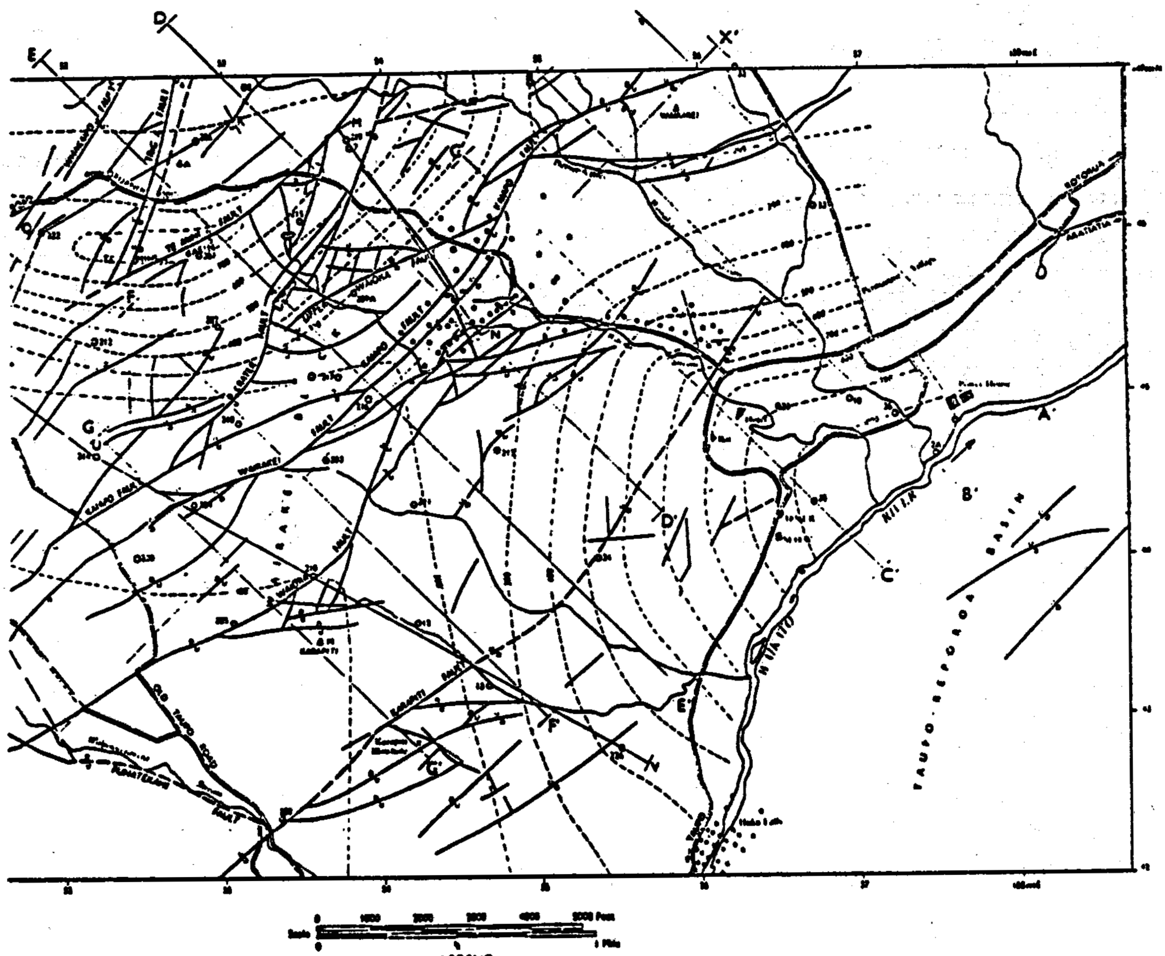


FIGURE 9 ISOPACHS OF HUKA FALLS FORMATION IN FEET. WAIRAKEI HYDROTHERMAL FIELD (from Grindley, 1965)

groups. Alteration by zeolitization and feldspathization has also been noted by Steiner.

2.3.6 Wairakei Breccia

Between the Recent to Late Pleistocene alluvium and the Huka Falls Formation are a series of pyroclastic deposits known as the Wairakei Breccia, consisting of vitric tuffs with pumice and rhyolite lapilli, and chalazoidite (accretionary lapilli) tuffs with tuffaceous sandstone. The composition of the tuff is that of a plagioclase hryolic with phenocrysts of fresh plagioclase quartz and hyperstheal (Grindly, 1965).

The Wairakei Breccia has been encountered by most of the drillholes at Wairakei, but is absent from some holes on the east, southeast and west edges of the field. The top of the unit represents an erosional surface, so total original thickness has not been determined. Maximum preserved thickness is about 550 feet (168 m) in the west part of the field. The age of the breccias is inferred to be Middle-Upper Pleistocene from its stratigraphic position.

2.3.7 Haparangi Rhyolite

In the western and southwestern part of the field, the Waiora Formation has been intruded by a rhyolite flow up to 1600 feet (490 m) thick. An older quartz bearing rhyolite sill is present lower in the Waiora Formation in the west part of the field. The rocks encountered during drilling include pumiceous, perlitic, spherulitic and banded lithoidal rhyolites, probably intruded from a source west of Taupo during early Upper Pleistocene time (Grindley, 1965).

2.3.8 Recent Pumice Cover

The Wairakei area is covered by pumice ash and pumice alluvium deposited following eruption and partial erasion of the Wairakei Breccia. These pumiceous deposits are of late Pleistocene to Recent age and are rarely more than 100 feet thick. Hendrickson (1976, p. A3) gives the composition of a pumice sample from a depth of 134 feet (41 m):

Composition	Percent by Volume
Matrix material and voids	43
Rock fragments	24
Feldspars	17
Altered Mafic minerals	6
Pyroxenes	3
Opaques	3
Quartz	2
Amphiboles	2

2.4 RESPONSE TO STRESS CHANGES

The physical properties of rocks at the Wairakei Geothermal Field have been investigated by Hendrickson (1976) of Terra Tek, Inc., who performed an extensive series of tests on representative core samples obtained from drillholes at the Wairakei field. Five sampling intervals were tested:

1. Pumice, Borehole No. 45, depth 134 feet
2. Huka Formation, Borehole No. 37, 700 to 730 feet

3. Waiora Formation, Borehole No. 37, 1130 to 1135 feet (referred to as "Waiora 1130 feet" in testing program)

4. Waiora Formation, Borehole No. 37, 2296 to 2618 feet (referred to as "Waiora 2618 feet" in testing program)

5. Wairakei Ignimbrite, Borehole No. 24, depth 2482 feet

The samples were approximately ten years old and were dry when received by Terra Tek's laboratory in California. The following is a summary of the rock properties determined by Terra Tek, Inc.

2.4.1 Physical Properties

Determination of saturated and dry bulk densities, effective porosity, total porosity, occluded porosity and grain density for the Wairakei samples are summaried in Table 2. For details of the methods employed by Terra Tek, Inc., the reader is referred to their report (Hendrickson, 1976).

2.4.2 Elastic Moduli

Terra Tek, Inc. (1976) calculated elastic moduli for all four formations using ultrasonic measurements of shear wave ("S" wave) and plane wave ("P" wave) velocities on representative samples. The tests were performed at hyrostatic confining pressures selected to simulate the range of in-situ stress. Tables 3 through 6, from Hendrickson (1976), summarize the velocity and moduli determinations at various confining pressures.

Terra Tek, Inc. also determined bulk moduli and shear moduli by means of hydrostatic and triaxial loading tests. Test results are

TABLE 2 SATURATED AND DRY BULK DENSITIES, EFFECTIVE POROSITY, TOTAL POROSITY, OCCLUDED POROSITY AND GRAIN DENSITY FOR CORE SAMPLES FROM WAIRAKEI GEOTHERMAL FIELD

Rock Dust	Bulk Density* Saturated g/cm3	Bulk Density* Dry g/cm3	Effective Porosity Percent By Volume	Total Porosity Percent by Volume	Occluded Porosity Percent by Volume	Grain Density* g/cm3
Pumice	1.88	1.39	48.8 ± 0.5	47.7 ± 0.3	0 ± 0.8	2.71
Huka Falls	1.97	1.56	30.7 ± 0.5	42.2 ± 0.3	1.5 ± 0.8	2.70
Huka Falls**	2.01	1.62	39.0 ± 0.5			-
Waiora 1130	2.01	1.59	41.6 ± 0.5	42.4 ± 0.3	0.8 ± 0.8	2.76
Waiora 1130**	2.04	1.65	39.1 ± 0.5			-
Waiora 1130**	2.07	1.69	37.9 ± 0.5			-
Waiora 2618	1.99	1.64	35.6 ± 0.5	38.8 ± 0.3	3.2 ± 0.8	2.68
Waiora 2618**	1.99	1.60	39.1 ± 0.5			-
Ignimbrite	2.34	2.20	13.8 ± 0.5	18.2 ± 0.3	4.4 ± 0.8	2.69
Ignimbrite**	2.38	2.23	15.0 ± 0.5			-

** Indicates different samples from same footage

* Bulk density and grain density measurements are accurate to within ± 005 Mg/m^3.

TABLE 3 VELOCITIES AND MODULI AT FIVE CONFINING PRESSURES IN PUMICE, 134'

CONFINING PRESSURE MPa	VELOCITIES P-WAVE Km/sec	S-WAVE Km/sec	POISSON'S RATIO	MODULI CONSTR. GPa	SHEAR GPa	BULK GPa	YOUNG'S GPa
.35	1.05	.532	.328	1.50	.385	.989	1.02
.69	1.17	.560	.332	1.70	.427	1.13	1.14
3.45	1.39	.827	.225	2.62	.930	1.38	2.28
5.52	1.51	.910	.215	3.10	1.13	1.60	2.74
6.89	1.58	.942	.224	3.40	1.21	1.79	2.96

TABLE 4 VELOCITIES AND MODULI AT SIX CONFINING PRESSURES IN HUKA FALLS FORMATION, 700'

CONFINING PRESSURE MPa	VELOCITIES P-WAVE Km/sec	S-WAVE Km/sec	POISSON'S RATIO	MODULI CONSTR. GPa	SHEAR GPa	BULK GPa	YOUNG'S GPa
0	1.64	1.17	0	4.31	2.21	1.36	4.30
3.45	1.73	1.18	.062	4.81	2.25	1.81	4.77
6.89	1.77	1.20	.070	5.02	2.32	1.93	4.96
10.3	1.77	1.19	.081	5.02	2.29	1.97	4.95
13.8	1.80	1.20	.104	5.19	2.29	2.13	5.06
17.2	1.88	1.25	.107	5.66	2.49	2.34	5.52

Note: 1 MPa = 10 bars

1 GPa = 10 kbars

TABLE 5 VELOCITIES AND MODULI AT SEVEN CONFINING PRESSURES IN WAIORA FORMATION, 2618'

CONFINING PRESSURE MPa	VELOCITIES P-WAVE Km/sec	S-WAVE Km/sec	POISSON'S RATIO	MODULI CONSTR. GPa	SHEAR GPa	BULK GPa	YOUNG'S GPa
0	2.22	1.08	.344	9.85	2.34	6.73	6.29
3.45	2.46	1.23	.333	12.1	3.02	8.05	8.06
6.89	2.59	1.31	.329	13.4	3.41	8.82	9.07
10.3	2.63	1.34	.324	13.9	3.60	9.06	9.54
13.8	2.66	1.37	.321	14.1	3.73	9.16	9.85
17.2	2.69	1.38	.322	14.5	3.79	9.40	10.0
21.0	2.71	1.39	.322	14.6	3.84	9.52	10.1

Note: 1 MPa = 10 bars

1 GPa = 10 kbars

TABLE 6 VELOCITIES AND MODULI AT SIX CONFINING PRESSURES IN WAIRAKEI IGNIMBRITE, 2482'

CONFINING PRESSURE MPa	VELOCITIES P-WAVE Km/sec	S-WAVE Km/sec	POISSON'S RATIO	MODULI CONSTR. GPa	SHEAR GPa	BULK GPa	YOUNG'S GPa
0	4.22	2.52	.223	41.6	14.8	21.8	36.2
3.45	4.25	2.54	.221	42.1	15.1	22.0	36.8
6.89	4.30	2.57	.223	43.1	15.4	22.6	37.6
10.3	4.33	2.59	.222	43.8	15.6	22.9	38.2
13.8	4.36	2.61	.222	44.3	15.8	23.2	38.6
17.2	4.38	2.62	.222	44.6	16.0	23.4	39.0

Note: 1 MPa = 10 bars

1 GPa = 10 kbars

summarized in Tables 7 and 8. A comparison of the moduli determined by deformation testing with these calculated from ultrasonic velocity measurements reveals that the utlrasonic determination gives significantly higher values for the moduli. Hendrickson (1976, p A37) reports that ... "while this a typical for competent materials, it is typical for porous or less competent rocks. Discrepancies of this sort normally show ultrasonic moduli from two to four times greater than those found by deformation tests."

2.4.3 Permeability

Permeability values for aquifer and overburden materials have been published by several investigators. Some of the more recent values are summarized in Table 9.

TABLE 7 BULK MODULUS MEASUREMENTS DETERMINED FROM HYDROSTATIC AND TRIAXIAL TESTS IN THE THREE FORMATIONS

SAMPLE IDENTIFICATION	CONFINING PRESSURE MPa	BULK MODULUS GPa ±10%
Pumice, B34, 134'	0 to 0.2	0.032
	0.2 to 0.4	0.057
	0.4 to 0.8	0.096
	0.8 to 1.1	0.29
Huka, B37, 700'-725'	0 to 1.0	0.89
	1.0 to 5.0	2.06
Waiora, 1130'	0 to 3.5	0.41
	3.5 to 10.4	2.03
	10.4 to 17.2	1.70
Waiora 2618', #1	0 to 3.5	0.69
Waiora 2618', #2	0 to 3.5	0.73
	3.5 to 10.4	1.98
	10.4 to 17.2	2.86

Note: 1 MPa = 10 bars
1 GPa = 10 kbars

TABLE 8 YOUNG'S MODULUS, POISSON'S RATIO AND SHEAR MODULUS MEASUREMENTS, DETERMINED FROM HYDROSTATIC AND TRIAXIAL TESTS

SAMPLE IDENTIFICATION	CONFINING PRESSURE, MPa	YOUNG'S MODULUS MPa ± MPa	POISSON'S RATIO	SHEAR MODULUS MPa ± MPa
Pumice B34, 134'	1.0	176 ± 2	.07 ± .003	82 ± .7
Huka, B37, 700'-725'	5.0	154 ± 2	.37 ± .008	56 ± 1
Waiora, 1130'	3.5	0.91	0.21	0.38
	10.4	1.48	0.24	0.60
	17.2	1.75	0.22	0.72
Waiora, 2618' #1	3.5	2.65	0.11	1.19
Waiora, 2618' #2	3.5	2.90	0.12	1.30
	10.4	4.20	0.15	1.82
	17.2	4.94	0.23	1.99

Note: 1 MPa = 10 bars
1 GPa = 10 kbars

TABLE 9 SOME PUBLISHED PERMEABILITY VALUES FOR ROCKS AT WAIRAKEI GEOTHERMAL FIELD

Rock Unit	Millidarcys	Source	Remarks
Waiora Formation	≥100	Grindley, 1965	Calculated from pressure downdraw for wells tapping fault zone
Waiora Formation	5-30	Grindley, 1965	Calculated from pressure drawdown for wells drawing on aquifer storage
Waiora Formation	< 1	Grindley, 1965	Calculated from pressure drawdown for wells in stongly cemented parts of aquifer
Waiora Formation	.100	Mercer, et al., 1975	Horizonal permeability, from Elder, 1966
Waiora Formation	.05	Hendrickson, 1976	From core test at effective stress = 50 bars (confining pressure = 150 bars)
Huka Falls	.10	Mercer, et al., 1975	Vertical permeability
Huka Falls Mudston	.063	Hendrickson, 1976	From code test at effective stress = 6.9 bars (confining pressure = 6.9 bars)

3. RESERVOIR CHARACTERISTICS

3.1 REGIONAL GEOHYDROLOGY

The Wairakei field produces primarily hot water, although dry steam has been tapped in one well and flashed steam is accumulating in the upper parts of the system because of decreased fluid pressures caused by production (Grindley, 1965). The water is mostly of meteroic origin (Grindley, 1965), but the chloride concentration, oxygen isotope ratio, and comparison of actual mass withdrawal with values calculated from gravity changes suggest that 5 to 10 percent of the water is magmatic (Hunt, 1970). The geohydrology of Wairakei is very complex as indicated below.

3.1.1 Wairakei Formation

At the surface, there is a catchment in the west, with runoff and percolation through the Wairakei Breccias directed eastward toward the Waikato River. Where temperatures are high, and densities therefore low, a greater depth of water is required to balance the cold water in the surrounding country; this results in a raised water table and hot springs. In the high country to the west is a zone in which water, though hot, does not reach the surface; steam rises from the water table, giving rise to perched pools and mudpots, or steaming ground.

3.1.2 Confining Beds

The Wairakei Formation aquifer is confined to the top two or three hundred feet of the rock sequence and has no direct bearing on conditions at greater depth, for it is underlain by the Huka Mudstones (see Figures 3, 6-8), which provide a relatively impermeable barrier to the vertical movement of water. The mudstones undoubtedly account for the large extent of the Wairakei field, since the hot water is forced to migrate laterally beneath these beds before it can escape to the surface. The escape paths are provided by a number of tension faults, mostly striking north-north-east, along which many surface hydrothermal features are aligned.

The long life and constancy of the heat flow may also be attributed to the influence of the mudstones. In fact, there are good reasons for believing that, without such an impeding layer, the hydrothermal system could not exist; the energy would be dissipated by eruption.

3.1.3 Waiora Formation

Beneath the Huka mudstones are the permeable Waiora Breccias (see Figure 3 and Table 1), which constitute the main hot aquifer, varying in thickness from about 1,200 feet in the west to more than 2,600 feet in the east of the field. Here, the low density of the hot water produces a pseudo-artesian pressure so that drillholes tapping the aquifer discharge spontaneously, or stand under pressure when shut in. The aquifer is not artesian in the conventional sense, for the water level may be as much as 200 feet below surface in drillholes that have been cooled by circulating cold water; pressure develops only when temperatures recover. This pressure, here referred to as "thermo-artesian" pressure, is entirely due to high temperature. not only in the aquifer itself, but also in the overlying beds, for this maintains a low density in the upper part of the water column.

3.1.4 Lower Formations

The Waiora Formation is underlain by the Wairakei Ignimbrite, a relatively impermeable confining material. There is wide speculation that a really extensive lower aquifer (called the Ohakuri aquifer) exists below the Wairakei Ignimbrites (see Figure 3). This lower aquifer is thought to be responsible for lateral movement of hot water to the production area. Where exposed at the surface 32 km away from the field, the Ohakuri Group contains several laterally-persistent breccia layers enclosed in less permeable tuffaceous sediments. If these layers are extensive beneath the production area, the formation may be an important second aquifer.

3.1.5 Faults and Fissures

A decrease in temperature with depth in the upper part of the Wairakei Ignimbrites indicates that heat is transferred upward by convection rather than conduction. Drilling results show that the Waiora aquifer is fed through linear fissures in the ignimbrites which are associated with the Wairakei, Kaiapo, and upper Waiora faults. The fissures are limited to an area of approximately 2.6 km^2 which overlies a small structural dome in the basement rock of the Wairakei block. The fissures, being voids whose drilled thickness may be as much as 1.5 m, are kept open by predominately normal, or tensional, fault movement. The highest water temperatures are found in the vicinity of the fractures, which are believed to communicate vertically with a crystallizing magma body 5 to 10 km deep. Additional upward flow may occur along feeder dikes linked to volcanic centers (see Figure 3). Entrapment of separating gases during lateral migration of the heated water may account for the dry steam which was encountered in one drillhole (Grindley, 1965).

3.1.6 Flow Patterns Through the Waiora Aquifer

In the vicinity of the Wairakei Field, Studt (1958) found that a strong pressure gradient decreasing from west to east occurs in the Waiora aquifer. The general movement of water through the Waiora aquifer must therefore be in the same direction, with recharge in the west and discharge in the east. This conclusion is supported by a surface magnetic survey reported by Cullington (1954) and Modriniak and Studt (1959). They found a general increase in magnetic intensity from west to east, indicating that the source of hot fluid is to the west, and that the general flow is from west to east.

There have been no direct measurements of the natural recharge rate at the Waiora Aquifer. Rough estimates presented by Hunt (1977) showed that the annual recharge rate was as low as 10% of the production rate during the early years and rose to about 90% or more during later years.

3.2 RESERVOIR GEOMETRY

3.2.1 Areal Extent

Resistivity measurements have been used to indicate the presence of hot water at depth. Low electrical resistivity ($\geq$ about 10 ohm meters) generally shows a geothermal anomaly.

A resistivity survey was carried out in the Wairakei area in 1963-1964; Figure 10 shows the resistivity contours resulting from that survey. These contours definitely indicate two large low resistivity regions, at Wairakei and at Tauhara, with a relatively narrow neck

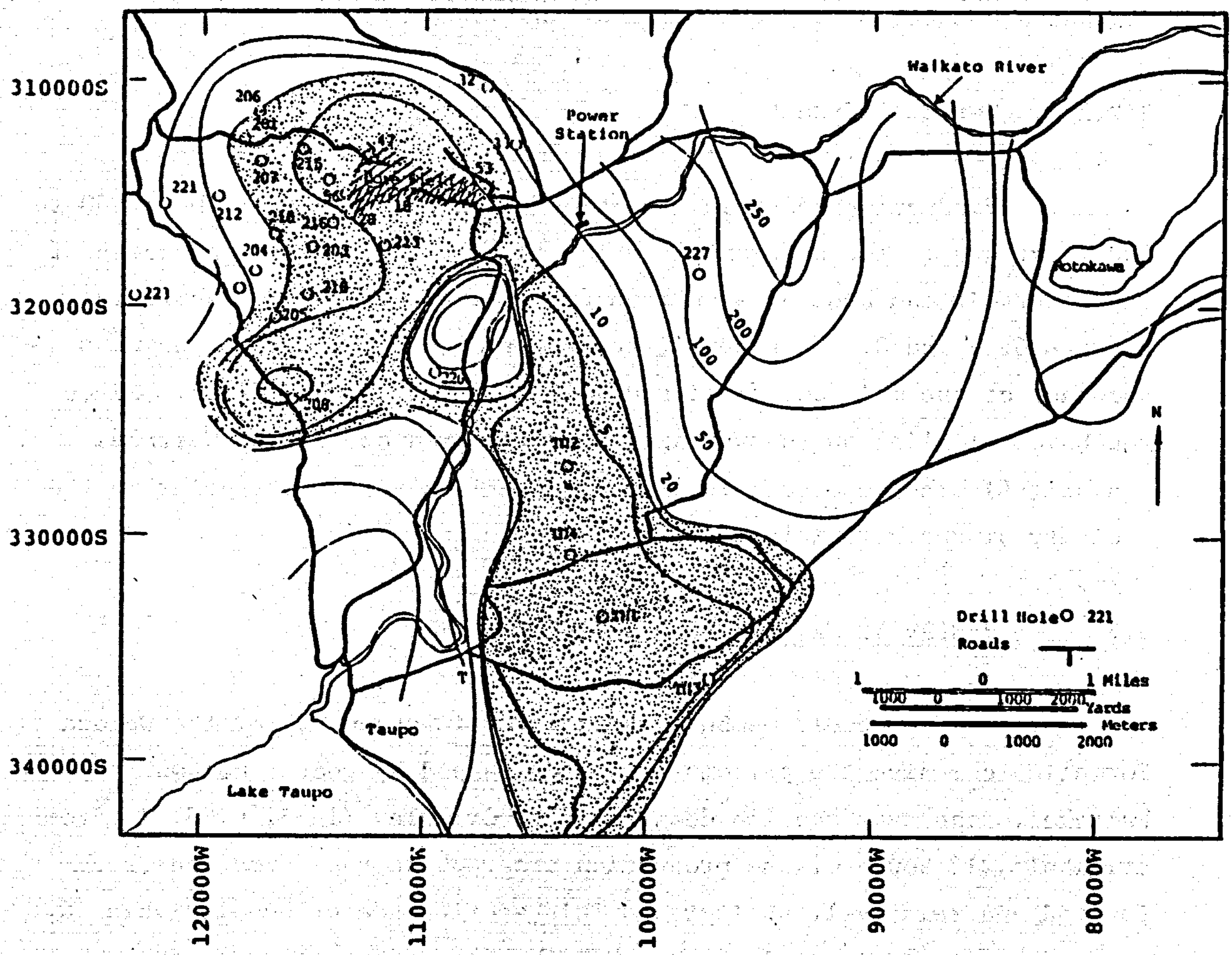


FIGURE 10 RESISTIVITY CONTOURS: WENNER ELECTRODE SPACING OF 1800 FEET. RESISTIVITY CONTOUR VALUES IN OHM-METERS. COORDINATES ARE WITH RESPECT TO MAKETU 1949. (from Pritchett, 1978)

connecting them. A few miles to the east, the resistivity low at Rotokawa also corresponds to a geothermally active region - two wells drilled at Rotokawa provide process heat for a sulfur plant located there, and temperature as high as 307°C have been measured downhole. No definite evidence (resistivity or otherwise) exists for a connection between Wairakei and Rotokawa. The resistivity data does, however, strongly suggest a connection between Wairakei and Tauhara.

3.2.2 Vertical Extent

Production wells in the Waiora aquifer range from about 450 to 4000 feet deep. The horizontal variation in the depth and thickness of the reservoir can best be seen from the geological sections shown in Figures 6, 7 and 8. In general, the reservoir is thicker to the west and east of the main borefield and quite thin at the borefield. Since the borefield lies on the Wairakei High (an area of shallow Wairakei Ignibrites), the reservoir is also at about its shallowest point in the vicinity of the borefield.

3.3 RESERVOIR MATERIAL PROPERTIES

The permeable members (stratigraphic subunits) of the Waiora Formation comprise the principal aquifer tapped by geothermal wells at Wairakei. The type section designated by Grindley (1965, p.23) is from drillhole 213 south of the production area, where the formation is unfaulted and relatively unaltered. This section, described in Table 10, shows the lithologic variation within the formation. The Haparangi Rhyolite is an instrusive unit, considered separate from the Waiora Formation.

"In the south-eastern part of the field where the Waiora Formation is thickest there tends to be a dominance of pumice breccias, some laid down as ash-flow deposits but some redposited. In general the strata are finer grained towards the western part of the field where interbedded sandstones and pumiceous tuffs of fine to coarse grade are dominant. There are also interbedded mudstones, siltstones and sandstones at all levels. The finer sediments contain numerous thin tuff bands and show good graded bedding and small-scale slump features. On the western limit of the area drilled the member of the Waiora Formation are soft to poorly compacted, but in the production area have a greater degree of compaction presumably due to the effects of hydrothermal alteration with deposition of secondary silica. The pumice breccias in some cases include appreciable amounts of rhyolite, especially at lower levels." (Healy, 19 , p. 218.4.)

The mineralogy of the Waiora Formation is variable because of the different rock types. The mineralogy of two core samples is given by Hendrickson (1976). One sample, from the depth interval 1130 to 1135 feet (344-346 m) was described in a whitish-green altered tuff with a dominant fine-grained glossy matrix and phenocrysts of feldspar. Its composition was as follows (Henrickson, 1976, p. A6):

COMPOSITION	PERCENT BY VOLUME
Matrix Material	63
Feldspars	35
Opaques	2
Zeolites	Trace

TABLE 10

Waiora Formation		Thickness (Feet)
Member 5:	Ignimbrite, quartz-plagioclase, rhyolite inclusion	130
	Pumice sandstone, quartz-plagioclase, rhyolite fragments	100
	Ignimbrite, quartz-olagioclase, rhyolite inclusions	70
	Pumice breccia, quartz-plagioclase, rhyolite fragments	40
Haparangi Rhyolite, Phyolite Sill		250
Member 4:	Pumice breccia and sandstone, quartz absent, small amount of rhyolite fragments	520
	Dark siltstone	20
Member 3:	Pumice sandstone and breccia, quartz absent	180
	Rhyolitic breccia, minor pumice, quartz	50
	Pumice breccia and sandstone, quartz plagioclase	50
	Grey siltstone	20
	Pumice sandstone, quartz-plagioclase	80
Member 2:	Dark grey silty mudstone	20
	Pumice sandstone, grit, siltstone, quartz absent	150
	Pumice sandstone, rhyolite fragments quartz	130
Member 1:	Ignimbrite, quartz-plagioclase, pumiceous	100
	Ignimbrite, quartz-plagioclase, lenticular pumice	230

A second sample from the depth interval 2296-2618 feet (700-800 m) is described as a light-brown altered tuff with a fine-grained matrix consisting of glass, quartz, feldspar and large fragments of altered mafic material. The feldspars show some alteration to clay. Hendrickson (1976, P. A6) gives the composition as:

COMPOSITION	PERCENT BY VOLUME
Fine-grain glassy matrix	82
Voids	14
Feldspars	2
Quartz	2
Opaques	Trace

The principal properties of reservior materials were also measured by Hendrickson (1976). These measurements include saturated and dry bulk densities, effective porosity, total porosity, occluded porosity and grain density which are summarized in Table 2. For details of the measurement methods employed by Terra Tek, Inc., the reader is referred to their report (Hendrickson, 1976).

Permeability values for aquifer materials have been published by several investigators. Some of the more recent values are summarized in Table 9 (page VII-34).

Pritchett et al., (1976) have reported that the effective permeability of the reservoir as a whole arises from the fracture network within the system. For this reason, laboratory measured permeabilities are much lower than those actually found in the reservoir based upon its performance.

Similarly, the measured porosities are higher than those actually found in the reservoir based upon its performance. Theoretical analyses of the reservoir response at Wairakei (Mercer, et al., 1975; Pritchett, et al., 1976) have used effective permeabilities of the order of 100 millidarcies and porosities of about 20 percent for the Waiora aquifer with fairly good success.

The elastic moduli characteristics of the reservoir are described in Section 2.4.2.

3.4 FLUID CHARACTERISTICS

3.4.1 Chemistry

Geothermal water from the Wairakei Field is remarkably pure, which is probably the reason why it is discharged directly to the Waikato River. The typical total mass fractions of dissolved species in Wairakei geothermal waters reported by Wilson (1955) and by Ellis (1970) are 3.94×10^{-3} and 4.46×10^{-3} respectively. These mass loadings are around one-eighth those of sea water.

3.4.2 Temperature and Phase

The Waiora reservoir originally produced hot water at a temperature of about 250°C. After years of production, flashed steam is accummulating in the upper parts of the system because of decreased fluid pressures caused by production. Isotherms at various depths were determined by Banwell (1958) during early production, and are presented in Pritchett et al., (1978 pp. 77-82). As stated earlier, the hottest waters are generally in areas close to faults and fissures.

