FACTORS AFFECTING THE DECLINE IN HOT-SPRING ACTIVITY IN THE STEAMBOAT SPRINGS AREA OF CRITICAL ENVIRONMENTAL CONCERN, WASHOE COUNTY, NEVADA

U.S. GEOLOGICAL SURVEY

Administrative Report for the Bureau of Land Management

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Menlo Park, California

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Dallas L. Peck, Director

For additional information write to:
Regional Hydrologist
U.S. Geological Survey
345 Middlefield Road, MS 470
Menlo Park, CA 94025

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Conversion Factors, Vertical Datum, and Abbreviations

Multiply	By	To obtain
feet (ft)	0.305	meters
mile (mi)	1.61	kilometers (km)
feet squared per day (ft /day)	7.481	gallons per day per foot (gpd/ft)

Abbreviations used:

δ - standard delta notation (isotopic ratios)
o/oo - parts per thousand, or per mil (isotopic ratios)
D - deuterium
^{18}O - oxygen-18
mg/L - milligrams per liter (chemical concentration)
ppm - parts per million (chemical concentration)
gal/min - gallons per minute (volumetric flow rate of wells)
MW_e - megawatts of electric power

Terms used:

The hydraulic head in a reservoir is given by the height of the water column above an arbitrary datum in a well tapping the reservoir. Hydraulic head, or head, is related to fluid pressure by the equation:

Hydraulic head = (pressure/specific gravity) + elevation above arbitrary datum

Piezometric surface - the surface to which the water from a given reservoir or aquifer will rise under its full head.

Storage coefficient - a dimensionless measure of the water released from storage due to compression of the reservoir rock and expansion of water per unit volume and unit decline of head.

Transmissivity - a measure of the volumetric flow rate of ground water per unit width of reservoir for a unit hydraulic gradient. It is equal to reservoir hydraulic conductivity times reservoir saturated thickness.

^{14}C activity - the amount of radioactive decay of the carbon-14 isotope

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ABSTRACT

A study was begun in 1988 to delineate the factors affecting hot-spring activity in the Steamboat Springs geothermal system in western Nevada. Hot springs formerly flowed primarily in the Steamboat Springs Area of Critical Environmental Concern (ACEC), which occupies the southern part of the main silica terrace adjacent to Highway 395. Significant declines in spring flows and water levels in non-flowing spring vents at the main terrace were first noted during the spring of 1986 and the spring of 1987. All spring flow ceased in 1987 and water levels in spring vents have generally declined since then. Short periods of rising water levels in many vents, lasting for weeks to months, have occurred within the longer-term period of decline. The available evidence indicates that the principal factor causing the reduction in spring activity is the water-level decline in the shallow ground-water system in the South Truckee Meadows, which between 1985 and 1989 exceeded 20 feet in places. The decline in ground-water level has been caused by increased ground-water use from wells and by reductions in ground-water recharge associated with successive years of below-normal precipitation beginning in 1986-87. A secondary factor affecting spring activity is production from geothermal wells. Following periods of well testing in 1986, full-scale production and injection began in January 1987 at the SB GEO geothermal well field located 0.5 miles northwest of the ACEC. Full-scale production began in February 1988 at the Caithness Power Incorported (CPI) geothermal well field, located 1.5 miles southwest of the ACEC.

By 1989, the hydraulic head beneath the ACEC had declined by about 17 feet. It is difficult to determine how much of this total decline to attribute to different factors because each has caused similar types of effects and because certain key hydrologic aspects of the problem are not adequately known. Most important in this regard are the location and hydraulic properties of permeable zones that may connect the hot springs with the developed geothermal reservoirs in the Steamboat Hills and with alluvial aquifers in the South Truckee Meadows, and the level of drawdown in the CPI well field. Records are available on changes in spring flow and water level at the main terrace, changes in water level in observation wells, and fluid production and injection at the geothermal well fields. From this information we estimate that most (80-95 percent) of the decline in spring activity at the main terrace may be attributable to water-level declines in the shallow ground-water system. Approximately 1-3 feet (5-20 percent) of the total may be attributable to the effects of production and injection from the Caithness well field; operations at the SB GEO well field appear to have caused less effect on the hot springs than have the CPI well-field operations.

Observation wells completed in the CPI production reservoir and in the reservoir that supplies the springs on the main terrace are needed to provide more accurate determinations

of the effects of the above-mentioned factors on hot-spring activity. Water-level data collected from such wells during interference tests or temporary shut-downs at the geothermal well fields could allow the degree of hydraulic communication between these fields and the hot springs to be better quantified. Such monitoring could also detect water-level rises that might accompany a return to normal precipitation conditions in the Steamboat area. However, it is unlikely that mitigation measures that might be carried out at the CPI and SB GEO well fields would be effective in returning the springs to their former flowing conditions because other factors, such as continued ground-water pumping in the South Truckee Meadows and geothermal production from sites currently being developed near the northern boundary of the ACEC, are likely to have significant negative effects on the hot springs.

INTRODUCTION

Background

The Steamboat Springs geothermal area is located approximately 9 miles south of the city of Reno, in and around the Steamboat Hills in western Nevada (figs. 1 and 2). The geothermal area includes numerous historically active hot springs and geysers at the northeastern end of the Steamboat Hills. The Steamboat Hills trend northeast, almost transverse to the nearby Carson Range, which is separated from the Sierra Nevada by the Lake Tahoe basin.

Because of the unique occurrence of a large number of hot springs and geysers in the Steamboat area, the U.S. Geological Survey did an extensive study of the Steamboat geothermal system between 1945 and 1952. During this study, existing thermal wells were evaluated, eight new wells were drilled and tested within the Steamboat Springs geothermal area, and physical aspects of the hydrology and thermal activity of the spring system were investigated (White, 1968). The study involved detailed documentation of the activity of 74 springs in two major areas, referred to as the main terrace and the low terrace (figs. 3 and 4). White (1968) noted that of 46 springs on the main terrace, 13 erupted as geysers and 6 were pulsating springs. Three springs discharged continuously from June 1945 to August 1955. Of the 20 springs on the low terrace, 9 erupted as geysers, 2 were pulsating springs, and 6 springs discharged continuously from June 1945 to August 1952. The total flow from hot springs on the main and low terraces averaged 65 gal/min and ranged from 30 to 80 gal/min during this period.

In 1975, delineation of the Steamboat Springs Known Geothermal Resources Area (KGRA), which includes the Steamboat Springs Unit (fig. 3), initiated exploration for, and development of, geothermal resources in the region (Chevron Resources, 1987). Numerous companies have been involved in geothermal exploration programs at Steamboat since 1975, including Phillips Petroleum, Chevron Resources, Yankee-Caithness, Caithness Power, Ormat Energy Systems, and Far West Capital. During this exploration period, Nehring (1980) studied the evolution and origin of thermal ground water in the Steamboat Springs geothermal area, utilizing chemical analyses of various thermal and non-thermal springs and wells, sampled mostly in 1977. Current geothermal power production consists of 7 MW_e from the SB GEO Binary Power Plant (SBG in fig. 3) on private land northeast of the Steamboat Hills and 12.5 MW_e (net) from the Caithness Power Incorporated single-flash power plant (CPI in fig. 3) on a combination of private and federal land near the crest of the Steamboat Hills. Full-scale operations began in January 1987 at the SBG field and in February 1988 at the CPI field.

In an effort to preserve and protect the unique natural thermal features at Steamboat Springs, a 40-acre parcel of public land was designated an Area of Critical Environmental Concern (ACEC) in 1983. This ACEC (fig. 3) encompasses the southern part of the main terrace spring area delineated by White (1968) and is under the jurisdiction of the BLM's Carson City District Office. Protected under the ACEC designation are both the hot springs and geysers and the federally listed endangered steamboat buckwheat, which grows in the silica-rich soils surrounding the main terrace.

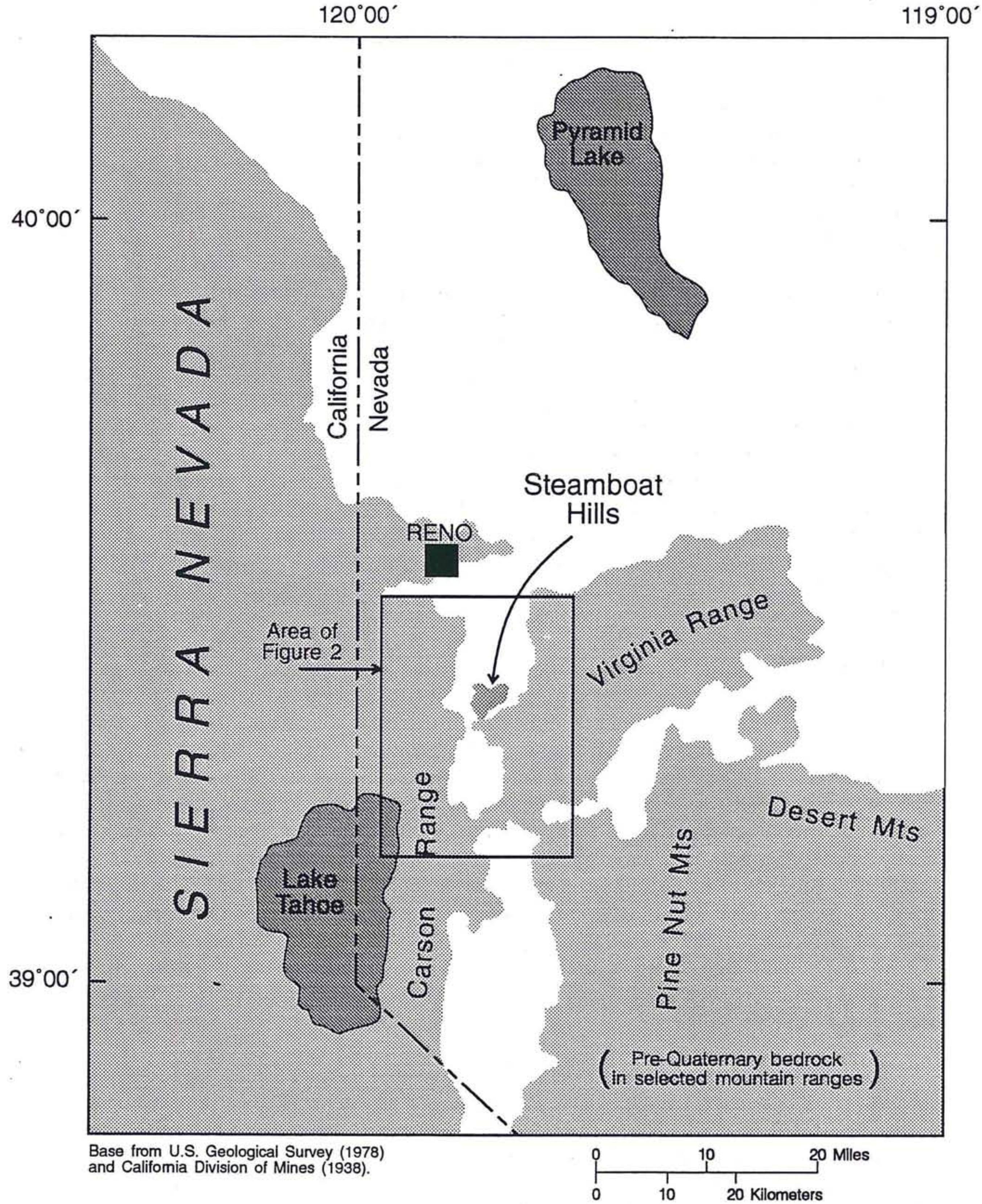

Figure 1. Location of the Steamboat Hills and adjacent ranges in western Nevada and eastern California.

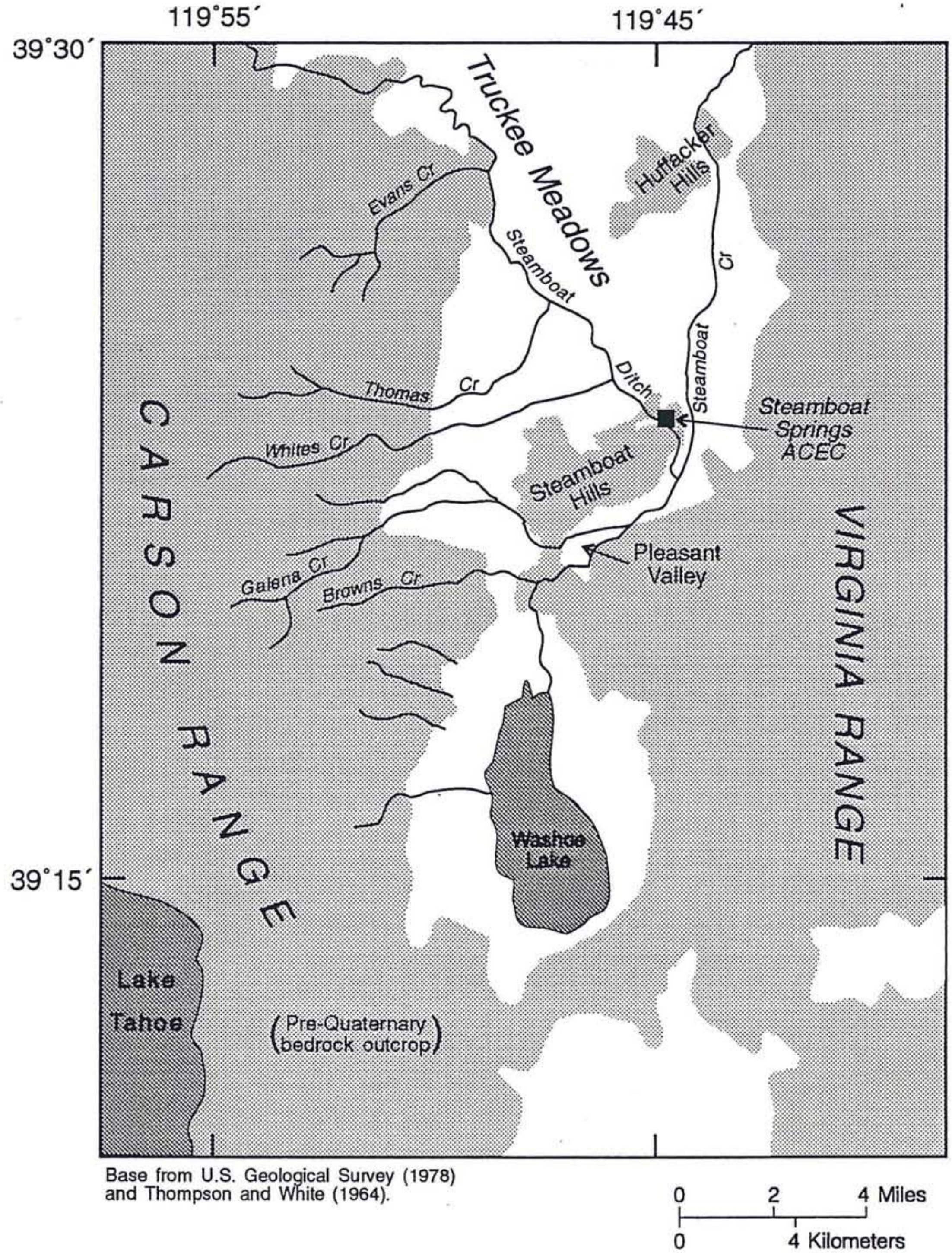

Figure 2. Location of Steamboat Hills and Steamboat Springs Area of Critical Environmental Concern (ACEC).

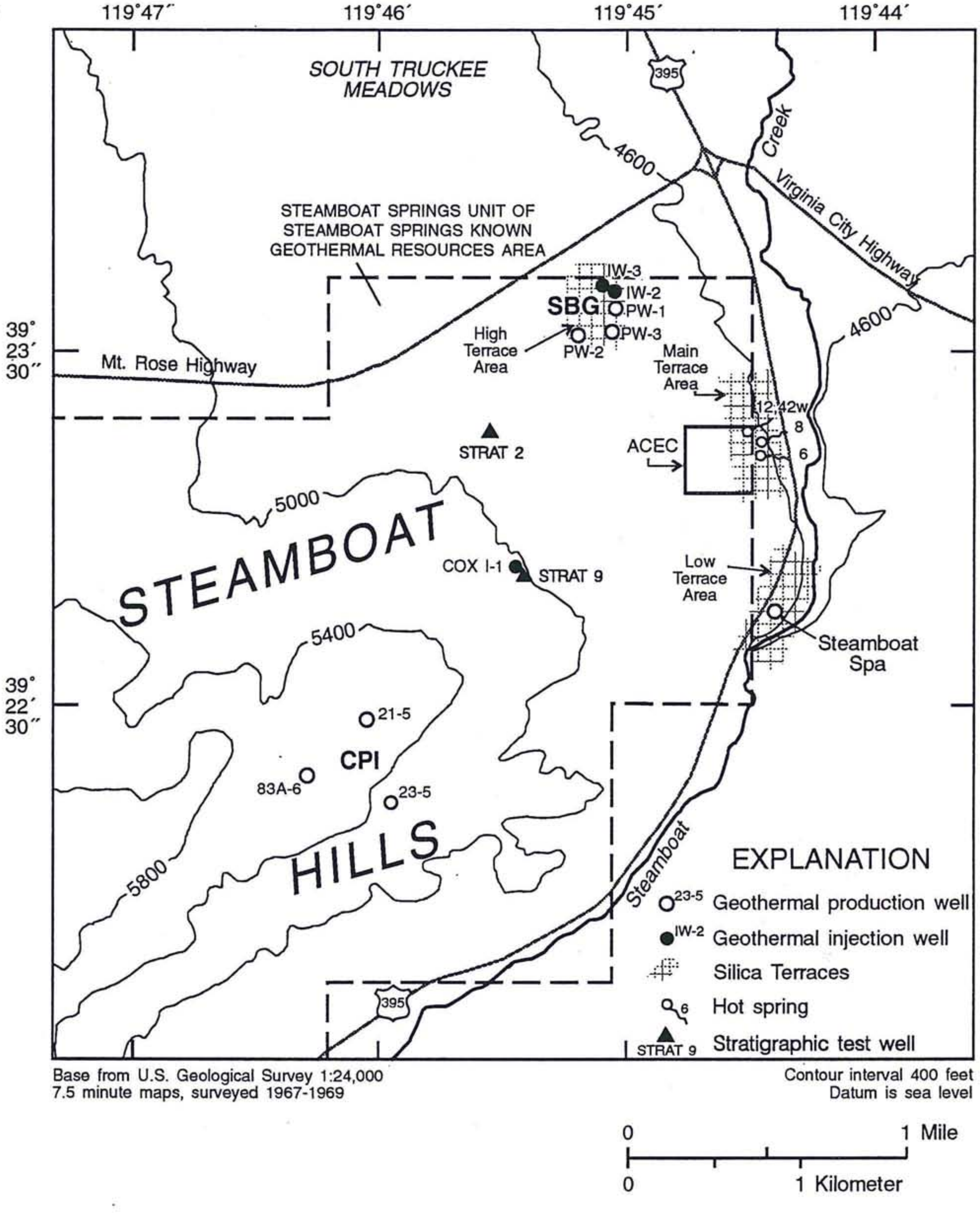

Figure 3. Location of Steamboat Springs Area of Critical Environmental Concern (ACEC) within the Steamboat Springs unit of the Steamboat Springs Known Geothermal Resources Area, which includes the Caithness Power, Inc. (CPI) and SB GEO (SBG) geothermal well fields.

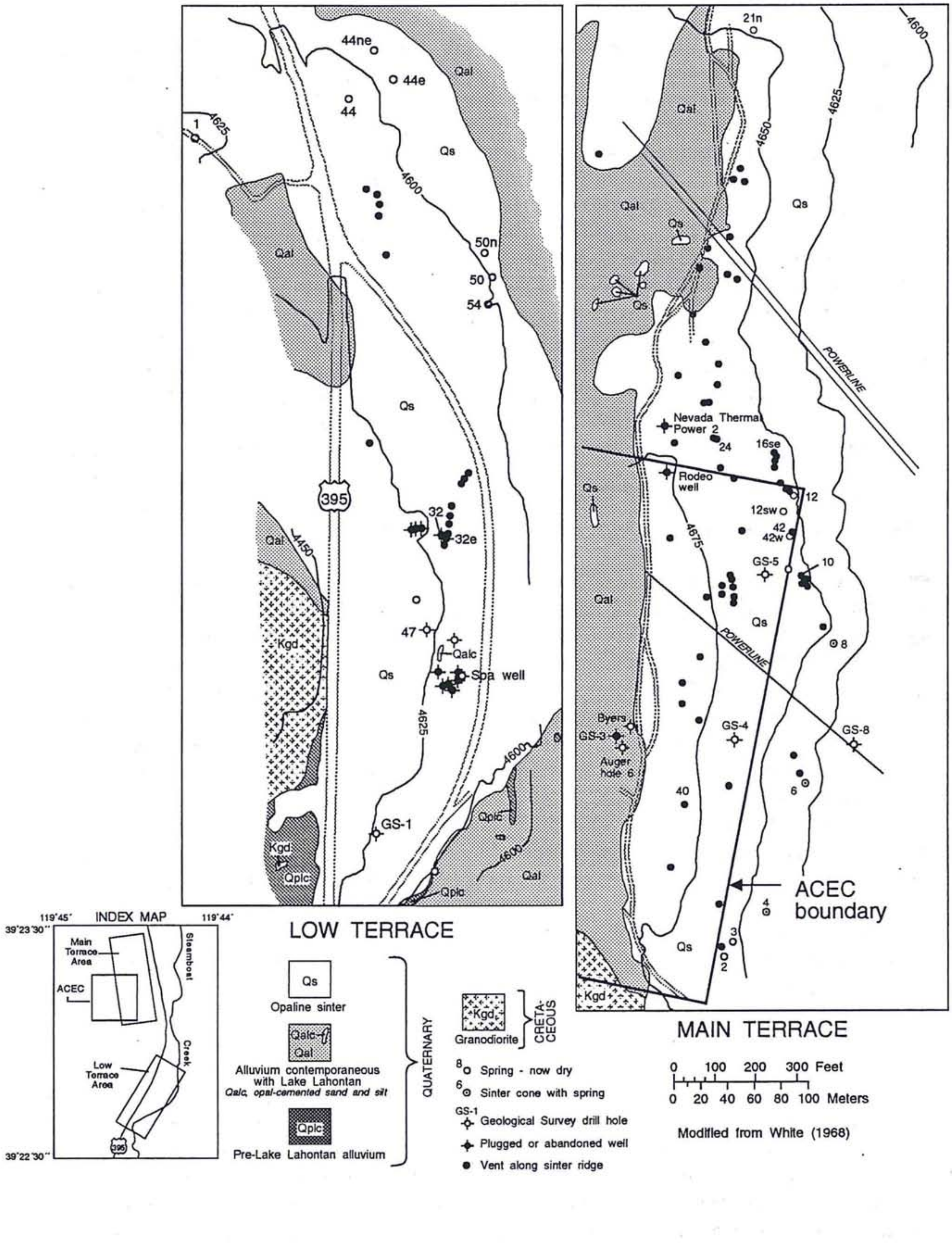

Figure 4. Geologic maps of the low terrace and the main terrace.

In April, 1986 the BLM was contacted by the Geyser Observation and Study Association (GOSA). GOSA noted that on a recent visit to the main terrace, spring and geyser activity was greatly reduced; water levels in many springs had decreased to the point that there was no flow, some springs were dry, and the geysers were inactive. GOSA considered that the decline in spring activity might be related to the discharging of a geothermal well approximately one and a half miles to the southwest, at the crest of the Steamboat Hills. Hudson (1987a), based on observations of main-terrace spring and geyser activity during the spring and summer of 1986, noted that hot-spring water levels fell within a few weeks of the start of the well discharge and recovered within 3 weeks of the end of the well discharge. In June, 1986, the BLM began weekly to bi-weekly visits to the main terrace, noting geyser activity, periods of spring discharge, and depths to water in many non-flowing springs. These observations, along with those made by GOSA, D.M. Hudson, and the Nevada Division of Environmental Protection (NDEP) were compiled from BLM files and are presented in Appendix A. Monitoring of several main-terrace springs also began in June 1986 on behalf of Caithness and resulted in a series of reports by Yeamans (1986a, 1986b, 1987a, and 1987b). Included in these data are the only quantitative estimates of total flow from springs on the main terrace since those reported by White (1968). The total flow from six springs was estimated to vary from about 10 gal/min to 30 gal/min over the period June 1986 to April 1987, although discharge was noted from other springs not monitored (Yeamans, 1987a).

An Environmental Assessment (EA) of the proposed development of the CPI well field and power plant southwest of the main terrace was completed in May, 1987. This document addressed, in part, the potential impact on the springs and geysers of the main terrace ACEC from geothermal fluid production and injection in the federally authorized CPI well field (Chevron Resources, 1987). Potential effects of geothermal production and injection on spring and geyser activity were judged to be insignificant based on reinjection of "95 percent of the proposed rate of withdrawal of fluids" and preliminary results from a one-month production/injection test begun in May 1987 (Yeamans, 1987c, included in Chevron, 1987). A by-product of the Environmental Assessment was a ground- and surface-water monitoring program to be implemented by CPI. This plan was agreed upon by both the BLM and NDEP as satisfying the objectives of each agency. One objective of the monitoring plan was to observe, assess, and correct adverse effects on the hot springs of the ACEC. The Environmental Assessment also discussed possible measures to be undertaken in order to mitigate impacts to the ACEC springs caused by the CPI well field, including adjusting production and injection well rates, drilling additional injection wells, and closing the facility (Chevron Resources, 1987).

Springs on the main terrace began a systematic decline in flow and water level in 1987; as of July 1987 only one main-terrace spring (spring 8) was discharging (Appendix A). Locations of springs referred to in this report are shown in figures 3 and 4. Figure 5 shows hydrographs for the three springs with the most complete records over the 1986-1989 period. More detailed hydrographs for all monitored springs are included in Appendix A. The spring numbers follow those designated by White (1968). The hydrographs have been constructed predominantly from depth-to-water measurements presented in Appendix A. Because spring discharge was only visually estimated since 1986, periods of active discharge are simply plotted as zero depth to water. Periods of decreasing spring discharge, therefore, are not apparent on these plots.

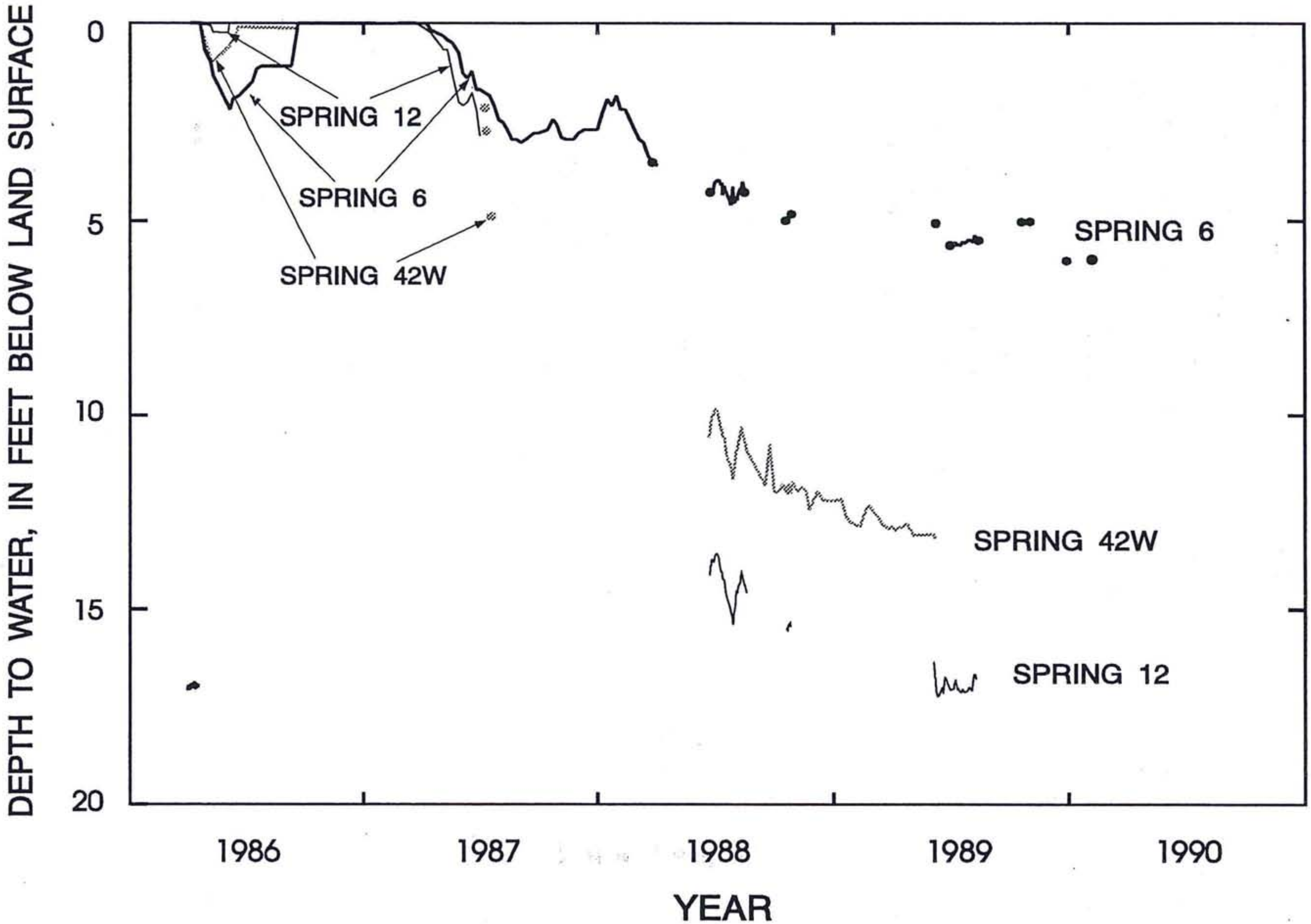

Figure 5. Hydrographs for springs 6, 12, and 42w on the main terrace at Steamboat Springs. Dots represent measured water-levels. Depth-to-water reference is the land surface at each spring.

Springs on the main terrace ceased flowing in early 1986 (except for spring 8) and water levels in the spring vents declined until mid-1986. This was followed by a period of rising water levels and renewed spring discharge, and then by another period of declining water levels that has continued with minor fluctuations until the present. Spring 8, one of the few springs that discharged continuously during the 1945-52 period, ceased flowing in March 1988. This recent decline in main-terrace spring activity is unprecedented when compared to White's (1968) seven-year study. An extreme example of the magnitude of the recent decline in spring activity is spring 12; this spring last discharged in March 1987 and in August 1988 it had a measured depth to water of slightly less than 17 feet (fig. 4).

White (1968) estimated the total rate of thermal-water discharge from the Steamboat geothermal system at 1110 gal/min in 1955, from measurements of chloride flux in Steamboat Creek, spring flow from the terraces, and estimates of well discharge on and near the terraces. We used measurements of chloride flux in Steamboat Creek in 1988 and 1989 to estimate the total natural discharge from the system as 500-700 gal/min. An average of 400 gal/min of thermal water is consumptively used at the CPI power plant, but this usage does not involve a loss of dissolved chloride from the geothermal reservoir.

Declines in thermal-water outflow, spring discharge, and spring water levels can be caused by a variety of factors. White (1968) described changes in spring discharge and water level caused by barometric pressure changes, variations in precipitation, earthquakes, and other natural influences. Determination of the primary factors responsible the recent decline in spring activity is complicated by the fact that the 1987 precipitation year (July 1986-June 1987) was the first in a series of five below-average precipitation years in the region encompassing the Steamboat Hills. The effects of this drought on water levels in the shallow ground-water system of the Steamboat region have been magnified by increased ground-water pumpage for domestic uses. An additional factor that could influence hot-spring activity is geothermal well production and injection at the CPI and SB GEO well fields and of production from the Steamboat Spa well at the low terrace (fig. 3).

Scope of the Study

This report was prepared by the U.S. Geological Survey, in cooperation with the Carson City District Office of the Bureau of Land Management (BLM), as part of a study of the Steamboat Springs, Nevada geothermal area. The study described in this report was a joint effort of the United States Geological Survey (USGS) and San Diego State University (SDSU), and was undertaken to determine the causes for the decline in hot spring and geyser activity within and surrounding the Steamboat Springs Area of Critical Environmental Concern (ACEC). The specific objectives of the study, as contained in the Intra-Agency Agreement No. NV950-IA8-002, were to:

1. Describe the hydrogeologic setting of the Steamboat basin and the natural processes that affect the thermal features of the ACEC.

2. Describe the relations of geothermal-fluid production and injection on public and private lands to the thermal features within the Steamboat ACEC, with particular emphasis on the relation of federally authorized production and injection to the ACEC.

3. Review the existing monitoring plans being implemented by BLM, the State of Nevada, and the geothermal operators. Evaluate and report on the ability of the monitoring efforts to detect changes in the hydrothermal system and to determine cause and effect relations. Make recommendations for changes to the monitoring plans, if necessary, including recommendations for monitoring wells.

4. Recommend methods to mitigate any effects to the thermal features from federally authorized geothermal production and injection.

A fifth objective, initially proposed by the BLM, was to recommend thresholds for determining significant changes to the thermal features of the ACEC that can be measured through the monitoring plan. This objective was not considered in the study because significant changes in the thermal features of the ACEC occurred before the study began and the existing monitoring plan no longer includes the collection of data from the ACEC or main terrace.

This report described the methods used to meet the stated objectives of the study, including (1) photo-interpretation of available imagery covering Steamboat Hills and surrounding areas to delineate fracture patterns, (2) compilation of a geologic map of Steamboat Hills and surrounding areas, (3) detailed monitoring of water levels in accessible hot spring vents and wells, (4) calculation of the thermal-water discharge in Steamboat Creek from measurements of stream discharge and chemical concentrations, (5) compilation and analysis of existing confidential and publicly-available geologic and hydrologic data, and (6) development of a conceptual hydrogeologic model of the Steamboat Springs geothermal system. We emphasize that it was not the intent of this study or of this report to provide a complete description of all hydrologic aspects of the Steamboat area, but rather to evaluate the existing information in terms of cause-and-effect relations and the relative effects of various stresses on hot-spring activity. Further, we have made suggestions for additional data collection to allow a better quantification of effects of different factors on the ACEC hot springs rather than recommendations for mitigation measures.

Permission was granted to the USGS and SDSU to review data contained in NDEP files regarding the SB GEO facility. Data regarding the CPI facility were furnished by Caithness and their consultants and was also accessed through the files held by the BLM and NDEP. Other useful information is contained in graduate theses, published reports by the USGS and others, aerial photographs, and unpublished reports by various consultants.

Acknowledgments

The authors wish to thank Daniel L. Jacquet of the Bureau of Land Management for his encouragement and coordination of the administrative aspects of this study. This report is based in part on field work, data collection, and interpretations presented in the M.S. thesis by R.J. Collar. The contributions of Collar, now with CH2M Hill, and David Huntley of San Diego State University are gratefully acknowledged. Jacquet and Richard Hoops (BLM) provided access to reports and data in BLM files. Valuable records of hot-spring observations were obtained from Terry Knight of the BLM and Paul Strasser and Heinrich Koenig of the Geyser Observation and Study Association. Douglas Zimmerman of the Nevada Division of Environmental Protection provided access to well-field and monitoring data furnished to the

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HYDROGEOLOGIC SETTING OF THE STEAMBOAT AREA

In the Steamboat area, thermal fluids are encountered at the surface on silica terraces north and northeast of the Steamboat Hills, in bedrock aquifers within the Steamboat Hills, and in alluvial deposits of the South Truckee Meadows. Possible relations between these thermal-water occurrences are discussed in this section of the report, following a summary of the important geologic and structural features of the area. A more detailed discussion of the hydrogeologic setting of the Steamboat area is given by Collar (1990), based on reports by Thompson and White (1964), White and others (1964), White (1968), Tabor and Ellen (1975), Cohen and Loeltz (1964), and Bonham and Rogers (1983).

Geology and Structure

The Steamboat Hills consist of a topographically prominent bedrock high surrounded by unconsolidated deposits (plate 1). The southern part of the hills are composed of Triassic and Jurassic metamorphic rocks; these rocks are intruded by Jurassic and Cretaceous granodiorite along a steeply dipping contact that strikes in an eastward or northeastward direction near the crest of the hills. North and west of the crest of the hills the metamorphic rocks are overlain by Tertiary volcanic rocks and younger sediments. A geothermal exploration well drilled north of the hills near the center of section 21, T18N, R20E (plate 1) encountered 1,966 feet of unconsolidated deposits, primarily lacustrine sediments, with minor interbedded basalt flows (Desormier, 1984).

The youngest volcanic rocks in the Steamboat area are 1.14 to 1.21 m.y. old Steamboat Hills Rhyolite and the 2.52 to 2.55 m.y. old basaltic andesite flows described by Silberman and others (1979). The Steamboat Hills Rhyolite crops out in three domes (Qsr in plate 1), one of which occurs at the southwestern end of the Steamboat Hills. These domes, together with the Washington Hill Rhyolite dome eight miles northeast of the main terrace (not shown), form a northeast-southwest-trending volcanic lineament. Flows of basaltic andesite erupted along this lineament midway between the dome of Steamboat Hills Rhyolite at the southwest end of the hills and the main terrace. Many authors (for example, White and others, 1964; Silberman and others, 1979) have associated the hydrothermal activity at Steamboat Springs with magma reservoirs that supplied these Pleistocene eruptions.