4. PRODUCTION HISTORY AND SUBSIDENCE

4.1 HISTORY OF DEVELOPMENT AND USE

The first experimental bores at Wairakei were drilled in 1950. A total of about 141 bores have been drilled since then. Of these, 65 bores account for about 95 percent of the total fluid produced from the entire field, which at the end of 1976 was about 2.33×19^{12} pounds (Pritchett et al., 1978). The early bores drilled from 1950 through 1952 were all shallow, ranging from 500 to 1500 feet deep, and relatively unproductive. Drilling of deeper bores, to 3000feet, began in 1953. These deeper bores marked the beginning of significant production from the area. The most productive drillholes are situated near fault traces in order to intersect fissures occuring along the fault zone at depths of 1500 to 2000 feet. The areal distributions of mass production, enthalphy and drilling activity are shown in Figures 11 and 12. A time history of total field production is presented in Figure 13. A steady increase in production occurred after 1958, when power generation began. The drilling of new wells ceased in 1968. The field mass production rate has steadily fallen since then, due primarly to reservoir pressure decline.

The location and cumulative production of each bore has been tabulated and presented by Pritchett et al. (1978, pp. 110-121).

The net mass loss in the Wairakei field was the subject of a paper by Hunt (1977). He concluded that" ... during the early stages of exploitation (1958-1962) the annual recharge, expressed as a percentage, diminished to about 10% and this was followed by a period (1963-1965) in which the annual recharge rose to about 90%, a value at which it has since remained. It appears that after 1965, a quasi-steady state developed

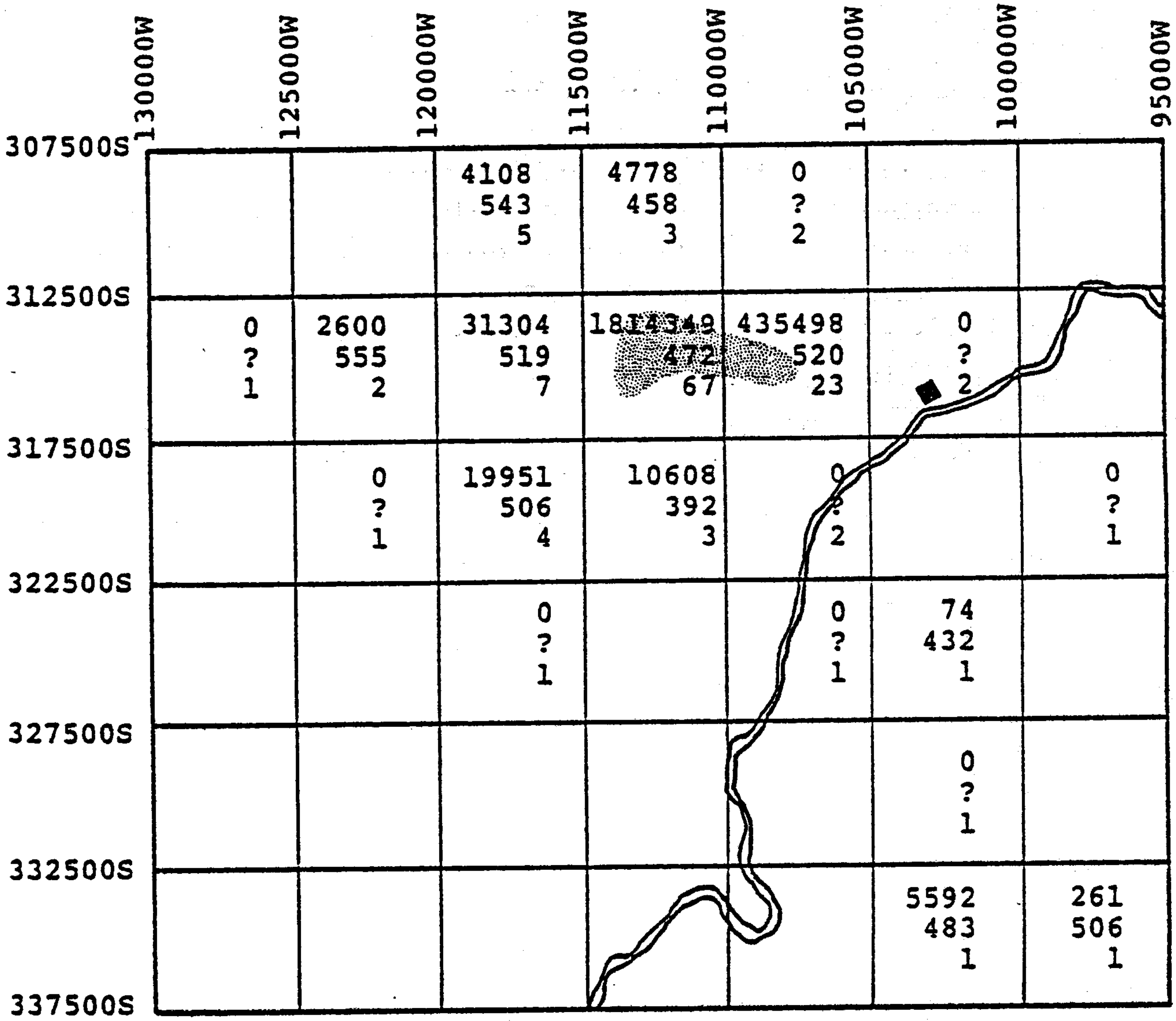


FIGURE 11 SPATIAL DISTRIBUTION OF MASS PRODUCTION, MEAN DISCHARGE ENTHALPY, AND DRILLING ACTIVITY, WAIRAKEI/TAUHARA FIELD

<u>K E Y</u>

31304 ← Total mass produced, 10^6 pounds

519 ← Mean discharge enthalpy, BTU/pound

7 ← Number of bores (monitor bores excluded)

Notes: 1. Shaded area is the main production area
2. From Pritchett et al, 1978

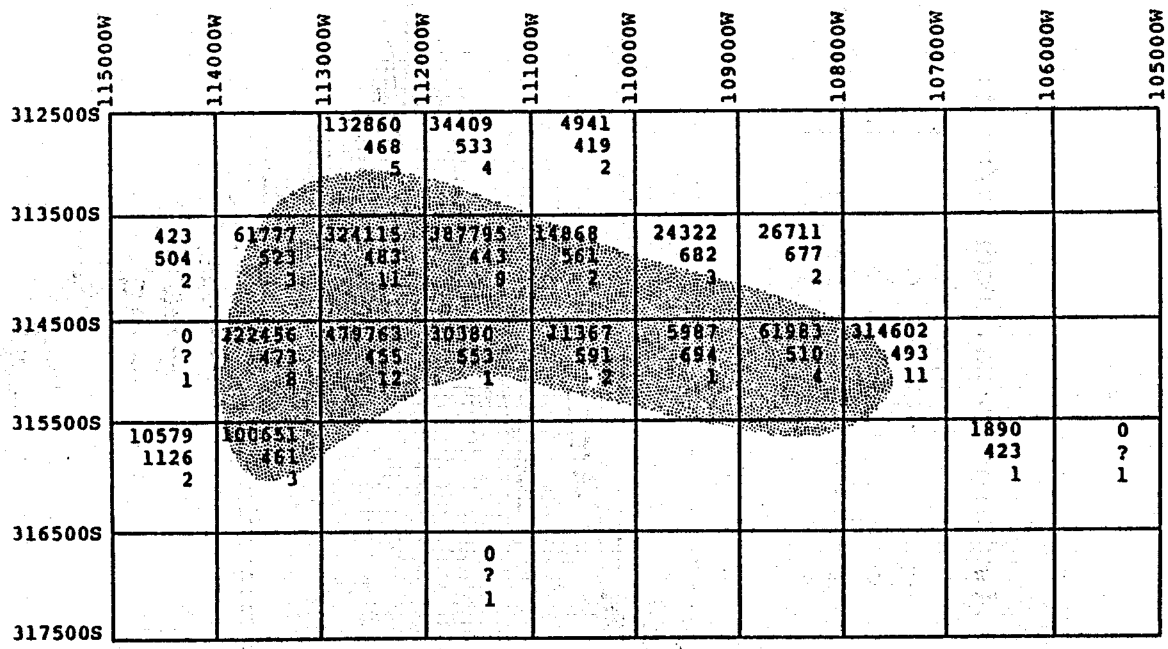


FIGURE 12

SPATIAL DISTRIBUTION OF MASS PRODUCTION, MEAN DISCHARGE ENTHALPY, AND DRILLING ACTIVITY, MAIN BORE FIELD AND VICINITY. (for key, see Figure 11)

Notes: 1. Shaded area is the main production area
2. From Pritchett et al, 1978

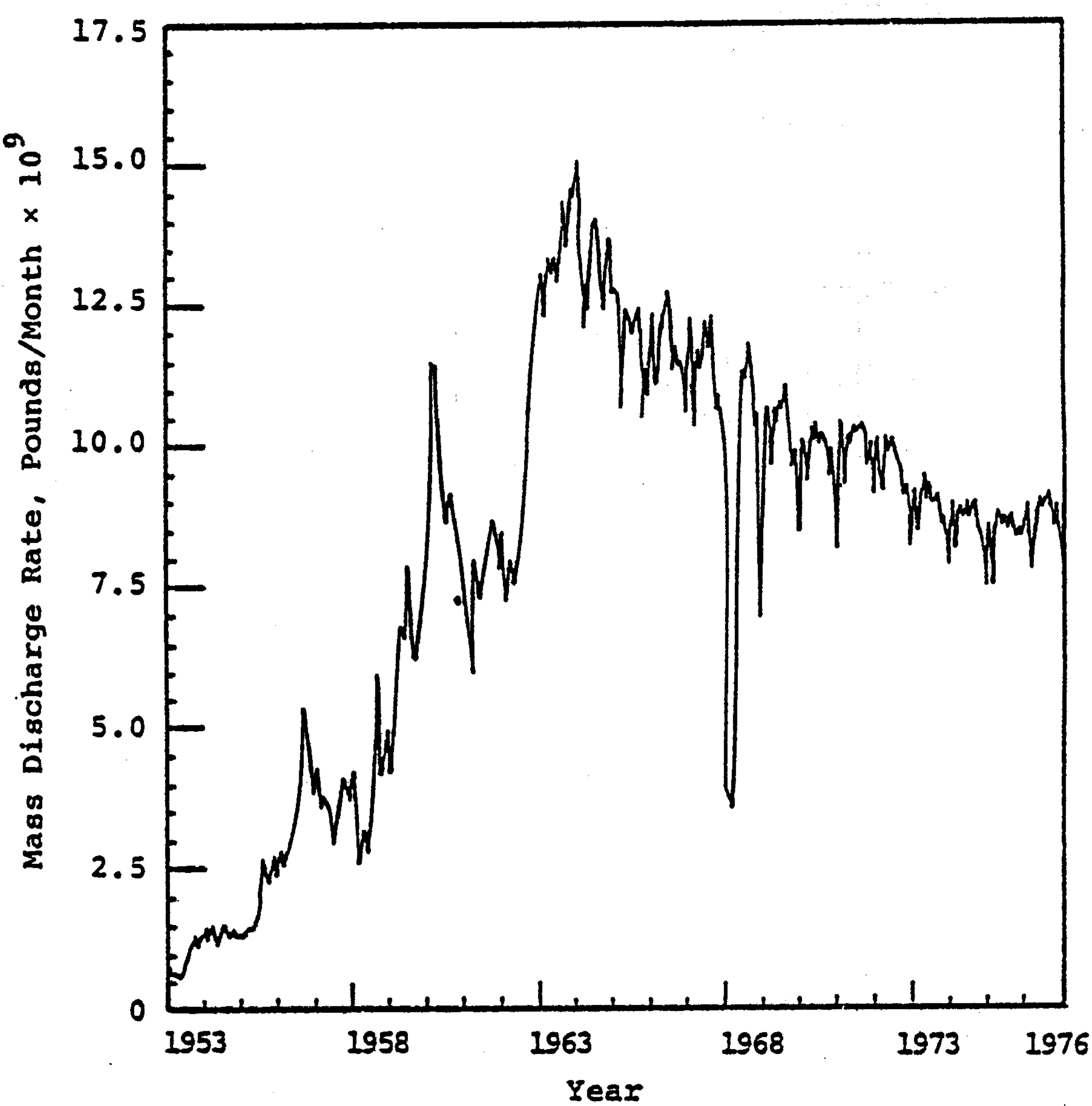


FIGURE 13 MASS DISCHARGE RATE (all bores) AS A FUNCTION OF TIME (from Pritchett, 1978)

in which mass inflow nearly balanced outflow, and at the present rate of withdrawal, the field will not be depleted of water for a long time.

Cumulative recharge values calculated from the annual recharge values are shown in Figure 14 and indicate that by the end of 1974 about 695×10^9 kg of water had replaced 965×10^9 kg of water withdrawn."

4.2 CHANGES IN RESERVOIR PROPERTIES DUE TO PRODUCTION

4.2.1 Pressure Decline

Extensive pressure measurements have been carried out over the years in the main Wairakei bore field as well as in surrounding holes. Due to their excellent coverage of this topic, much of this section is drawn from reports by Bolton (1970) and by Pritchett et al., (1978).

The raw pressure data from all holes is contained in files occupying about fifteen linear feet of book shelf space at the Ministry of Works laboratory near Wairakei. In order to reduce the amount of data analyzed, Bolton (1970) and Pritchett et al., (1978) have focussed on data at two representative horizontal planes, 500 and 900 feet below sea level (RL-500 and RL-900). Since the pressure distribtuion is essentially hydrostatic within the shut-in bores, a single datum such as at RL-500 or RL-900 can then approximate the entire pressure profile at a particular point in time.

Bolton (1970) found that the pressure reponse of the main bore field to fluid withdrawal has been quite uniform across the entire area, suggesting a high degree of horizontal communication and permeability in the Waiora aquifer. Figures 15 and 16 show pressures as a function of

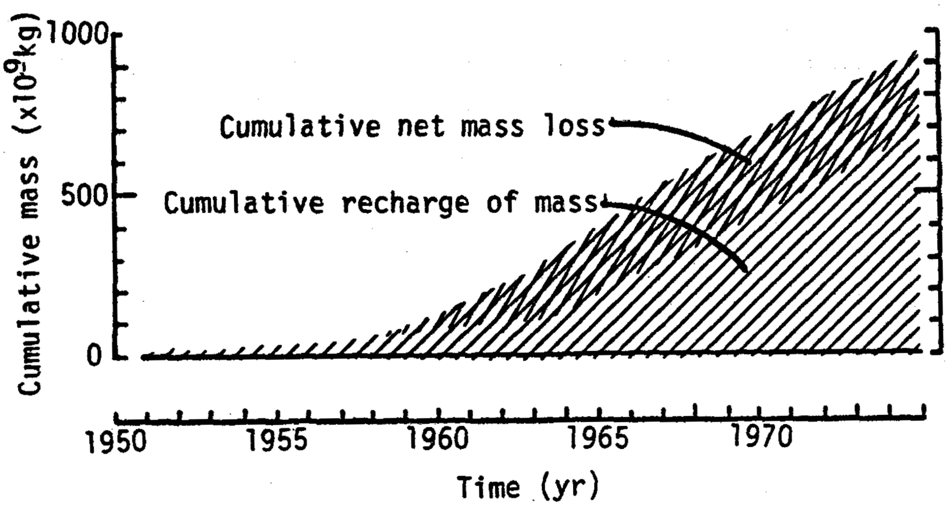


FIGURE 14

CUMULATIVE RECHARGE AND CUMULATIVE NET MASS LOSS, ESTIMATED FROM CORRECTED GRAVITY DIFFERENCES AT BENCH MARK A97, WAIRAKEI GEOTHERMAL FIELD (from Hunt, 1977)

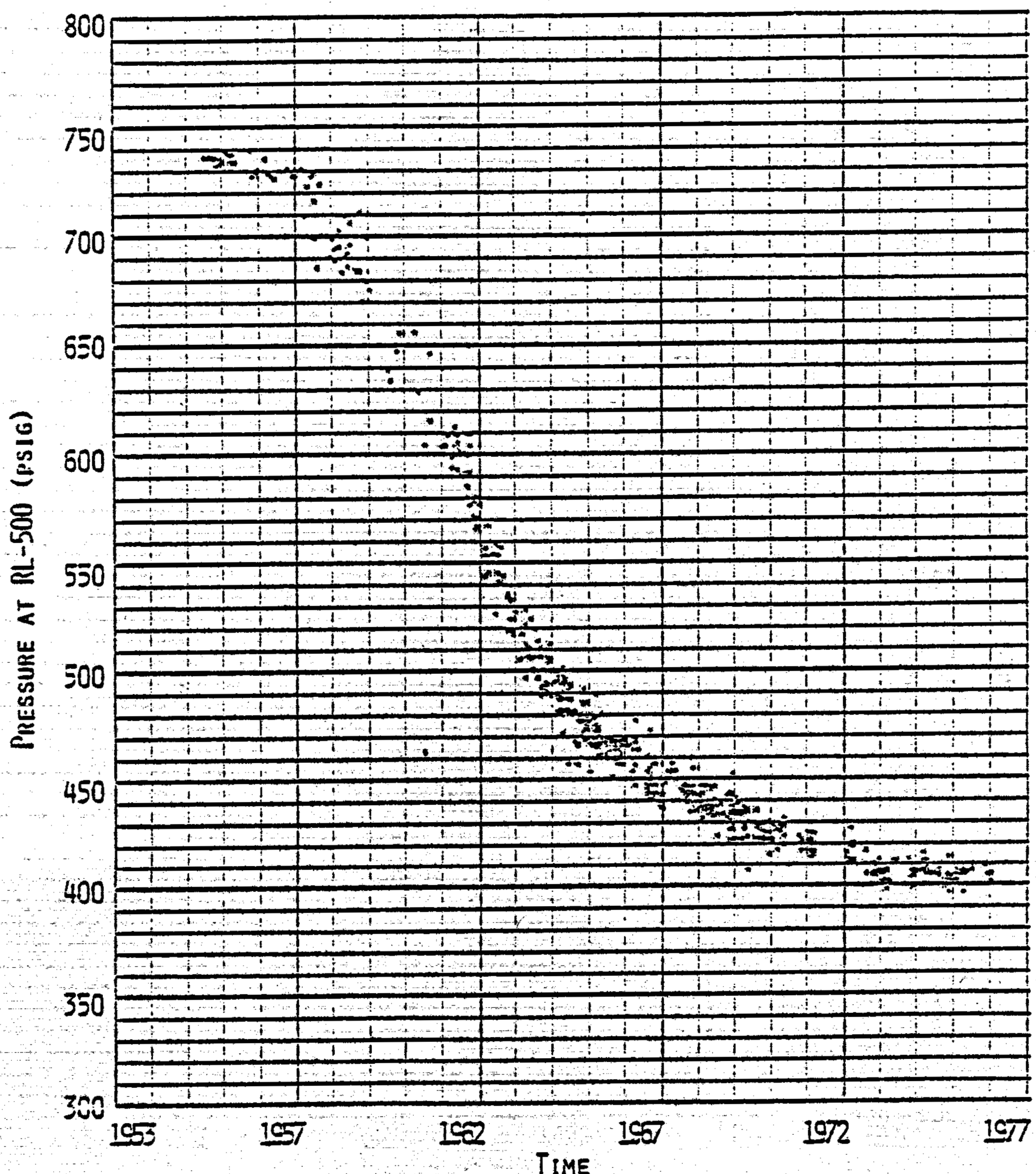


FIGURE 15

PRESSURE MEASUREMENTS AT RL-500 AS A FUNCTION OF TIME FOR BORES FOLLOWING THE TREND OF THE MAIN BORE FIELD (from Pritchett, 1978)

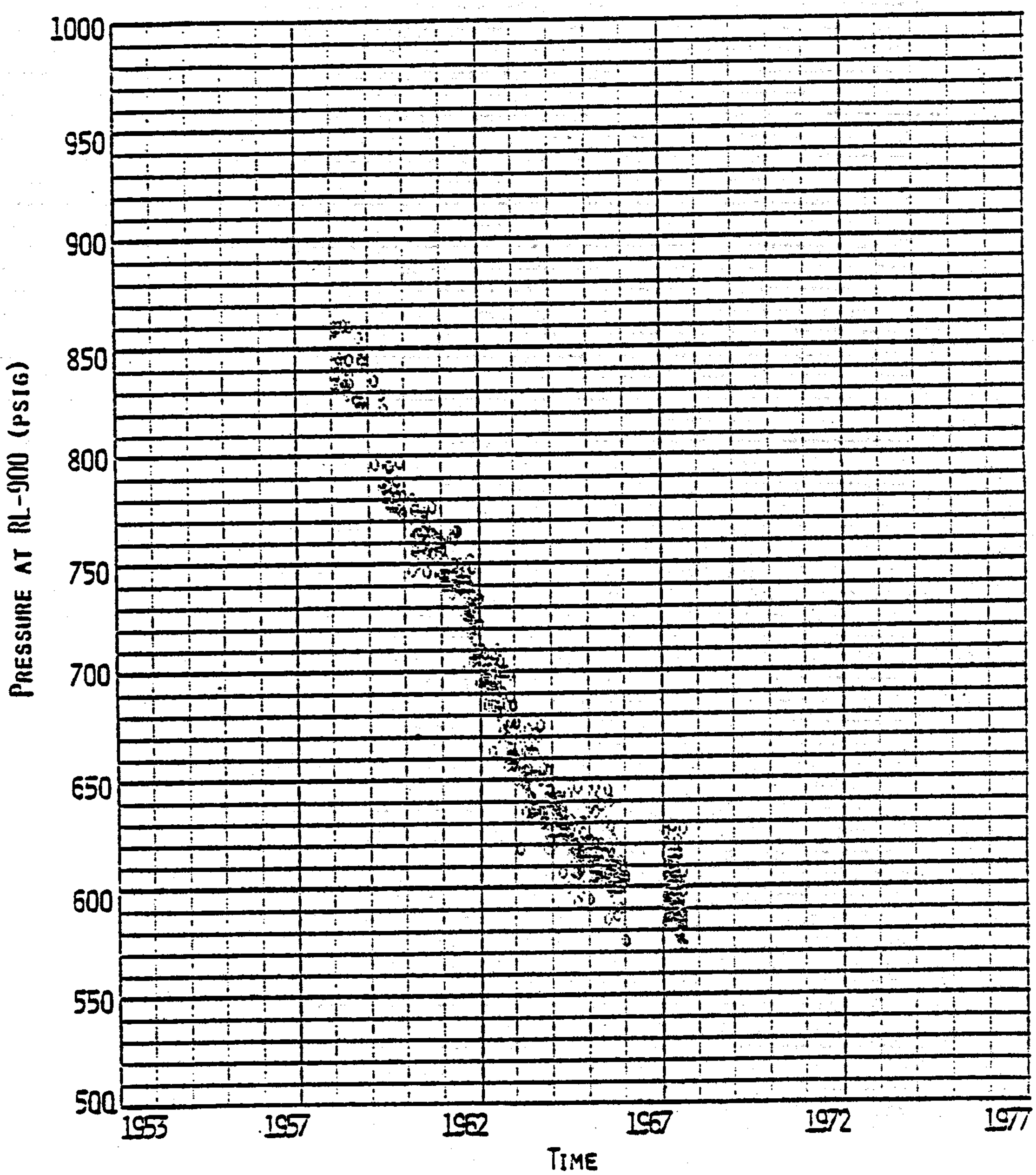


FIGURE 16 PRESSURE MEASUREMENTS AT RL-900 AS A FUNCTION OF TIME FOR BORES FOLLOWING THE TREND OF THE MAIN BORE FIELD (from Pritchett, 1978)

time for all measurements taken at the RL-500 and RL-900 levels. It can be seen that there is little difference between the RL-500 and RL-900 data, except for a shift in scale due to the greater hydrostatic head at RL-900 (equivalent to about 173 psia). There is a definite areal change of pressure reduction, as shown in Figure 17. This figure shows that the pressure reductions are as much as 30% greater (~90 psi greater) in the eastern part of the production zone.

Magnetic tapes of all pressure data at RL-500 and RL-900 have been compiled by Pritchett et al. (1978). They anticipate using these data in their continuing model development work on Wairakei.

4.2.2 Temperature Changes

There have been several thousand temperature runs taken in the Wairakei bores over the years. Temperatures vary both with bore location and depth. Bolton (1970) illustrated this variation by dividing the bores into three groups geographically, and the depths into intervals of 400 feet. Figures 18, 19, and 20 show the average maximum temperatures with depth for each of the three groups.

Figure 18 shows that a strong temperature/depth relationship exists in the eastern area, that there have been no changes in the average temperature for the lowest depth interval (1000 ft), and that above this level temperatures have fallen with time. The rate of temperature falloff has increased with decreasing depth, from 1000 feet below sea level to about 200 feet above sea level.

In the western production area bores, the dependence of temperature on depth is not so well defined, as shown in Figure 19.

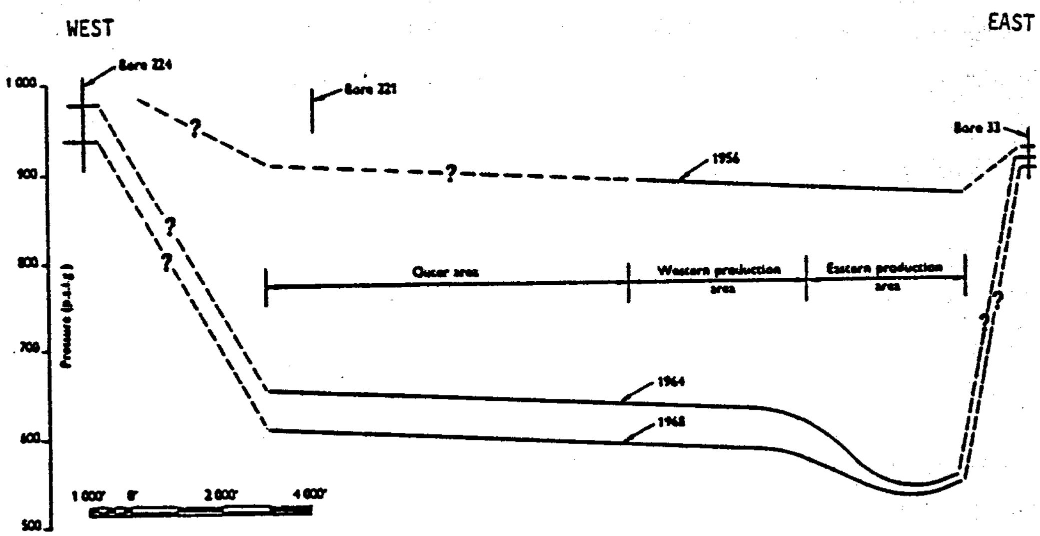


FIGURE 17 EAST-WEST PRESSURE DISTRIBUTION AT WAIRAKEI AT RL-900 FOR 1956, 1964, AND 1968 (from Bolton, 1970)

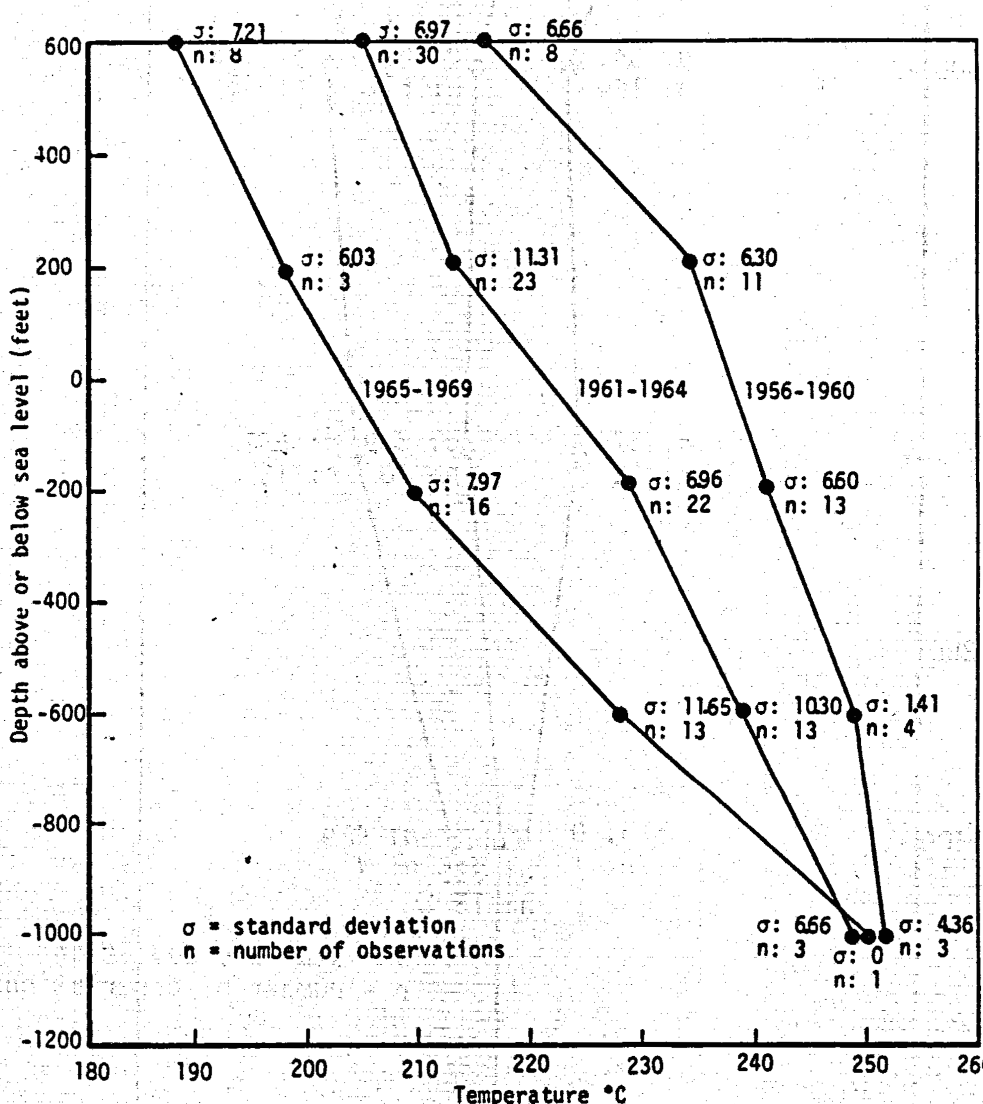


FIGURE 18 EASTERN PRODUCTION AREA BORES: AVERAGE MAXIMUM TEMPERATURE AGAINST DEPTH (from Bolton, 1970)

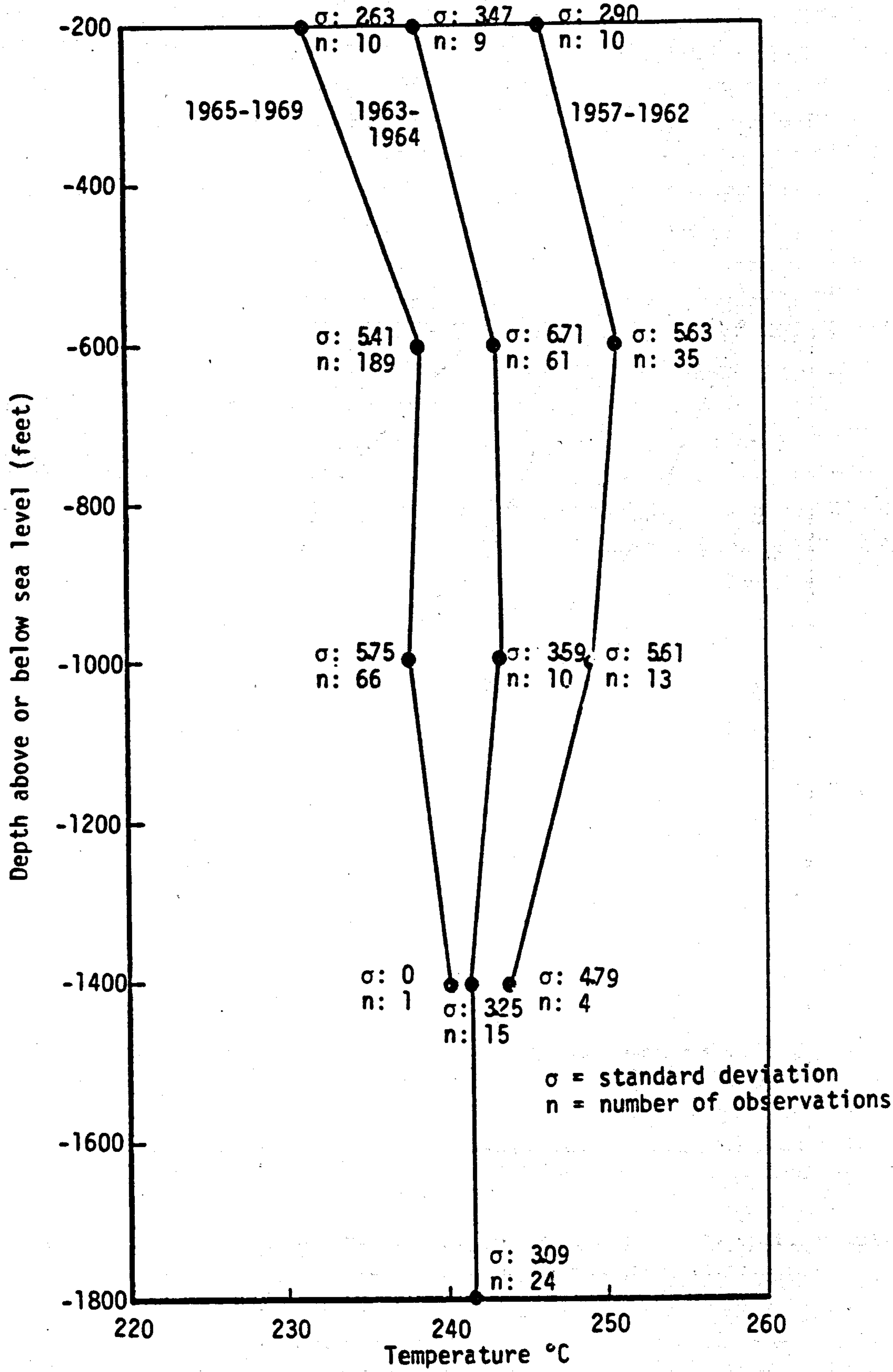


FIGURE 19 WESTERN PRODUCTION AREA BORES: AVERAGE MINIMUM TEMPERATURE AGAINST DEPTH (from Bolton, 1970)

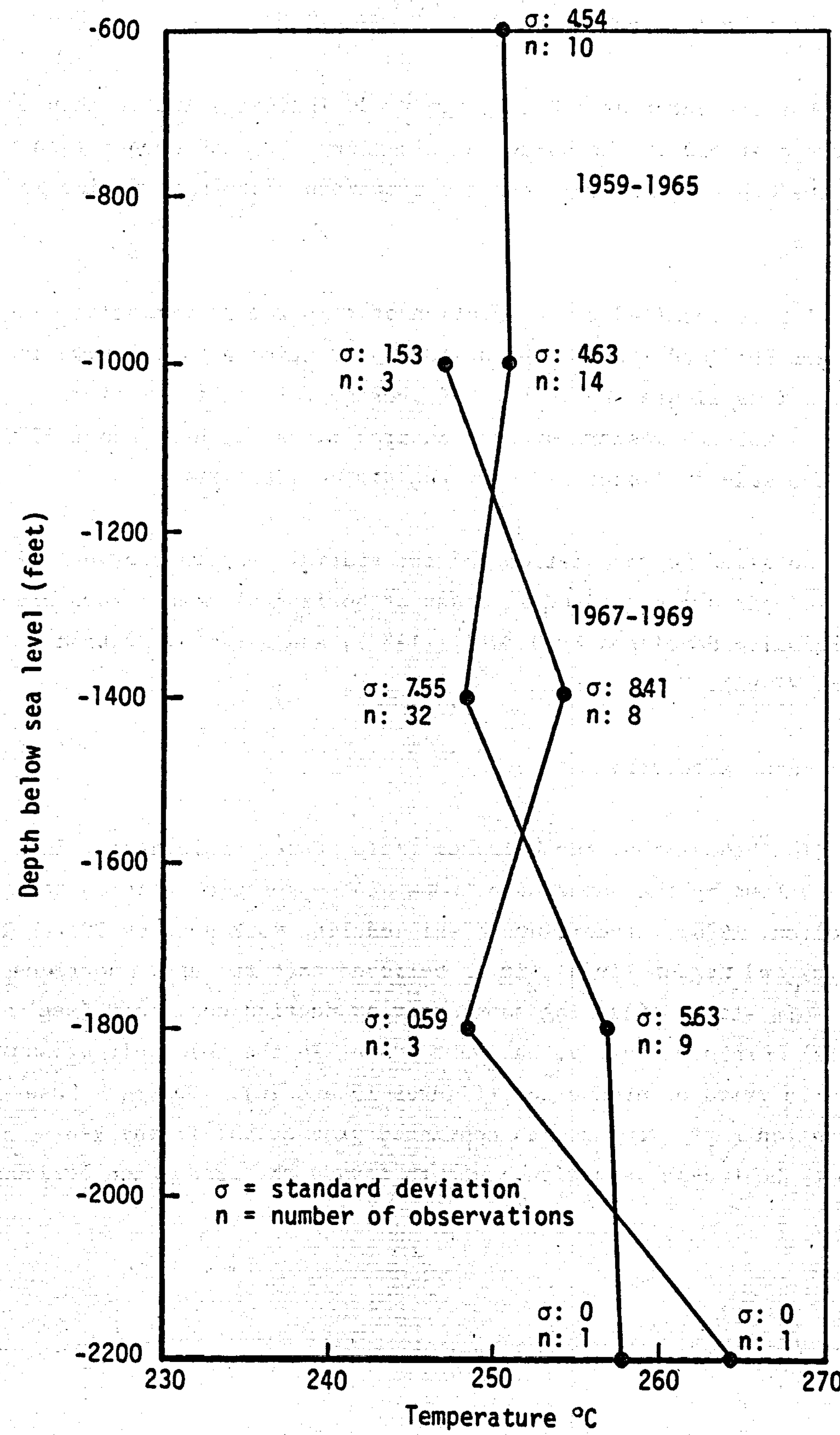


FIGURE 20 OUTER AREA BORES: AVERAGE MAXIMUM TEMPERATURE AGAINST DEPTH (from Bolton, 1970)

For the outer area bores, Figure 20 indicates little change in temperature over time. The bores in this group are much deeper than those in the other two groups, and the temperature/depth variation is slight.

A more detailed representation of temperature variation with time between 1957 and 1969 in the western production area is shown in Figure 21. This figure shows that the average fall in the maximum temperatures for the western production area bores has been about 12°C, and that the main fall occurred over the period 1963-1964.

Detailed representations of the spatial temperature variations in the reservoir are presented in a set of horizontal temperature profiles originally developed by Banwell (1958), and given by Pritchett (1978, pp. 77-98).

4.2.3 Phase Alteration

The behavior of the Wairakei field, under explotation, is largely governed by the saturation temperature-pressure relation for water (Bolton, 1970). According to the modeling work done by Pritchett et al., (1976) and Mercer (1975), it is believed that the upper portions of the reservoir started flashing soon after production commenced (see Figure 22a). This would have helped to maintain the reservoir pressures in the early years of production (Figures 15 and 16). The two-phase boiling region kept growing with continued production; in the years 1959-1960, the two-phase region began to invade the production horizon

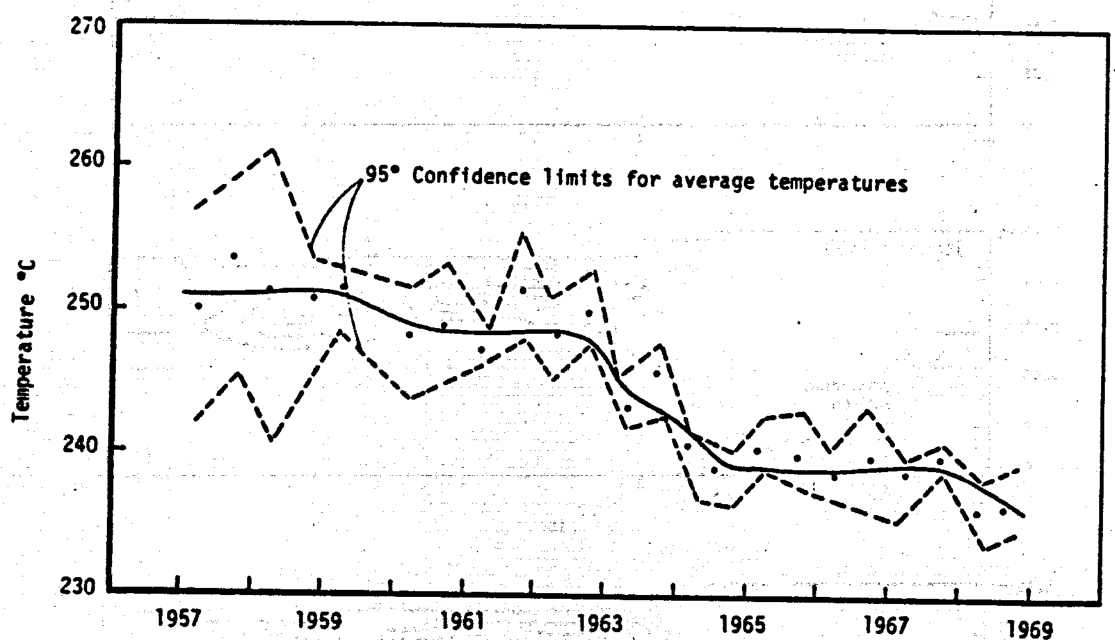


FIGURE 21 WESTERN PRODUCTION AREA BORES: AVERAGE TEMPERATURE (from Bolton, 1970)

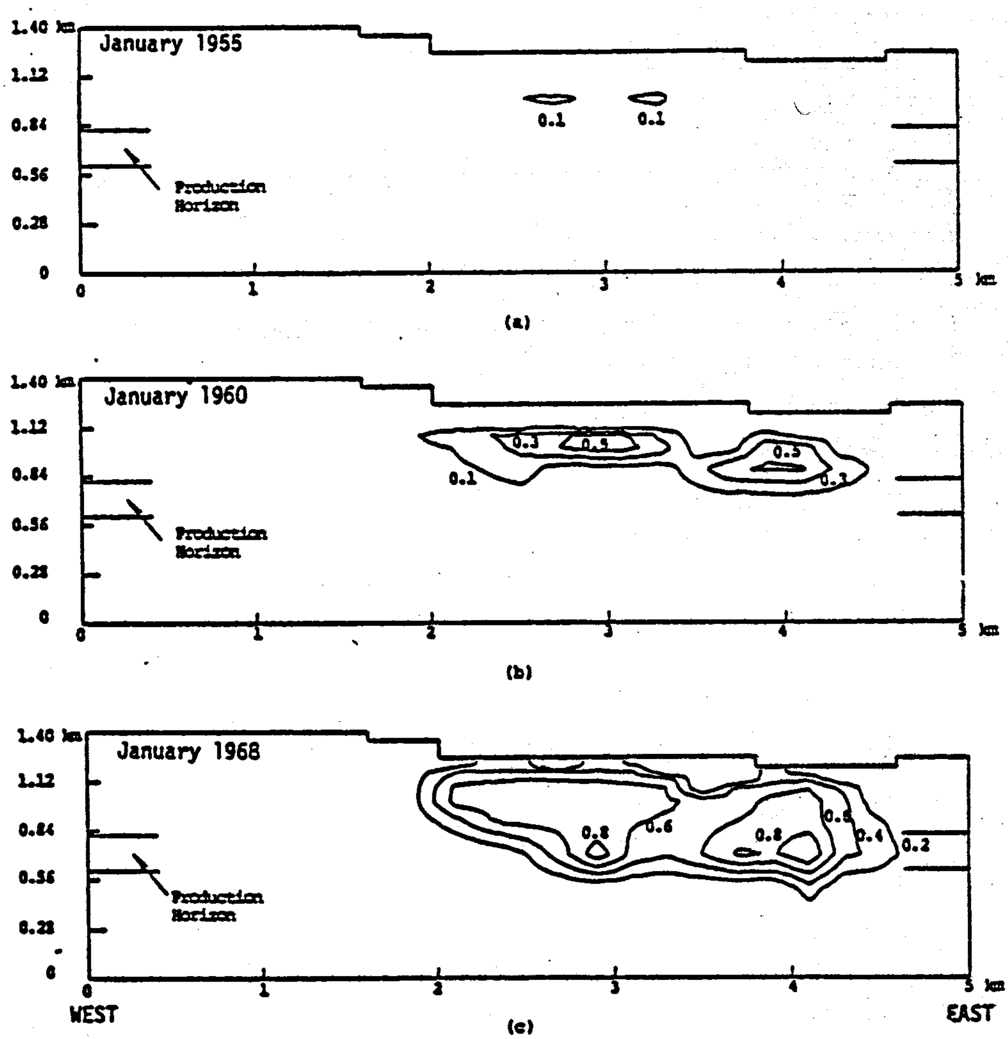


FIGURE 22 VARIATION OF VAPOR SATURATION CONTOURS WITH TIME (from Pritchett et al, 1976)

(Figure 22b). Field pressures then (1959-1960) began to drop rapidly (see Figures 15 and 16) due to the relative permeability effect* in two-phase flow. Eventually (around 1964) the entire production region started to boil (see Figure 22c), which marked the onset of the relative flattening of the pressure drop curve (Figure 15).

4.2.4 Apparent Rock Strength Changes

An analysis by Pritchett, et al., (1976) suggests that the compressibility of the Waiora reservoir rock may have increased by a factor of 15 times between 1953 and 1975. This conclusion was drawn from a cross plot of reservoir pressure drop (at elevation -150 m) versus subsidence of bench mark A97 -- a pseudo stress-strain curve. From 1953-1963 the deformation was linear elastic, at a rate of 36 bars pressure drop per meter of subsidence. Between 1963 and 1971 the slope decreased smoothly; the rock must have been failing progressively. From 1971-1975 it again behaved essentially linearly, but at a rate of 2.4 bars/meter, 15 times more compressible than initially. These initial and final compressibilities were three and 45 times greater, respectively, than those determined from laboratory tests on small samples.

The above findings indicate the dangers in making predictions of future subsidence at Wairakei, and even more so for a virgin geothermal field. Apparent increases in work compensibility is typical of many reservoirs. But neither laboratory tests on small core samples nor

---

* The relative permeability effect depends upon a variation of the "permeability to two-phase fluid" over a range from "permeability to 100% water" to "permeability to 100% steam". The latter permeability is obviously many times greater, enabling more rapid pressure adjustment.

preproduction seimic measurements are likely to be of much help in determining in advance the required long-term non-linear stress-strain relations. It appears more likely that some guidance might be obtained from the analysis of geological, subsidence, and production data for geothemal and oil/gas reservoirs with well-documented production and subsidence histories, to try to identify the mechanisms which cause non-linear behavior.

4.3 INSTRUMENTATION USED TO MEASURE EFFECTS

The temperatures discussed in Section 4.2.2 were recorded using geothermograph runs, Pritchett et al., (1978). These data were recorded inside cased boreholes, thus surrounding rock temperatures may not have been properly measured. This temperature measurement technique requires a long standing time before recording can be properly taken. Even with long standing times, the convective patterns within the measured wellbore may cause spurious recordings. With these factors in mind, the temperature data presented here, and by Pritchett et al., (1978), must be used with caution.

Pressures, discussed in Section 4.2.1, were not directly measured prior to 1959. However, using water level and temperature data (whose accuracy is questionable as discussed above), and assuming hydrostatic equilibrium, pressure estimates were made.

Starting in about 1959, Amerada Bourdon tube type pressure gauges were used to directly measure pressures. Bolton (1977) estimates the accuracy of the earlier indirect determinations as ± 20 psi, and of the direct measurement as ± 10 psi.

Ground subsidence at Wairakei was first measured in 1956 when bench mark levels were compared with those established in 1950 (Hatton. 1970). A subsidence measurement network was then established, and evolved over a period of time, first on the steam main supports and then outward into the field. Figure 23 shows the location of various bench marks in use in 1971.

Bolton (1970) gave the following description of the bench marks and leveling operations at Wairakei:

> "Primary bench marks generally comprise reinforced concrete cast in 8 inch diameter holes drilled to depths up to 20 feet. The top of the concrete is enlarged to incorporate a stainless steel pin and an identification plate.
>
> Along the steam mains, stainless steel pins set approximately 160 feet apart in the concrete pipe supports serve as bench marks. Elsewhere, steel pins embedded in approximately one cubic foot of concrete and driven steel rods have been used.
>
> The costly primary bench marks which are generally necessary for first-order geodetic levelling offer no appreciable advantage when measuring ground subsidence. In areas of substantial subsidence close spacing of the bench marks (100 to 200 per square mile) is considered desirable if such is to be learned of the subsidence pattern. When an adequate number of bench marks have been installed initially, the loss or disturbance of a few can generally be tolerated.
>
> Bench marks made from 6 inch diameter wooden posts, suitably treated and painted are at present under trial. Projecting 2 feet above ground level, bench marks of this type require no separate identification markers.
>
> Levelling
>
> First and second-order levelling has been used to achieve a high degree of accuracy over a large area.

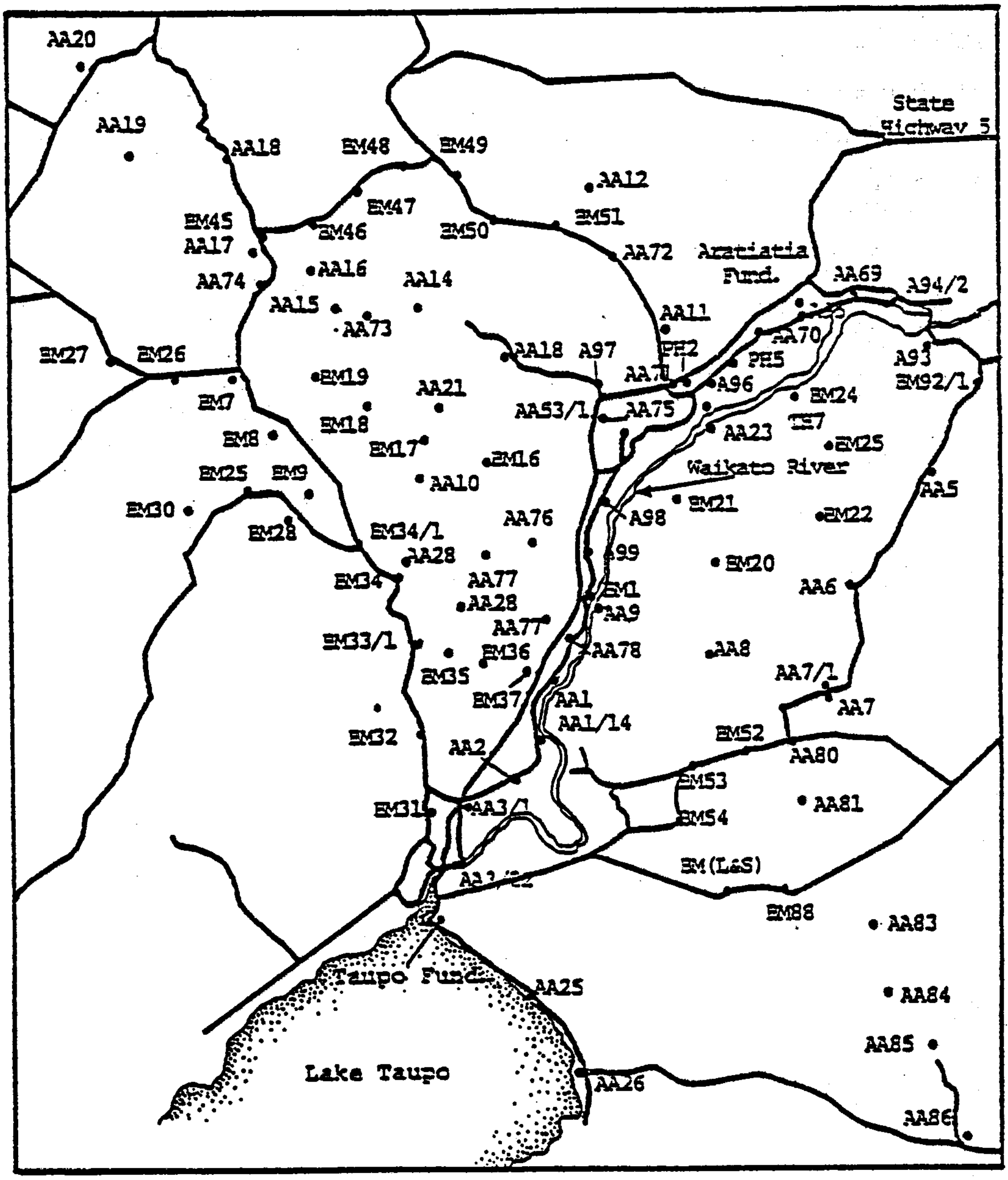


FIGURE 23 BENCH MARK LOCATIONS FOR 1971 SURVEY (from Pritchett et al, 1978)

However, the procedures are slow and unsatisfactory results are obtained if the rate of subsidence is large. In areas of known ground subsidence speed is essential if reliable levels are required. It has been found that a compromise between accuracy and speed of levelling generally produces the best results. In the Wairakei production field the duration of a re-levelling survey is normally confined to a period of 2 weeks. This entails double-levelling at speeds up to 3 miles per day."

Most of the leveling at Wairakei has been second order leveling due to the need for rapid measurements. Between 1956 and 1971, checking of the precise level network took place every 3 or 4 years (Stillwell et al., 1975). Local subsidence in the bore filed was checked every six months until 1968; then annually. The last check was made in 1977 (Pritchett et al., 1978).

A bench mark (A93) situated about 3 miles northeast of Wairakei was arbitrarily chosen as datum for precise leveling. Indications are that any subsidence that may be occurring at this point is likely to be small. Local subsidence in the bore field is measured relative to bench mark TH7 located in the power house. The power house is not completely outside the zone of subsidence; it is, however, believed to be sufficiently so for local subsidence checks. Bench mark TH7 moved 0.7 feet relative to Bench mark A93 during the period 1960-1974.

A horizontal control network was set up in 1966 (Figure 24), and repeated in 1968, 1969, 1972, and 1973. In 1973, a descripancy was discovered between coordinates and measured lengths between Lands and Survey second order trig stations Ngangiho and 1471. A braced quadrilateral (Figure 25) was then adopted and new coordinates obtained for the two trigs which have become "fixed" points for recomputation. The last horizontal survey was performed in 1977 (Rogan, 1977).

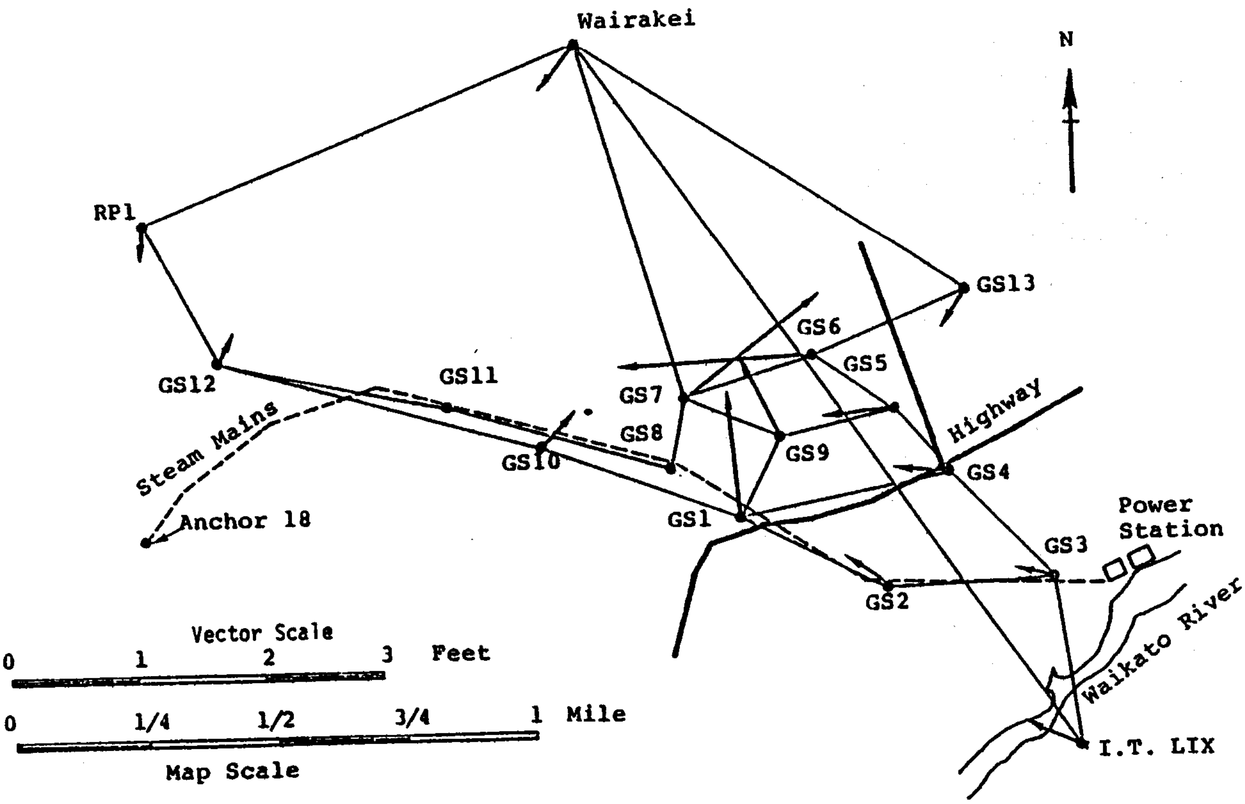


FIGURE 24 WAIRAKEI SURVEY CONTROL NETWORK. VECTOR MOVEMENT PERIOD 1966 TO 1974 (from Stilwell et al, 1975)

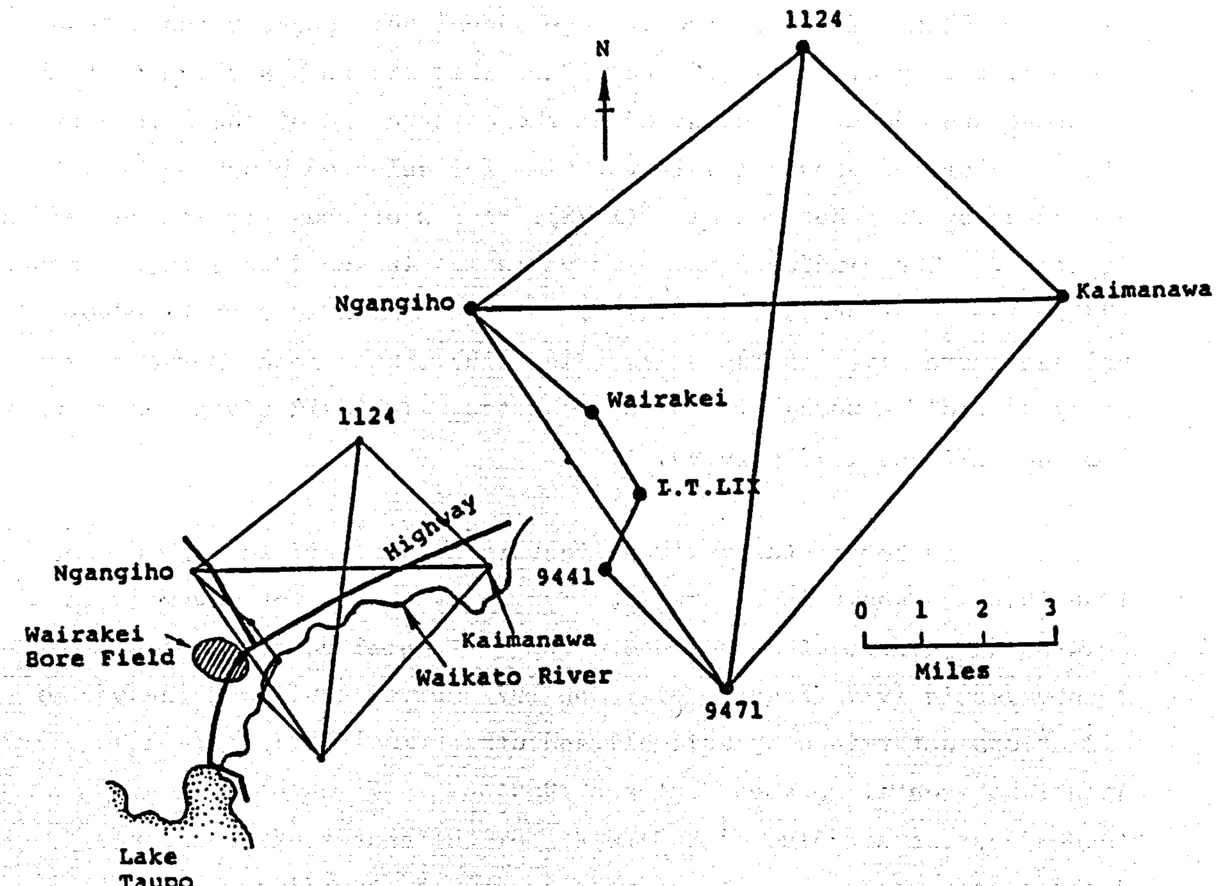


FIGURE 25 ORIGIN OF WAIRAKEI SURVEY CONTROL NETWORK (from Stilwell et al, 1975)

4.4 SUBSIDENCE CHARACTERISTICS

Subsidence at Wairakei has been thoroughly reported by Hatton (1970) and Stilwell (1975), and subsequently by Pritchett et al., (197 , 1978). Most of the information contained in this section is from these sources.

Figure 26 shows the average annual subsidence rates around the area, over 15 years from 1956 to 1971. This figure has shown that the greatest subsidence has occurred at the eastern end of the main production field. Plots of ground levels vs. time for selected bench marks were presented by Pritchett et al., (1978). A few of these are presented in Figure 27. They indicate the time variation in subsidence rates through 1971. The first and second order leveling results as summarized by Pritchett are given in Table 11. Since 1971, only local surveys (steam mains control network) have been conducted. Table 12 gives the results for the 1974 and 1977 surveys.