Extensive deposits of silica sinter (opal and chalcedony) exist on the high, main, and low terraces (plate 1 and figs. 4 and 5). The sinter has been deposited primarily from discharging hot-spring waters and thermal ground water saturated with amorphous silica. In general, the sinter overlies unconsolidated alluvium and glacial outwash, but it may also cement these deposits. Drill-hole information indicates that the sinter is as thick as 80 feet at the main terrace, the top of which sits about 100 feet above the level of Steamboat Creek (fig. 4).

Active hot springs occur only at the low and main terraces. However, hot springs formerly discharged at several other areas within the Steamboat Hills, as evidenced by silica deposits and hydrothermally altered rock (for example, Sinter Hill and Silica Pit in fig. 6 and plate 2). Hydrothermal eruption breccia along the Mud Volcano Basin fault west of the high terrace and near the Mount Rose Highway (State Highway 431) indicates hot-water upflow and probable seismically activated phreatic eruption activity in the middle or late Pleistocene

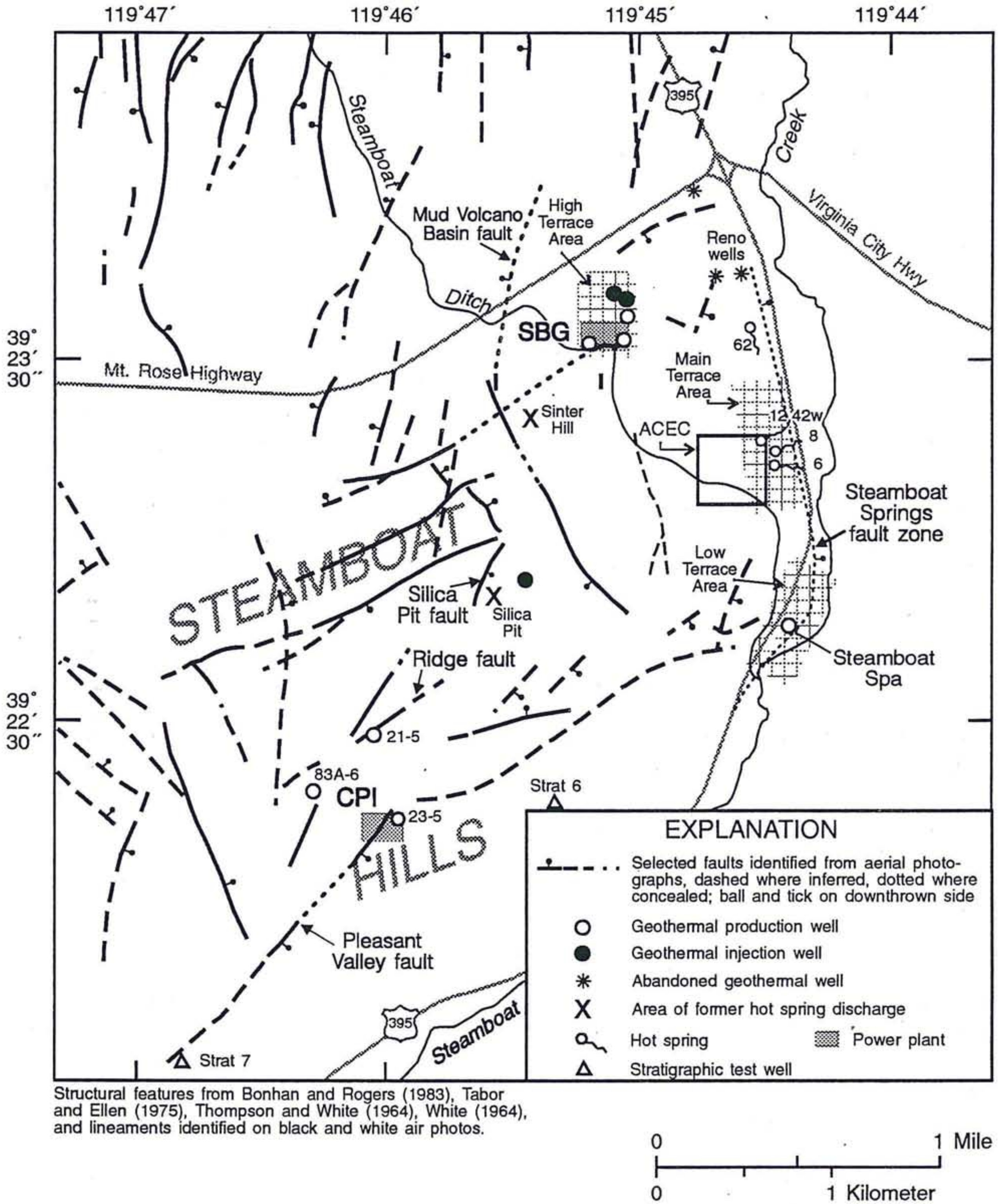

Figure 6. Map of the Steamboat Hills and surrounding areas showing faults and lineaments of probable structural origin identified from aerial photographs, selected wells, and general locations of silica terraces. CPI stands for Caithness Power Incorporated; SBG stands for SB GEO.

(White, 1955; White and others, 1964). The distribution of these features, along with data from geothermal wells discussed below, suggests an extensive geothermal system within the Steamboat Hills involving upflow of thermal fluid beneath the crest of the hills and outflow to the north and northeast. The piezometric surface corresponding to the present-day geothermal system beneath the Steamboat Hills is at depths of 300-1,000 feet below land surface.

The Steamboat Hills structural block was uplifted approximately 2,000 feet above adjacent areas to the east, west, and north along E-NE and N-NE trending normal faults. Faults of unknown displacement but E-NE and N-NE orientations cut through the hills and could provide zones of enhanced permeability for fluid flow at depth. Faults and lineaments identified from black and white areal photographs, as described by Collar (1990), are shown in figure 6 and plates 1 and 2. Many more lineaments were noted than actually appear on these maps; only those lineaments with distinct topographic expressions are shown.

White and others (1964) noted that fault traces within the Steamboat Hills fall into three categories: north-trending, east-northeast-trending, and northwest-trending. North-trending faults are the most common in the unconsolidated deposits surrounding the hills. Included in this set is the Steamboat Springs fault zone denoted by White and others (1964) and White (1968) as controlling the occurrence of hot springs at the main and low terraces (fig. 6 and plate 2). Control on the dip of this fault is based largely on drill-hole data and gravity surveys (Thompson and Sandberg, 1958). These data indicate at least 1,000 feet of vertical displacement across the fault zone. Additional evidence for extensions of this fault zone to the north and south of the terraces is discussed by Collar (1990). Also significant are the Mud Volcano Basin fault referred to previously and the Silica Pit fault, both of which appear to have been associated with surficial hydrothermal activity in the past. The north-trending faults (and faults with N-NE and N-NW orientations) are the most recently active faults in the Steamboat Hills (White and others, 1964) and are probably related to the dominant north-south structural trend of the Basin and Range province.

Northwest-trending structures are largely restricted to the bedrock of the Steamboat Hills. These include a fault mapped in two mine adits in the ACEC and faults forming a small graben approximately a mile west of the ACEC (fig. 6 and plate 2). The westernmost fault vertically offsets basaltic andesite by at least 100 feet and forms a prominent scarp; the easternmost fault forms a low scarp recognizable on areal photographs. A northwestward extension of this fault intersects the Mud Volcano Basin fault west of Sinter Hill.

The E-NE trending structures are most prominent west of the ACEC and north of Silica Pit, where three parallel faults have been mapped (White and others, 1964). One of these faults appears to offset the previously mentioned northwest-trending graben. To the south of these faults, a few east-northeast lineaments can be identified at the crest of the Steamboat Hills. These may be related to the Ridge fault shown on the map of Thermasource (1987), but no evidence for faulting was found in this area during this study. The steeply dipping contact between metamorphic and granitic bedrock also occurs along the crest of the hills and strikes in an east-northeast direction. Several of the Caithness wells drilled along this trend penetrate an alternating sequence of metamorphic and granitic rocks, indicating intrusive tonguing along an irregular contact (fig. 7). It is not known whether significant offset has

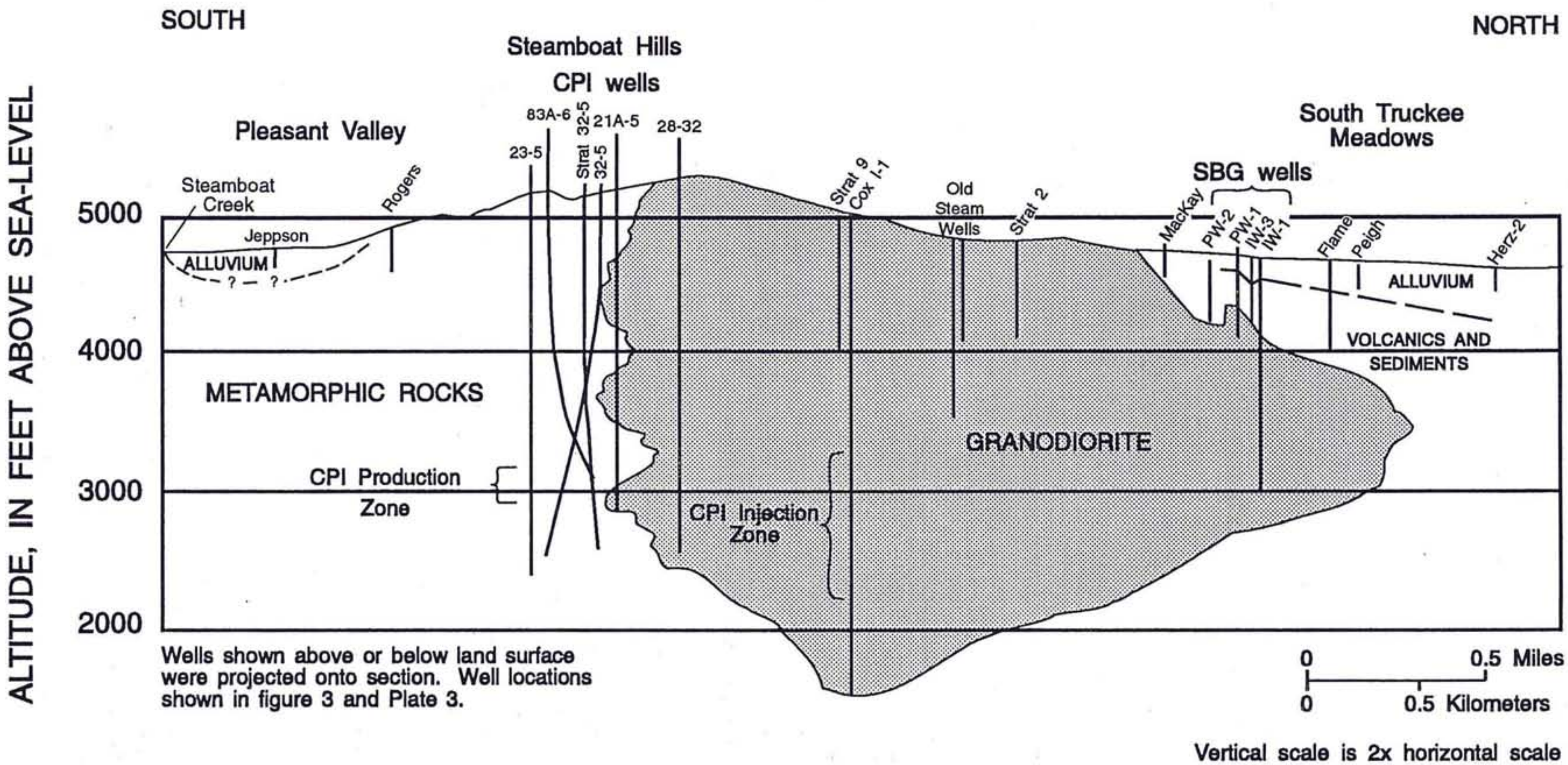

Figure 7. Generalized north-south lithologic section through the Steamboat Hills (modified from Goranson and others, 1990) and positions of selected wells. CPI stands for Caithness Power Incorporated; SBG stands for SB GEO.

occurred along this contact or to what extent production zones in these wells are related to the hypothesized Ridge fault. Near vertical fractures (85°-90° dip) striking in a north-northeast direction have been identified by borehole logging techniques in permeable zones encountered in the Cox I-1 injection well and one other (unspecified) CPI well (Goranson and others, 1990). These authors suggest that a southward extension of the Mud Volcano Basin fault provides a major structural control on permeability within the CPI production and injection reservoirs (C. Goranson, oral communication, 1991; P. van de Kamp, written communication, 1992).

To the south of the CPI production wells, the Pleasant Valley fault may form a boundary between the geothermal system within the Steamboat Hills and the ground-water system in Pleasant Valley (Yeamans, 1984). Stratigraphic test wells strat 6 and strat 7 are completed in bedrock at depths of 1500-1900 feet on the south, or hanging wall side of the Pleasant Valley fault (fig. 6), and encounter bottomhole temperatures of 80°-90°C. These temperatures are considerably cooler than temperatures in wells drilled into bedrock on the north side of the fault. This fault is shown in plate 2 and figure 6 as a combination of faulted segments and lineaments following the location in Thompson and White (1964). However, Tabor and Ellen (1975) depict the fault as continuing on its same trend from the vicinity of CPI well 23-5 toward the Silica Pit fault. No field evidence was found to support locating the continuation of the Pleasant Valley fault in either of the above positions (Collar, 1990).

Geothermal System Characteristics

Regional Flow

Several lines of evidence suggest that thermal waters encountered in fractured bedrock at depths of 1,000-3,000 feet in the Steamboat Hills, in hot springs and associated reservoirs beneath the silica terraces, and in alluvial aquifers in the South Truckee Meadows are hydrologically connected within a regional-scale geothermal system. These include similarities in chemical characteristics of thermal water (for example, Cl/B ratios), systematic decreases in hydraulic head and reservoir temperature to the north and east of the CPI production reservoir, and regional-scale E-NE and N-NE fault orientations. The study by White (1968) indicates that fluid discharge from this geothermal system and from the associated regional ground-water system occurs predominantly as seepage into Steamboat Creek. It has proven very difficult, however, to delineate the actual flow paths for thermal water and the degree of hydraulic (pressure) communication between features spaced a few miles or even a few thousand feet apart.

The age of thermal water from hot springs at Steamboat was estimated from its ^{14}C activity as about 40,000-43,000 years (Flynn and Ghusn). The estimated error in these determinations is large (standard deviation 12,000 years) because the ^{14}C activity is near minimum detection limits and approaches background. In contrast, thermal waters discharging from hot springs in the Moana geothermal area northwest of Huffacker Hills (at latitude 39° 30′ in figure 8) show carbon ages of about 8,000 years (Flynn and Ghusn, 1983). Although the ^{14}C activities in these waters indicate that they are relatively old, there are several sources of error that are difficult to properly account for in age determinations of this type. Principal among these is the addition of dead carbon from calcareous rocks.

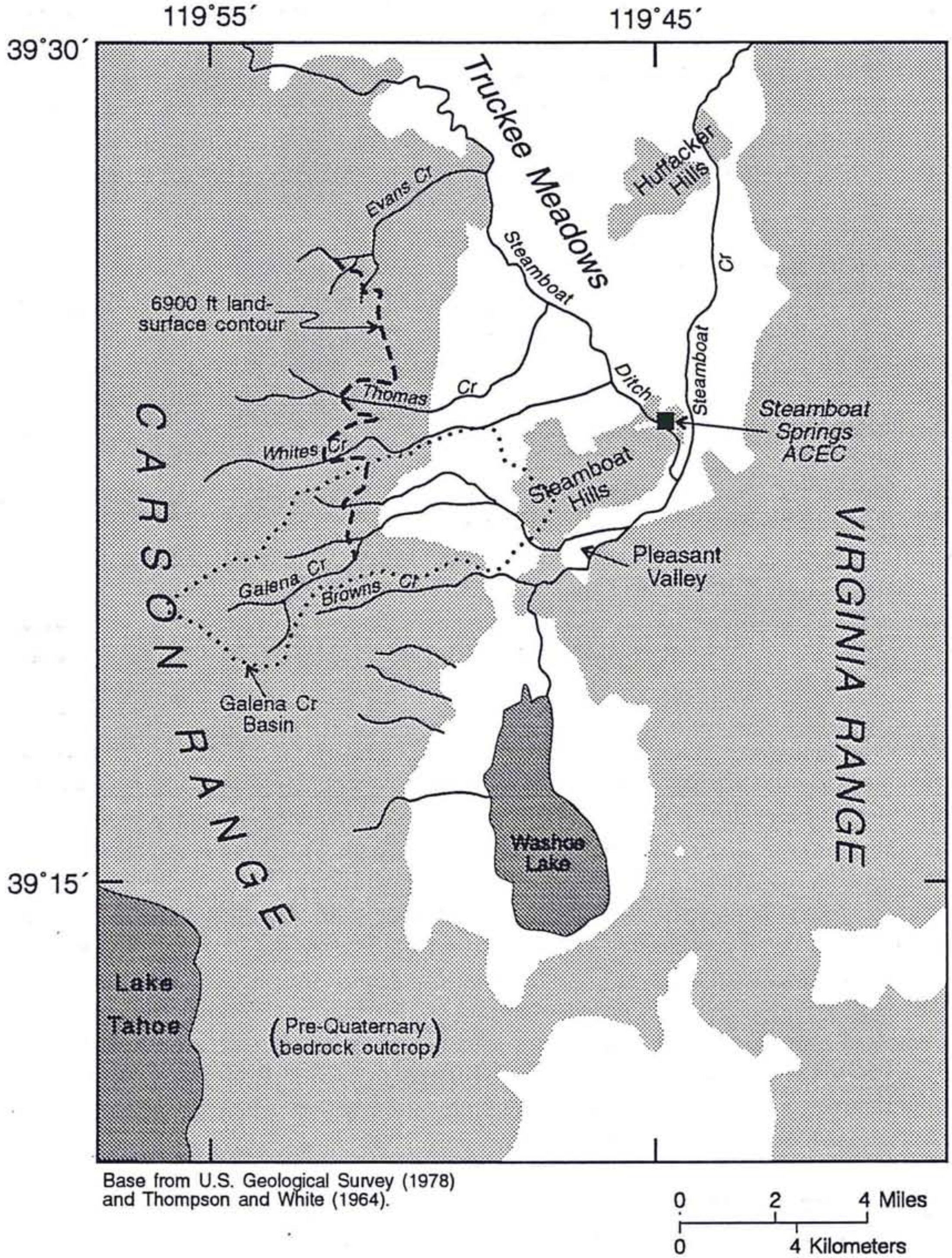

Figure 8. Map of Steamboat Hills area showing locations of Galena Creek drainage basin and 6,900 foot land-surface contour (sea-level datum) in the Carson Range, between Galena Creek and Evans Creek.