The horizontal movement vectors at Wairakei for the period 1966-1974 are shown in Figure 24. Typically the vector movement is towards the center of subsidence. The horizontal control network was resurveyed in 1977 (Figure 28). The 1977 survey confirmed the vector directions determined by Stilwell and others in 1975 (Figure 24). Annual horizontal movement between 1968 and 1977 was between 4.3 inches/year at a radius of 800 feet from the center of subsidence decreasing to about 0.6 inches/year at 2500 feet radius (Pritchett 1978).

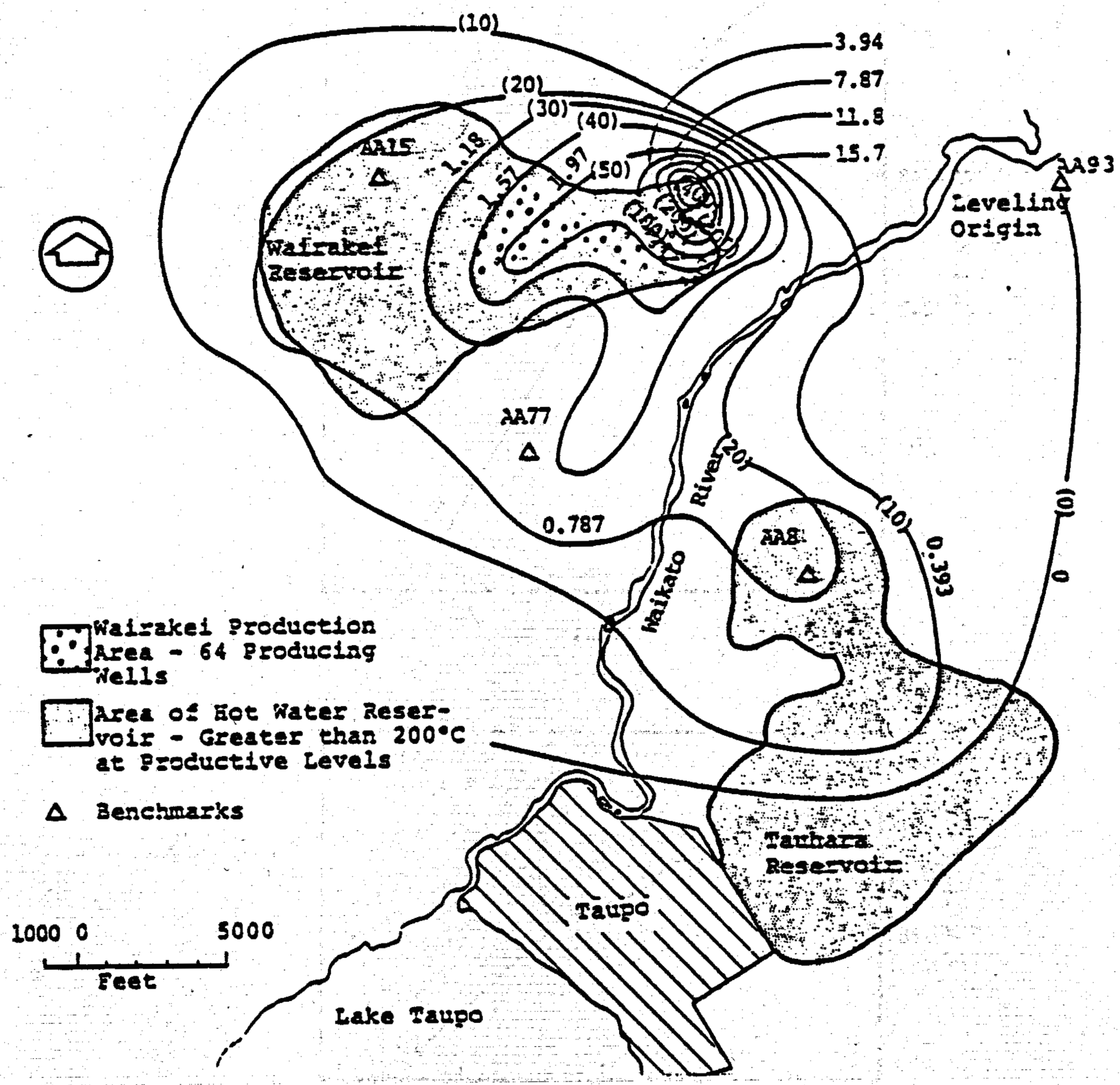


FIGURE 26 AVERAGE LAND SUBSIDENCE RATES, 1956-1971. CONTOURS OF EQUAL SUBSIDENCE IN INCHES PER YEAR. VALUES IN PARENTHESIS ARE MILLIMETERS PER YEAR. (from Pritchett et al, 1978)

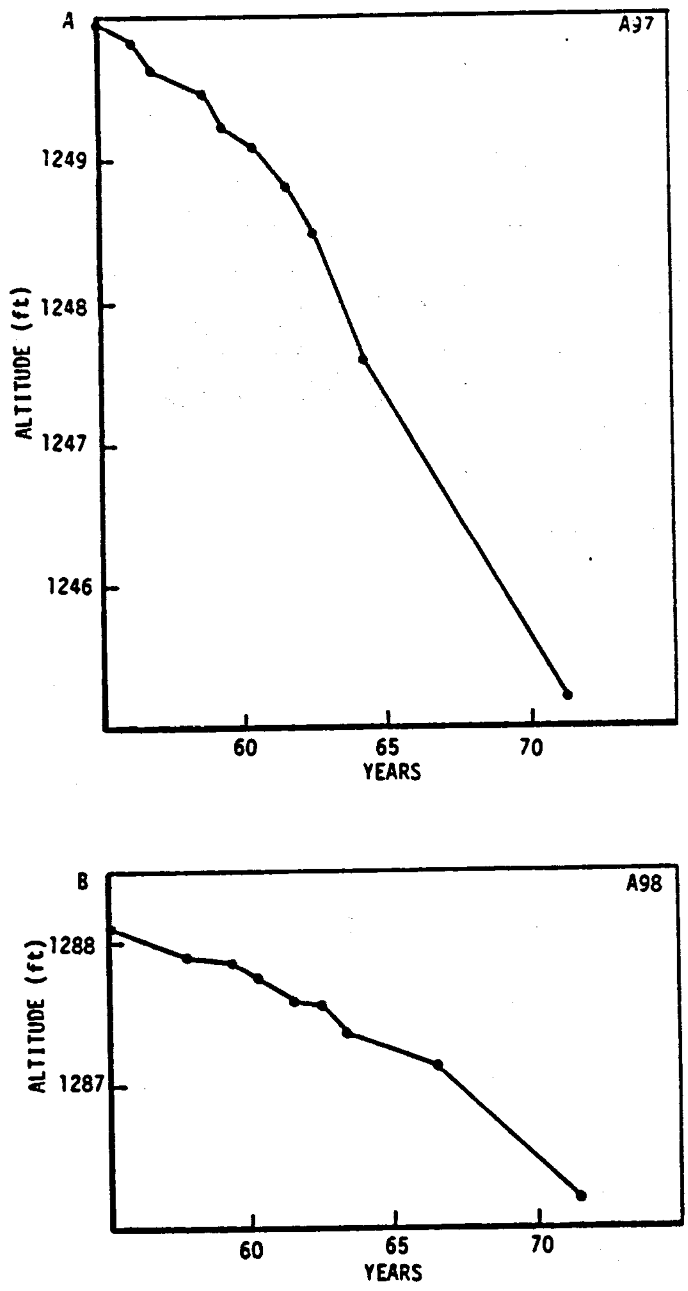
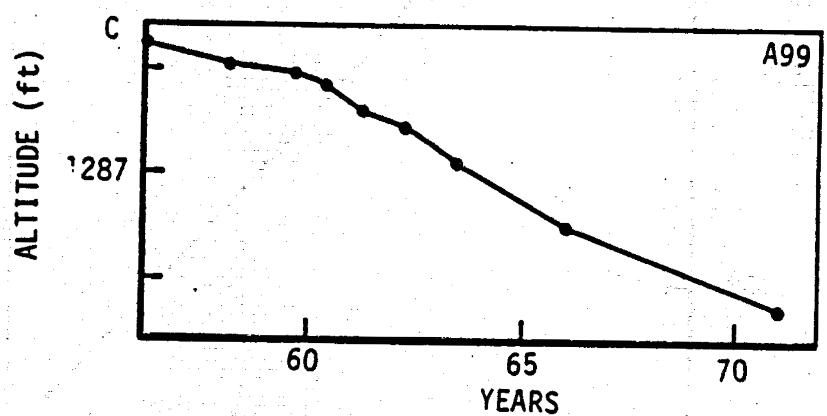


FIGURE 27 SUBSIDENCE HISTORY AT SELECTED BENCH MARKS. ABSCISSA IS TIME, YEARS, I.E., 19--; ORDINATE IS SURFACE ALTITUDE, FEET RL (from Pritchett et al, 1978)



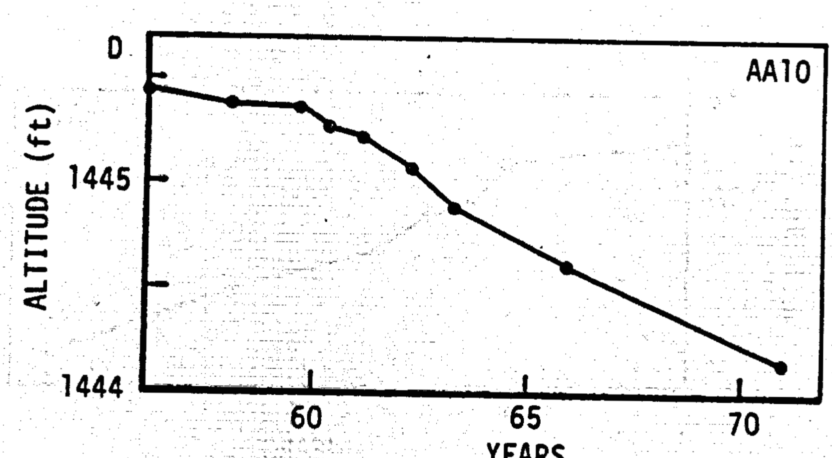
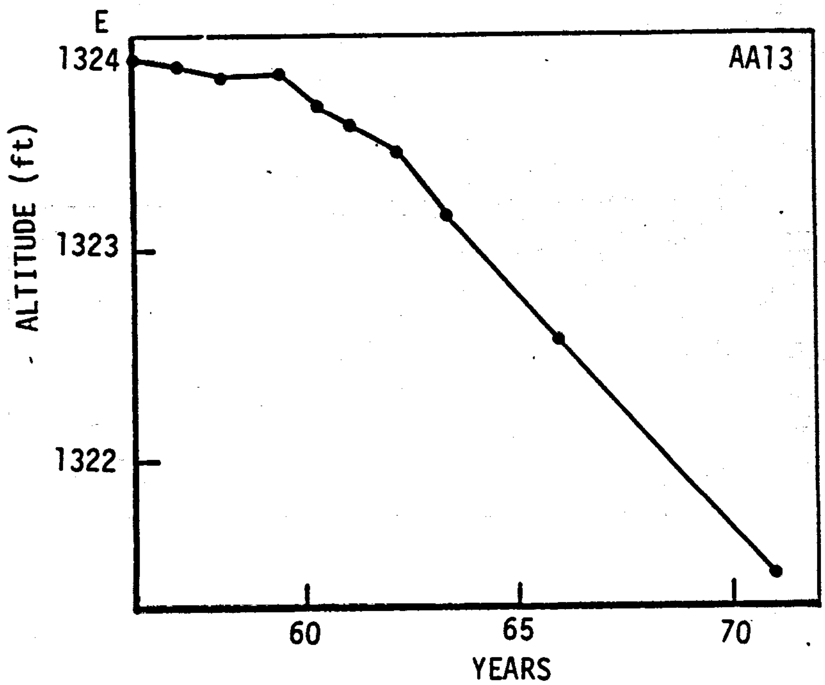


FIGURE 27 (continued)



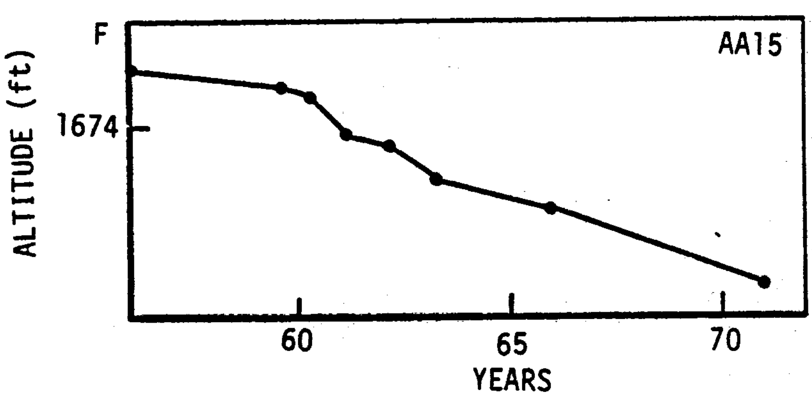


FIGURE 27 (continued)

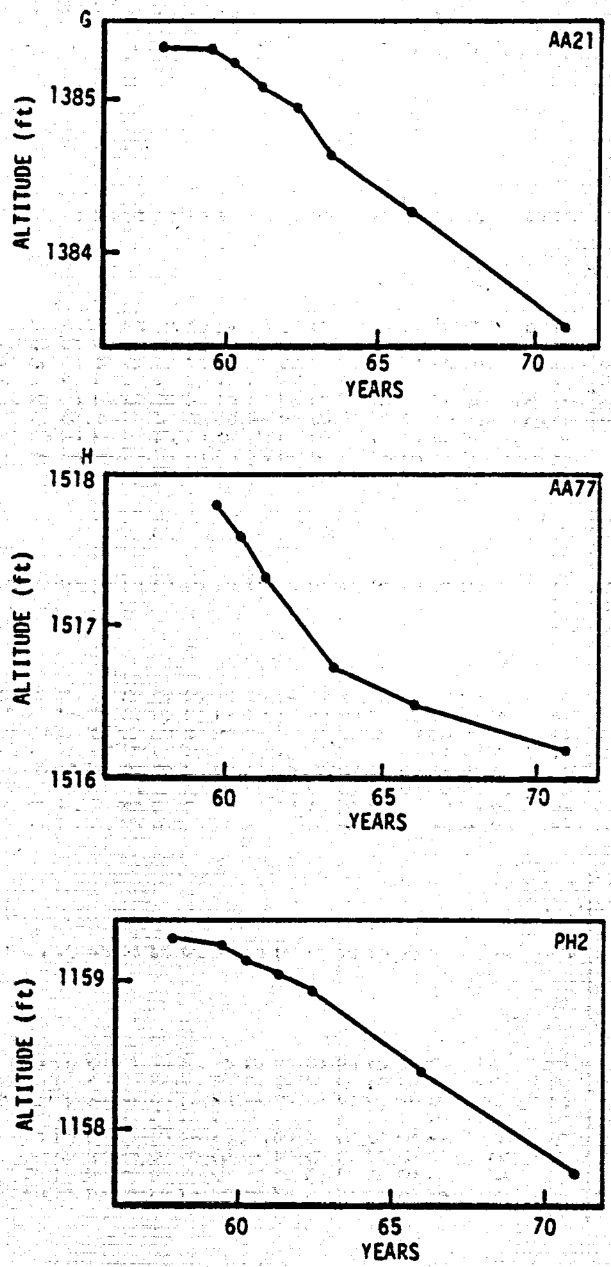


FIGURE 27 (continued)

Table 11 FIRST AND SECOND ORDER LEVELING RESULTS
1963/1964, 1966, 1971
from Pritchett (1978)

Maraetai Datum

Origin A.93 = 1193.320

Bench Mark	1963-1964	Order of Leveling	1966	Order of Leveling	1971	Order of Leveling	Difference 1971 to 1966 or 1963,64	Annual Rate of Subsidence
Aratiatia Fund.	1152.254	2	1152.248	2	1152.206	2	- .042	-0.008
Taupo Fund.					1199.618	2		
Rangitaiki Fund.	2455.068	1	2455.217				+ .149	+0.058
B.M.1(Huka)			1174.743	2	1174.350	2	- .393	- .079
B.M.7	1681.646	2	1681.507	2	1681.255	2	- .252	- .051
8	1668.263	2	1668.109	2	1667.744	2	- .365	- .073
9	1528.780	2	1528.687	2	1528.464	2	- .223	- .045
15	1306.261	2	1306.074	2				
16	1388.648	2	1388.446	2	1388.122	2	- .324	- .064
17	1522.363	2	1522.171	2	1521.666	2	- .505	- .099
18	1713.138	2	1713.138	2	1712.702	2	- .436	- .085
19	1652.717	2	1652.717	2	1652.321	2	- .396	- .077
20	1391.572	2	1391.432	2	1391.275	2	- .157	- .031
21	1268.941	2	1268.795	2	1268.585	2	- .210	- .041
22	1478.130	2	1478.085	2	1478.077	2	- .008	
23	1142.136	2	1142.031	2	1141.873	2	- .158	-0.031
24	1162.629	2	1162.613	2	1162.589	2	- .024	-0.005
25	1310.081	2	1309.618	2	1309.604	2	- .014	-0.003
26	1701.485	2	1701.426	2	1701.265	2	- .161	-0.031
27	1760.210	2	1760.214	2	1760.114	2	- .100	-0.019
28	1598.309	2	1598.187	2	1597.952	2	- .235	-0.045
29	1613.281	2	1613.180	2	1613.090	2	- .090	-0.017
30	1625.814	2	1625.726	2	1625.543	2	- .183	-0.035
31	1400.713	2		2	1400.703	2	- .010	
32	1480.865	2			1480.763	2	- .102	-0.013
33/1					1562.364	2		
34	1455.530	2	1455.272	2	1454.964	2	- .308	-0.059
34/1					1501.460	2		
35	1536.246	2	1536.098	2	1535.830	2	- .268	-0.026
36	1434.646	2	1434.603	2	1434.451	2	- .152	-0.015
37	1333.756	2	1333.717	2	1333.492	2	- .225	-0.043

Table 11 FIRST AND SECOND ORDER LEVELING RESULTS
1963/1964, 1966, 1971
from Pritchett (1978)

(continued)

Maraetai Datum

Origin A.93 = 1193.320

Bench Mark	1963-1964	Order of Leveling	1966	Order of Leveling	1971	Order of Leveling	Difference 1971 to 1966 or 1963,64	Annual Rate of Subisdence
B.M.88					1480.397	2		
A.92/1	1262.827	1	1262.838	1				
A.93	1193.320		1193.320		1193.320		Datum	
A.94/1	1141.613	2			1141.610	2	-0.003	-
A.94/3	1117.361	2	1117.373	2				
A.95	1151.184	2	1151.181	2	1151.138	2	-0.043	-0.009
A.96	1144.509	2	1144.310	2	1143.978	2	-0.332	-0.067
A.97	1248.536	2	1247.610	2	1245.343	2	-2.267	-0.447
A.98	1287.428	2	1287.120	2	1286.661	2	-0.459	-0.090
A.99	1287.047	2	1286.774	2	1286.368	2	-0.406	-0.080
AA.1	1195.346	2	1195.222	2	1194.949	2	-0.273	-0.054
AA.1/14	1238.250	2			1237.224	2		
AA.2	1355.910	2			1355.835	2	-0.075	-0.010
AA.3/1	1362.700	2			1362.687	2	-0.013	
AA.3/22	1193.710	2			1193.771	2	+0.061	+0.008
AA.4	1235.728	2						
AA.4/16	1197.311	2						
AA.4/18	1195.004	2						
AA.5	1528.653	1	1528.656	2			+0.003	
AA.6	1593.557	1	1593.545	2	1593.512	2	-0.033	-0.007
AA.7	1468.150	1	1468.072	2	1467.893	2	-0.179	-0.036
AA.7/1					1465.278			
AA.7/2					1416.025			
AA.8	1364.007	2	1363.857	2	1363.501	2	-0.356	-0.071
AA.9	1166.159	2	1166.016	2	1165.737	2	-0.279	-0.056
AA.10	1444.893	3	1444.605	3	1444.168	2	-0.437	-0.084
AA.11	1264.572	3	1264.429	3	1264.181	2	-0.248	-0.047
AA.12	1396.179	3	1396.112	3			-0.067	-0.026
AA.13	1323.156	2	1322.552	2	1321.432	2	-1.120	-0.223
AA.14	1491.760	2	1491.556	2	1491.092	2	-0.464	-0.092
AA.15	1673.766	2	1673.603	2	1673.286	2	-0.316	-0.063
AA.16	1597.386	2	1597.238	2	1596.961	2	-0.277	-0.055
AA.17	1587.037	2			1586.648	2	+0.389	-0.051

Table 11 FIRST AND SECOND ORDER LEVELING RESULTS
1963/1964, 1966, 1971
from Pritchett (1978)

(continued)

Maraetai Datum

Origin A.93 = 1193.320

Bench Mark	1963-1964	Order of Leveling	1966	Order of Leveling	1971	Order of Leveling	Difference 1971 to 1966 or 1963,64	Annual Rate of Subisdence
AA.18	1655.762	2						
AA.19	1696.767	2						
AA.20	1804.528	2						
AA.21	1384.659	3	1384.291	3	1383.549	2	-0.742	-0.145
AA.22	1401.877	3	1401.670	2	1401.363	2	-0.307	-0.061
AA.23	1469.896	3	1469.657	2	1469.374	2	-0.283	-0.056
AA.25	1197.271	2						
AA.26	1193.751	2						
AA.53	1250.897	2	1250.392	2			-0.505	-0.195
AA.53/1					1246.777	2		
AA.69	1124.551	2	1124.560	2	1124.532	2	-0.028	-0.006
AA.70	1160.655	2	1160.622	2	1160.547	2	-0.075	-0.015
AA.71	1229.482	2	1229.057	2	1228.178	2	-0.879	-0.177
AA.72	1331.560	3	1331.489	3	1331.351	2	-0.138	-0.028
AA.73	1687.549	2	1687.403	2	1687.091	2	-0.312	-0.062
AA.74	1599.679	2	1599.484	2	1599.246	2	-0.238	-0.048
AA.75	1285.497	2	1285.228	2	1284.768	2	-0.460	-0.090
AA.76	1301.111	2	1300.688	3	1300.091	2	-0.597	-0.115
AA.77	1516.728	2	1516.494	3	1516.203	2	-0.291	-0.056
AA.78	1182.074	2	1181.941	2	1181.697	2	-0.244	-0.050
AA.79	1302.446	2	1302.286	2			-0.160	-0.062
AA.79/1					1300.945	2		
AA.80	1419.231	1	1419.066	1	1418.701	2	-0.365	-0.071
AA.81	1518.504	1	1518.478	1	1518.374	2	-0.104	-0.020
AA.82	1531.721	1	1531.826	1	1531.885	2	+0.059	+0.011
AA.83	1628.191	1	1628.228	1			+0.037	+0.014
AA.84	1715.098	1	1715.146	1			+0.048	+0.019
AA.85	1855.369	1	1855.443	1			+0.074	+0.029
AA.86	1803.767	1	1803.864	1			+0.097	+0.038
AA.87	2240.760	1						
AA.88	2245.002	1	2245.165	1			+0.163	+0.063

Table 11 FIRST AND SECOND ORDER LEVELING RESULTS
1963/1964, 1966, 1971
from Pritchett (1978)

Maraetai Datum (continued)

Origin A.93 = 1193.320

Bench Mark	1963-1964	Order of Leveling	1966	Order of Leveling	1971	Order of Leveling	Difference 1971 to 1966 or 1963,64	Annual Rate of Subisdence
AD.1	1395.465	1						
AD.2	1462.710	1						
AD.3	1582.082	1						
AD.4	1787.615	1						
AD.5	1843.958	1	1844.052	1			+0.094	+0.036
AD.6	1901.569	1	1901.686	1			+0.117	+0.045
AD.7	1947.372	1	1947.503	1			+0.131	+0.051
AD.8	1991.809	1	1991.947	1			+0.138	+0.053
AD.9	2082.228	1	2082.366	1			+0.138	+0.053
AD.10	2041.847	1	2041.991	1			+0.144	+0.056
AD.11	2254.442	1	2254.590	1			+0.148	+0.057
AD.12	2378.017	1	2378.172	1			+0.155	+0.060
AD.13	2408.085	1	2408.229	1			+0.144	+0.056
AD.14	2449.446	1	2449.590	1			+0.144	+0.056
AD.15	2446.110	1	2446.252	1			+0.142	+0.055
AD.16	2464.598	1	2464.742	1			+0.144	+0.056
AD.17								
AD.18	2518.569	1	2518.723	1			+0.154	+0.060
AD.18/1(H.148)	2459.680	1	2459.827	1			+0.147	+0.057
AD.18/2(H.147)	2329.634	1	2329.781	1			+0.147	+0.057
AD.18/3(H.146)	2274.974	1	2275.124	1			+0.150	+0.058
AD.18/4(H.145)	2265.389	1	2265.544	1			+0.155	+0.060
P.H.2			1158.398	2	1157.693	2	-0.705	-0.143
P.H.5	1144.170	2	1144.071	2	1143.915	2	-0.156	-0.032
B.M. L & S					1425.025	2		
TH7	1134.339	2			1133.968	2		

Table 12 WAIRAKEI STEAM MAIN CONTROL NETWORK
SUBSIDENCE RATE
GROUND SURVEY MARKS
from Pritchett et al (1978)

Station	Reduced Levels (ft.) 1977	1974	1968	1968 - 1977 Δ R.L. (ft.)	Annual Rate (ft./year)
GS 1	1267.34	1268.54	1271.00	-3.66	-.407
GS 2	1240.02	1240.26	1240.74	- .72	-.080
GS 3	1134.91	1134.91	1134.91	0.00	.000 *
GS 4	1228.59	1228.95	1229.96	-1.37	-.152
GS 5	1237.17	1237.60	1238.47	-1.30	-.144
GS 6	1245.49	1247.21	1250.87	-5.38	-.598
GS 7	1331.37	1333.53	1338.32	-6.95	-.772
GS 8	1247.45	1248.97	-	-1.52 **	-.507 **
GS 9	1229.04	1231.41	1236.93	-7.89	-.187
GS 10	1273.55	1274.25	1275.61	-2.06	-.229
GS 11	1276.12	1276.68	-	-0.56 **	-.187 **
GS 12	1491.81	1492.27	1494.29	-2.48	-.276
GS 13	1336.84	1336.90	1338.94	-2.10	-.233
RP 1	1566.40	1566.59	1567.01	-0.61	-.068
Wairakei	1624.88	1625.08	1625.66	-0.78	-.087

* Origin

** For 1974 - 1977 only

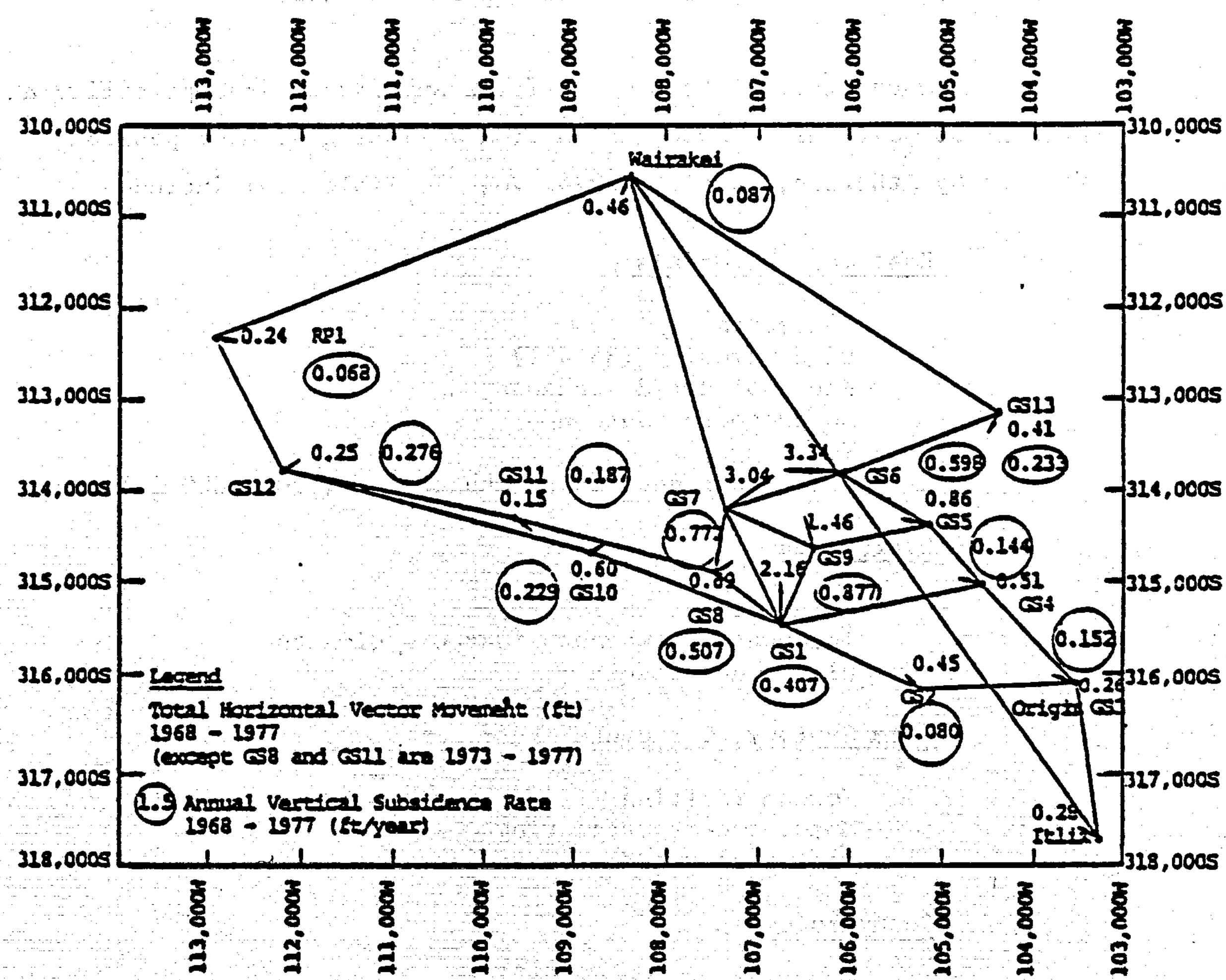


FIGURE 28 HORIZONTAL GROUND MOTION, 1968-1977 (from Pritchett et al, 1978)

4.5 CAUSES OF SUBSIDENCE

The most obvious cause of subsidence at Wairakei has been the large pore fluid pressure drop in the Waiora Formation reservoir caused by fluid withdrawal without reinjection. This has been greatly assisted by the apparently large decrease in the strength of the Waiora reservoir rock during production, as described in Section 4.2.4.

Many other factors which favor subsidence susceptibility are present at Wairakei. These, taken from a listing of many possible factors by Atherton, et al., (1976, Vol. 1, Table 5.5) include:

Reservoir Materials

- Sediments
- High porosity (35-42%)
- Unconsolidated, uncemented
- No preconsolidation
- Young age
- Large thickness in communication (1200-2600 ft)

Overburden

- Thin (less than 100 ft)
- Incompetent, unconsolidated sediments
- Highly deformable

Site Geology, Structure

- Normal faulting
- Much, recent fracturing
- Tensional regional stresses

Geohydrology

- Restricted recharge rates, particularly during early production

Maximum subsidence at Wairakei occurs away from the main production area, in the eastern part of the field. There are a number of possible explanations for this pheonomenon. Probably the most important explanation is the much greater thickness of the Waiora Formation reservoir under the eastern area (see Figure 8). In addition, the groundwater pressure gradient falls strongly from west to east in the Waiora aquifer, as reported in Sections 3.1.6 and 4.2.1. As a result, pressure drops due to production would tend to be greater in the east; this is suggested by Figure 22. Further explanations for this phenomonon, such as the possible spatial variation in reservoir material strength, have been pointed out, but are not sufficiently backed by the available data base.

5. REFERENCES (WAIRAKEI)

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THE GEYSERS

TABLE OF CONTENTS

1. INTRODUCTION

The Geysers is a predominately dry stream geothermal resource area in Central California. In many respects it is a unique geothermal resource, being the only U.S. geothermal site in geologic category VI (see Section III), and one of the few dry steam resources of the world. However, the Geysers reservoir is made up of predominately hard fractured rock, a characteristic of many of the U.S. geothermal sites, yet not a characteristic of the other three case study subsidence sites of this project. Thus, the project team considered it worthwhile to examine the behavior of the hard rock reservoir and overburden under the effect of geofluid withdrawal.

Commercial power production was commenced at the Geysers in 1960. Exploitation of the resource has increased since then, with the present production being about 80×10^5 lb/hr. Geodetic surveys since 1972 reveal that a maximum ground subsidence of about 13 centimeters has occured at the area of maximum fluid withdrawal. Horizontal ground movement as much as two centimeters per year has also been measured during this period.

2. NATURAL CONDITIONS

2.1 PHYSIOGRAPHY

The Geysers geothermal area is located in the northern Coast Ranges of California, about 75 miles north of San Francisco (Figure 1). The area of steam production lies predominantly in the northeastern corner of Sonoma County and extending partly into Lake County, in T11N and R8 and 9W. An area of hot water potential exists at the north and northeast, but since production has not begun in this area, it will be discussed in this report only insofar as it pertains to the regional setting. Access to the main Geysers area is by two narrow roads from either Healdsburg or Cloverdale on Highway 101.

The Mayacmas Mountains trend northwesterly across the area and are dissected by a series of northwest-flowing streams. Elevations range from about 1300 feet in the stream beds to 4722 feet at Cobb Mountain. The slopes are partly wooded or covered with chaparral and partly open grassland. The area is sparsely settled and largely undeveloped, except for the geothermal steam production and generating units. Natural hot springs and fumaroles are spread over an elongated area on the northeast side of Big Sulphur Creek.

2.2 GEOLOGY

The Geysers area is characterized by a complex series of generally northwest-trending fault blocks and thrust plates (Figure 2). This pattern is obscured to the northeast and southeast by later volcanic deposits. Most of the area is underlain by one of four major geologic units: the Franciscan assemblage, ophiolite, the Great Valley sequence, or the Clear Lake Volcanics. In some places, these rock units are

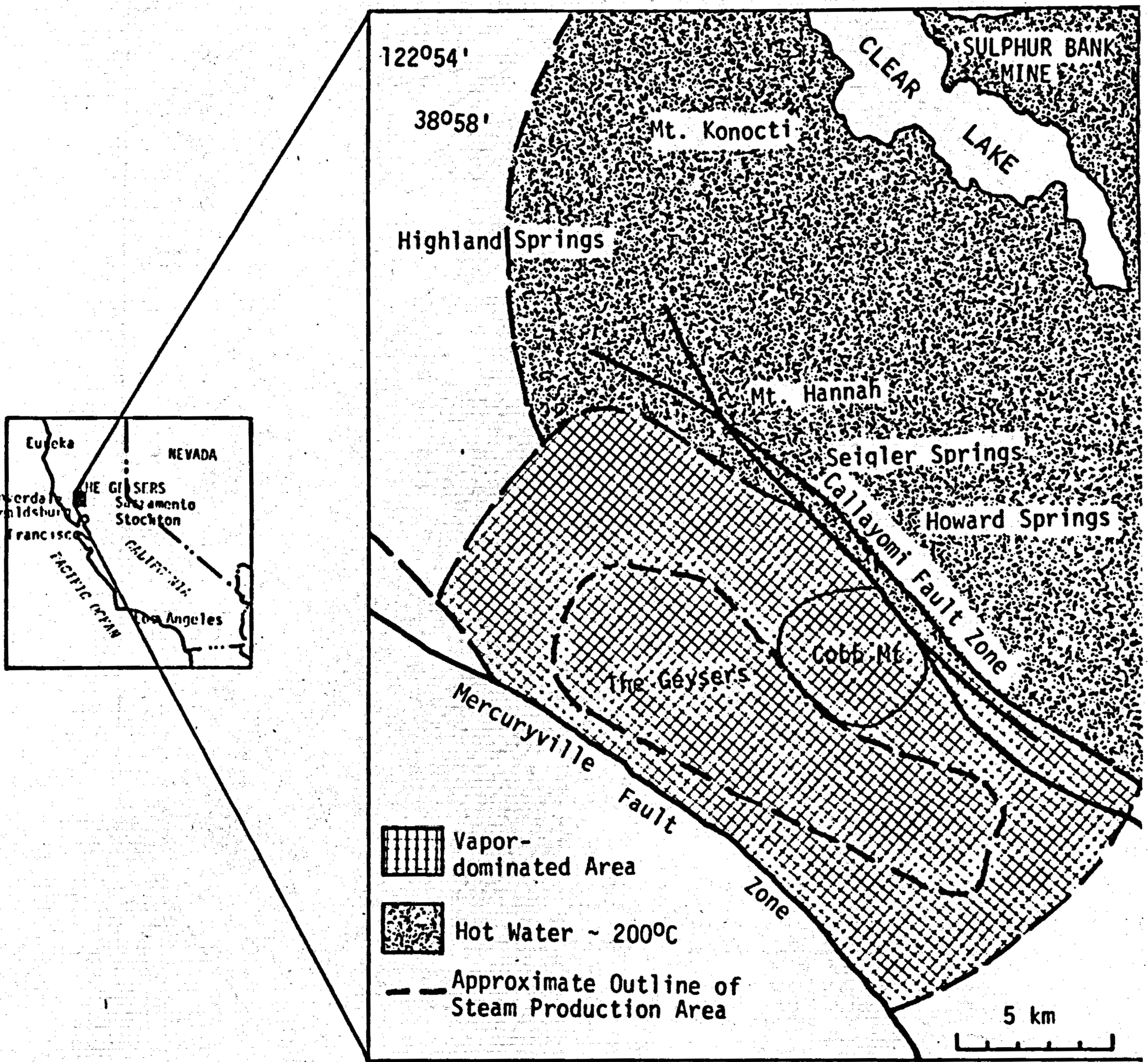


FIGURE 1 LOCATION MAP OF THE GEYSERS SHOWING APPROXIMATE LIMITS OF GEOTHERMAL RESOURCE. (from Goff and others, 1977)

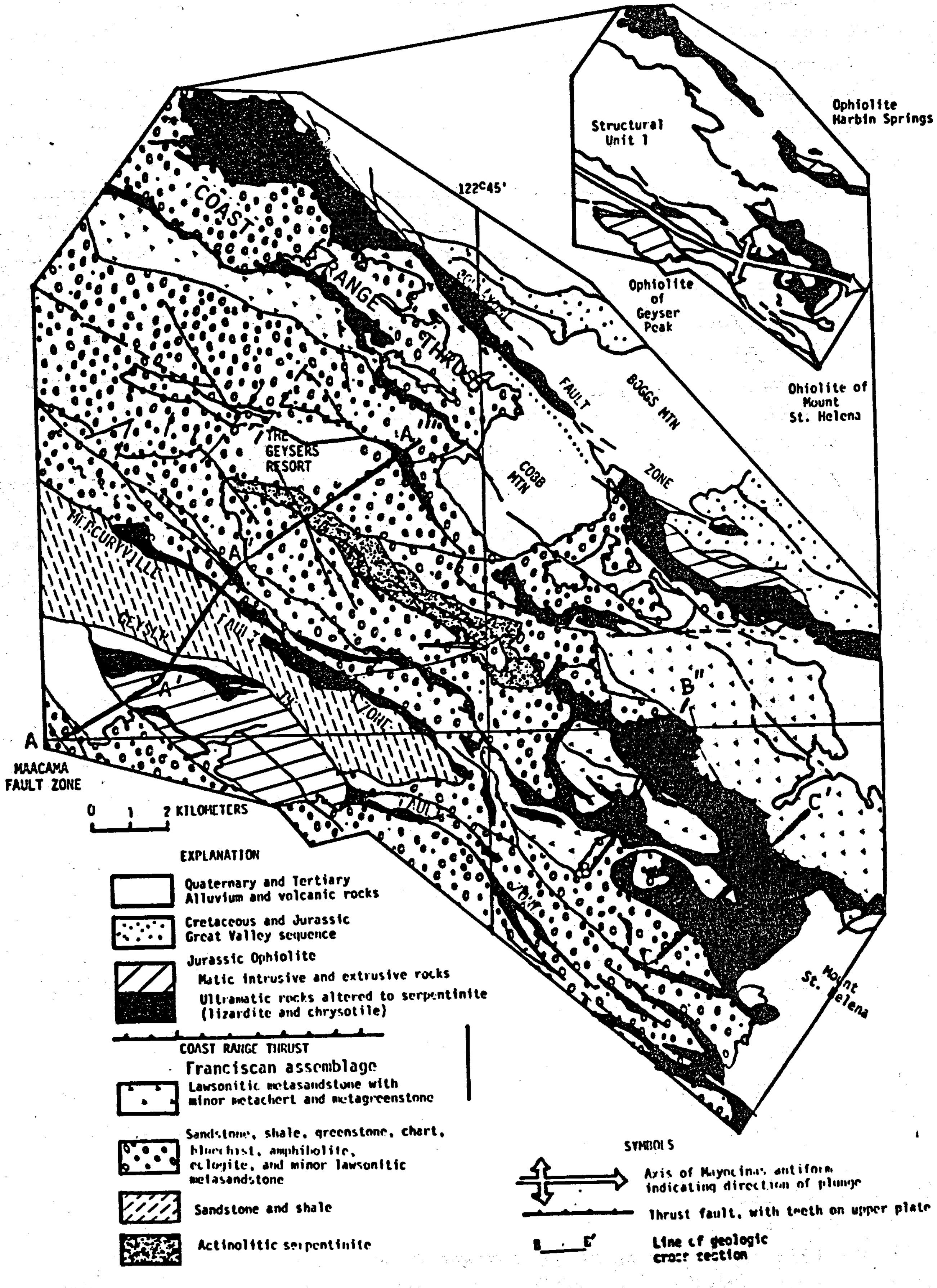


FIGURE 2 GENERALIZED GEOLOGIC MAP OF THE GEYSERS AREA. (from McLaughlin, 1977)

covered by geologically recent (Quaternary) sedimentary deposits including alluvium, colluvium, terrace deposits, and landslide debris. Most of the area is mantled by residual and/or slopewash soils to variable depths. Several cross-sections of the area are given in Figure 3.

2.2.1 Geologic Units

- Franciscan Assemblage. The Franciscan assemblage can be divided into three major structural units, based on 1) gross lithology, and 2) degree of shearing or metamorphism, that are separated by faulting into complex thrust plates. The first, structurally lowest, Franciscan unit is referred to here as the sheared shale and sandstone unit. This unit also contains masses of chert, "high grade" metamorphic rocks, greenstone, and serpentinite. The second, or middle, structural unit is here called the metagraywacke unit. This unit also contains minor metagreenstone and metachert. The third, or upper, structural unit is here designated as the graywacke sandstone and shale unit. Minor amounts of greenstone, conglomerate, chert, and limestone also occur within this unit. Due to its widespread exposure within the area and its lithologic and structural complexity, the sheared shale and sandstone unit is described in more detail than the other Franciscan units.

The sheared shale and sandstone unit contains resistant masses of hard rocks of several lithologic types, and is exposed over major parts of the area, particularly in the vicinity of The Geysers geothermal development. This unit corresponds to the lower Jurassic-Cretaceous unit of McNitt (1968), and to McLaughlin's (1974) upper Franciscan structural units. Most of the sheared rock in the Franciscan assemblage, together with masses of shattered sandstone, is assigned to this unit. The sheared rock in this unit is characterized by high clay content, low permeability, and an abundance of landslides. The term "melange" has

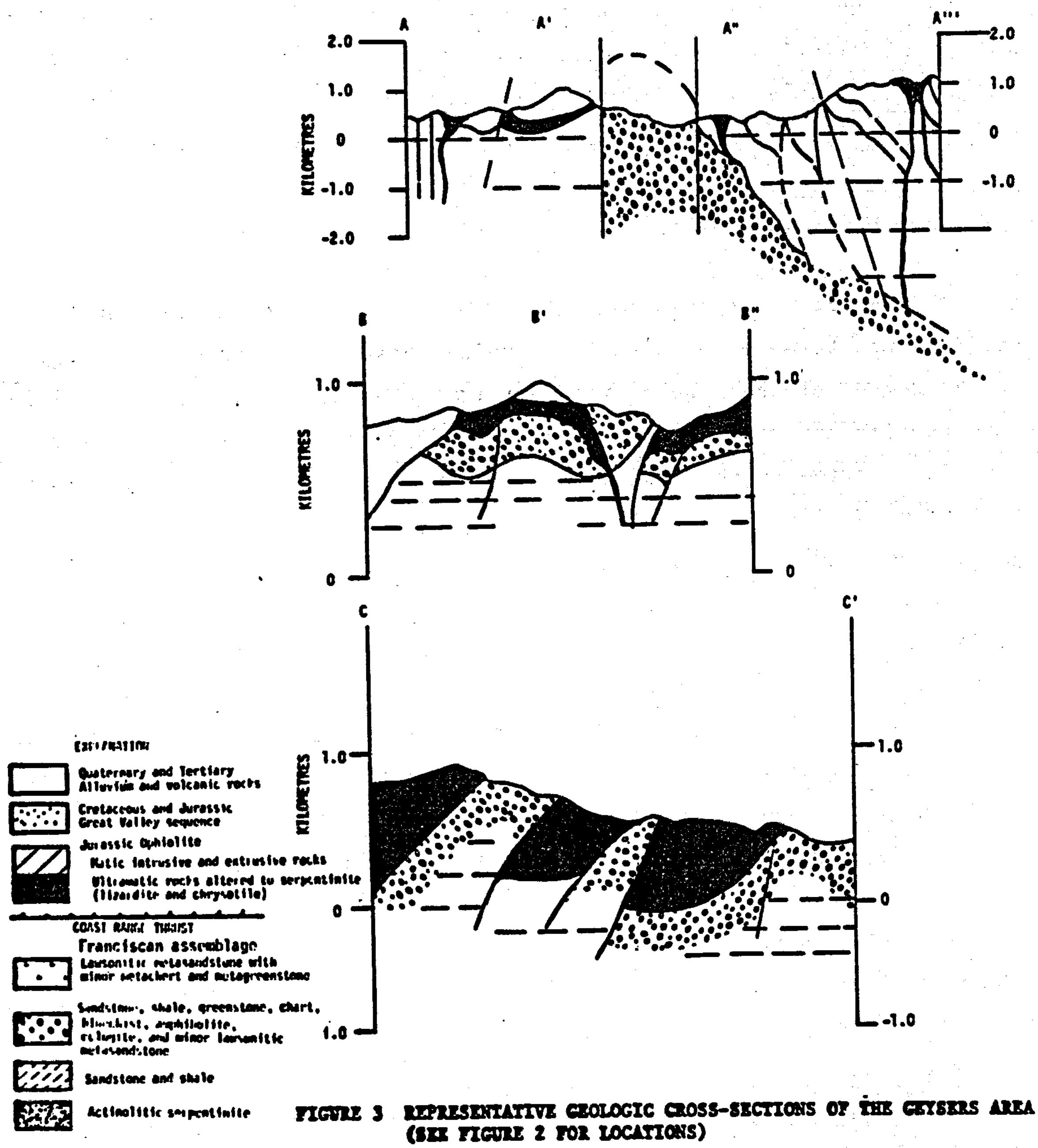


FIGURE 3 REPRESENTATIVE GEOLOGIC CROSS-SECTIONS OF THE GEYSERS AREA (SEE FIGURE 2 FOR LOCATIONS)

been applied to Franciscan rocks of similar characteristics by Hsu (1969). The melange generally consists of a highly sheared, lustrous gray to black shale matrix containing abundant, hard, resistant blocks of metagraywacke type sandstone, chert, greenstone, serpentinite, silica carbonate rock and metamorphic rock (including glaucophane schist, eclogite, and amphilbolite). Sheared conglomerate or sedimentary breccia (McLaughlin, 1974) also occurs locally within melange units. Most of the metamorphic rock types mentioned above occur as hard, resistant blocks ranging from less than 1 foot up to about 100 feet long. However, greenstone, serpentinite, and silica carbonate rocks may occur in blocks up to 5 miles long.

Greenstones are altered mafic submarine volcanic rocks that include gray to greenish gray spilitic basalts in the form of pillow lavas, massive flow rock, tuffs, and breccias. In many parts of the area, they occur as discrete masses no more than a few hundred feet thick, but McNitt (1968 has estimated a thickness of 7000 feet for the massive pile that trends northwestward for several miles from the vicinity of The Geysers Resort. In some places, these rocks contain minor amounts of fossiliferous limestone; in others, the greenstone contains incipient blueschist minerals or is reconstituted to blueschist. Greenstone units are slightly to extensively sheared and are commonly fractured at spacings from inches to a few feet.

Serpentinite, including relatively fresh ultramafic masses, "intrudes" into the lower or melange unit of the Franciscan assemblage and occurs as sheets, lenses, and irregularly shaped masses, both within and along the boundaries of the unit. Serpentinite varies from a hard, strong rock to a soft, moderately plastic clay-like material, depending on the degree of internal shearing.

Silica-carbonate rock, a product of the hydrothermal alteration of serpentinite, can be a relatively hard and strong rock and often crops out as a cliff-forming unit. It occurs most often in blocks and masses of highly variable size associated with serpentinite.

The second unit of the Franciscan assemblage corresponds to the metagraywacke unit of Blake and others (1971) and consists of principally of metagraywacke sandstone with lesser amounts of other metamorphic constituents including metagreenstone and metachert. This unit is characterized by blueschist metamorphic-grade minerals such as glaucophane, lawsonite, and jadeitic pyroxene.

The third, upper, Franciscan unit corresponds to McNitt's (1968) upper Jurassic-Cretaceous unit, and has widespread outcrops in the area, particularly west and north of The Geysers geothermal development. It consists predominantly of graywacke-type sandstone and shale with minor greenstone, limestone, and chert, and some lenses of conglomerate. The sandstone ranges from massive to thin bedded, but the rock is frequently shattered and commonly veined with laumontite.

- Ophiolite. Igneous rocks, including basaltic pillow lavas and breccias, quartz diabase, diorite gabbro and diabase, and ultramafic rocks, largely pyroxenite and serpentinite, are in fault contact with underlying Franciscan rocks and form the base of the Great Valley sequence. These rocks represent oceanic crust on which the Great Valley sequence and Franciscan assemblage were deposited.

- Great Valley Sequence. The Jurassic and Cretaceous Great Valley sequence consists mainly of well bedded sandstone and shale, and siltstone or mudstone with minor sandstone, and conglomerate lenses and beds. Carbonate rocks occur locally as thin lenticular beds and concretionary masses but aggregate to only a very small percentage of the total volume of Great Valley sequence rocks in the area. Swe and Dickinson (1970), in their studies of a nearby area, have described 35,000 feet of clastic sedimentary strata, ranging in age from Late Jurassic to Late Cretaceous, as belonging to the Great Valley sequence. They have divided the entire sequence into four main stratigraphic units, three of which, although relationships are complicated by faulting, are apparently conformable successions of strata. The fourth consists of several segments of similar age, each bounded entirely by faults.

• <u>Clear Lake Volcanics</u>. The Clear Lake Volcanics cover much of the area northwest of The Geysers development. Volcanism apparently began about 2.5 million years ago in the early Pleistocene epoch (Hearn and others, 1975). The volcanic activity continued into the Holocene epoch, as evidenced in part by geothermal activity and the presence of mafic ash beds as young as about 10,000 years old in cores of sediments beneath Clear Lake (Sims and Rymer, 1975).

In addition, a regional gravity low (Chapman, 1966, 1975) and a regional resistivity low (Stanley and others, 1973) may be interpreted as indicating a large body of magma at fairly shallow depths - 10 km or less (Chapman, 1975).

Flows and beds, associated with the Clear Lake Volcanics, having a maximum collective thickness of 7500 feet, have been described by Brice (1953). Most of these rocks were deposited upon a surface of considerable topographic relief. Cobb Mountain and Boggs Mountain were formed by local extrusion of lavas and thus represent vents (Goff and McLaughlin, 1976).

Many of the volcanic rocks are hard, strong, and thus cliff-forming. The fresh unweathered appearance of outcrops of the flows and domes is a further indication of their young age and physical strength. Previous workers (Brice, 1953) delineated two massive landslides, one involving andesitic and other rhyolitic rocks, on the southeast flanks of Boggs and Cobb Mountains, respectively. However, Goff and McLaughlin (1976) present convincing evidence that the Ford Flat area southeast of Cobb Mountain is not a landslide complex but that a series of northeast-trending normal faults accounts for the topographic and lithologic relationships in the area. They do, however, indicate that numerous smaller, shallower landslides occur in the area. On the other hand, work by Hearn and others (1975) supports the presence of massive landslides on the south-southeast flanks of Boggs Mountain.

- Alluvium. A few mappable alluviated areas occur in the Mayacmas Mountains and represent an older drainage system disrupted by block faulting and tilting (McNitt, 1968). Sizable deposits of alluvium are also found along most of the larger streams in the area even though major parts of the stream courses are narrow and lie along steep walled canyons and valleys.

The alluvial deposits consist of locally variable proportions of generally unconsolidated clay, silt, and gravel deposited as flood plain, alluvial fan, channel, or lake deposits. Thicknesses of alluvial deposits are also highly variable.

- Landslide Deposits. Landsliding is common in much of The Geyser area. According to Bacon and others (1976), about 50 percent of the wells and two power plants (Units 1 and 2 and Units 3 and 4) at The Geysers steam field are sited on mapped landslide deposits.

Types of landslides range from rockfalls to mudflows and include earthflows, block glides, and rotational slumps. Individual landslides vary in area from a few tens of square feet to several hundred acres and in depth from less than 5 feet to more than 100 feet. The factors influencing slope stability in the area include slope steepness, nature of the bedrock and overlying surficial deposits, high seasonal precipitation, man's disturbance, and seismic shaking.

In general, the Franciscan assemblage is unstable under natural conditions because of chemical alteration and abundant faults and shear zones. Most of the natural landslides that occur in the Franciscan assemblage are caused either directly or indirectly by the poor slope-stability characterictics inherent to the melange unit.

According to Frizzell (1974), about 48 percent of the area underlain by melange, the middle Franciscan unit, metagraywacke, is the most stable unit in the assemblage. However, landslides do occur in this unit, especially where stability conditions are altered by man's activity. The shattered graywacke and shale unit is intermediate in landslide susceptibility between the other two Franciscan units with about 30 percent of the unit being landslide terrain. About 45 percent of the greenstone outcrop area is involved in landsliding. Areas underlain by serpentinite range from stable to extremely unstable, depending on the degree of alteration and shearing of the rock. In addition to landsliding, some of the highly sheared and altered serpentinites are subject to settlement under foundation loading. Generally, silica carbonate rock is quite stable, with landslides frequently occurring within serpentine or other susceptible rocks adjacent to the silica carbonate.

Great Valley sequence rocks have relatively good slope stability. However, the shaley units may have poor slope stability, especially where they abut steep outcrops of another rock type or where soil has been removed or slopes have been undercut by natural or human processes.

The ophiolite rocks at the base of the Great Valley sequence are not generally unstable themselves, but they may promote instability in shales where the shale slopes are steepened abutting the more resistant ultramafics.

Landsliding in the Clear Lake Volcanics seems to be relatively uncommon, judging by recent detailed geologic mapping by Hearn et al. (1975). However, a large, complex slide mass exists on the southeast slopes of Boggs Mountain in andesitic bedrock.

- Soils. Because there is such a variety of rock types and topography in the area, the soils that have developed range widely in slope, surface texture, and horizon development. In general, the soils are easily eroded, especially if natural vegetative cover is removed or disturbed. They occur on slopes ranging from 15 to 75 percent, have loamy textures with moderately good to somewhat excessive natural drainage, and subsoil permeability ranging from very slow to rapid (Miller, 1972).

Highly expansive soils are present in the Big Sulphur Creek valley downstream from The Geysers Resort and scattered elsewhere in the area. Soils near large serpentine bodies are plastic when wet, and dry with much shrinkage (Bacon and others, 1976). These soils can present engineering problems for structures which are very sensitive to differential vertical movement.

2.2.2 Structure

The geologic structure of The Geysers area is dominated by generally northwest-trending faults and folds with the faults exhibiting normal, reverse, thrust, or strike-slip displacement. Figure 4 is a schematic cross section trending northeast through The Geysers showing

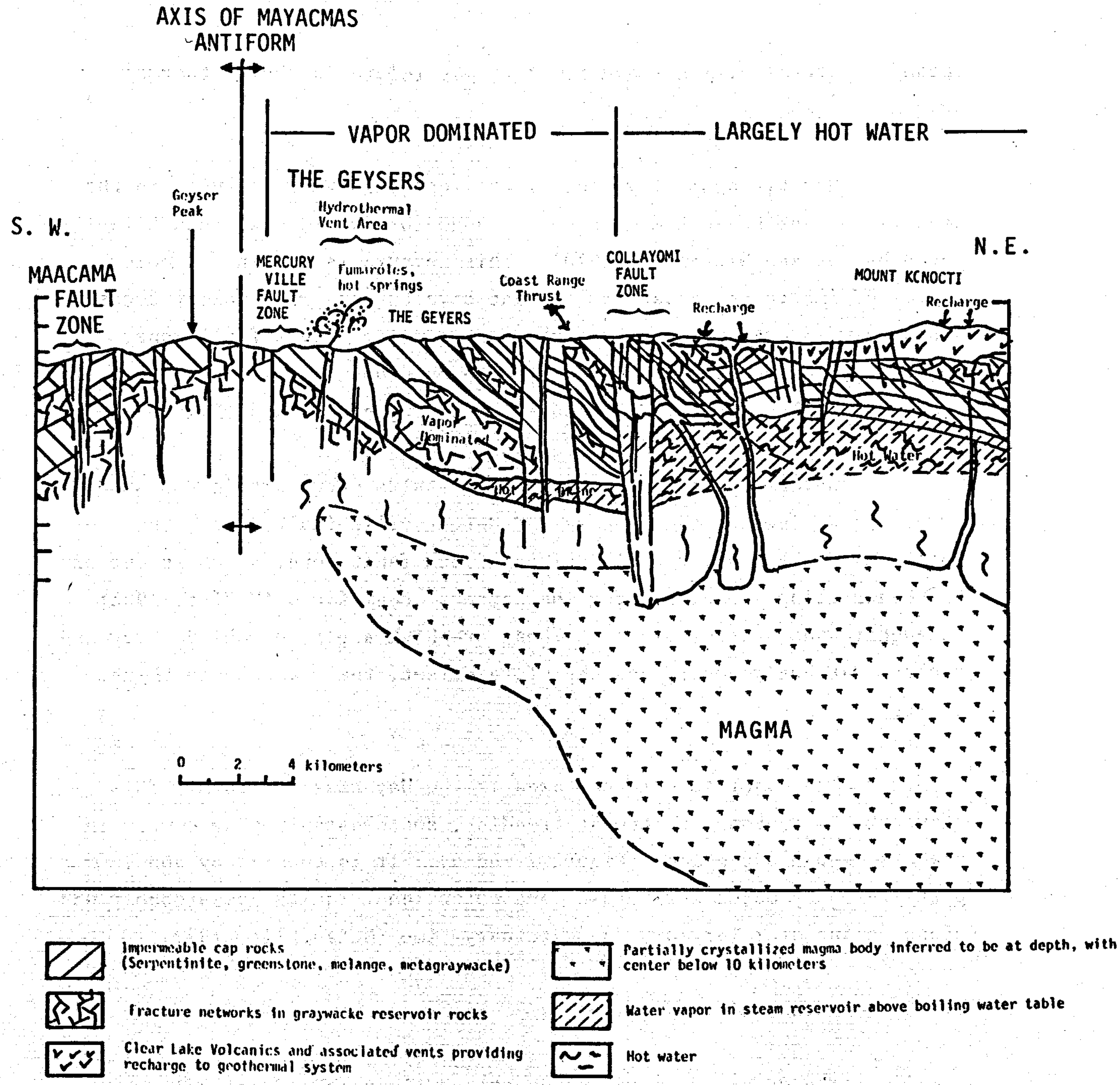


FIGURE 4 SCHEMATIC CROSS-SECTION OF THE GEYSERS GEOTHERMAL SYSTEM. CROSS-SECTION THROUGH THE GEYSERS-CLEAR LAKE REGION, FROM THE MAACAMA FAULT ZONE ON THE SOUTHWEST, TO MOUNT KONOCTI ON THE NORTHEAST, DEPICTING STRUCTURAL ELEMENTS OF THE GEYSERS-CLEAR LAKE GEOTHERMAL SYSTEM. (from McLaughlin, 1977)

these structural elements and how they may relate to the geothermal system.

Stratigraphically, one of the most significant faults in the area is the northwest-trending Coast Range (or Soda Creek) thrust fault noted by Swe and Dickenson (1970). This feature is one in a complex series of imbricate thrust faults that have thrust Great Valley rocks southwestward over Franciscan rocks. This major thrust fault zone apparently follows the line of ophiolite outcrops trending northwestward from Long Valley between Cobb Mountain and Boggs Mountain (Figure 2).

Several additional significant faults occur within the study area. These include the Maacama and Mercuryville fault zones, the Collayomi fault zone, and Big Sulphur Creek fault zone, which is one of the controlling structures for The Geysers steam field (McNitt, 1968; McLaughlin and Stanley (1975). These are high angle, normal and reverse faults that are younger, and therefore offset, the Coast Range thrust faults.

The major fold in the area is the Mayacmas antiform. This structure is a broad, northwest-trending, southeast-plunging upwarp in the Franciscan assemblage (Figure 2 and 4). It is bounded by and in part broken by major strike-slip and extensional faults and probably was produced in later Tertiary to Quaternary time (McLaughlin, 1977).