An alternative estimate of the age of thermal waters discharging from the Steamboat system is obtained by calculating the travel time through an assumed volume of the geothermal system. For a system volume of 6 mi^3 (width 3 miles, thickness 1,000 feet, length 10 miles), the travel time from recharge to discharge area would be close to 2,000 years for an average rock porosity of 0.05 and a total flow of 1,100 gal/min. This estimate of the total flow through the system matches that calculated from measurements of chloride-flux in Steamboat Creek, as discussed in subsequent sections of this report. The travel-time calculation demonstrates that unreasonably large system volumes would be required to yield thermal-water ages close to 40,000 years, and implies that the actual age of the thermal water may be closer to a few thousand years.

Possible areas of recharge to the Steamboat geothermal system have been delineated from differences in stable isotopes of oxygen and hydrogen in thermal and nonthermal waters in different parts of the Steamboat region. The isotope data from Nehring (1980) show that the hot spring waters are isotopically enriched in ^{18}O relative to the meteoric water line due to high-temperature water-rock reactions, but that the deuterium value of meteoric water recharging the hot springs matches the deuterium value for present-day precipitation at elevations near 6,900 feet in the Carson Range (fig. 9). Nehring's isotope data would further narrow the likely recharge area to the region between Galena Creek in the south and Evans Creek in the north (fig. 8), provided the isotopic characteristics of precipitation in this area are the same now as they were when recharge took place. This assumption would be valid for recharge occurring several thousand years ago, but would be questionable for water that is 40,000 years old. The isotope data of Flynn and Ghusn (1983), which show deuterium values of -120 to -130 o/oo for the Moana thermal waters, lead to the inference that these waters were recharged at higher elevations in the Carson Range than were the thermal waters discharging at Steamboat.

We have augmented the stable-isotope data from Nehring (1980) with two values for geothermal wells - one representing the average value for six samples collected over a one-week period in the summer of 1980 from well SB-1 (from Yeamans, 1984) and one representing the average of total flow samples collected in November 1991 from several production wells in the SB GEO well field. These data plot along the trend line for the hot-spring waters, suggesting common origins. Isotope values for samples collected in November 1991 from the CPI production wells are not yet available, but should prove useful, along with the associated chemical analyses, in delineating relations between thermal waters in different parts of the Steamboat Region.

Katzer and others (1984) used a water-budget for the Galena Creek basin to calculate a loss of approximately 2,700 gal/min into the fractured bedrock beneath the basin. For comparison, White (1968) estimated the total thermal-water discharge from the Steamboat geothermal system to be 1,110 gal/min. Ground water discharges into Galena Creek as it flows eastward through the bedrock gorge between the Galena Creek basin and Pleasant Valley. Thus, any recharge from Galena Creek to the geothermal system must occur upstream of the Steamboat Hills. Locations of recharge and discharge areas for the geothermal system, and hydraulic head data discussed below, are consistent with an overall southwest to northeast flow within the geothermal system, parallel to the topographic axis of the Steamboat Hills and the east-northeast structural trends discussed above.

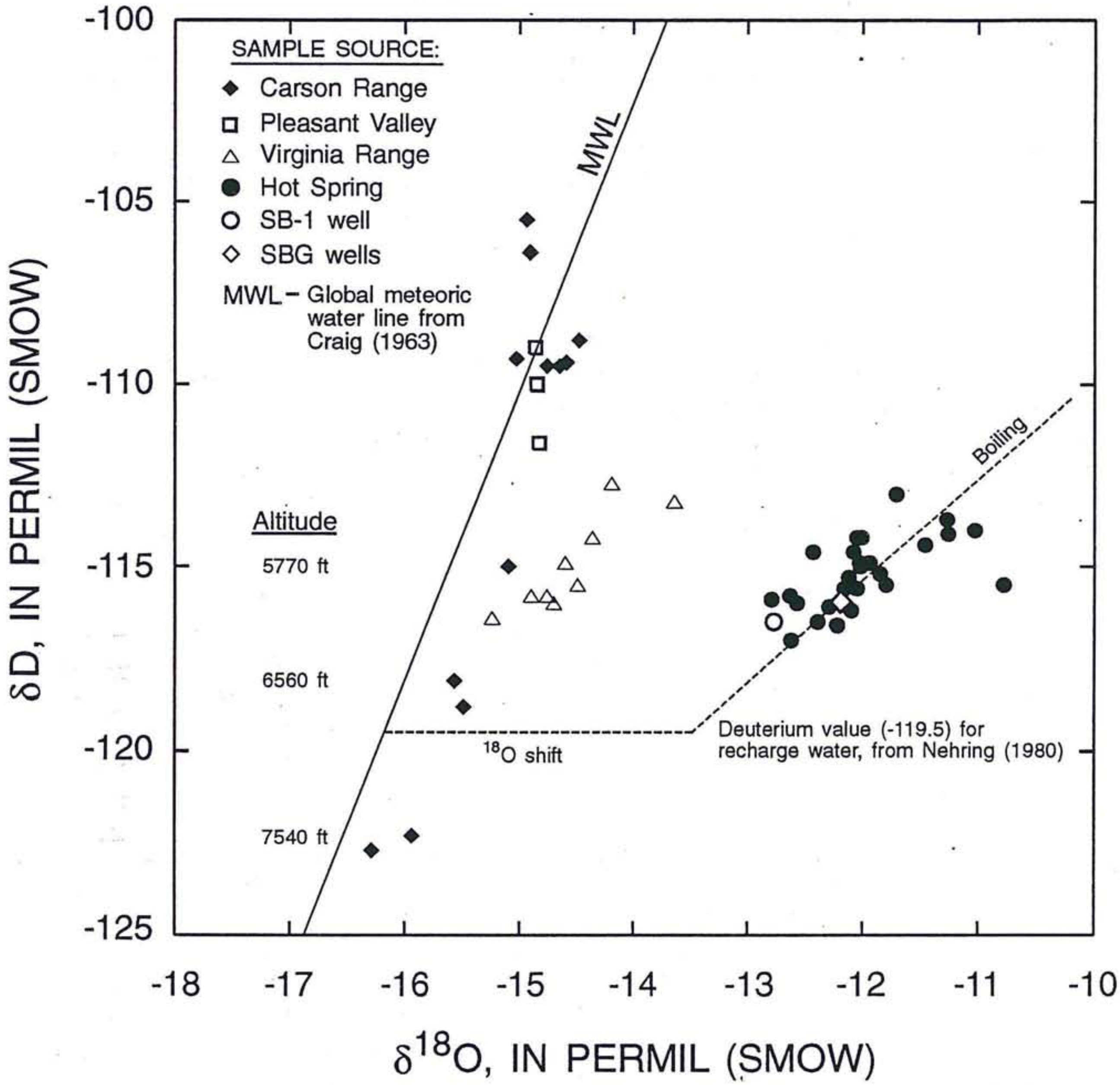

Figure 9. Stable water isotope values for waters from the Steamboat region showing the change in deuterium (D) with altitude in the Carson Range and how oxygen-isotope shift (from rock-water interactions) and boiling could account for the compositions of waters from hot springs on the main terrace and wells in the Caithness Power Incorporated (CPI) and SB GEO (SBG) well fields. All spring data is tabulated by (1980). SMOW stands for Standard Mean Ocean Water, used for reference.

The Steamboat geothermal system is part of a larger regional ground-water flow system that extends north of the Steamboat Hills toward the Truckee River (fig. 10). Contours of ground-water table altitude show that the general direction of flow in the unconsolidated deposits is from the valley margins (the Carson and Virginia Ranges) toward Steamboat Creek in the South Truckee Meadows. There is also a northward component of ground-water flow towards Huffacker Hills. Streamflow measurements made during this study and those reported by Shump (1985), White (1968), and Cohen and Loeltz (1964), show that Steamboat Creek is a gaining stream throughout the South Truckee Meadows and, consequently, a region of discharge of both thermal and nonthermal ground water. Piezometers installed in the bed of Steamboat Creek east of the main and low terraces show a hydraulic gradient for upward flow (Shump, 1985), also indicating ground-water discharge into the creek.

Steamboat Hills

Thermal water at temperatures of 50°-230°C is encountered in wells drilled in the Steamboat Hills. Goranson and van de Kamp (1989) and Goranson and others (1990) postulate that there are several isolated geothermal systems in the Steamboat region, including the high-temperature (210°-230°C) system tapped by the CPI production wells near the crest of the hills, the moderate-temperature (170°C) system tapped by the SB GEO wells on the northeast flank of the hills, and "several low-temperature systems" within the alluvial aquifers surrounding the Steamboat Hills that feed hot springs on the silica terraces and the surrounding valleys. The evidence cited for separate flow systems includes differences in altitudes between thermal reservoirs in each area, differences in reservoir temperature and in lateral temperature gradient between the CPI well field and strat 9 and between strat 9 and strat 2 (fig. 3), and a lack of convincing evidence of pressure communication between the CPI production and injection wells and various wells and hot springs. The degree of connection between thermal areas in the Steamboat region is clearly important to an assessment of the factors influencing changes in hot-spring activity on the main terrace. The information on system characteristics presented in this section does not in itself prove or disprove that there is hydraulic communication between any two areas. As in most geothermal settings, it is necessary to stress the system and measure subsequent changes to provide a clearer indication of cause and effect relations and hydraulic connections. This approach has not been fully successful at Steamboat because more than one stress has been in effect and the existing monitoring program has lacked adequate observation of pressure changes in production reservoirs and beneath the main terrace.

Production and injection zones in the various Caithness wells occur at similar altitudes, but at depths of 2,500-3,000 feet and about 2,000 feet, respectively (fig. 7). The altitudes of these zones are about 1,000 feet lower than that of the SB GEO production zone. The prevalence of normal faults of different orientations in the Steamboat Hills and temperature reversals in many of the thermal wells suggest that zones of thermal-water flow are related to fractures and perhaps fault intersections in the metamorphic and granitic bedrock. There are some data from core drilling and well logging indicating fracture control on production zones at the CPI and SB GEO well fields (Goranson and others, 1990 and 1991). However, the relations between permeable zones encountered in different wells are poorly understood. The maximum temperatures in the three CPI production wells vary from 210° to 230°C and temperature reversals below the main production zone in each well indicate hydraulic

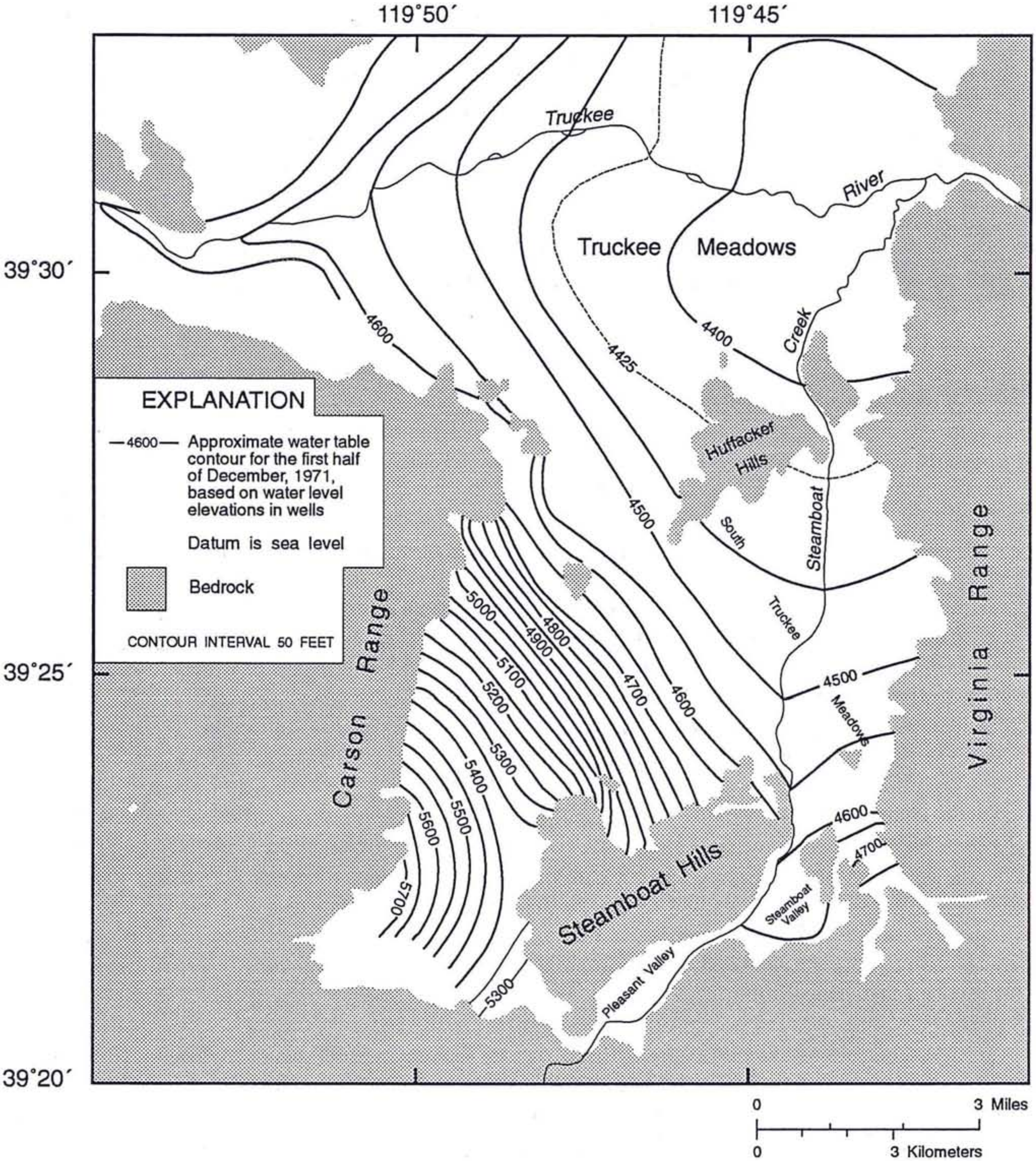

Figure 10. Water-table elevation map for the Truckee Meadows - Steamboat Hills area (from Cooley and others, 1971).

isolation of the fractures transmitting hot water to each well from deeper rocks. Somewhat surprisingly, pressure data from well interference tests indicate that the CPI and SB GEO reservoirs can be simulated as radial and homogeneous (Collar and Huntley, 1990; C. Goranson, written communication, 1991; and results discussed in subsequent sections of this report). Because the Caithness injection well (Cox I-1) is located closer to the main terrace than are the Caithness production wells (21-5, 23-5, and 83-A6), either heterogeneous reservoir conditions or a hydraulic boundary is required to explain the lack of evidence for pressure increases beneath the main terrace from operation of the CPI well field. At the SB GEO well field, injection wells IW-2 and IW-3 are located farther from the main terrace than are production wells PW-1, PW-2, and PW-3.

A schematic section drawn northeastward from the Caithness well field to the main terrace (fig. 11) illustrates relations between temperature and hydraulic head within the Steamboat Hills. Location of the section onto which various features were projected is shown in figure 12. The designated production and injection zones are based on drilling results which consistently show permeable fractures within these zones and low-permeability fractures and wall rocks above (and in some cases below) these zones. Although the permeable features penetrated by these wells may actually be related to steeply dipping faults, it appears that such structures are sealed by mineral deposits above altitudes of about 3,200 feet in the CPI well field and 4,300 feet in the SB GEO well field. Such sealing could be related to lower temperatures above the permeable zones. The injection zone in Cox I-1 must be hydraulically connected to the CPI production zone to the southwest because it appears to provide injection-pressure support, but must not be simply connected to the main-terrace hot springs because there is no evidence of rapid pressure increases beneath the main terrace from injection in Cox I-1. This matter is more fully discussed in subsequent sections of the report.

Piezometric-surface altitudes (hydraulic head) were calculated either from pre-production downhole pressure surveys (Caithness wells 83-A6 and Cox I-1) or water-level measurements. The pre-production water level in strat 9 was estimated at 375 feet below land surface, from measurements beginning in December 1987 and comparisons with hydrographs for strats 2 and 5 prior to that date. These data show consistent decreases in maximum temperature and head along this section, except that the injection zone in Cox I-1 is characterized by lower temperature and head than found at shallower depths at this site and lower head than that corresponding to spring altitudes at the main terrace. There is a suggestion from the data for strats 2 and 9 and Cox I-1 that each well penetrates a permeable zone containing thermal water at temperatures of 170°-180°C at similar altitudes near 4,300 feet. The altitude, temperature, and head of this zone are consistent with lateral flow of thermal water at this level toward the main terrace and the SB GEO well field. It is not known whether there is in, in fact, a continuous thermal aquifer connecting these areas, or whether hydraulic connections that may exist between these areas involve fracture-controlled flow along complex paths. White (1968) notes that temperatures below a depth of about 350 feet at the main terrace are relatively constant at about 175°C, lending support to the concept of hydrologic connection between the main terrace and a "shallow thermal-water flow zone" in the Steamboat Hills.