2.2.3 Stress History

The deformed ophiolite sheet underlying the Great Valley sequence between Cobb and Boggs Mountains represents the upper plate of the Coast Range Thrust. This feature is the remnant of an eastward-dipping subduction zone of Jurassic and Cretaceous ages. During this period, a spreading oceanic ridge lay to the west of the subduction zone. Volcanic activity along this ridge spewed forth new oceanic crustal rocks which, combined with the overlying Franciscan sediments, moved eastward toward the subduction zone. Upon reaching the subduction zone, these rocks were dragged downward beneath the Great Valley sequence that was accummulating along the continental margin east of the subduction zone. As seafloor spreading progressed, the Franciscan sediments were thrust-faulted to form a series of imbricate wedges in the subduction zone. These units locally accreted with the overlying rocks. The subduction zone shifted westward between later Jurassic and early Tertiary time. Following this event, the Franciscan wedges were further compressed beneath the over-riding Great Valley rocks and were faulted upward, and in some places, through the ophiolite sheet.

During the past three to six million years, the prevailing compressive stress orientation changed from east-west to a north-south orientation. Subduction thrusting terminated and strike-slip motion was initiated. During this period, some of the older thrust faults were reactivated as strike-slip features.

The geologically current principal stress orientation is northeast-southwest. This has produced both vertical and right-lateral offsets on both the Maacama and Collayomi fault zones. With maximum stress (compression) trending northeast, minimum stress (tension) is oriented northwest, a relationship resulting in northeast-trending pull-apart type faults. These latter faults commonly are characterized by zones of fractured rock along which the geothermal fluids can migrate upward. This is the reason geothermal developers are particularly interested in northeast-trending faults (McLaughlin, personal communication, 1978).

2.2.4 Holocene Tectonism

The Geysers is in an area of moderately high seismicity, with several major active fault systems to the south, east and west, and several major potentially active faults are present within and near the area, such as the Healdsburg - Rogers Creek, the Maacama, the Collayomi, and the Big Sulphur Creek. These faults all trend northwesterly and exhibit predominantly right-lateral strike-slip offset. This fits well with the regional tectonic pattern of the San Andreas system, suggesting that continued movement along one or more of these faults is likely. Table 1 outlines earthquake parameters for the major faults affecting The Geysers area.

No major earthquakes have originated within The Geysers area, but many events of Richter Magnitude less than 4.6 have occurred. The greatest concentration of these small earthquakes are in the area of geothermal steam production (Marks and Bufe, 1978).

A microearthquake study in the area by Hamilton and Muffler (1972) indicated that most epicenters lie in a zone about 2-1/2 miles long and 2/3 miles wide centered on the producing geothermal field and extending a short distance east and northwest. Associated focal depths ranged from near surface to about 4 km (Figure 5).

Bufe and Lester (1975) conducted another microearthquake survey at The Geysers field and found a diffuse pattern of faulting at depth in the reservoir. They found both normal and right-lateral strike-slip faulting on a north-northwest-trending plane dipping steeply southwest.

Because microseismic baseline studies were not conducted prior to geothermal development, the effect of steam production or reinjection on the current seismic pattern is not known.

Table 1 EARTHQUAKE PARAMETERS FOR FAULTS AFFECTING THE GEYSERS AREA

Fault	Distance From Geysers Area Miles	Max. Probable Earthquake Magnitude	Max. Credible Earthquake Magnitude
Healdsburg	12	5 3/4±	6 3/4±
San Andreas	28	8 1/4±	8 1/2±
Hayward	46	7±	7 1/2±
Concord	47	6±	7±
Cleveland Hill	57	6±	7±

from: Slosson and Associates, 1976.

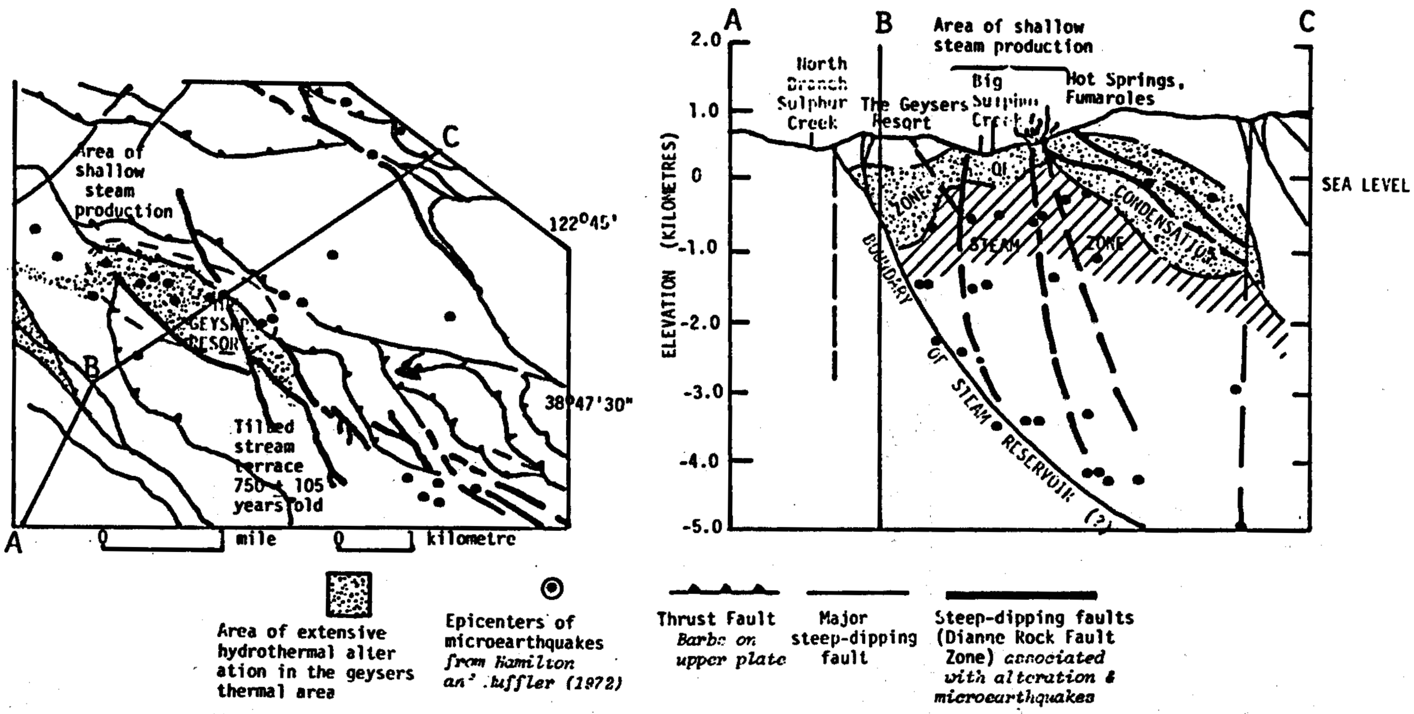


FIGURE 5 DIAGRAMS SHOWING LOCATION OF MICROEARTHQUAKES NEAR THE GEYSERS. LEFT: MAP VIEW. RIGHT: VERTICAL CROSS SECTION SHOWING DISTRIBUTION OF MICROEARTHQUAKE HYPOCENTERS AND INFERRED RELATION TO STEAM RESERVOIR. (from McLaughlin & Stanley, 1975)

2.3 RESERVOIR CHARACTERISTICS

2.3.1 Regional Geohydrology

The Mayacmas Mountains are the major drainage divide in the region. Precipitation falling on the southwest side of the mountains flows generally west to the Russian River Basin, while that falling on the northeast side flows generally east into the Sacramento River Basin.

Streamflow varies directly with amounts of precipitation; high streamflow periods follow periods of high rainfall. Approximately 88 percent of the annual precipitation is received from November through April, which is also the time of the greatest peak flows. Flows are lowest from July through September, when there is little or no rainfall. Most streams within the region are intermittent, indicating their flow is from runoff, with little contributing ground water base flow.

The geologic formations of The Geysers area characteristically have low porosity and permeability. The average Franciscan graywacke, for example, is 5 percent water by volume (Bailey and others, 1964). Ground water is generally confined to those zones where tectonic forces have fractured or faulted the rock.

Big Sulphur Creek follows one of these major fracture systems. This system also acts as a conduit for thermal fluids to reach the surface where they appear as springs and fumaroles (Lipman and others, 1977). About thirty thermal springs exist in The Geysers Resort area; about two-thirds of these reach 80°C and about one-half are 90°C (Allen and Day, 1972). Total discharge of these springs is about 3000 gallons per hour in the winter and spring and about 2000 gallons per hour during the dry season. This variation in discharge indicates that seasonal mixing of thermal water with near surface water occurs.

Goff and others (1977) have described the thermal spring water as being composed of steam condensate, mixed in some cases with cold surface water, and in some cases with oxidized H_2S gas. The thermal waters are acidic, with pH values as low as 1.8. They are undersaturated relative to amorphous silica in the temperature range of the spring, and most contain appreciable sulfate. These waters have reacted primarily with near surface rocks at temperatures less than 100°C.

The reservoir fluid-flow system currently envisioned for The Geysers is illustrated in Figure 4. Recharge of the hot water reservoir takes place through volcanic vents consisting of fractured lava or breccia zones. Two of these vents are located in the area of The Geysers (Cobb Mountain and Boggs Mountain), and another eighty are located to the northeast (Goff and others, 1977). The hot water reservoir northeast of The Geysers is probably separated from the predominantly steam reservoir by a ground water barrier formed by the Collayomi fault zone. Recharge of the hot water reservoir is sufficient to keep it supplied with water.

In the steam field, natural recharge is not sufficient to keep up with discharge, and the hot water level has dropped enough to allow a vapor-dominated phase to develop above the hot water or brine. Steam flows along fractured zones in the reservoir rock to areas of lower pressure and eventually surfaces as fumaroles or through wells that intersect these fractured zones. Warm springs in the area form by near surface condensation of steam in the vapor-dominated reservoir or by direct flow to the surface of liquid from the hot water reservoir.

2.3.2 Reservoir Geometry

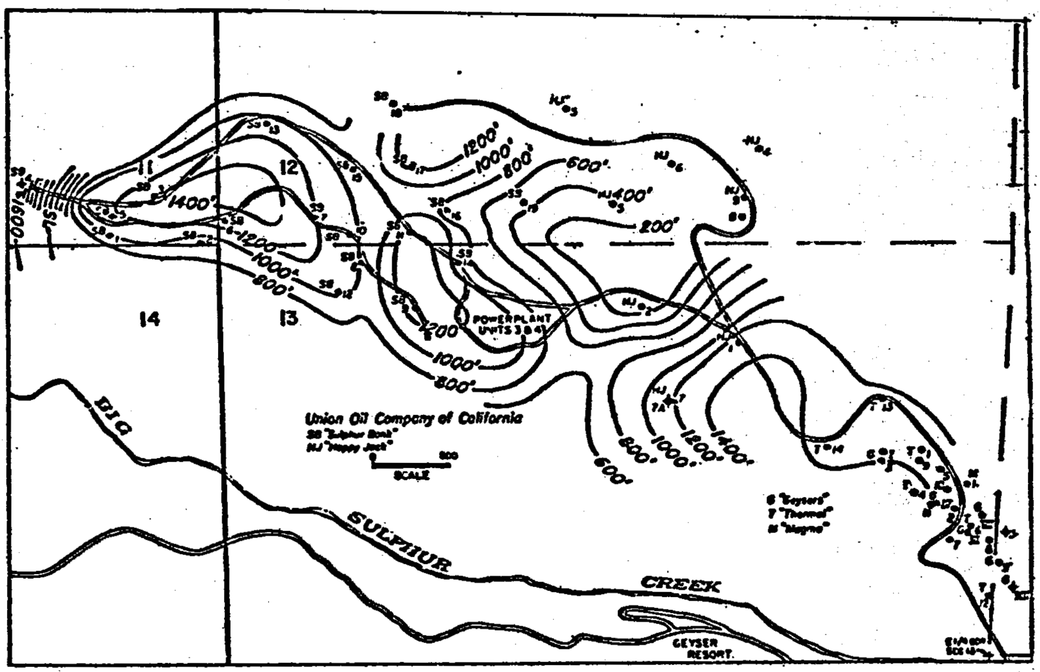
The inferred outline of the vapor-dominated reservoir and the area of present steam production at The Geysers is indicated on Figure 1.

A generalized cross section through the area is shown on Figure 4. The vapor-dominated reservoir is bounded by the Collayomi fault zone on the northeast and the Mercuryville fault zone on the southeast. The northwestern boundary is drawn midway between The Geyser and Highland Springs where the water is chemically different from that found in The Geysers area (Goff and others, 1977). The southeastern limit is uncertain at this time due to a lack of data. Estimates of the vertical extent of the vapor-dominated reservoir range from abount 10,040 feet beneath the surface (Lipman and others, 1977) to on the order of 15,000 feet beneath the surface, based on geophysical studies (Stanley and others, 1973). Beneath the vapor-dominated reservoir lies a hot water (or brine) reservoir that has not yet been tapped. Depth to the underlying magma chamber is estimated to be about 30,000 feet (Goff and others, 1977).

Drilling at The Geysers has revealed a two part, vapor-dominated reservoir: 1) a small, shallow reservoir, and 2) a much more extensive deep reservoir. Early steam wells drilled to depths less than 2100 feet produced from the shallow reservoir. Figure 6 shows contours on the top of this reservoir. Pressures encountered in the shallow reservoir increased toward the center of the field, indicating the area of the steam source. Reservoir studies predict an ultimate recovery of 110 billion pounds of steam from this reservoir (Garrison, 1972). As deeper drilling proceeded, the main, deep reservoir was eventually penetrated at depths ranging from 2500 to 5000 feet. A cross section showing the inferred relationship between the two reservoirs is presented on Figure 7. The significant pressure differentials between the shallow and deep reservoir indicate that an interval with no significant vertical permeability separates the two reservoirs.

2.3.3 Overburden Properties

Geologic units above the steam reservoir generally include soils, landslides, and Franciscan units but locally include alluvium,



(elevations relative to sea level)

FIGURE 6 CONTOURS ON FIRST STEAM AS ENCOUNTERED IN WELLS AT THE GEYSERS (from Garrison, 1972)

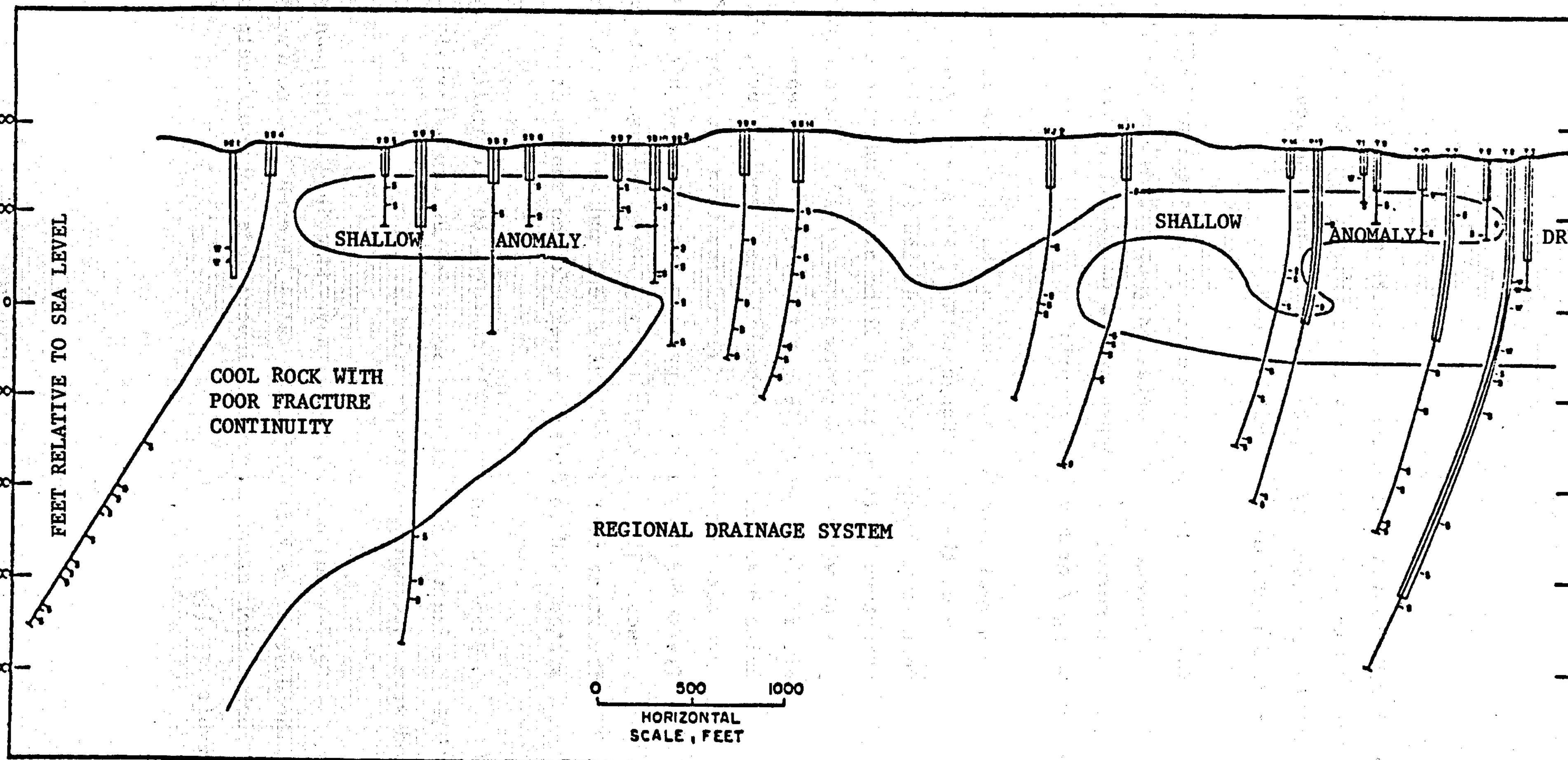


FIGURE 7 CROSS SECTION THROUGH THE GEYSERS STEAM RESERVOIR (from Lipman & others, 1977)

Clear Lake Volcanics, ophiolite, and rocks of the Great Valley sequence. The barrier that caps the reservoir is theorized as being either 1) impermeable Franciscan rocks, 2) permeable, but chemically sealed Franciscan, or 3) a high, meteroic water table.

The first theory is supported by McLaughlin (1977) who has done the most recent and most detailed geologic mapping in the area. He contends the reservoir is capped by low permeability rocks (see Figure 4). He writes on p. 7 of his 1977 report:

> "Ultramafic rocks belonging to the ophiolite in the upper plate of the Coast Range thrust, structurally overlie Franciscan rocks over much of this region; and in addition, another structurally lower thrust slice of actinolitic serpentinite is present within The Geysers steam field. These thick sheared ultramafic sheets, along with sheet-like, sheared shaly melange units have very low permeabilities, and as such, they also have poorer thermal conductivities than interlayered slabs of fractured graywacke carrying water in the liquid and vapor phases. The serpentinites and shaly melange units are thus important both in retaining heat and water in the geothermal system, and in directing heat to the southwest."

Lipman and others (1977) concur with McLaughlin's opinion, but add that the fracturing that does occur in the cap material is normally sealed with secondary quartz or calcite.

Bailey and others (1964) have described Franciscan graywacke near The Geysers as being hydrothermally altered to a montmorillonite-rich rock. Such clays tend to be impermeable and could help seal the reservoir locally.

Core samples taken near the surface of the production area were described by Ramey (1970) as being effectively sealed by crystalline deposits which he contends serve as the cap rock. Silica may be deposited by hot water flowing into cooler regions or calcium may be deposited by cool water flowing into heated regions (Garrison, 1972). Grindley and Browne (1976) also describe a 900 feet thick cap sealed with hydrothermal minerals.

The third type of reservoir cap involves a near surface ground water body in hydrostatic equilibrium with the steam reservoir. This type of cap has been described by McNitt (1963), whose calculations support the validity of the theory.

2.3.4 Reservoir Material Properties

The reservoir rock is entirely Franciscan graywacke that has undergone slight to moderate metamorphism. Not much data exist concerning the physical properties of these rocks because of the hesitancy of companies involved in energy exploration to divulge information and the difficulty in obtaining samples and readings in a high temperature environment. In general, Franciscan "sandstones" are very dense and have permeabilities less than 1 millidarcy and porosities less than 10 percent (Decius, 1961). These figures are probably high, except for shear zones and other localized fractured areas (Garrison, 1972). Lipman and others (1977) have tested cores from exploration wells and found interstitial porosities of 3 to 7 percent and permeabilities to helium and air of less than 1 millidarcy.

Since the rock itself is nearly impereable, steam must be confined to open fractures and fault zones. Near vertical fractures are present in most of the cores tested, although some have been filled with secondary quartz and calcite (Lipman and others, 1977). The fissures reported are generally less than 6 inches wide (Ramey, 1970). Drillers' logs report thick sections of "soft formations" where caving or sloughing is common and where circulation is often lost when drilling with mud. In some instances, a 10 foot drop of the drill bit has been reported (Ramey, 1970). Another indication of the degree of fracturing in some zones is the high fluid reinjection rates of about 1200 gallons per minute with no back-pressure. The permeability-thickness products with respect to water is from 20,000 to 150,000 millidarcy feet (Chasteen, 1976).

The extent of the fracture network is unknown, but it may connect at depth to the hot water reservoir (McLaughlin, 1977). Since 90 percent of the development wells in The Geysers are successful (Reed and Campbell, 1976), the fracture network must be quite pervasive.

2.3.5 Fluid Characteristics

Water vapor is not the only gas present in The Geysers steam field. Of the emitted vapor in new wells, up to 2 percent by weight is noncondensable gases. This amount tends to decrease as the wells are produced and eventually stabilizes at about 0.4 to 0.5 percent (Anderson and Axtell, 1972). CO_2 is the most abundant noncondensable gas, amounting to about four times the total of all other noncondensable constituents (see Table 2). Rock dust and radon also come to the surface with the water vapor. The maximum amount of radon reported in the vapor is 8.3 pico curies per liter (Reed and Campbell, 1976).

The temperature of the reservoir increases with depth. The normal geothermal gradient in California is about 0.015 to 0.030°F per foot. By comparison, Ramey (1970) found the near surface gradient to be

Table 2 CONSTITUENTS CARRIED IN THE STEAM FROM WELLS AT THE GEYSERS FIELD*

Constituent		Concentration (mg/kg) Low	Average	High	Average† flow into 110 MW unit (kg/hr)
Carbon dioxide	(CO_2)	290	3260	30 600	2700
Hydrogen sulfide	(H_2S)	5	222	1 600	180
Methane	(CH_4)	13	194	1 447	160
Ammonia	(NH_3)	9.4	194	1 060	160
Boric acid	(H_3BO_3)	12	91	223	75
Nitrogen	(N_2)	6	52	638	43
Hydrogen	(H_2)	11	56	218	46
Ethane	(C_2H_6)	3	8	19	6.6
Arsenic	(As)	0.002	0.019	0.05	0.016
Mercury	(Hg)	0.00031	0.005	0.018	0.004

*From measurements of 61 steam wells from 1972 through 1974, Pacific Gas and and Electric Company.

†Based on steam input of 821 000 kg/hr.

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from: Reed and Campbell, 1976.

about 0.5°F per foot down to 350 feet. Below 300 feet, the gradient decreased downward to the limit of his data at 5000 feet. Figure 8 presents subsurface temperature data for both the Big Geysers area and the Sulphur Bank - Happy Jack area. There is no significant difference in the temperature gradients between these two producing areas.

The pressure gradients in individual wells in the area follow that of saturated steam (Lipman and others, 1977). The initial pressure at sea level is 514 psia (35 atm), but this changes with production, as discussed in Section 3. Figure 9 indicates pressure at sea level for the production area in 1977.

Temperature and pressure in the reservoir are directly related. The change in both of these quantities with depth is shown on Figure 10.

Chemical analyses and other pertinent data for thermal springs in the vapor-dominated area are indicated on Table 3. These waters cannot be used to estimated subsurface temperature because they are steam condensates and do not reflect equilibrium at depth (Goff and others, 1977).

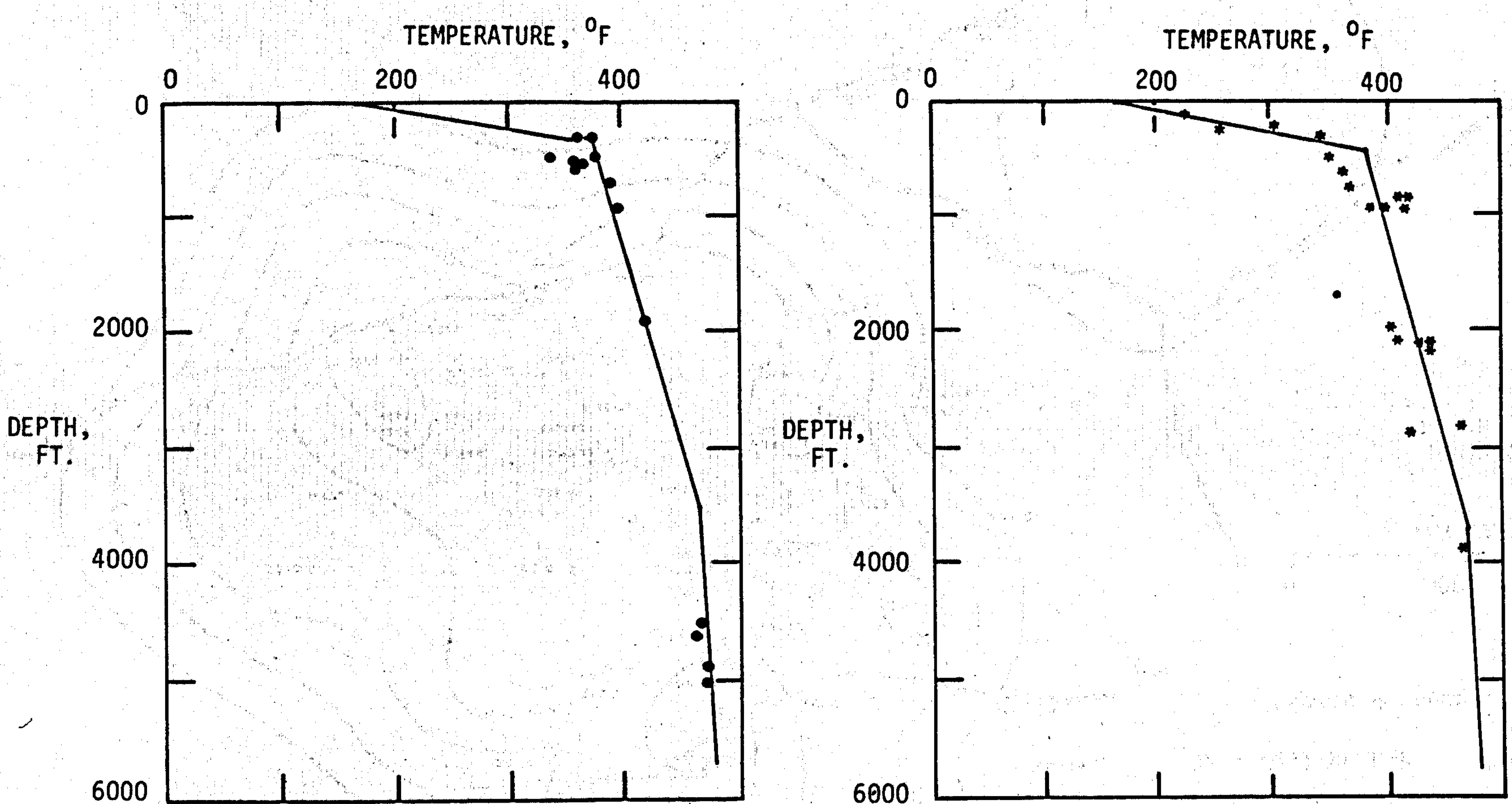


FIGURE 8 SUBSURFACE TEMPERATURES IN THE GEYSERS AREA (from Ramey, 1970)