Hydraulic connection between the Caithness production zone and the hypothesized shallow thermal flow zone could be provided through an upflow zone between the production

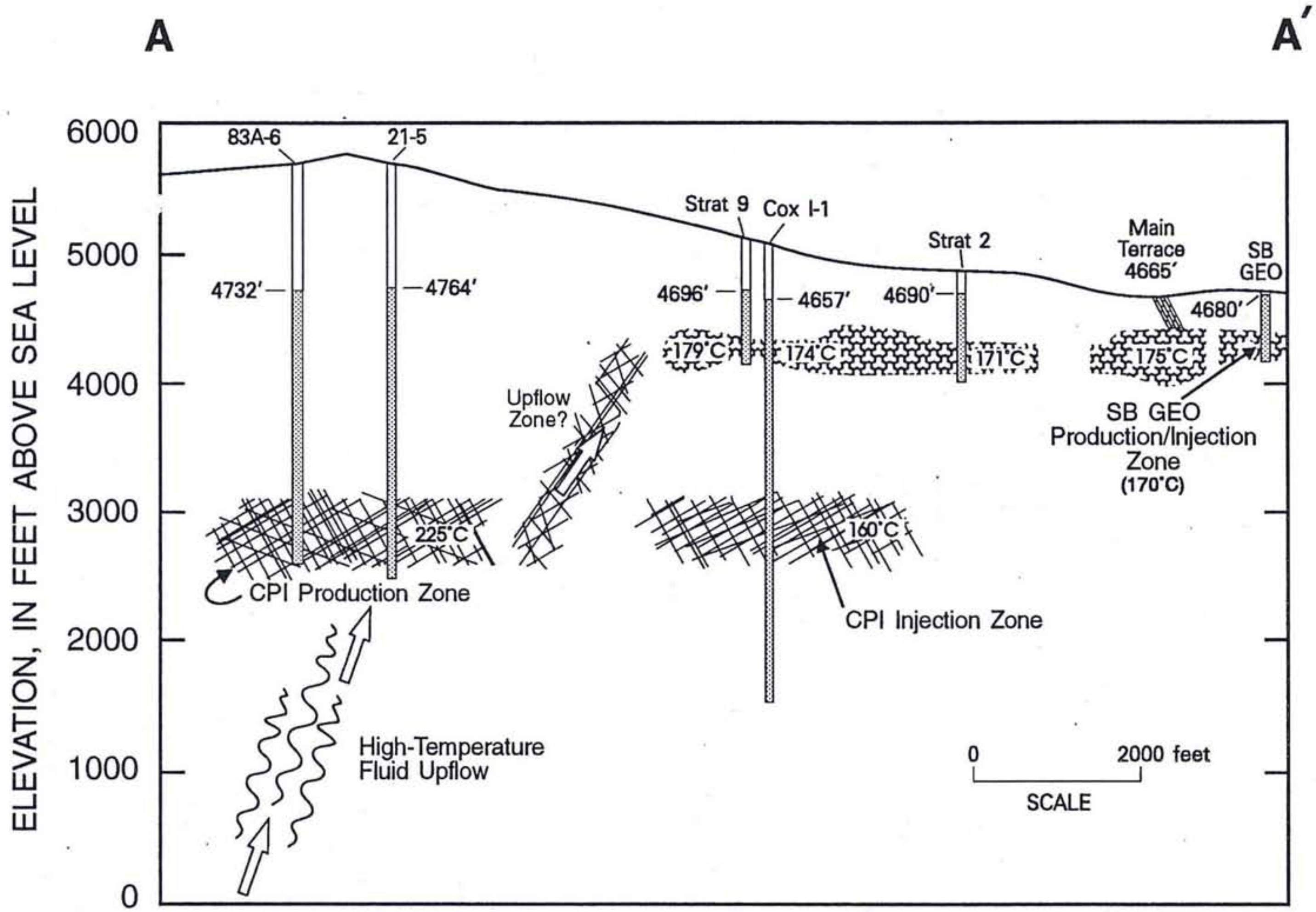

Figure 11. Schematic section through the Steamboat Hills geothermal area showing relations between zones of thermal-water flow (patterned) encountered in wells (labeled with well name). CPI stands for Caithness Power Incorporated. Measured temperatures are shown, along with altitudes of the piezometric surface determined from downhole-pressure surveys or water-level measurements. Section location shown in figure 11.

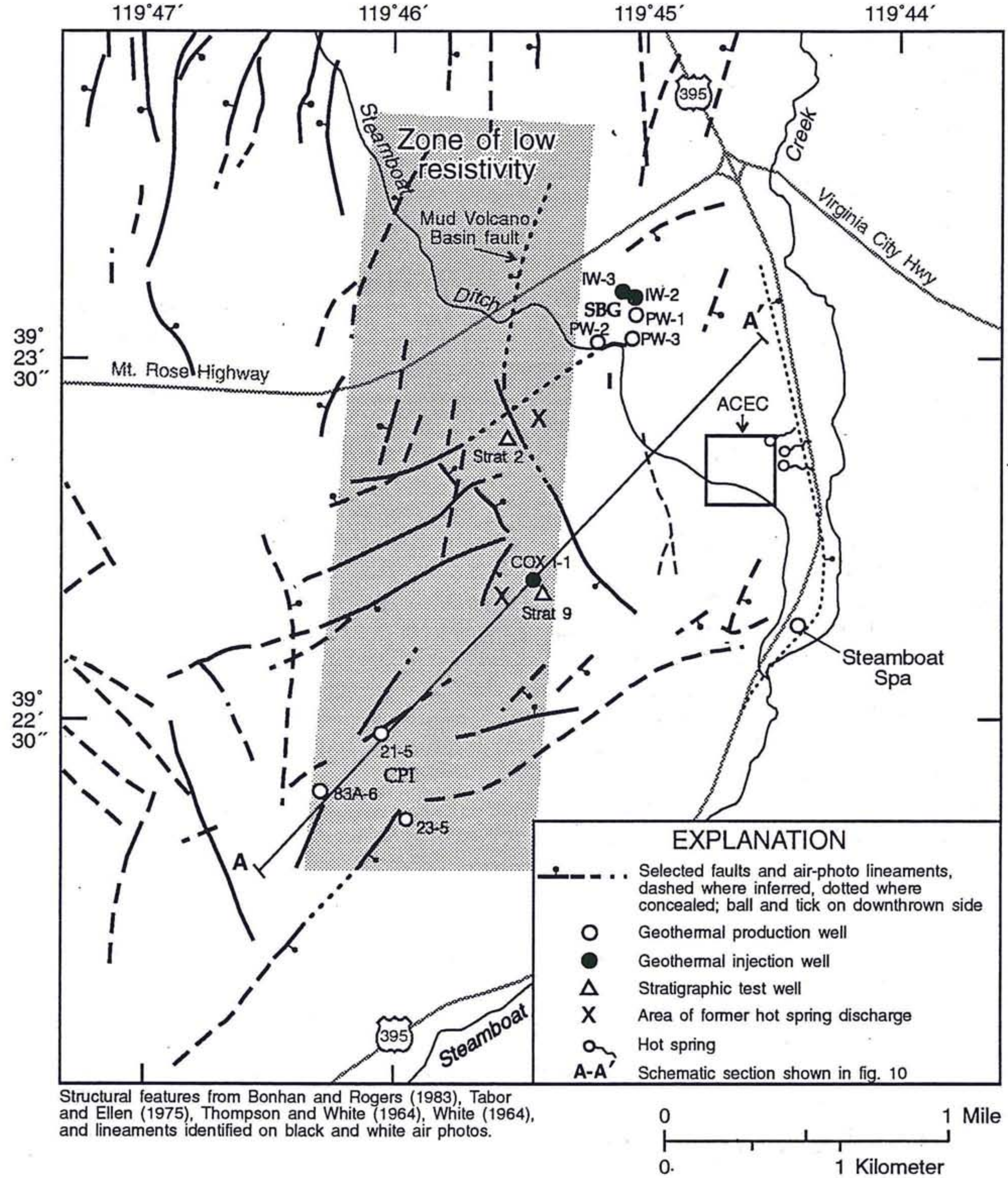

Figure 12. Zone of low electrical resistivity identified by telluric, audiomagnetic, and airborne electromagnetic surveys (Corwin and Hoover, 1979; Christopherson and others, 1980, Long and Brigham, 1975; and D.B. Hoover, written communication, 1991). Line A-A′ represents location of schematic section shown in figure 10. CPI stands for Caithness Power Incorporated; SBG stands for SB GEO; ACEC stands for Area of Critical Environmental Concern.

and injection wells. The existence of such a connection is not unreasonable, given the abundance of steeply dipping structures crossing the Steamboat Hills. Well interference data, discussed in a later section, do in fact demonstrate pressure communication between the CPI production wells and strats 2 and 9. For the purposes of this report, we will refer to a shallow thermal-water flow zone as existing beneath the Steamboat Hills and penetrated by strats 2 and 9 and the Cox I-1 well, recognizing the possible oversimplifications that this terminology may convey.

The production and injection zones at the SB GEO well field occur at similar altitudes and contain fluids with temperatures similar to those in permeable zones encountered in drill holes in the ACEC portion of the main terrace. However, higher hydraulic heads were indicated beneath the high terrace than beneath the main terrace under pre-development conditions, suggesting that thermal water did not flow directly from the main terrace to the high terrace. Electrical geophysical studies (discussed below) and well interference tests give some indications of thermal-water flow and hydraulic connections between the CPI well field and the SB GEO well field.

Goranson and others (1990) show a schematic section through the Steamboat Hills similar to that depicted in figure 11, but with "hydraulic pressure boundaries" separating the Caithness reservoir from the shallow thermal zone, the main terrace springs, and the SB GEO reservoir. In their conceptual model, each of these areas is fed by separate deep-seated upflow zones at different temperatures. No discharge points are indicated by these authors for thermal water flowing through either the Caithness reservoir or the shallow thermal reservoir. The existing subsurface information does not allow us to determine if either of these simplified models is close to reality. Although comparisons with other liquid-dominated geothermal systems suggests to us that a single, interconnected geothermal system is the simplest and most reasonable way to explain the occurrences of thermal waters within the Steamboat Hills area, the actual connections between areas may occur along deeper and more complex flow paths.

Regardless of which conceptual model is preferred, the response of different parts of the system to stresses such as those imposed by geothermal production and injection operations at two different well fields cannot be adequately predicted. Responses to stress must instead be measured after the fact because the hydraulic properties of the system are unknown, except in the immediate vicinity of the well fields. A further complication is that changes in water level in the ground-water system into which thermal water from beneath the main terrace flows could also affect heads and rates of hot-spring discharge at the main terrace. Hot springs in the ACEC are situated approximately 100 feet above the level of Steamboat Creek and may be particularly sensitive to such changes.

Geochemistry

The geochemistry of the main- and low-terrace springs and of the thermal ground water in the vicinity of the Steamboat Springs geothermal area has been studied by numerous authors (for example, Brannock and others, 1948; White, 1968; Bateman and Scheibach, 1975; Nehring, 1980; Yeamans, 1984; and Goranson, 1991). As noted by these authors, the geochemistry of the hot-spring water and thermal ground water in the Steamboat Hills is distinctly different from other ground water in the vicinity of the Steamboat Hills and the South Truckee Meadows. Some characteristics of the thermal water include temperatures in excess of 20°C (Bateman and Scheibach, 1975), high total dissolved solids, elevated concentrations of arsenic, boron, and chloride ions, and a generally uniform chloride/boron ratio of about 18 (White, 1968).

The most characteristic and useful property for tracing thermal ground water from the Steamboat Springs geothermal area is chloride concentration, because it is high relative to the chloride concentration in nonthermal ground water and acts conservatively. White (1968) concluded that the most representative thermal ground water from the discharge part of the Steamboat Springs geothermal area has a chloride concentration of 820 mg/L. In contrast, chloride concentrations in nonthermal ground water from wells adjacent to the Steamboat Hills range from 0-30 ppm, but are generally less than 15 mg/L (Cohen and Loeltz, 1964; White, 1968; Bateman and Scheibach, 1975; Yeamans, 1984). Furthermore, surface water from streams draining the Carson Range and from Steamboat Creek upstream of the low terrace commonly has chloride concentrations of less than 10 ppm, though concentrations may be as great as 23 ppm (D. White, oral. communication, 1988). Cold springs in the region generally have chloride concentrations of <11 mg/L (White, 1968; Nehring, 1980). This marked difference in the chemistry of thermal and nonthermal waters can be used to identify areas of discharge from the Steamboat Springs geothermal system.

Representative chemical data for hot-spring and well waters are listed in table 1. For the SB GEO wells, the reported analyses are for total flow samples; for the CPI wells, analyses for flashed samples were corrected (by us) for flash using the cation geothermometer-temperature estimates to calculate the amount of boiling at the wellhead. From these data the general similarity in thermal-water chemistry between these waters is apparent, particularly in terms of the constancy of ratios of conservative elements such as Cl/B (19.3 ± 1.7, neglecting the Cox well) and Cl/Li (122.5 ± 9.9, neglecting the Cox well). The hot-spring waters, as exemplified by samples from spring 6 and from the seep that currently issues from a casing break in well GS-5, are more concentrated than waters from the geothermal production wells. The spring waters are also more concentrated than waters from shallow wells completed in granodiorite bedrock on the main terrace (for example GS-5). Nehring (1980) attributed this difference to varying degrees of boiling from a source water at 230°C with a Cl concentration of about 700 mg/L. This source-water temperature was determined from cation geothermometer calculations for spring waters. The flash-corrected Cl for CPI wells 83A-6 and 21-5 (697-737 mg/L) are close to that of the hypothesized source water, whereas Cl concentration in the SB GEO wells (801-811) are more similar to those in the reservoir underlying the main terrace (820 mg/L). These observations, along with relatively low dissolved gas in the SB GEO wells (R.H. Mariner, oral communication, 1992), could be explained by a common source water that flows from the CPI production reservoir to the reservoir beneath the main terrace, boiling and exolving gas enroute, and then flowing at depth to the SB GEO production reservoir. The chemical data set does not, of course, prove that such a flow system exists; a more direct flow connection between the CPI and SB GEO reservoirs is also possible as long as there were opportunities for Cl concentration and gas loss by boiling. Based on the existing flash-corrected chemical analyses, there appear to be significant differences between thermal water produced by CPI well 23-5 and the other two CPI production wells. The water from 23-5 is more concentrated (Cl=793 mg/L), has a

Table 1. *Chemical data for thermal waters from the Steamboat Springs area*

[Results are given in milligrams per liter and are corrected for steam loss at amospheric flash, assuming constant enthalpy equal to that at production-zone temperature; --, no data]

Feature		Date	T_{WH}[1]	T_{DH}[2]	T_{Cation}[3]	pH[4]	SiO_2	Na	K	Ca	Mg	Li	HCO_3	CO_3	Cl	B	F	SO_4
CPI[5]	21-5	04/13/90	216	221	238	8.99	296	589	56	1.5	--	5.5	166	41	737	40	2.5	114
	83A-6	04/12/90	221	221	237	8.74	323	537	63	2.0	--	5.5	181	30	697	38	2.5	102
	23-5	04/18/90	232	238	256	8.82	420	594	88	2.0	--	6.8	212	34	793	44	2.5	91
COX I-1		04/30/81	120	160	215	8.06	265	581	56	5.6	--	7.4	323	--	750	33	2.1	112
SBG[6]	PW-1	12/90	170	170	212	--	276	618	59	16	0.8	--	273	--	811	42	2.0	118
	PW-2	12/90	170	170	217	--	275	576	59	14	--	--	248	--	802	36	2.1	101
	PW-3	12/90	170	170	218	--	293	613	62	13	--	--	233	--	811	37	2.1	102
Hot spring 6[7]		06/10/77	97	--	217	7.4	214	660	65	6.8	0.016	7.8	387	--	871	48	2.2	123
Well GS-5[8]		1950	--	173	--	--	--	--	--	--	--	--	--	--	820	--	--	--
Spring GS-5[9]		06/25/91	97	--	234	8.87	--	693	68	3	0	--	98	70	1000	53.1	2.7	151

[1]Temperature measured at well head, in degrees Celsius.
[2]Temperature measured downhole in production/injection reservoir, in degrees Celsius.
[3]Temperature calculation from Na-K-Ca geothermometer, in degrees Celsius.
[4]From lab measurement on flashed sample.
[5]Flashed sample analyses from University of Utah Research Institute (UURI) for Caithness Power Incorporated (CPI) production wells 21-5, 83A-6, and 23-5; Cox well sample analyzed by AMTEC.
[6]Total flow sample analyses from Goranson (1991) for SB GEO (SBG) production wells PW-1, PW-2, and PW-3, sampled in 1990.
[7]Analysis from Nehring (1980).
[8]From White (1968).
[9]New seep adjacent to well GS-5, analysis by Nevada Division of Health Laboratory.

higher gas content (100 psi versus 33 partial pressure), and enters the well from a higher temperature zone (238°C versus 221°C). Cation geothermometer temperature estimates may exceed the measured reservoir temperatures for these CPI wells because of Ca loss from the use of scale inhibitor. In spite of these apparent differences in thermal-fluid characteristics, each well is in hydraulic communication with the other (Faulder, 1987).

Ground water with relatively high concentrations of Cl, B, and other elements associated with thermal waters from the Steamboat geothermal system is found in various parts of the sediment-filled region north and east of the Steamboat Hills. These waters are detected in wells and in thermal springs, as discussed by Goranson (1991) and Goranson and van de Kamp (1991). Some of these low-temperature geothermal waters are clearly related to the Steamboat geothermal system, and are probably derived from northward flow within alluvial or bedrock aquifers. Ground water with chemical characteristics similar to the Steamboat geothermal waters detected in wells east of Steamboat Creek and Damonte Springs (fig. 13) could be derived from secondary recharge, or infiltration of Steamboat Creek water diverted into various irrigation ditches during the irrigation season. In contrast, ground water with high concentrations of calcium and sulfate but low concentrations of Cl, which occurs in the general vicinity of Toll Road east of the low terrace at Steamboat, is most likely derived from the Virginia Range.

Electrical Geophysics

Various electrical geophysical surveys have been undertaken by the U.S. Geological Survey to delineate the distribution of thermal fluids beneath the Steamboat Hills. White and others (1964) summarize the results of resistivity measurements at the silica terraces, which show general correspondence between resistivity and depth to the saline water table and the thickness of relatively low porosity (and high resistivity) sinter. Self potential, telluric, audiomagnetotelluric (AMT), and airborne electromagnetic (AEM) surveys conducted in the 1970's (Corwin and Hoover, 1979; Christopherson and others, 1980; Long and Brigham, 1975; and D.B. Hoover, written communication, 1991) delineate a significant north-northeast trending conductive zone west of the main terrace (fig. 12). This zone of low resistivity is truncated south of the CPI well field, indicating a possible fault control to the southern extent of the geothermal system in the Steamboat Hills. Lower resistivities in the northern part of the anomaly (as low as 2 ohm-meters) could reflect a combination of thicker alluvial cover and shallower depths to hot-water. The telluric anomaly appears to extend northward toward Huffaker Hills but survey stations did not extend north of the intersection of Highway 395 and the Mt. Rose Highway. Although not shown in figure 12, a corresponding zone of high self potential (SP) occurs along the eastern edge of the resistivity trough; high SP is also found along the main terrace.

These geophysical data are consistent with movement of thermal water along a major west-dipping structure associated with the Mud Volcano Basin fault west of the high terrace and its possible southward extension across the Steamboat Hills. However, more detailed studies of this type along with comparisons of surface geophysical measurements with borehole measurements of resistivity and temperature are needed to differentiate between the effects of thermal fluid flow, hydrothermal alteration, and fluid chemistry on these results.