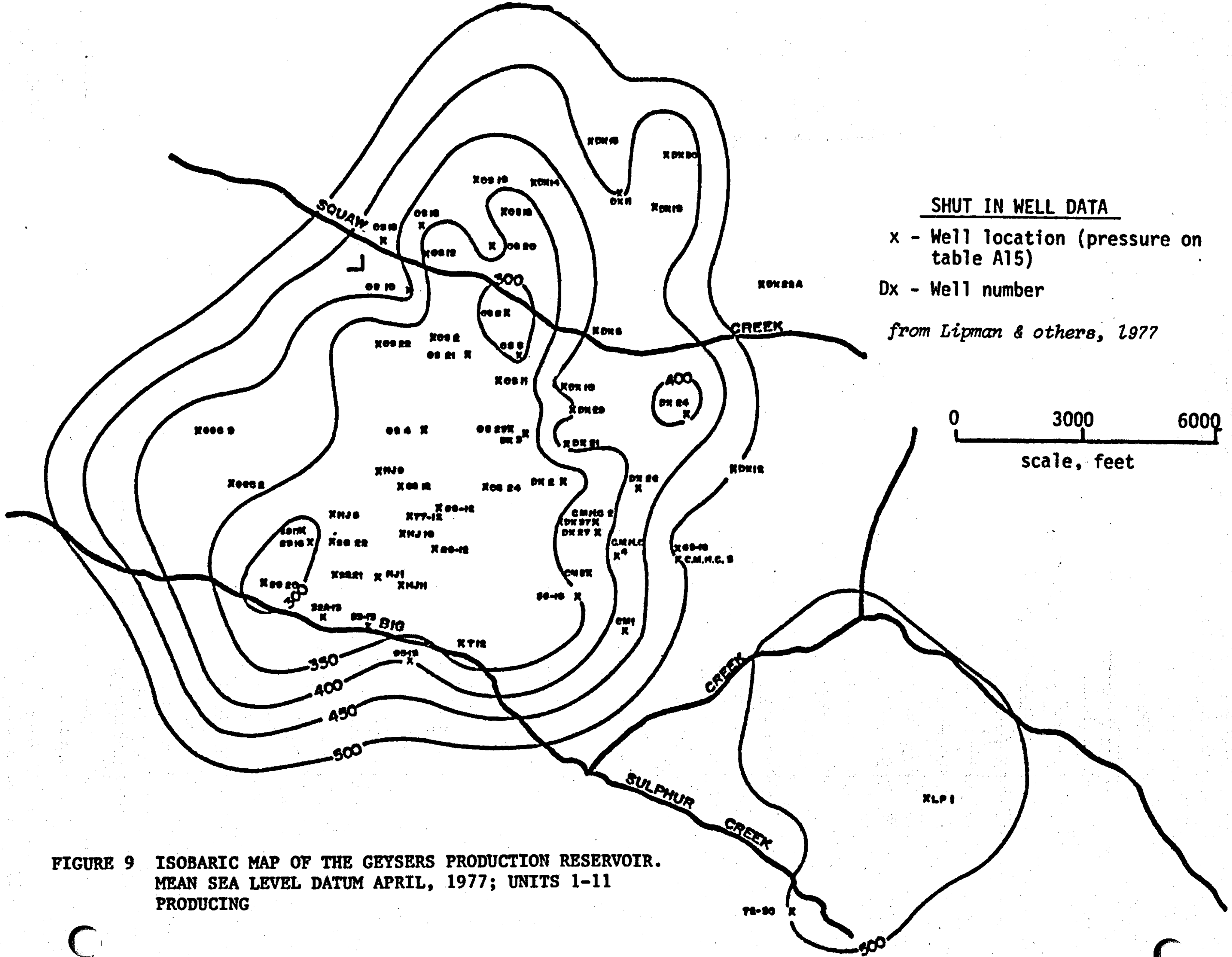
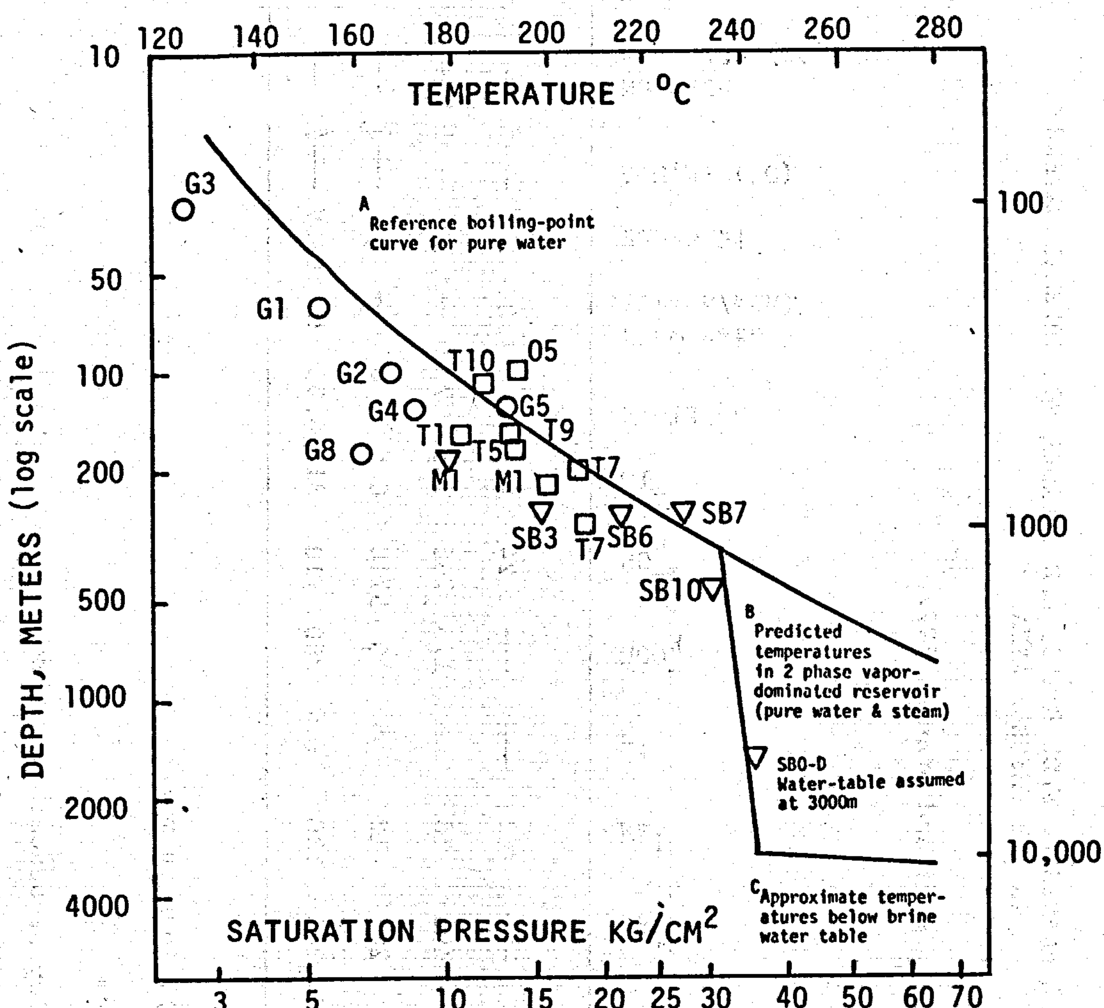


FIGURE 9 ISOBARIC MAP OF THE GEYSERS PRODUCTION RESERVOIR. MEAN SEA LEVEL DATUM APRIL, 1977; UNITS 1-11 PRODUCING



○ G1 Maximum temperature at the surface in flowing wells, plotted at drilled depth (allen 8 day, 1927)

▽ T1 Maximum temperature measured in hole by thermocouple at plotted depth (MC Nitt, 1963)

□ M1 Maximum temperature measured in hole by geothermograph at plotted depth (white, 1957a)

◊ SB3 Sulphur bank area of the geysers; saturation temperatures calculated from shut-in well head pressures corrected for weight of steam, plotted at drilled depths (number wells, O-D, Otte & Dondanville, 1968 from generated pressures of field assumed in-hole, absolute, and no effect from other gases)

FIGURE 10 BOILING POINT/DEPTH CURVE FOR THE GEYSERS (from White & others, 1971)

Table 3. PARTIAL CHEMICAL ANALYSES, FLOW RATES, AND BEDROCK FOR THERMAL WATERS IN THE GEYSERS AREA

from: Goff and others, 1977

Name	Measured Temp (°C)	SiO_2	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{-2}	Cl^{-}	Field pH	Flow rate (liters/min)	Bedrock†	A.M.M. (°C)	Na-K-Ca β = 4/3; (°C)	Na-K-Ca β = 1/3; (°C)	Source**
Thermal Springs and Wells																
Castle Rock Spring	73	113	<62	---	<62	---	---	24	6	---	30	F	---#	---	---	w
Geysers Spring #1	100	66	58	108	18	6	176	766	1.5	∿7	---	F	---#	---	---	wh
Geysers Spring #2	100	225	47	281	12	5	0	5710	0.5	1.8	---	F	---#	---	---	wh
Harbin Spring	48	53	2.7	1.8	130	0.7	260	10	31	8.93	30	G&GV	---#	---	---	m

**Analyses from the following sources:

m = R. Mariner and others (unpub. data), ions in mg./1.
w = Waring (1915), ions in ppm.
wh = White and others (1971), ions in ppm.

†F, Franciscan assemblage; GV, Great Valley sequence; G, gabbro.

3. PRODUCTION HISTORY, SUBSIDENCE, AND HORIZONTAL DEFORMATION

3.1 HISTORY OF DEVELOPMENT AND USE

Discovery of The Geysers was first recorded by a hunter in 1847 who identified the area as the "Gates of Hell". By 1852, a hotel was established. The hotel flourished as a nationally known health spa during the last half of the nineteenth century and first part of the twentieth century. Early development of the steam field was described by Laizure (1926) of the State Mining Bureau.

In 1920, John D. Grant of Healdsburg took a lease and option on The Geysers property and conceived the idea of developing steam for power generation. A well was begun in the summer of 1921, but was abandoned when the casing collapsed. A second well (called No. 1) was drilled in 1922, cased to 118 feet, and then drilled to 204 feet in open hole. At that depth, a crevice was penetrated, and the pressures that developed in the hole were so great that the drill string was forced 12 to 15 feet off the bottom. With valves open, a pressure of 60 pounds and a temperature of 530°F was registered at the well head. These encouraging results led to the organization of the Geysers Development Company, J.D. Grant, president, which purchased several thousand acres of the "heat belt".

Well No. 2 was drilled to a depth of 320 feet in 1922-1923, and Well No. 3 to 150 feet in 1924. These wells were drilled by pouring cold water into the hole to control the steam. The water would blow out each half hour or so by geyser action. A rotary drill rig with circulating water drilled the next five wells in the first seven moths of 1925. Holes were terminated at 400 to 500 feet depths, when return water nearly reached the boiling point. Static pressure in these wells ranged from 67.5 to 291 psi. Calculations indicated wells No. 4 to No. 7 would deliver steam totaling 137,500 pounds per hour or generate 4500 kw. Although the wells proved successful, there was no market for the energy at that time, and the project was suspended. The steam was used to run the engines of the drill rigs for nine months and two small reciprocating steam engine generators for light at the resort. These wells were abandoned in 1969.

In 1955, Magma Power Company obtained a ninety-year lease on The Geysers Development Company property, and a joint venture was formed with Thermal Power Company. The first well, Magma No. 1, reached 817 feet and produced steam at 157,000 pounds per hour (Kilkenny, 1975).

In 1957, four successful wells were drilled by the joint venture, the deepest being 1414 feet. On the basis of flow tests, Pacific Gas and Electric Company (PG&E) was approached to construct a steam-electric power plant at The Geysers, and a contract between the companies was signed October 30, 1958. In June 1960, a 12,500 kw generating plant went on line using about 250,000 pounds per hour of steam supplied by four wells. Five more wells were drilled in 1959 and another in 1960 at The Geysers to supply a second 12,500 kw generating plant.

In 1961, exploration began a mile northwest of The Geysers on Big Sulphur Creek. From 1961 to 1965, nineteen wells were drilled in the Sulphur Bank area, many bottoming between 2000 and 4000 feet depths. A shut-in pressure of 480 psi was measured in several of these wells, and flow tests justified the construction of a 27,500 kw generating plant, completed in 1967. A second 27,500 kw generating plant was completed in the Sulphur Bank area in 1968.

Between 1965 and 1968, six wells were drilled in the Happy Jack area between Sulphur Bank and The Geysers. Productivity was variable with depths ranging from 3000 to 4500 feet, but pressures were comparable to the Sulphur Bank area (Kilkenny, 1975), and two 53,000 kw generating units were completed here in 1971.

In 1966, Union Oil Company acquired a tract of land adjacent and north of the Thermal-Magma lease and drilled a 5392 feet deep well. An agreement in 1967 pooled all properties of both parties with Union as the operator. Between 1967 and 1975, seventy-one wells were drilled by this group (about one well per month), and PG&E increased their generating capacity to 502 mw. As of 1975, Union-Magma-Thermal was producing about 80×10^5 pounds per hour in The Geysers area from one hundred ten productive geothermal wells plus five injection wells.

There are several other operators in The Geysers geothermal area. These include: 1) Pacific Energy Corporation, with thirteen wells south of Big Sulphur Creek; 2) Burmah Oil and Gas Company, with fourteen wells in the Castle Rock Springs area; 3) Aminoil, USA, which will supply steam for a 135 mw generating plant (Unit 13) in the southeastern part of the field; 4) Thermogenics, which will supply steam to a 55 mw plant (Unit 15) south of Big Sulphur Creek; 5) McCulloch, which has apparently drilled successful wells north and northwest of the current producing field; and 6) Shell, which has drilled successful wells on the south end of the field (Lipman and others, 1977).

Potentially productive wells in the field by all operators in 1975 totaled one hundred thirty-seven; total producing wells was ninety-five; total unproductive wells was nine. Average total depth of recent wells is between 7000 and 8000 feet. The location of wells and generating units is shown on Figure 11. Table 4 lists the capacity and date of each of PG&E's generating units. Total projected capacity in 1982 is 1570 mw.

STEAM WELLS IN THE GEYSERS GEOTHERMAL AREA — NOVEMBER 1974

FIGURE 11

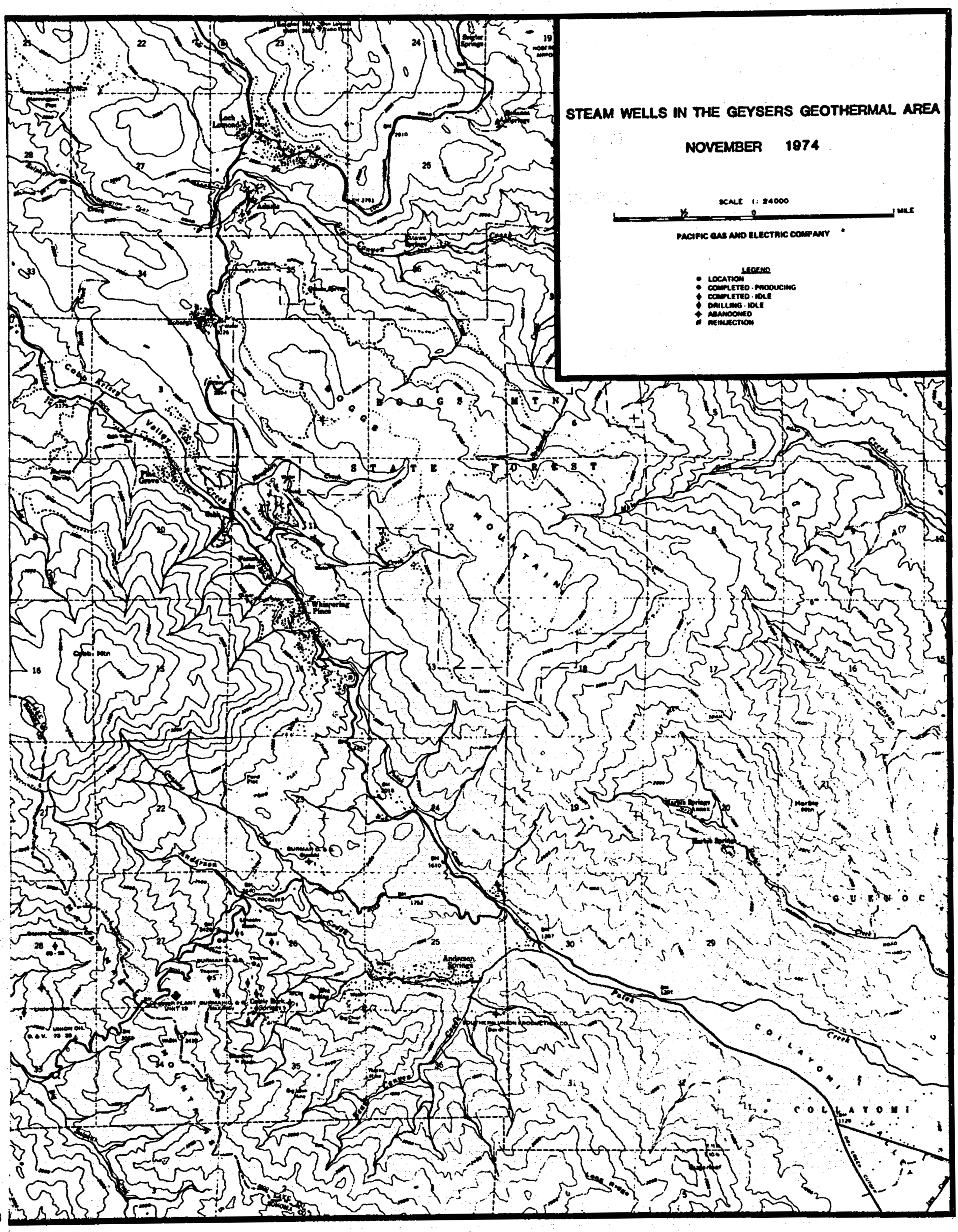


FIGURE 11 (continued)

XBL 7510-8375

TABLE 4

GEYSERS ELECTRICAL DEVELOPMENT

Unit	Operation	Net Capacity (MW) Unit	Net Capacity (MW) Cumulative
1	1960	11	11
2	1963	13	24
3	1967	27	51
4	1968	27	78
5	1971	53	131
6	1971	53	184
7	1972	53	237
8	1972	53	290
9	1973	53	343
10	1973	53	396
11	1975	106	502
12[1]	1978	106	608
14[1]	1978	110	718
15[1]	1979	55	773
13[1]	1979	135	908
16[2]	1981	110	1018
17[2]	1981	110	1128
18[2]	1982	110	1238
19[2]	1982	110	1348
20[2]	1982	110	1458
21[2]	1982	110	1568

Notes:
[1] under construction
[2] proposed

From Houland & Storchillo, 1977

Reinjection of steam condensate into the reservoir began in 1969 and amounted to 4,149,000,000 gallons by 1975. In 1975, 4,700,000 gallons per day were injected into six wells (Chasteen, 1975) which amounts to about 25 percent of the daily steam output (Budd, 1975). The injection wells were originally drilled as steam production wells and then converted to reinjection by installing perforated casing all the way to their total (bottom) depths, which range from 2364 to 8045 feet. Reservoir fluids steam pressure is less than hydrostatic pressure, so the injected flow without pumping to depths below adjacent producing wells.

Steam production from The Geysers reservoir is a confidential matter and has not been released directly by the producers. Table 5 gives four estimates of steam production. Ramey's (1970) reservoir engineering study, conducted for an Internal Revenue Service hearing, although covering production from the shallow reservoir only, is probably the most accurate through 1962, when exploration of the deep reservoir began. The production values of Weres and others (1977) come from the Northern Sonoma County Air Pollution Control District and are probably the most accurate for the interval 1967 to 1977. The values of Weres and others (1977) are very close to those of Ramey (1970) through 1962, but increase at a greater rate than Ramey's, reflecting greater utilization of the deep reservoir. The California Department of Oil and Gas provided us with steam production figures based on amounts of steam needed for actual generating plant capacities (Dennis Olmstead, California Division of Mines and Geology, personal communication, February 1978). By figuring back from power generation values of Finn (1976) and using a conversion value of 20 pounds of steam per kwh, a general idea of steam production can be gained.

Factors that determine the productivity of a specific well include hold diameter, total depth, and fracturing in the rock penetrated.

TABLE 5

STEAM PRODUCTION AT THE GEYSERS

Year	From Ramey, 1970		From Weres & Others, 1977		From DOG, 1978		From Finn, 1975*	
	10^5 lb/hr	10^9 lb/yr	10^5 lb/hr	10^9 lb/yr	10^5 lb/hr	10^9 lb/yr	10^5 lb/hr	10^9 lb/yr
1957	1.267	1.110						
1958	3.681	3.224						
1959	3.912	3.427						
1960	5.363	4.698	4.81	4.21	2.0	1.75	.8	.70
1961	4.847	4.246	5.03	4.41	2.0	1.75	2.2	1.9
1962	4.977	4.378	5.11	4.48	2.0	1.75	2.4	2.1
1963	6.050	5.300	6.87	6.02	4.4	3.85	4.0	3.5
1964	7.074	6.198	8.90	7.80	4.4	3.85	4.8	4.2
1965	6.290	5.510	8.69	7.61	4.4	3.85	3.3	2.9
1966	5.640	4.941	9.61	8.42	4.4	3.85	4.5	3.9
1967	4.390	3.847	11.6	10.2	9.4	8.23	7.5	6.6
1968			13.1	11.5	14.4	12.61	10	9.1
1969			19.1	16.7	14.4	12.61	15	13
1970			19.4	17.0	14.4	12.61	13	11
1971			21.7	19.0	34.4	30.13	13	11
1972			41.40	36.27	54.4	47.65	34	30
1973			56.07	49.12	74.4	65.17	47	41
1974			68.98	60.43	74.4	65.17	58	51
1975			79.78	69.89	94.4	82.69	87	76
1976			87.3	76.5	94.4	82.69		
1977			90.1	78.9	94.4	82.69		

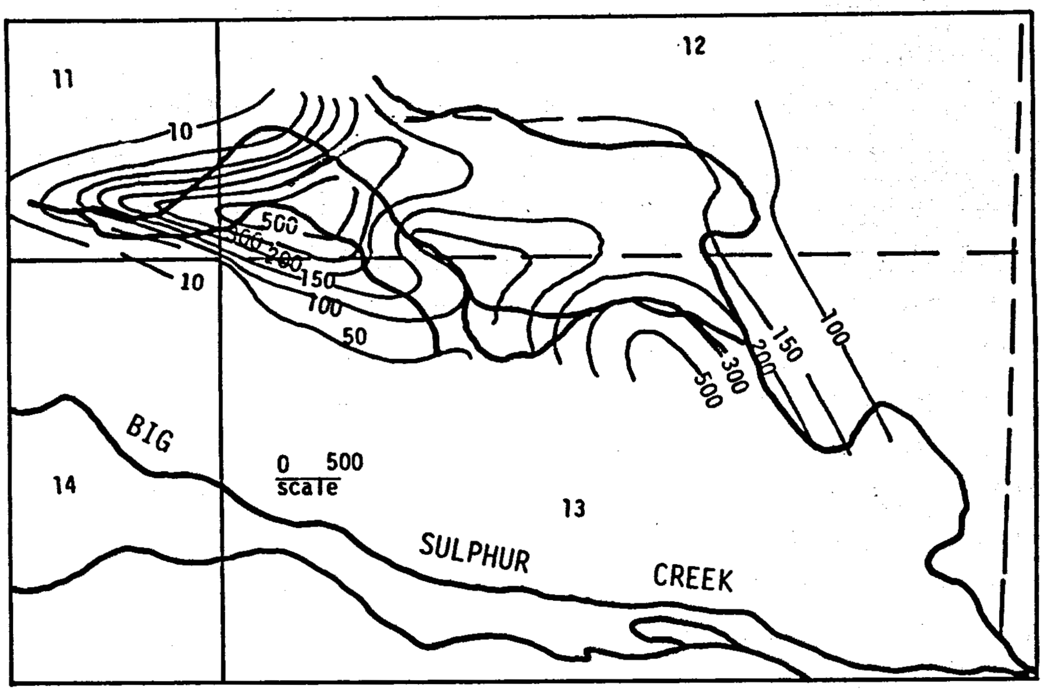
* Calculated from gross generation assuming 20lb/KWH

Since these factors are not constant over the reservoir, some areas will be more productive than others. Figure 12 indicates productivity in relation of the variables of depth and hold size.

The values on Table 5 do not reflect total steam removed from The Geysers reservoir. Steam is lost from the reservoir in a variety of ways. A constant amount of vapor is released through the naturally occurring fumaroles and in the form of water from the hot springs. Steam is also vented during the drilling operation and while testing for production capacity. Idle wells are continuously vented, often at 3000 to 4000 pounds per hour and periodically vented for twenty-four hours or more at full output to loosen and blow out particulate materials. The cyclone separators used to remove dust and water vent about 3000 to 4000 pounds per hour (Freeman and others, 1977). Much steam was lost by the once-common practice of free flowing new wells for an extended period, but this practice is now declining. The occasional blow-out of a well releases probably 50,000 to 150,000 pounds per hour for periods that have lasted several years in duration. In this respect, the production figures of Weres and others (1977) are most complete, including total man-made steam production.

3.2 CHANGES IN RESERVOIR PROPERTIES WITH USE

As steam production at The Geysers continues, pressure within the production zone drops. This is illustrated on Figure 13. The Lakoma Fame No. 2 well is a static well (not producing) outside the areas of steam production. The median pressure in this well is 480 psi with cyclic pressure fluctuations of ± 9 psi. On the other hand, Cobb Mountain No. 1, another static well, is located between Generating Units 1 to 8 and 11 on the west and Units 9 and 10 on the east. This well has been on a 1/4 inch vent most of the time since 1971, and static pressure



Productive Index: Steam 000's#/hr. according to volume of hole,first steam-T.D.

FIGURE 12 PRODUCTIVE INDEX MAP OF THE GEYSERS (from Garrison, 1972)

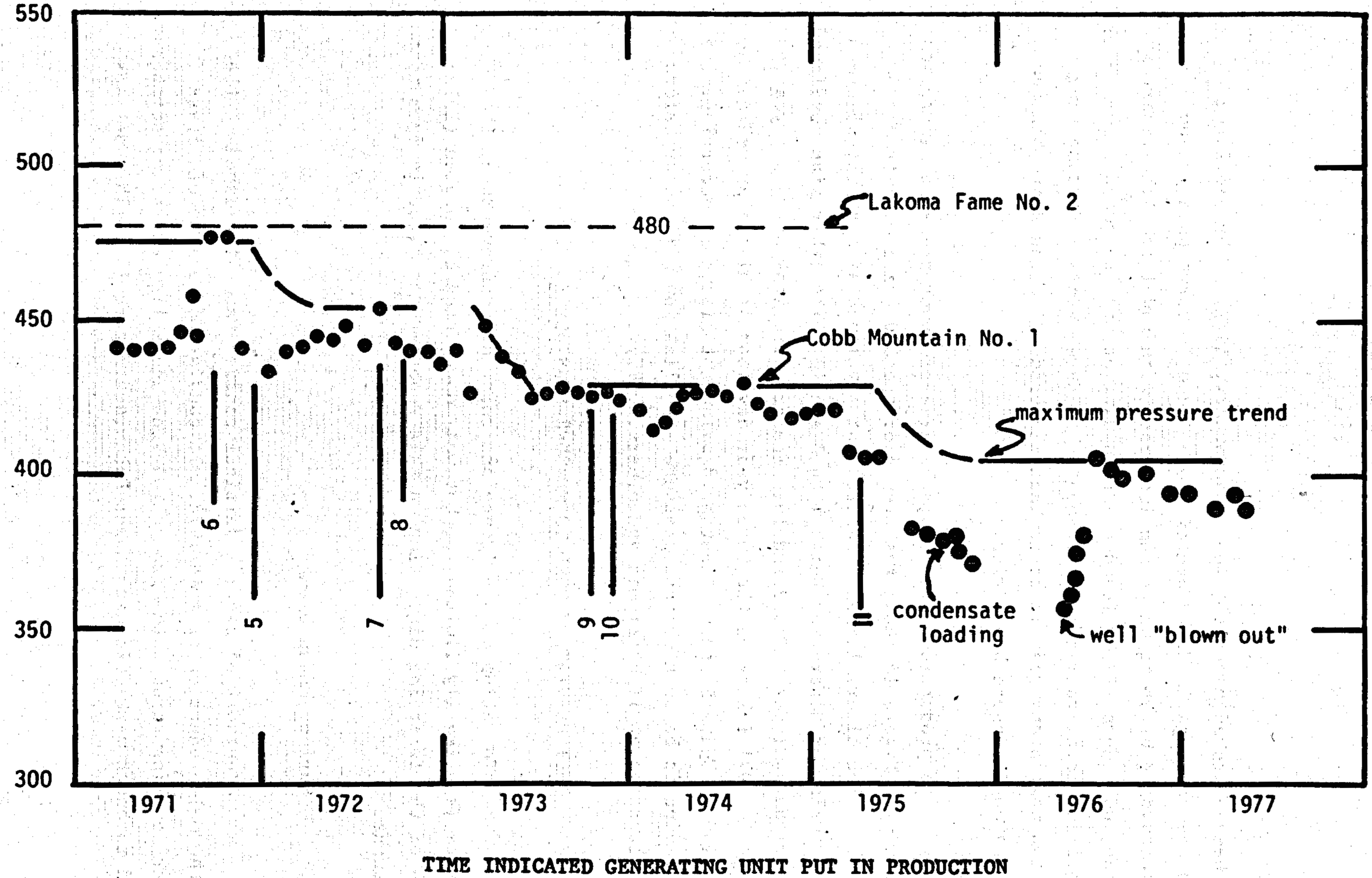


FIGURE 13 PRESSURE HISTORIES OF TWO STEAM WELLS OF THE GEYSERS
(from Lipman & others, 1977)

has been measured monthly (Lipman and others, 1977). The declining pressure readings in Cobb Mountain No. 1 seem to correspond to the addition of generating units and increased withdrawal from the reservoir. Lipman and others (1977) found the readjustment time to reach a new stabilized level varies from six months to three years. By comparing the two well pressures, it seems that the production zones are bounded by constant pressure boundaries.

As production increases, the area of lower pressures increases with time. Figure 14 shows the growth of the 500 psi isobar from 1966 to 1977. The older, larger pressure sink developed as a result of steam withdrawals for Generating Units 1 to 8 and 11. The other sink developed from withdrawal for Units 9 and 10. The pressure sink has grown yearly except in 1971 following the three year development hiatus preceding the addition of Units 5 and 6. Another development hiatus is occurring, and it remains to be seen whether pressure stabilization will occur before Unit 12 comes on line (Lipman and others, 1977).

3.3 INSTRUMENTATION USED TO MEASURE SUBSIDENCE

Information on subsidence and related measurements at the Geysers is primarily limited to, but well documented by Lofgren (1978). Much of the foregoing discussion in this report comes directly from that document.