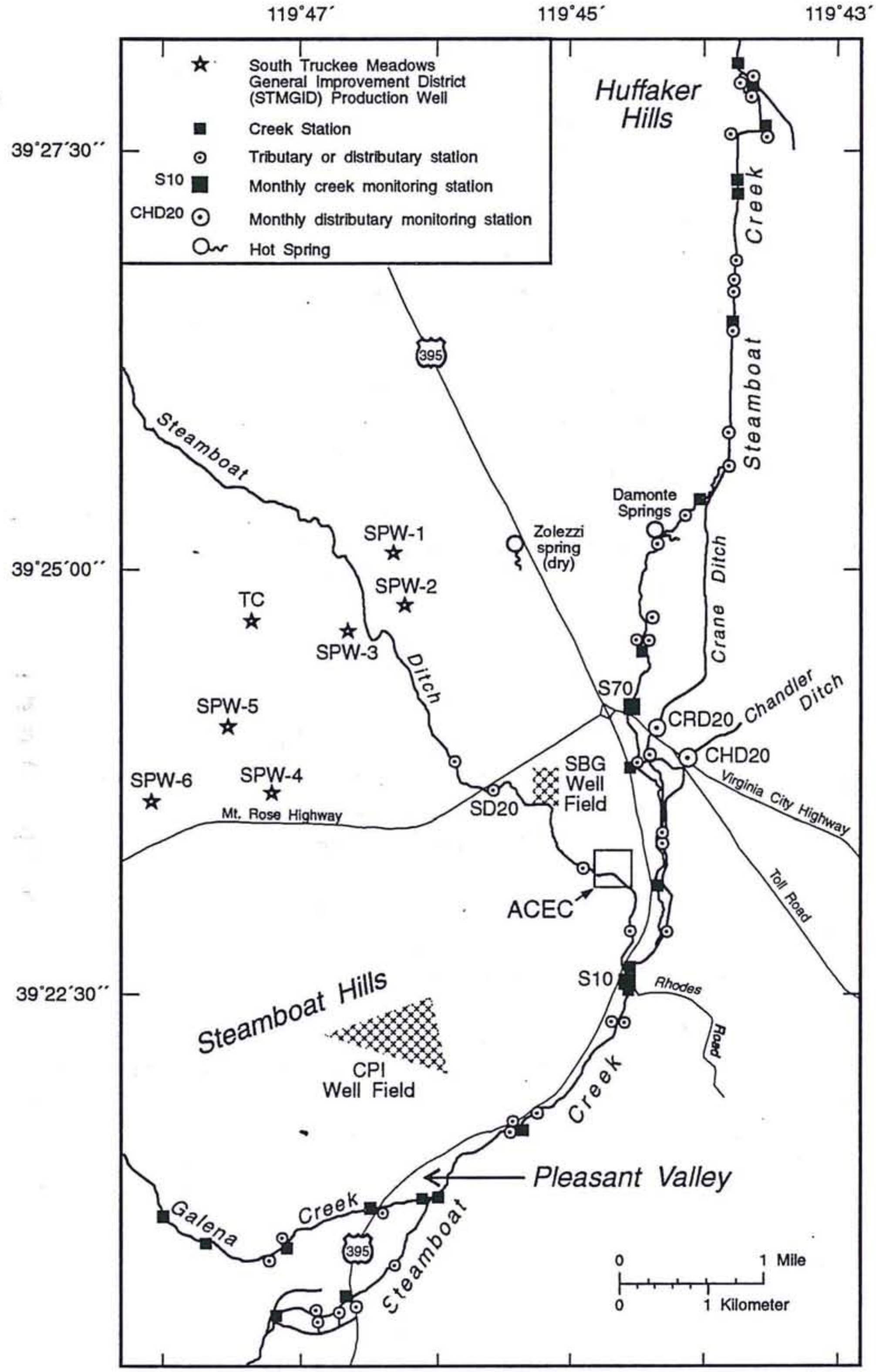

Figure 13. Locations of stream gaging stations.

Thermal-Water Discharge

Thermal water discharges in the Steamboat area from wells and springs and as seepage into Steamboat Creek. During the 1945-52 period, White (1968) estimated the total thermal-water discharge from the "Steamboat geothermal system" as 1,110 gal/min, 50 percent of which occurred as unseen seepage into the creek between Rhodes Road and Huffaker Hills (plate 3 and fig. 13). During that period, thermal water discharged from springs at the main terrace (60 gal/min), the low terrace (5 gal/min), and in the South Truckee Meadows (85 gal/min). This latter group of springs (plate 3) includes Damonte Springs (SW 1/4, sec. 16, T18N, R20E), Drainage Ditch Springs (SW 1/4, sec. 15, T18N, R20E), Huffaker Springs (S 1/2, sec. 3, T18N, R20E), Double Diamond Springs (N 1/4, sec. 9, T18N, R20E), and the Zolezzi spring (SE 1/4, sec. 17, T18N, R20E). The total flow rate noted above for these springs is based on an assumed thermal-water component with Cl = 820 mg/L for each spring and represents the sum of the calculated component of high-chloride (820 mg/L) thermal water in their discharge. Measured chloride concentrations in these springs range from 94-130 mg/L (Zolezzi Spring) to 560 mg/L (Damonte Spring). Ratios of Cl/B for these spring waters and for water from Steamboat Creek north of Rhodes Road are similar to values for hot springs on the main terrace and thermal wells in the Steamboat Hills and South Truckee Meadows, leading White (1968) to suggest that thermal water originating in the Steamboat Springs geothermal area flows eastward and northward and discharges as springs and seepage into Steamboat Creek south of Huffaker Hills. This is consistent with the general direction of ground-water flow in the South Truckee Meadows (fig. 10) and with streamflow, conductivity, and chloride-flux measurements in Steamboat Creek by White (1968), Cohen and Loeltz (1964), Shump (1985), and those made during this study (Appendix F).

White (1968) used April 1955 measurements of stream discharge and chloride concentration upstream of the low terrace (Rhodes Road), at State Highway 341 (also known as the Virginia City Highway), and at Huffaker Hills to calculate a total seepage rate of 660 gal/min of thermal water with a chloride concentration of 820 mg/L. This rate was calculated by subtracting the rates of discharge from springs and wells entering the creek from the total rate of thermal-water entering the creek (1,110 gal/min from table 2). A similar calculation made by White (1968) for stream measurements made in April 1964 yielded a total discharge of 1,385 gal/min. White (1968) suggested that the greater chloride flux in 1964 could be due in part to input of chloride salts stored in shallow soils and mobilized with infiltration derived from a snow storm the previous week. Shump (1985) used averages for the 1981-82 period of measurements of stream discharge and specific conductance to estimate that 1,300 gal/min of thermal water discharged to Steamboat Creek. Shump's estimate of thermal-water discharge is considered less reliable that those of White because it is based on specific conductance measurements rather than chloride measurements and involves average values of streamflow and specific conductance instead of values from synoptic measurements, as discussed by Collar (1990). One important difference between conditions during the times of White's measurements and those of Shump is that geothermal wells discharged at significant rates at the north end of the main terrace and on the low terrace in the 1950's and 1960's, but had been abandoned or were little used before the 1980's. The general agreement between each set of results and comparisons with estimates of spring flow on the main terrace in 1916, as discussed in a later section, suggests that the discharge from these wells in the 1950's and 1960's (averaging about 300 gal/min) represents thermal water that would have flowed from

Table 2. *Thermal-water discharge from different sources in the Steamboat Springs area*

Source and date of measurements	Well discharge[1] gal/min	Spring discharge from terraces[2] gal/min	Unseen discharge in Steamboat Ck above Virginia City Highway[3] gal/min	Discharge into Steamboat Ck below Virginia City Highway[4] gal/min	Total discharge from geothermal system gal/min
White (1968) 4/55	300	65	260	485	1110[5]
White (1968) 4/64	--	--	--	--	1385[6]
Collar (1990) 6/88	(380)	3	180[7]	340[7]	523[8]
Collar (1990) 8/88	(380)	3	150	--	--
Collar (1990) 3/89	(380)	3	230	430	663[8]

[1]For 4/55, discharge from wells occurred only at Reno, Mt Rose, and Steamboat Resort and flowed on the surface into Steamboat Creek. Value reported by White (1968) has been adjusted to a volumetric flow rate at 90°C. For this study, the value shown in parentheses is the average of the net production rate for the CPI well field, calculated for an evaporative fluid loss of 12 percent of an average production rate of 4,000 gpm and adjusted to a volumetric flow rate at 90°C with 820 mg/L Cl.

[2]Values from Collar (1990) are for spring 50 on the Low Terrace.

[3]From chloride flux measurements, assuming Cl in thermal and nonthermal water of 820 mg/L and 4 mg/L, respectively.

[4]Same as in 3 above, except that the totals include inflow from thermal springs (85 gpm for 4/55, and Damonte Springs in our study).

[5]Value listed differs from the 1125 value of White (1964) because of lower well discharge calculated for 90°C conditions.

[6]Based on chloride-flux measurements only.

[7]Values shown are averages of 160-190 gpm and 330-340 gpm ranges.

[8]Not counting net production from Caithness Power Incorporated (CPI) wells.

springs on the main terrace, entered the creek as seepage, and/or flowed into alluvial aquifers in the South Truckee Meadows had the wells not been flowing. As such, it should be considered part of the natural discharge of thermal water from the Steamboat system.

RECENT HYDROLOGIC CHANGES

Hydrologic changes that have occurred in the Steamboat area in recent years are discussed below. These changes include successive years of below-average precipitation (since 1986), general declines in water levels in the shallow ground-water system in much of the South Truckee Meadows and in many stratigraphic test wells in the Steamboat Hills, and cessation of discharge from hot springs at the main terrace (since 1987). Declines in water level in the shallow ground-water system, which have been observed since 1985, result from decreases in recharge from precipitation and seepage from the Steamboat Ditch and increases in pumpage of ground water for domestic use. Geothermal production and injection operations at the CPI and SB GEO well fields began in 1986, with the SB GEO power plant going on line in January 1987 and the CPI plant going on-line in February 1988. These changes are described in this section of the report and apparent cause-and-effect relations are noted. Other less significant influences on spring activity, such as barometric pressure changes and earthquakes, are also discussed in the following section.

Changes in Precipitation

Precipitation data were evaluated primarily for two stations in the Steamboat area - the Reno Airport and the Sky Tavern (fig. 14). The Sky Tavern site was chosen because it lies at an altitude of 7,620 feet in the Galena Creek basin, which is the postulated recharge area for the Steamboat geothermal system. In addition, precipitation records for three sites closest to Sky Tavern (Tahoe City, Truckee Ranger Station, and Boca weather station) with data extending back to the period of White's study were utilized to extend the record for the Sky Tavern site. The methods used are described by Collar (1990). For this purpose we consider a precipitation-year to extend from July to June to match the data tabulations obtained for most other sites. Annual precipitation at the Reno Airport and Sky Tavern sites for the period 1938-1990 is shown in figure 15.

White (1968) considered precipitation to be the most important natural influence on spring discharge during the 1945-1952 period of observation, and noted four scales of precipitation that could affect spring activity at Steamboat. These scales include (1) individual storms, (2) seasonal, (3) annual, and (4) long term. Effects of individual storms on spring discharge and water level were not clearly delineated by White (1968), in part because their effect is probably of short duration (days) and also because of differences in amounts of precipitation between individual storms in the immediate Steamboat area and at the Reno Airport, where most of the data were collected. Changes in precipitation on the scale of individual storms would not affect the overall decline in spring activity since 1987, but could possibly account for short-term changes in some vents.

Seasonal Variations

Significant seasonal variations in spring discharge at the main terrace were recorded during the 1945-52 period (fig. 16). On the basis of quarterly averages, White (1968) concluded that spring discharge was highest during the winter (January-March) and lowest during the summer (July-September). He also noted that weighted-average chloride concentration of this discharge was lowest during the winter and highest during the summer,

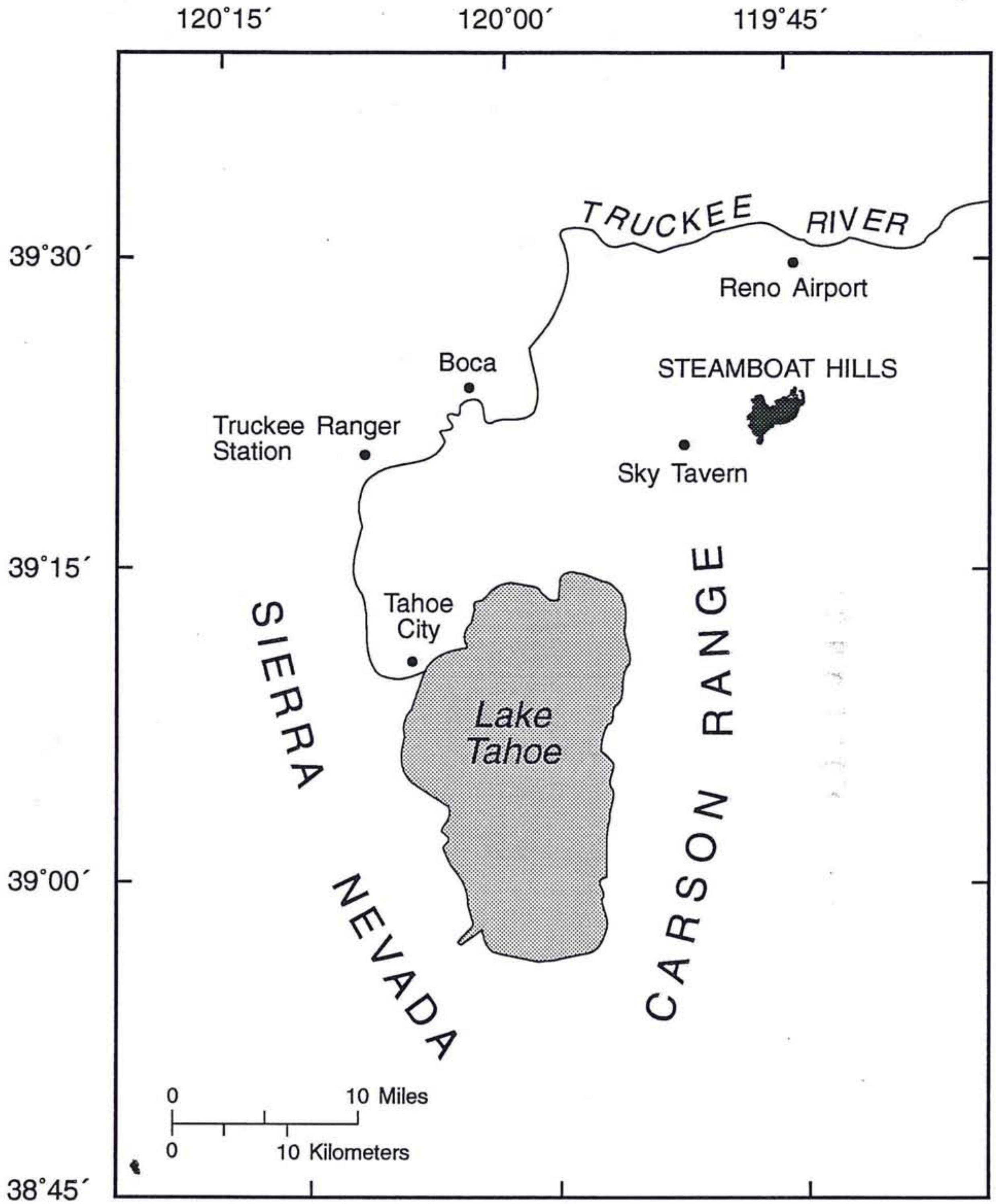

Figure 14. Location of selected precipitation-measurement stations in the vicinity of the Steamboat Hills for which data were used in this study.

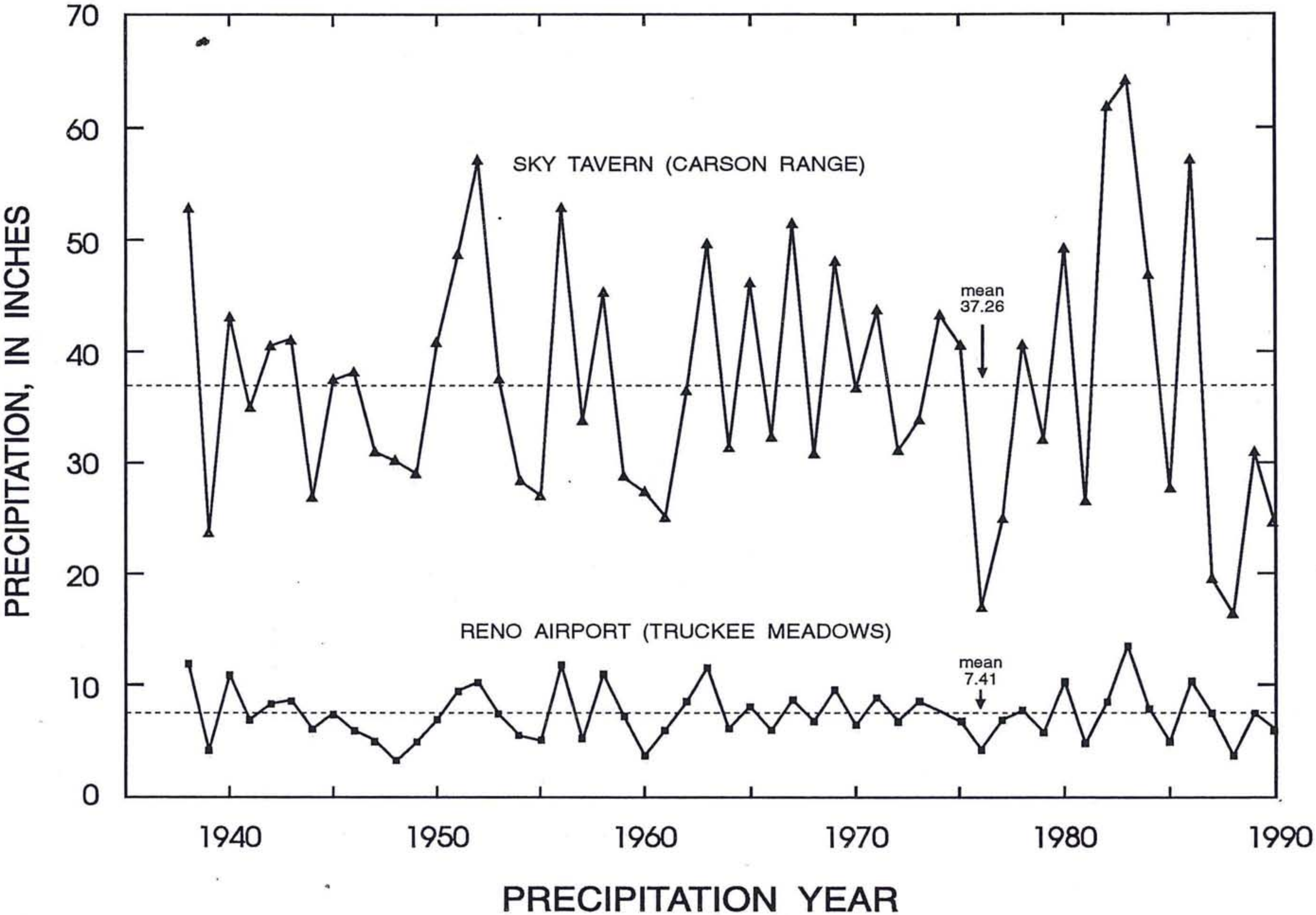

Figure 15. Annual precipitation for the Reno and Sky Tavern stations, 1938 to 1990. Each precipitation-year runs from July to June.

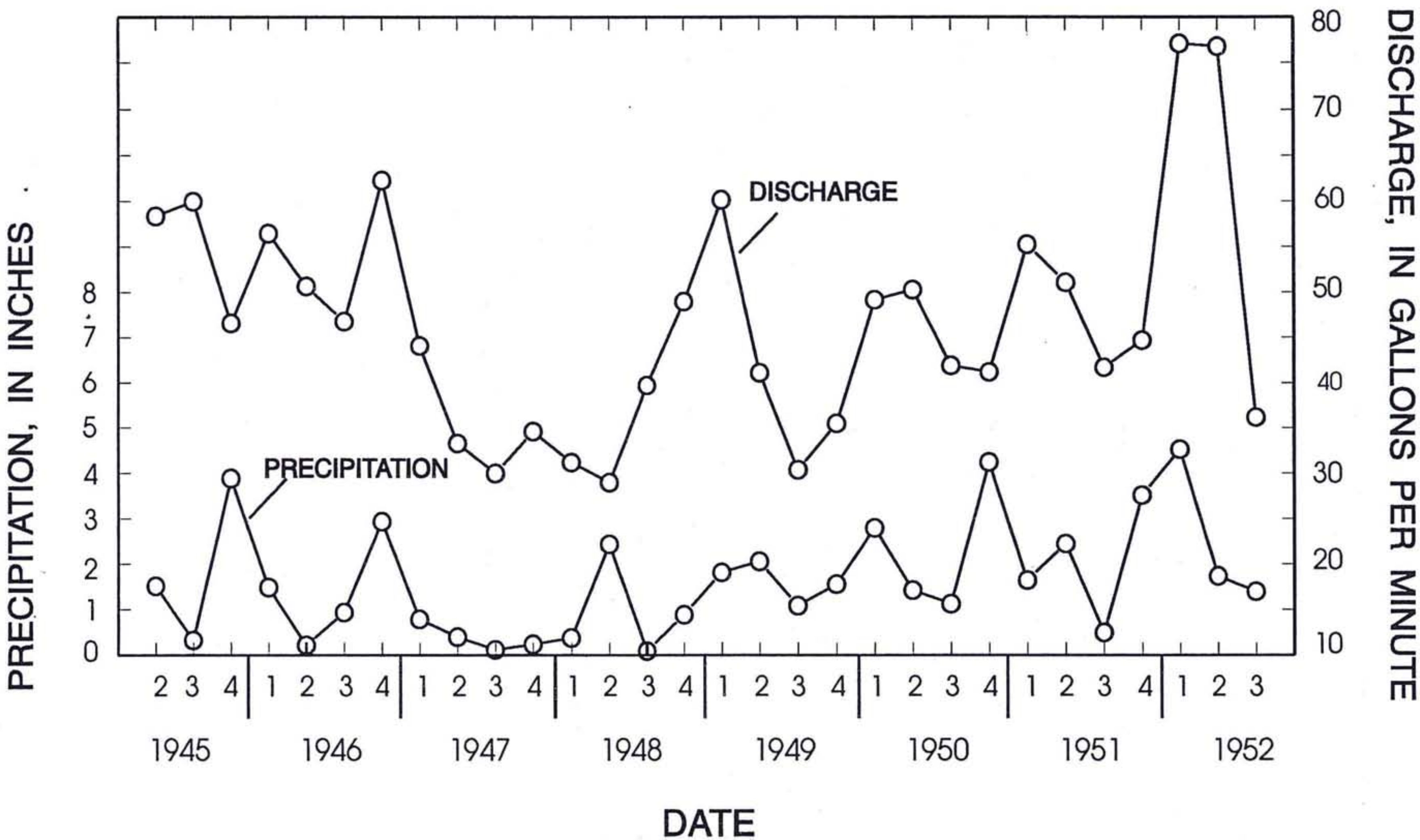

Figure 16. Total spring discharge from the main and low terraces and precipitation at the Reno Airport, averaged by quarters for the period 1945 to 1952 (data from White, 1968).

suggesting that these seasonal variations were due to dilution of the spring discharge by precipitation (or inputs of nonthermal ground water entering the spring vents at shallow depths). White also recognized that warmer outside air temperatures during the summer could enhance evaporation and increase spring chloride relative to winter conditions.

Our review of the quarterly spring-discharge data from White (1968) indicates a pattern of seasonal variation in spring discharge, but little correlation between spring discharge and quarterly averaged precipitation. In fact, in only two of the six years of record did the quarter of highest spring discharge coincide with the quarter of highest precipitation, and in only three quarters did lowest discharge coincide with lowest precipitation. This lack of correlation between seasonal variations in spring flow and precipitation probably indicates that interactions between the hot-springs and the ground-water system are complex, involving time delays on different scales at different times of the year superimposed on longer-term effects. Simple mixing of local nonthermal ground water with thermal water beneath the main terrace is unlikely to be significant, given the small range reported for the variation in spring chloride (9 mg/L out of 900 mg/L) and lack of a clear inverse relation between spring flow and chloride concentration.

Both the quarterly averaged discharge record (fig. 16) and the weekly measurement record (plate 4 in White, 1968) show a range in total spring flow at Steamboat from about 30 to 80 gal/min. Only about 5 gal/min of this total is from springs on the low terrace. Although the level of variability in spring discharge is comparable to the decline in discharge delineated since 1987, the recent decline involves a cessation of all spring flow from the main terrace which was never observed during White's study. Thus, the recent decline in hot-spring activity must be related to stresses that either were not present during the 1945-52 period or were present but of smaller magnitude in the past than at present. Significant variations in precipitation occurred during White's study, as did variations in water levels in the shallow ground-water system related to seasonal recharge from irrigation ditches (Cohen and Loeltz, 1964). These two influences are the only ones likely to have accounted for the seasonal changes in spring flow measured during the earlier period. During the 1986-1989 period of hot-spring observation, these influences as well as those of ground-water pumpage for domestic use and geothermal fluid production for electric power generation could have affected hot-spring activity at the main terrace.

Annual and Long-Term Variations

Correlations exist between yearly-averaged spring discharge at Steamboat and precipitation at the Reno Airport and Sky Tavern sites over the 1945-52 period (fig. 17). Correlation coefficients for these data sets are 0.40 and 0.48 for the Sky Tavern and Reno Airport sites, respectively. Even higher degrees of correlation (with correlation coefficients approaching 0.9) exist for the 1945-49 and 1949-52 periods considered separately (White, 1968). In effect, there was a shift in the spring flow - precipitation relation during the 1949-50 water year. The reason for this apparent shift is unknown. These data, although limited in number, indicate that consecutive years of drought can result in decreased spring activity.

The precipitation records for the 1938-90 period show that drought conditions occurred during parts of White's period of observation and at other times in the past, most notably

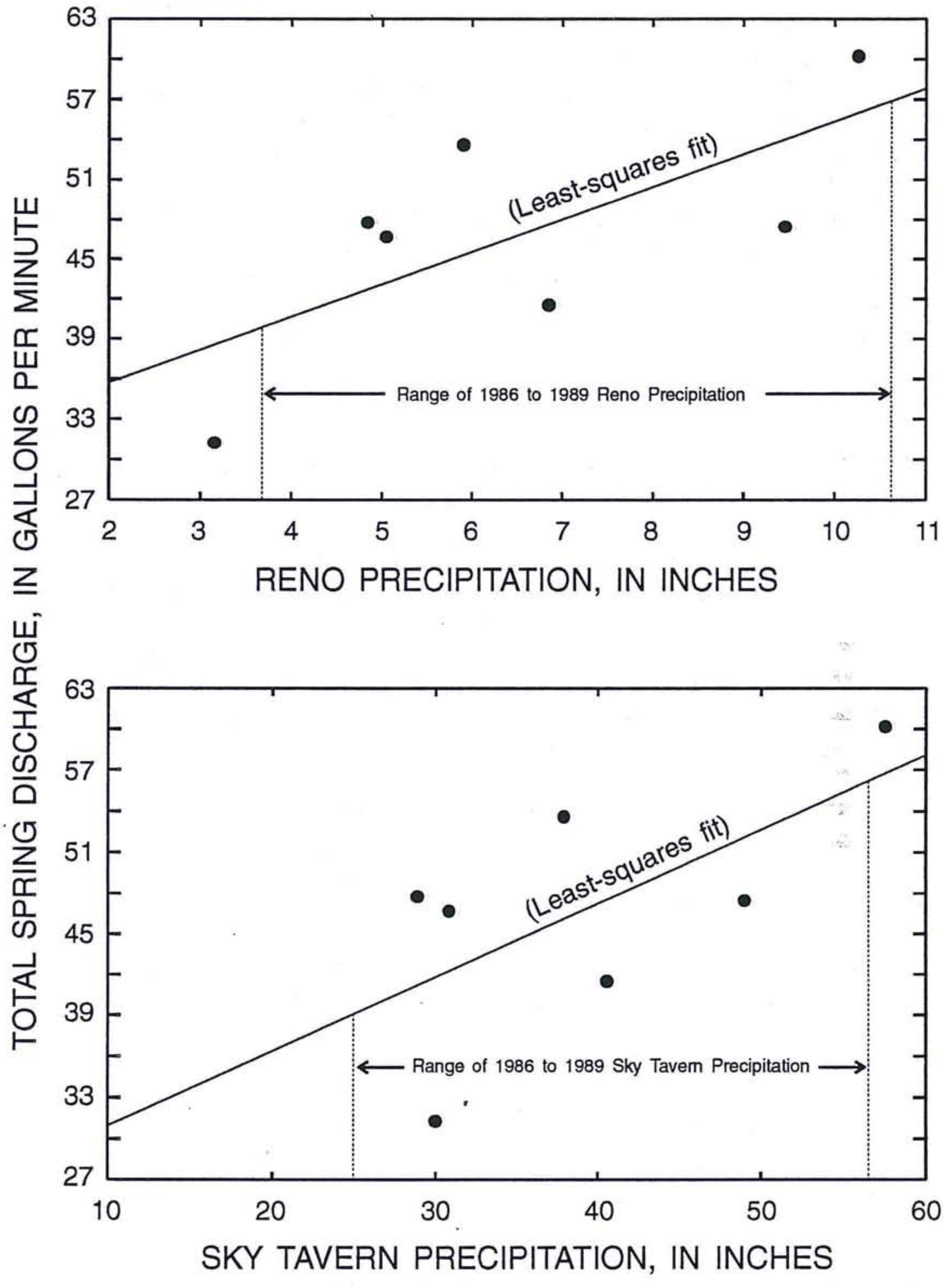

Figure 17. Total spring discharge from the main and low terraces and annual precipitation at the Reno Airport and Sky Tavern stations, 1946 to 1952 (from White, 1968). Annual precipitation is computed for the precipitation year, which runs from July to June.

during the 1976-78 period. This is more clearly seen in plots of cumulative deviation from mean precipitation for the Sky Tavern site (fig. 18), in which periods of above-average precipitation are shown as positively sloping parts of the graph and periods of below-average precipitation correspond to negatively sloping parts. The change in cumulative deviation from precipitation-year 1986 to 1989 was -46 inches and represents the most severe drought for the period of record. However, the change in cumulative deviation from the mean was only about -30 inches by July 1987, when all but spring 8 on the main terrace had ceased flowing. Periods of comparable drought severity, as indicated by cumulative deviations from the mean precipitation, occurred during White's study and that of Nehring (1980) when spring flow on the main terrace was substantial. Thus, successive years of below normal precipitation cannot, by itself, account for the recent cessation of spring flow at the main terrace. It is likely, therefore, that differences in the distribution of precipitation within each year or other hydrologic factors are involved.

White (1968) noted that L.H. Taylor (unpublished report) estimated the total spring flow from the main terrace at about 180 gal/min in October 1916 and mapped numerous points of discharge in the northern part of the main terrace that did not exist in the 1945-52 period. White (1968) considered that the difference between total spring discharge in October 1916 and the October average during the 1945-52 period (180 gal/min as compared with 45 gal/min) reflected the influence of two geothermal wells at the Reno Resort (fig. 19), rather than a long-term decline in spring discharge. This inference was based in part on observations of spring responses north of the ACEC (for example, spring 62) to discharge from the Reno wells. In contrast, no response from the Reno-well discharge was observed by White in springs further south within the ACEC.

Since 1952, spring flow from the main terrace has only been quantified during the period from June 1986 to April 1987 (Yeamans, 1987a). The total visually estimated flows from six main-terrace springs during this period ranged from 8-30 gal/min as discussed in a later section. Although these estimates suggest that total spring flow at this time was lower than during the 1945-1952 period, at least five springs with visible discharge were not included in the totals. Qualitative observations of spring flow and geyser activity during the 1979-1985 period (Appendix A) do not indicate any obvious decline in spring flow compared with the 1945-1952. Thus, systematic changes in spring flow and geyser activity that began in 1986 and have continued until the present represent a relatively abrupt shift that cannot be accounted for by long-term trends that might accompany natural geologic processes such as self-sealing from mineral deposition.

Changes in Wells in the Shallow Ground-Water System Surrounding the Steamboat Hills

Water levels in the shallow ground-water system surrounding the Steamboat Hills have been monitored in numerous wells, as part of the monitoring programs carried out by the geothermal operators and by the South Truckee Meadows General Improvement District (STMGID). Water-level data from monitored wells are available from monthly measurements for all or part of the 1985-90 period. At some sites where the monitored well or a nearby domestic well is pumped periodically, geochemical data are also available. Such data were of interest in our study because head changes in the ground-water system, induced by various factors, could propagate to the geothermal system in the vicinity of the main terrace and

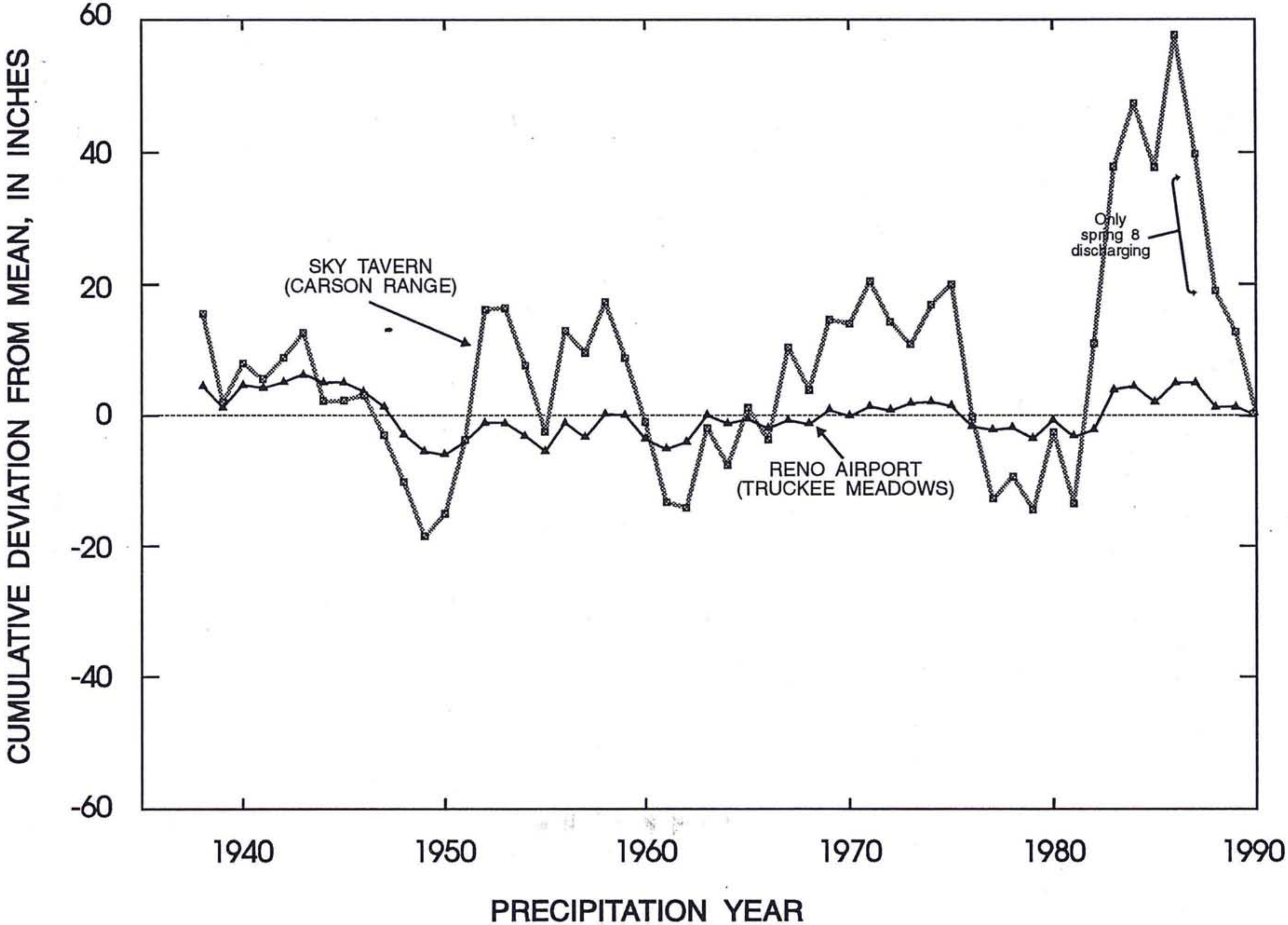

Figure 18. Cumulative deviation from mean annual precipitation for the Reno Airport and Sky Tavern stations, for the period 1938 to 1990. Each precipitation year runs from July to June.