3.3.1 Surface Measurements

A network of precise vertical control was established in the geothermal production area in 1973. It consists of a loop of first-order leveling through the production area and a line extending northeastward to bench mark Y626 near Lower Lake (see Figure 15). This net was

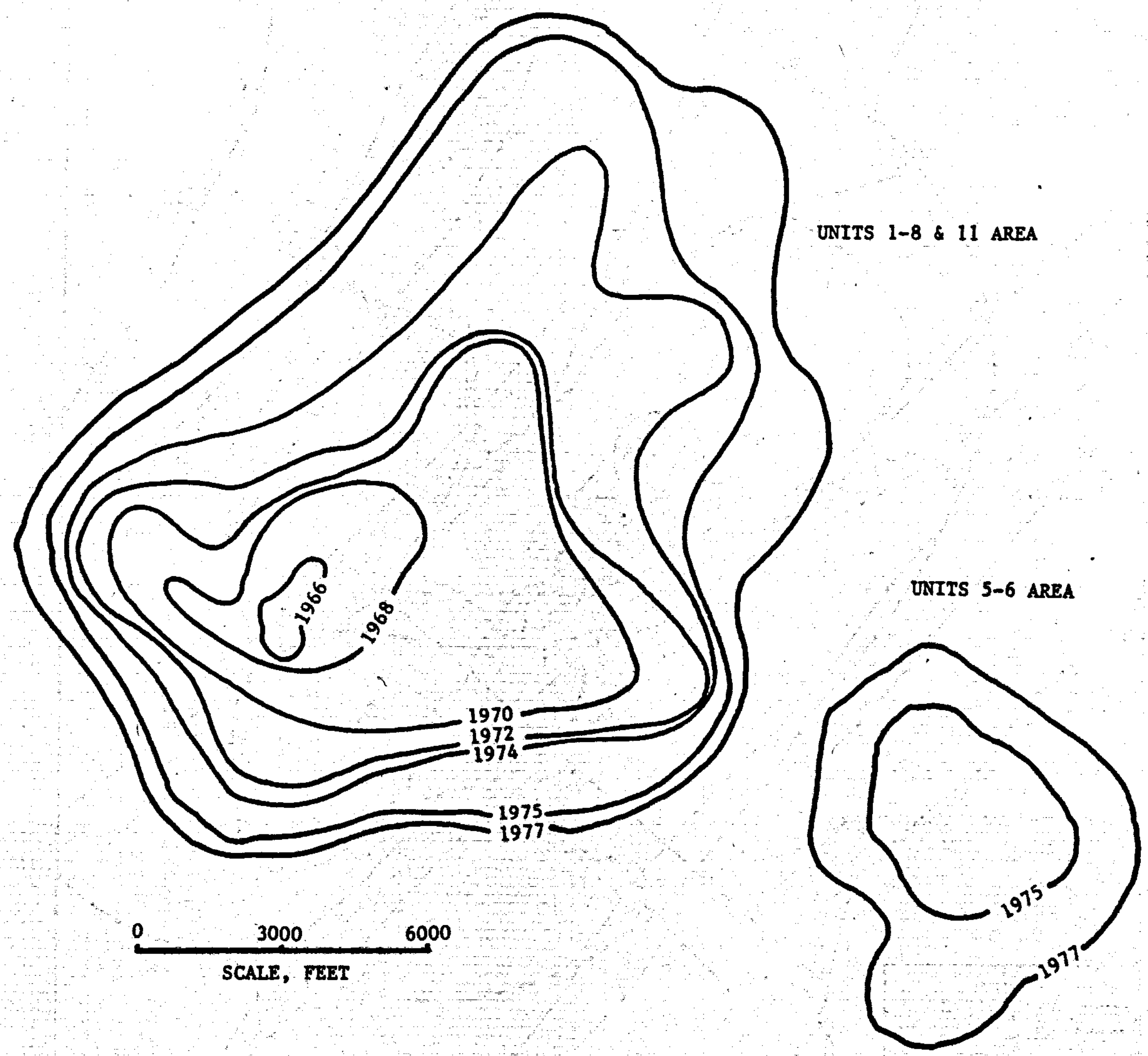


FIGURE 14 GROWTH OF THE 500 PSIA ISOBAR PRESSURE SINK WITH TIME, BIG GEYSERS FIELD. SEA LEVEL DATUM (from Lipman & others, 1977)

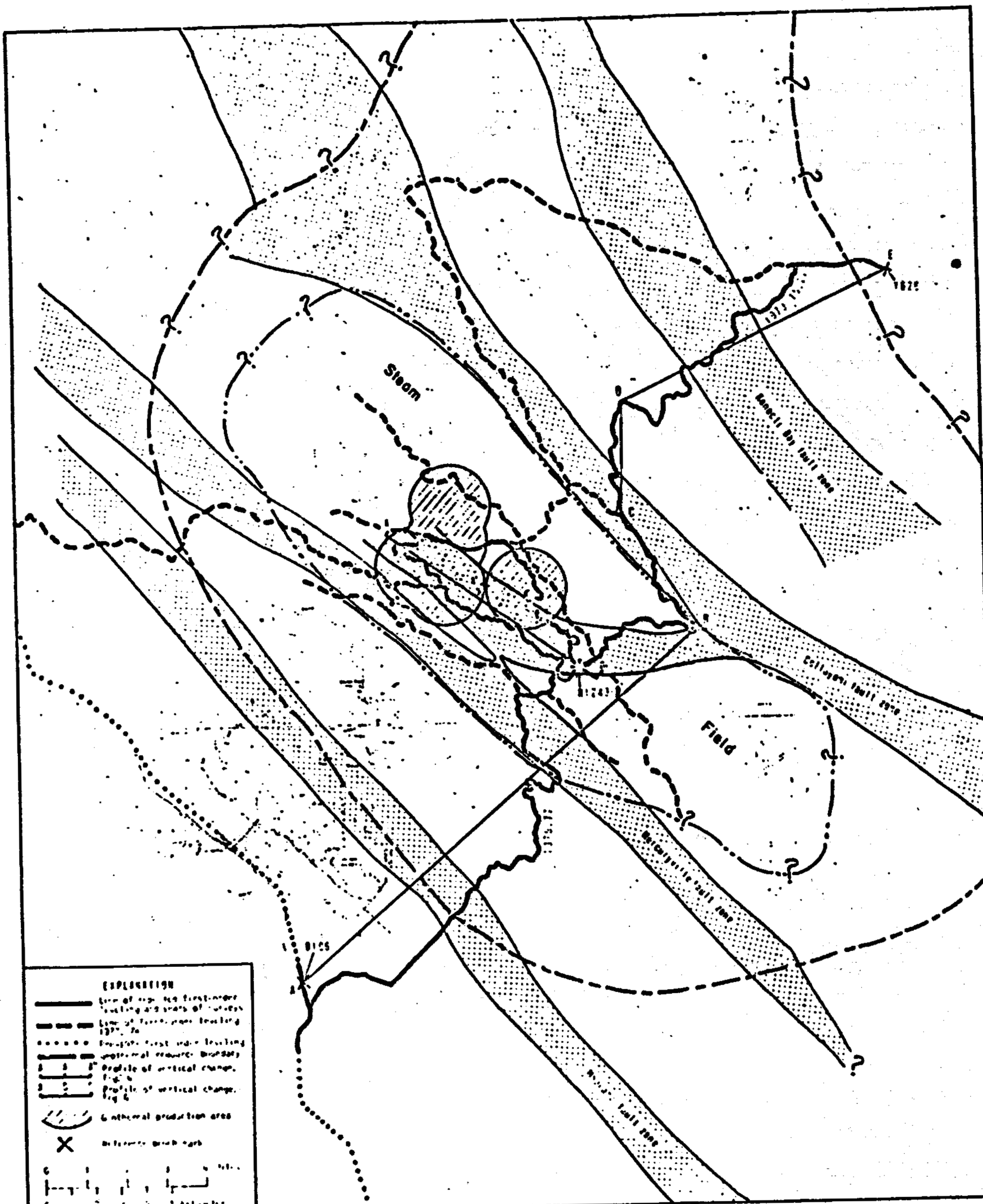


FIGURE 15 REGIONAL SETTING OF THE GEYSERS GEOTHERMAL PRODUCTION AREA AND NETWORK OF FIRST-ORDER LEVELING IN THE GEYSERS-CLEAR LAKE AREA (from Lofgren, 1978)

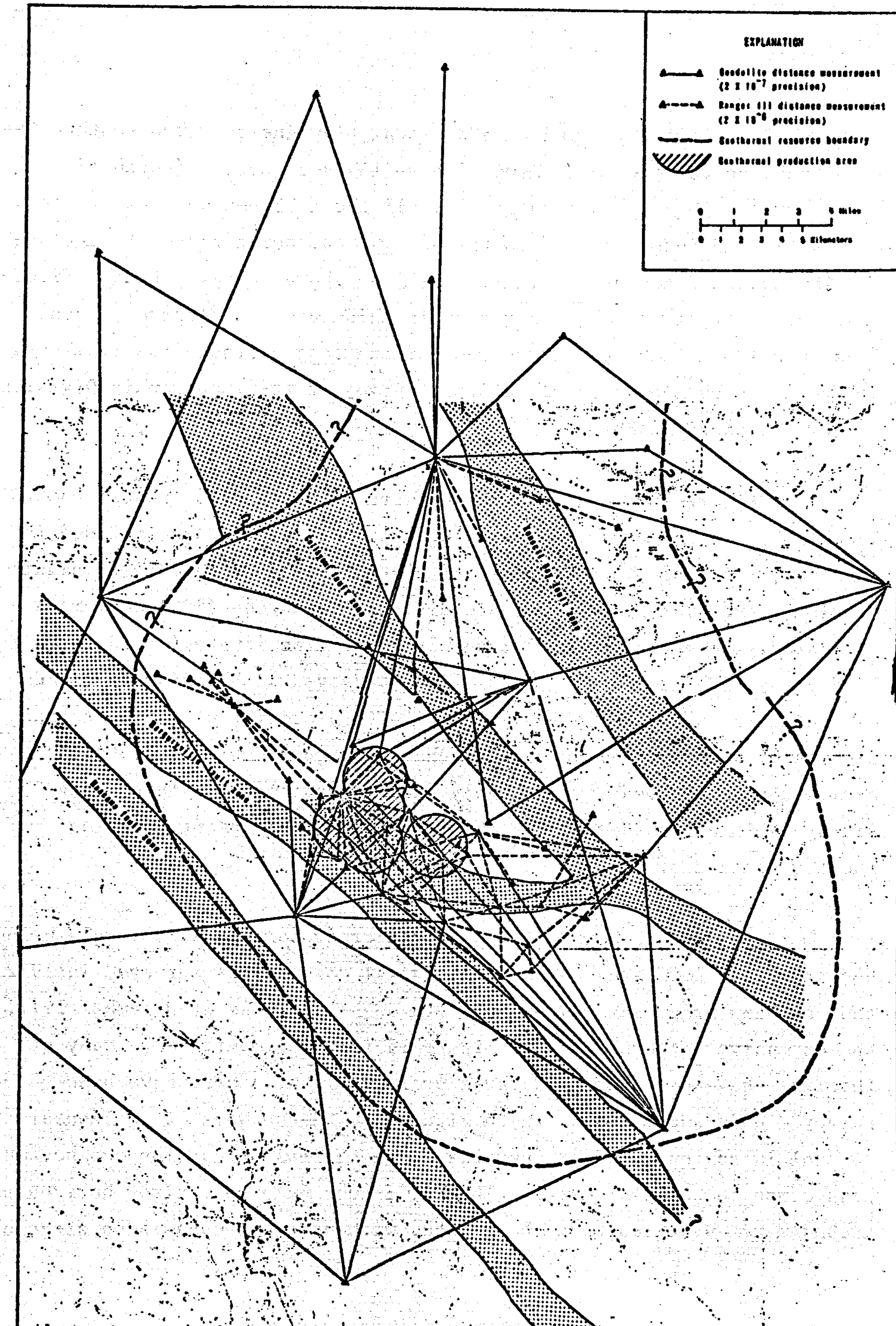


FIGURE 16. NETWORK OF PRECISE HORIZONTAL CONTROL IN RELATION TO AREAS OF PRESENT AND POTENTIAL GEOTHERMAL PRODUCTION AND MAJOR FAULT (from Lofgren, 1978)

resurveyed in fall 1975, and an additional tie line surveyed southwestward from the loop to bench mark D106 (Figure 15) near Lytton (north of Healdsburg). Then in late fall 1977, all the 1975 net was resurveyed, and continuing into spring 1978 the net was further expanded to include all the dashed lines of Figure 15. All the above surveys were of first-order accuracy, first order accuracy in this case had closure errors, less than 1 mm times the square root of the loop distance in kilometers and were run by the National Geodetic Survey or the Topographic Division of the U.S. Geological Survey.

Figure 16 shows the network of precise horizontal control established in The Geysers area. Two types of surveys are included in this net, (1) long-distance regional control lines surveyed with highly precise, long-distance, electronic distance measuring (EDM) equipment -- with precision better than 3 mm per 10 km of line length (solid lines in Figure 16), and (2) local control lines surveyed with medium-range EDM equipment (dashed lines, Figure 16) -- with a precision of better than 3 mm per 1 km of line length. For changes occurring in a relatively narrow zone, the accuracy of highly precise equipment spanning long distances is about the same as the less precise equipment spanning shorter distances.

Layout of the network of first-order horizontal control in The Geysers-Clear Lake area began with several dozen lines surveyed in 1972 and has been progressively expanded through 1977. As of December 1977, the extensive network array of Figure 16 is being monitored. Many of the lines have been surveyed three or four times; others have been surveyed only once. As shown in Figure 16, the network of horizontal control is concentrated in the area of geothermal production and becomes less dense in outlying areas. The net is designed to monitor horizontal ground movement throughout the region, with special emphasis on areas of suspected movement -- areas of active steam production and principal fault zones.

In a region as tectonically active as The Geysers, absolute stability of any area is unlikely. Relative movement within the region, however, is of principal concern in detecting both natural or induced surface changes. Thus, all surveys have been referenced to bench marks outside the region potentially affected by geothermal steam production. Bench mark Y626 near Lower Lake has been assumed to be stable and its elevation, established in 1942, was held fixed for the 1973, 1975, and 1977 surveys. This bench mark is east of the principal fault zones, and near the edge of probable geothermal development. In the interpretive analysis of changes within the loop through the production area, Figures 16 and 17, bench mark R1243 was assumed to be stable. Actually, bench mark R1243 had subsided 5.56 centimeters with respect to stable Y626 from 1973 to 1977.

3.3.2 Subsurface Measurements

William F. Islerwood of the U.S. Geological Survey established a 150 gravity station network in the region of steam production and to the north in 1974 (Islerwood, 1976). These measurements are being used to evaluate changes in the reservoir that may accompany subsidence.

3.4 <u>SUBSIDENCE CHARACTERISTICS</u>

3.4.1 Verticle Movement

Figure 17 shows the location of bench marks around the survey loop through the geothermal production area and the measured vertical changes in relation to areas of fluid withdrawal, generalized by circles

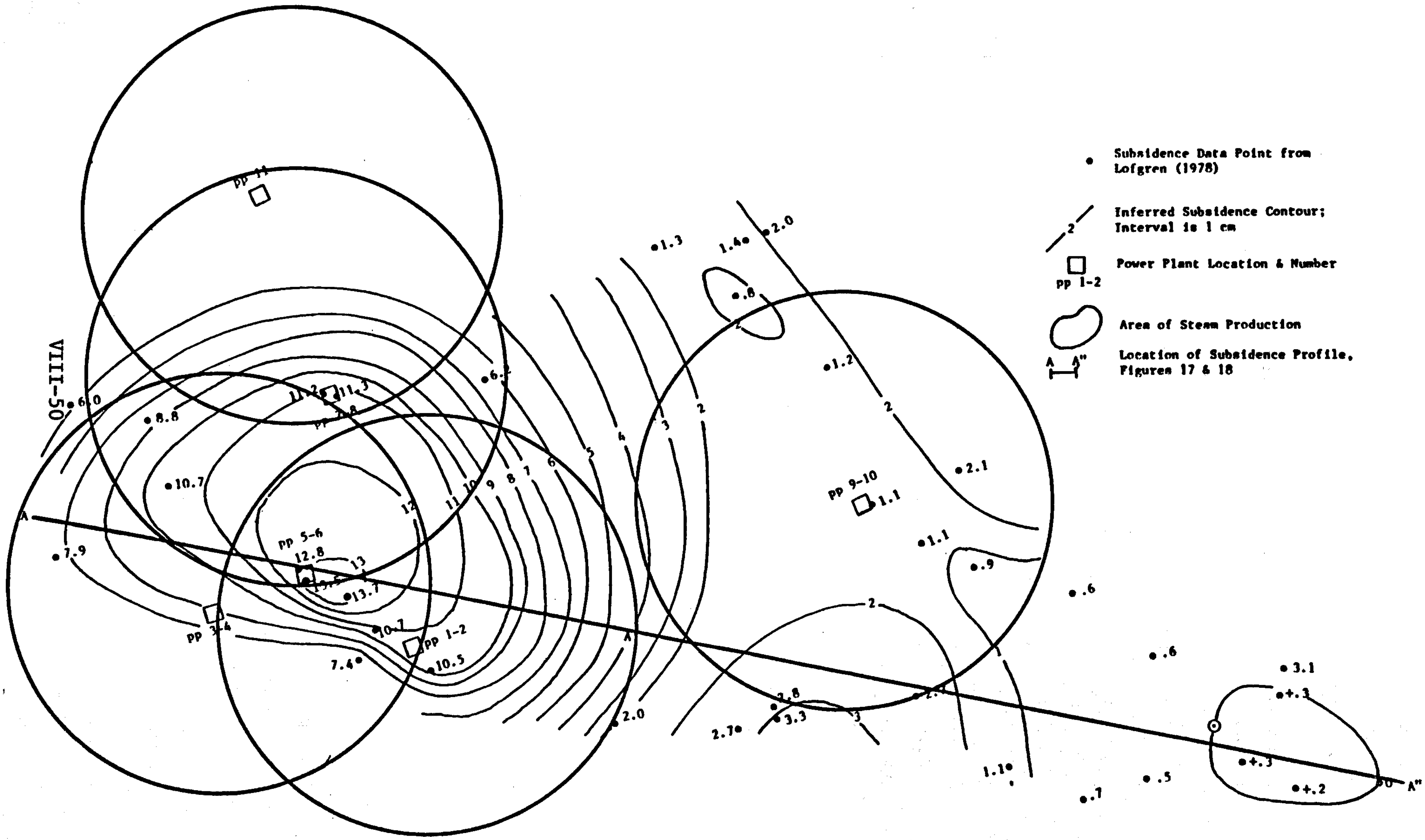


FIGURE 17 RELATIVE ELEVATION CHANGE MAP OF THE GEYSERS AREA, 1973-77

of 1.6-km radius around each producing power plant. Changes shown at each bench mark are for 1973-77, calculated relative to bench mark R1243 (at the south end of the loop) assumed to be stable during the 4-1/2 year period. Bench mark R1243 was arbitrarily selected because it is outside the area of steam production, is common to control lines of Figure 18, and appears as stable as any mark of the region. Also shown in Figure 17 is the northwest-trending line of profile A-A" (Figure 18) which graphically shows the relative change in elevation of bench marks along the southwestern limb of the survey loop near Big Sulphur Creek.

Vertical changes during 1973-75 and 1975-77 along profile A-A'-A" (Figure 18) suggest two types of ground movement: (1) a tectonic local tilt, apparently downward toward the northwest, for about 3.5 km and (2) substantial subsidence in areas of steam production for power plants 1-2, 3-4, 5-6, 7-8, and 11. Maximum subsidence rates occurred where the circles of influence of power plants 1-2, 3-4, 5-6, and 7-8 overlap, and decreased from about 4.0 centimeters per year (bench mark W1244 at power plants 5-6) in 1973-75 to 2.0 centimeters per year in 1975-77. The more or less uniform apparent relative uplift from 1975 to 1977 southeast of the area of fluid withdrawal may be real -- possibly due in par to thermal expansion of the overburden in areas of new drilling, or may be computational -- resulting from holding bench mark R1243 stable. It is interesting that vertical changes in the vicinity of power plants 9-10 are minimal (Figure 17), even though large-scale steam production began in 1972.

Declines in deep reservoir pressure and rates of subsidence a) are greatest soon after new sources of steam are put on line, and b) diminish as recharge gradients tend to reach steady-state conditions. It is interesting that in the vicinity of power plants 9-10, even though steam withdrawals had produced a sizable cone of pressure decline by

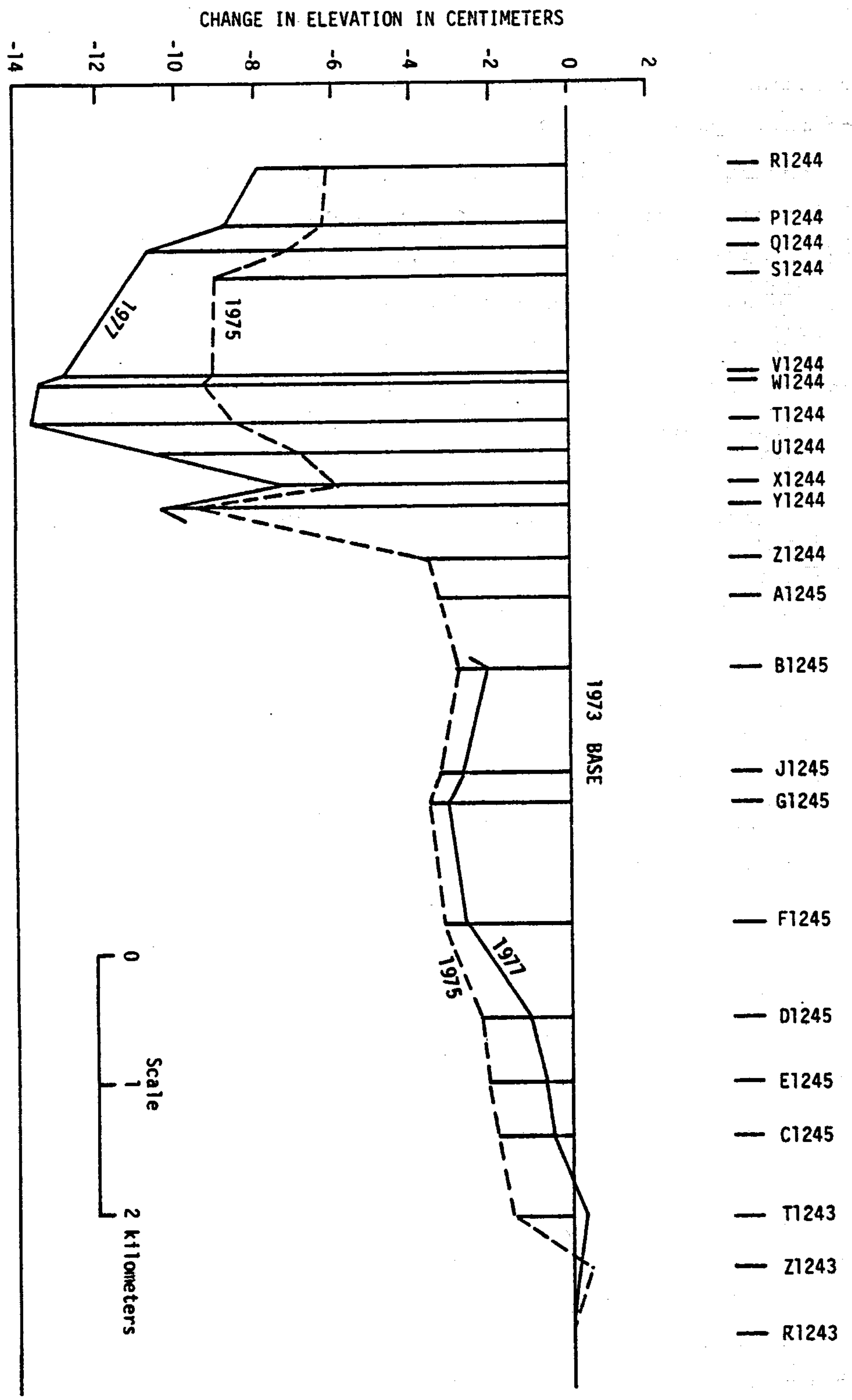


FIGURE 18 PROFILES OF VERTICAL CHANGE THROUGH THE GEOTHERMAL PRODUCTION AREA, 1973-77 (From Lofgren, 1978)

1977 (Lipman, Strobel, and Gulati, 1977, Figure 19) most of the pressure change and thus most of the net fluid extractions were considerably west of the line of control bench marks through the area.

Figure 19 shows the relation between subsidence of bench marks along line A-A' (Figure 17) and fluid pressure in the geothermal-reservoir system (Lipman, Strobel, and Gulati, 1977, Figure 7). In the area of maximum subsidence, reservoir pressures had declined about 126 meters of hydraulic head (180 psia) from 1969 and 1977 due to steam extractions. Also, 13.7 centimeters of subsidence, largely due to reservoir compaction, occurred from 1973 to 1977. This suggests a crude correlation of about 1 centimeter of subsidence (reservoir compaction) per 5 meters of hydraulic head decline or a ratio of 2.0×10^{-3} meters of subsidence per meter of head decline. Although neither the length of record nor the accuracy of data (reservoir compaction and pressure change) in this computation are adequate to predict long-term trends, this type of correlation has proved effective in defining the relationships of stress and strain related to fluid production and the compressibility characteristics of subsurface reservoir systems.

3.4.2 Horizontal Movement

Two types of horizontal ground movement were anticipated during the layout of the control net -- (a) slow right-lateral tectonic creep, principally along major fault zones, and (b) radial inward horizontal compression of the geothermal production area. Control lines (Figure 16) were laid out to accommodate the monitoring of both processes. Survey data of 1972-77 indicate that both types of movement are continuing in The Geysers-Clear Lake region.

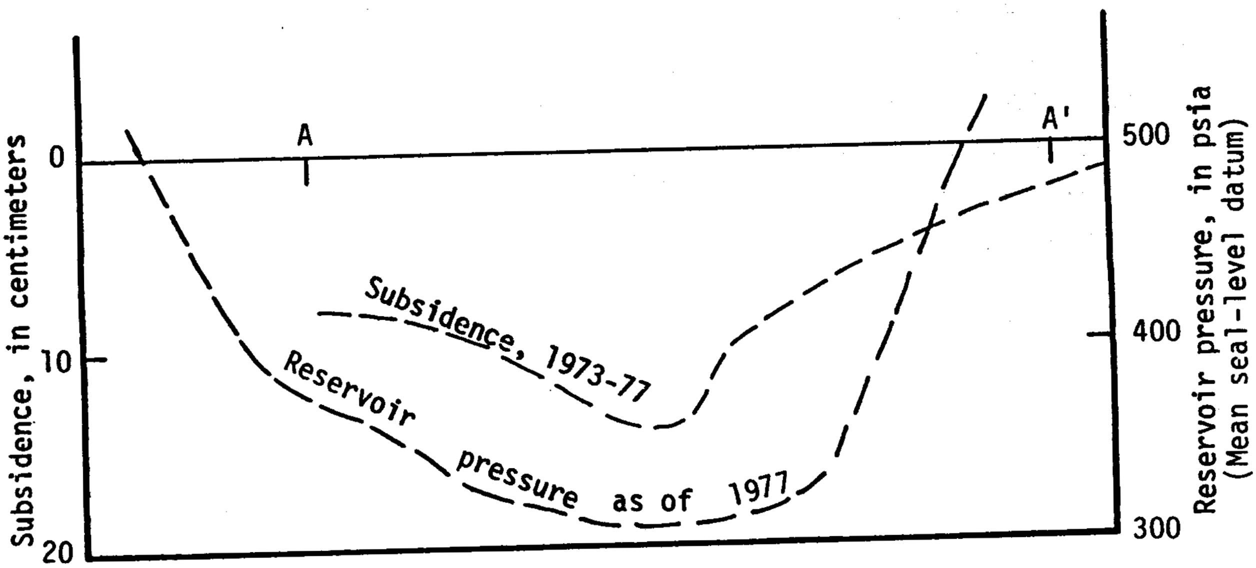


FIGURE 19 RELATION OF SUBSIDENCE TO RESERVOIR PRESSURE IN THE AREA OF PRINCIPAL CONSUMPTION. (PRESSURE DATA from Lipman, Strobel, and Gulati, 1977, Figure 7)

Only a few lines of the control net are alined directly across the steam production area but would include at least a component of right-lateral tectonic change that might occur in the Big Sulphur Creek fault zone. The generalized local vectors of horizontal movement in the production are resolved from measured changes along local control lines after removal of apparent regional tectonic changes. These vectors denote calculated rates of relative movement within the production area and are not changes in lengths of survey lines. The rates of horizontal movement in the production area, in all instances in a direction toward the center of fluid withdrawal, range from about 15 millimeters per year in areas of heaviest fluid production to about 14 millimeters per year in the peripheral area.

Of particular interest are the abrupt changes in rate of movement, and sometimes reversal in direction of ground movement, in areas of new steam production (Figure 20). Survey lines spanning the well field supplying steam to power plant 11 (upper two graphs) showed marked changes in rate soon after steam production began in 1975. Lines crossing the older producing areas (lower two graphs) show double the rates of horizontal compression and much more uniform changes. As with vertical compression of the geothermal reservoir system, surface measurements to date suggest that the horizontal compression of the deep reservoir system is directly related to fluid-pressure changes -- changing rapidly soon after the effects of new steam production are felt, and gradually establishing more or less steady-state rates of compression as the rate of pressure decline stabilizes.

3.5 IMPLIED CAUSES OF SUBSIDENCE

Both the areal extent and magnitude of reported pressure change in the vicinity of power plants 1-8 closely agree with measured

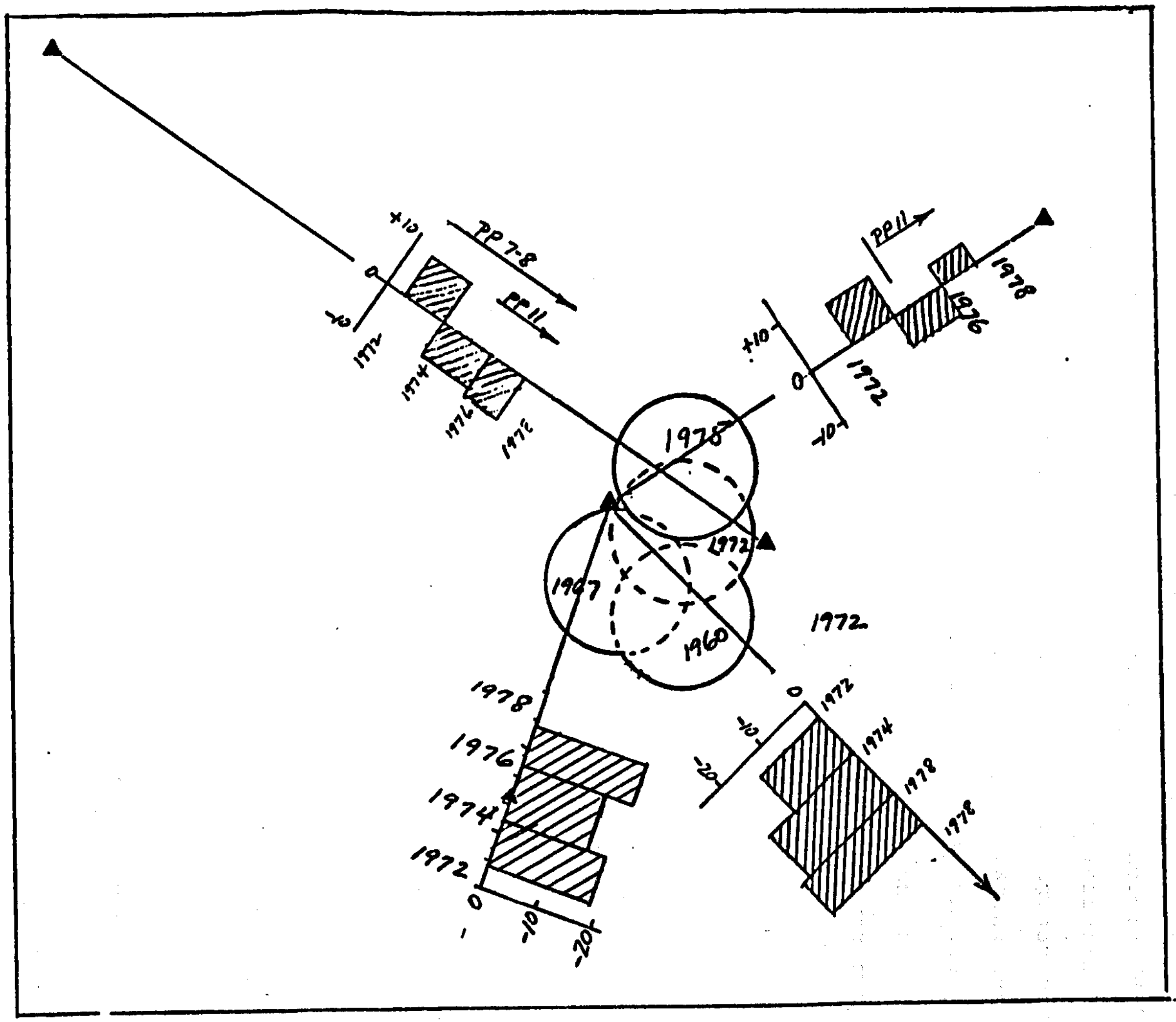


FIGURE 20 RATES OF HORIZONTAL GROUND MOVEMENT ON LINES CROSSING THE GEYSERS AREA. RATES ARE IN MILLIMETERS PER YEAR; LENGTHENING (+) ABOVE LINE, SHORTENING (-) BELOW. (From Lofgren,]978)

subsidence, and suggest a direct causal relationship. Also, the marked change in subsidence rates between the 1973-75 and the 1975-77 periods agrees in time and magnitude with stepped pressure drops caused by periodic increases in steam production (Lipman, Strobel, and Gulati, 1977, Figure 9).

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