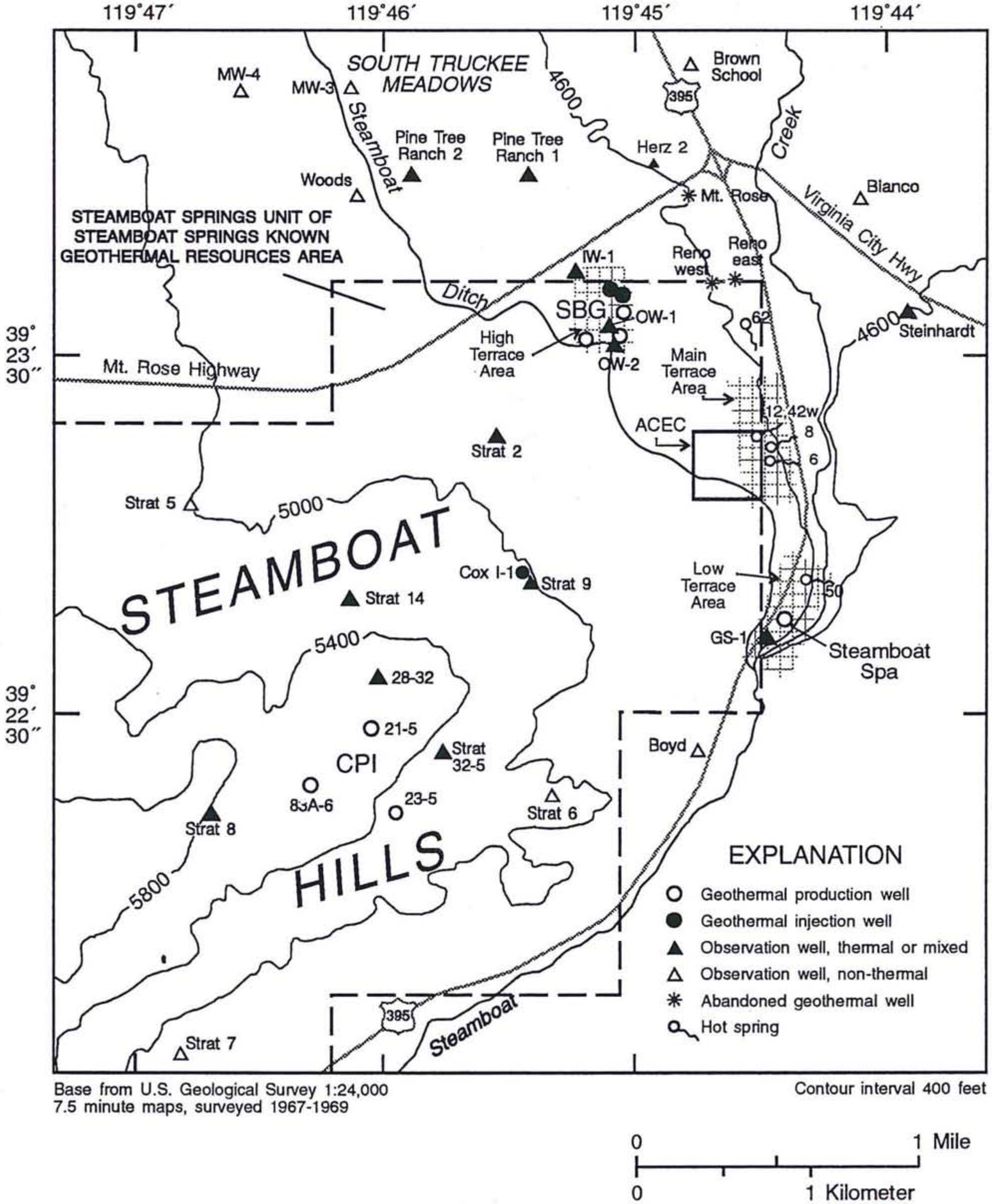

Figure 19. Location of observation wells in the Steamboat Hills and South Truckee Meadows being monitored by Caithness Power, Inc. (CPI) and SB GEO (SBG) geothermal developments. STMGID stands for South Truckee Meadows General Improvement District.

Steamboat Creek and affect hot-spring discharge, water levels, and seepage into the creek. Monitoring of these wells by the geothermal operators has also been carried out to detect any movement of injected geothermal water into shallow aquifers.

Water levels in the shallow ground-water system may vary in response to recharge of nonthermal ground-water from precipitation and infiltration from creeks draining the Carson and Virginia Ranges and leakage from Steamboat Ditch and other irrigation ditches (fig. 2). Water-level variations also occur in response to ground-water pumpage for municipal, industrial, and domestic use. Some wells in the South Truckee Meadows tap aquifers with a mixture of thermal and nonthermal ground water, as evidenced by higher-than normal temperatures and chloride concentrations.

STMGID currently operates six production wells in the South Truckee Meadows to supply ground water to domestic, municipal, and industrial users. These wells are located within distances of 2.1 to 2.9 miles northwest of the ACEC (fig. 13). STMGID well SPW-2 is not currently used, and well SPW-4 produces from permeable zones within bedrock below a depth of 650 feet; such production appears to have no effect on heads in the overlying alluvium (Mike Widmer, Washoe County Utility Division, oral communication, 1992). The other STMGID production wells (SPW-1, 3, 5, 6, and the Thomas Creek well denoted TC) were drilled to depths of 500-760 feet, cased to depths of 250-410 feet, and are completed in alluvial aquifers. The record of total production from four of the STMGID wells (fig. 20) shows summer maxima near 1,000 gal/min and winter minima near 200 gal/min since the system went into operation in August 1985. The total annual water withdrawal from all six wells was 1,144 acre-feet in 1990 (Mike Widmer, Washoe County Utility Division, oral communication, 1992), which is equivalent to an average production rate of 715 gal/min.

Ground water is also pumped from domestic wells and private utility/water company wells in the South Truckee Meadows and other regions surrounding the Steamboat Hills south of the Mt Rose and Virginia City Highways. Although the total number of wells drilled in the entire alluvial-filled region between Huffacker Hills and Pleasant Valley (figs. 2 and 13) exceeds 2,000, only about 160 wells are situated in that part of the South Truckee Meadows between the ACEC and the northernmost STMGID well SPW-1 (Leonard Crowe, Washoe County Comprehensive Planning, written communication, 1992). Using the County's figure of 1 acre-foot per year (AFA) or 0.63 gal/min per well, a total ground-water usage of about 100 gal/min beyond the STMGID usage is indicated for this area in closest proximity to the ACEC.

The available water-level records for eight wells penetrating the shallow ground-water system surrounding the Steamboat Hills are shown in figures 21-26. Well locations are shown in figure 19, and well completion and temperature information is listed in table 3. Several of these wells produce mixtures of thermal and nonthermal water, as evidenced by temperatures of 43 -76°C and average chloride concentrations of 50-360 mg/L. Such wells show seasonal variations in water level and chloride concentration indicative of changes in the proportions of nonthermal and thermal water at those sites. This is best illustrated by the data for the Pine Tree Ranch wells PTR-1 and PTR-2, located northwest of the high terrace (fig. 19). Well PTR-1 is 110 feet deep and produces water at about 43°C; well PTR-2 is 435 feet deep (but cased only to 101 feet) with a bottom-hole temperature of 76°C. Water-level

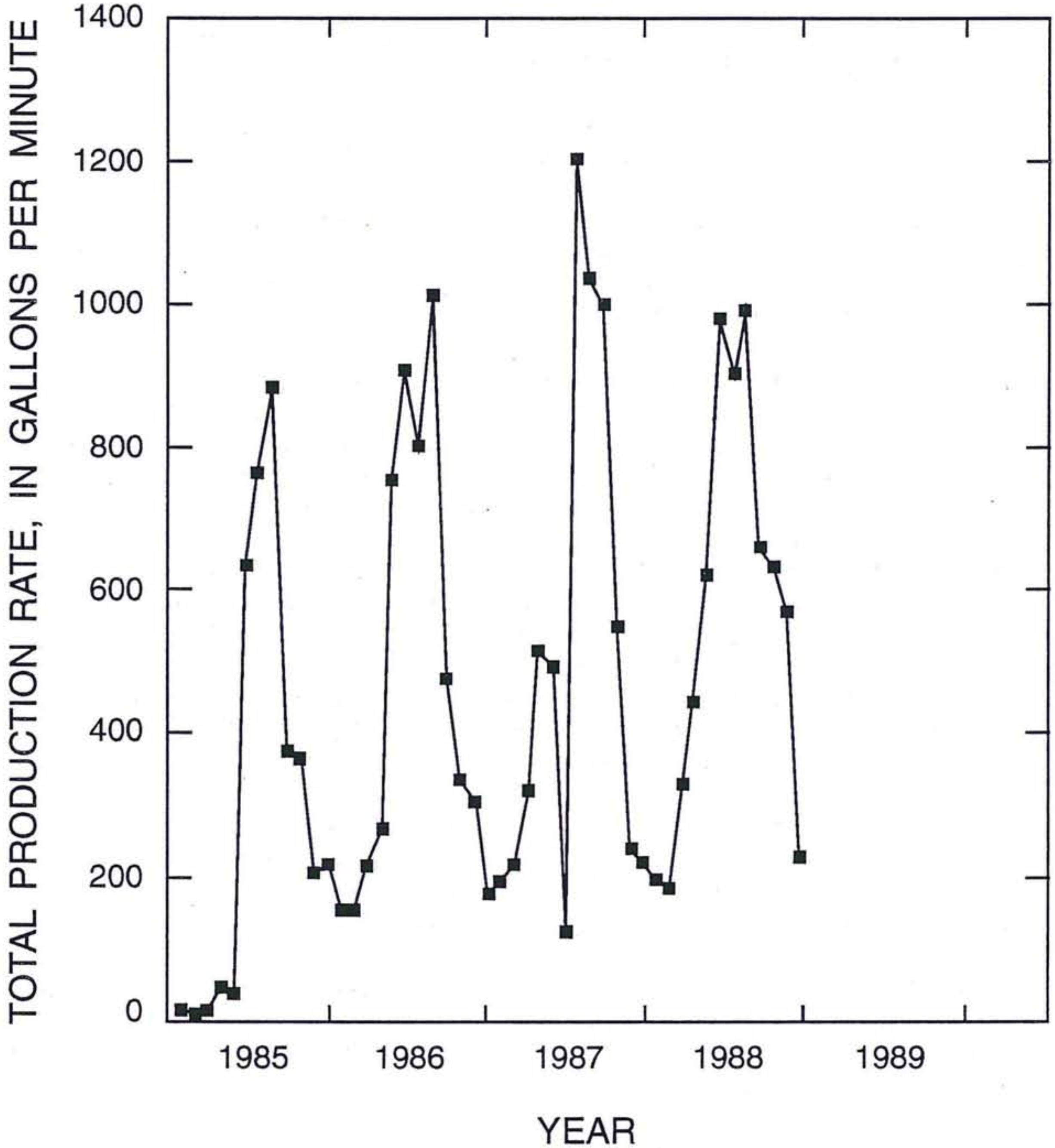

Figure 20. Total production rate from South Truckee Meadows General Improvement District (STMGID) wells SPW-1, SPW-3, SPW-4, and TC (from van de Kamp and Goranson, 1990).

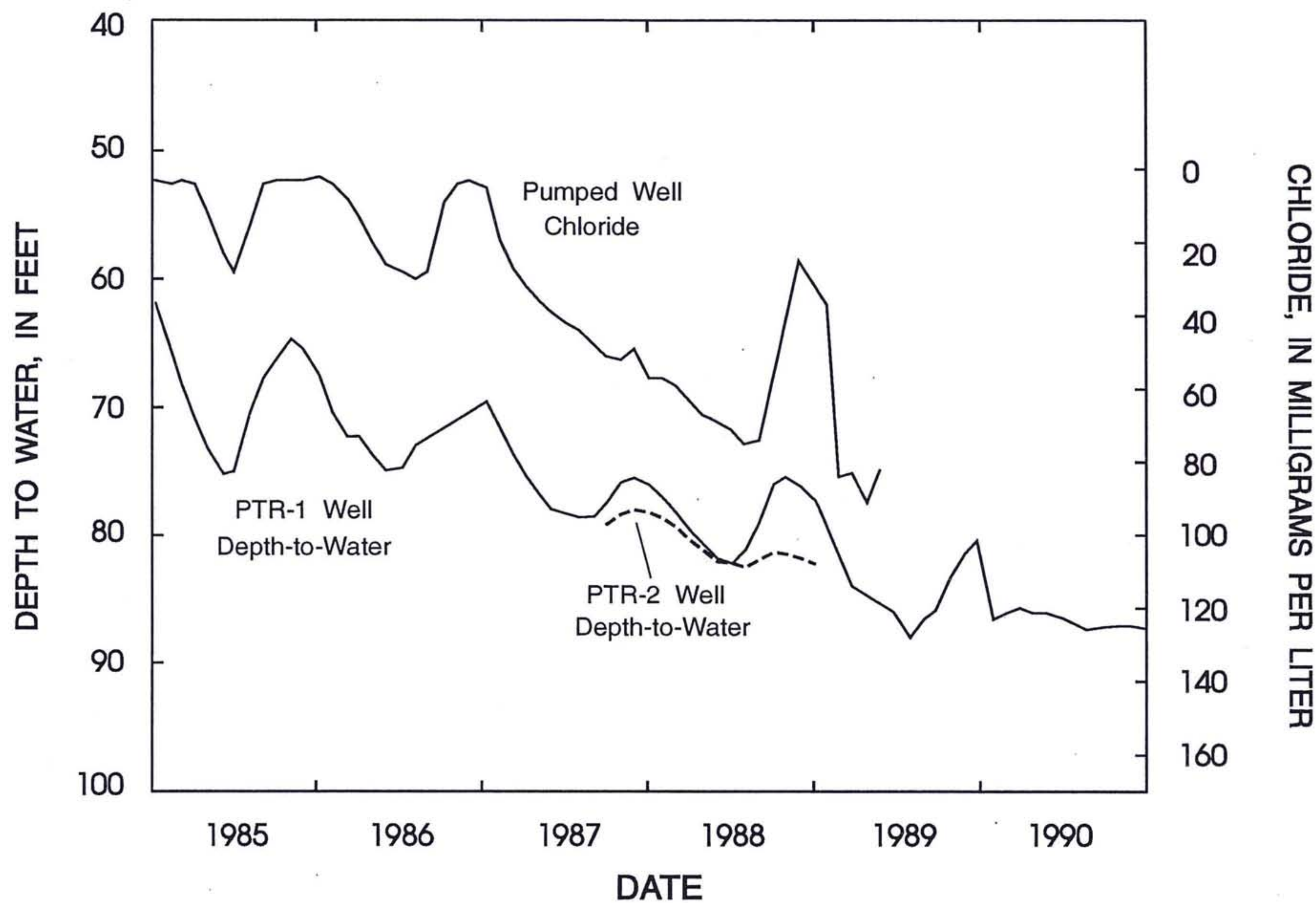

Figure 21. Water levels in Pine Tree Ranch wells PTR-1 and PTR-2 and chloride concentrations in a nearby pumped well of unknown depth, 1984 to 1991.

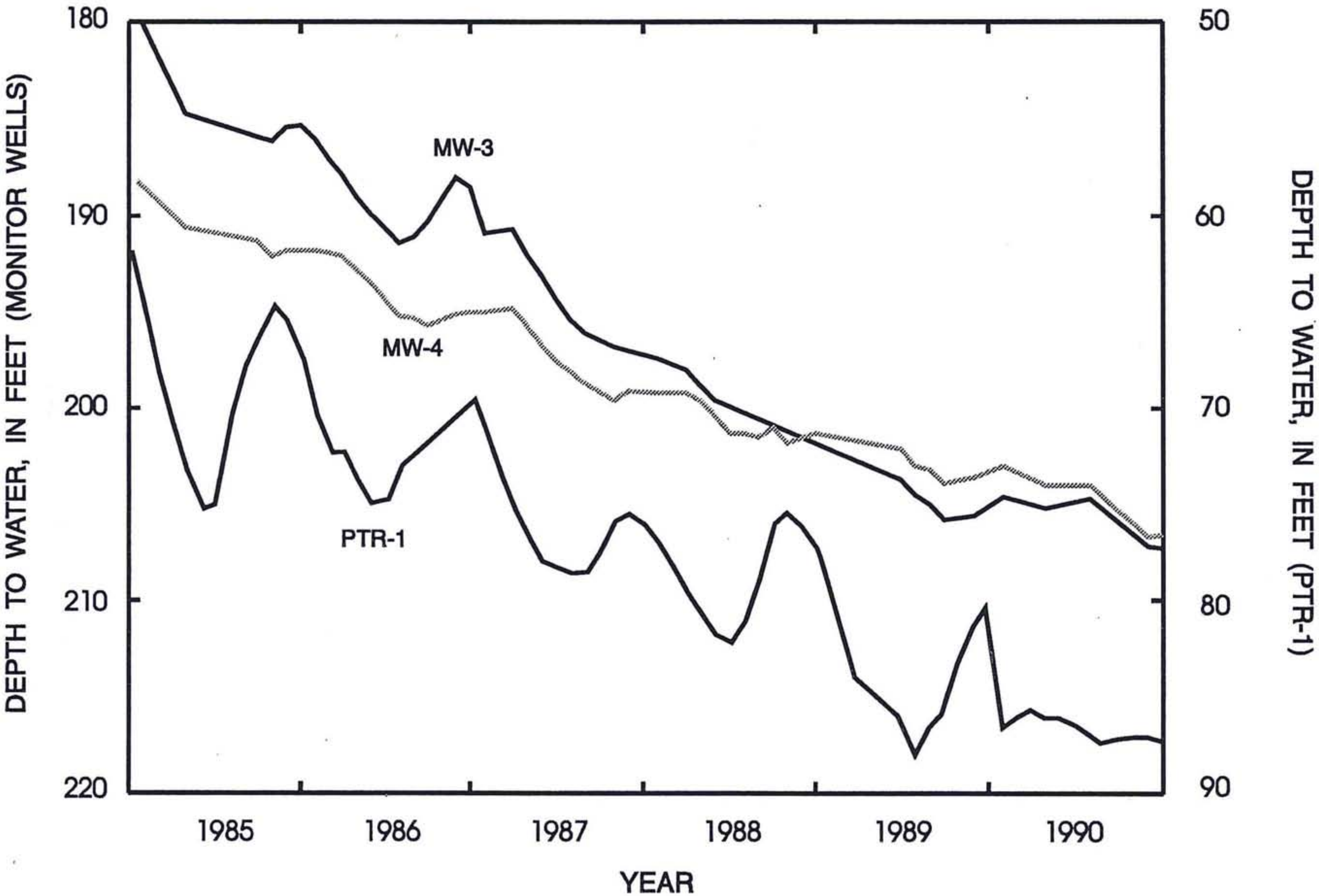

Figure 22. Water levels in the Pine Tree Ranch-1 (PTR-1) well and South Truckee Meadows General Improvement District (STMGID) monitor wells MW-3 and MW-4, 1985-1990.

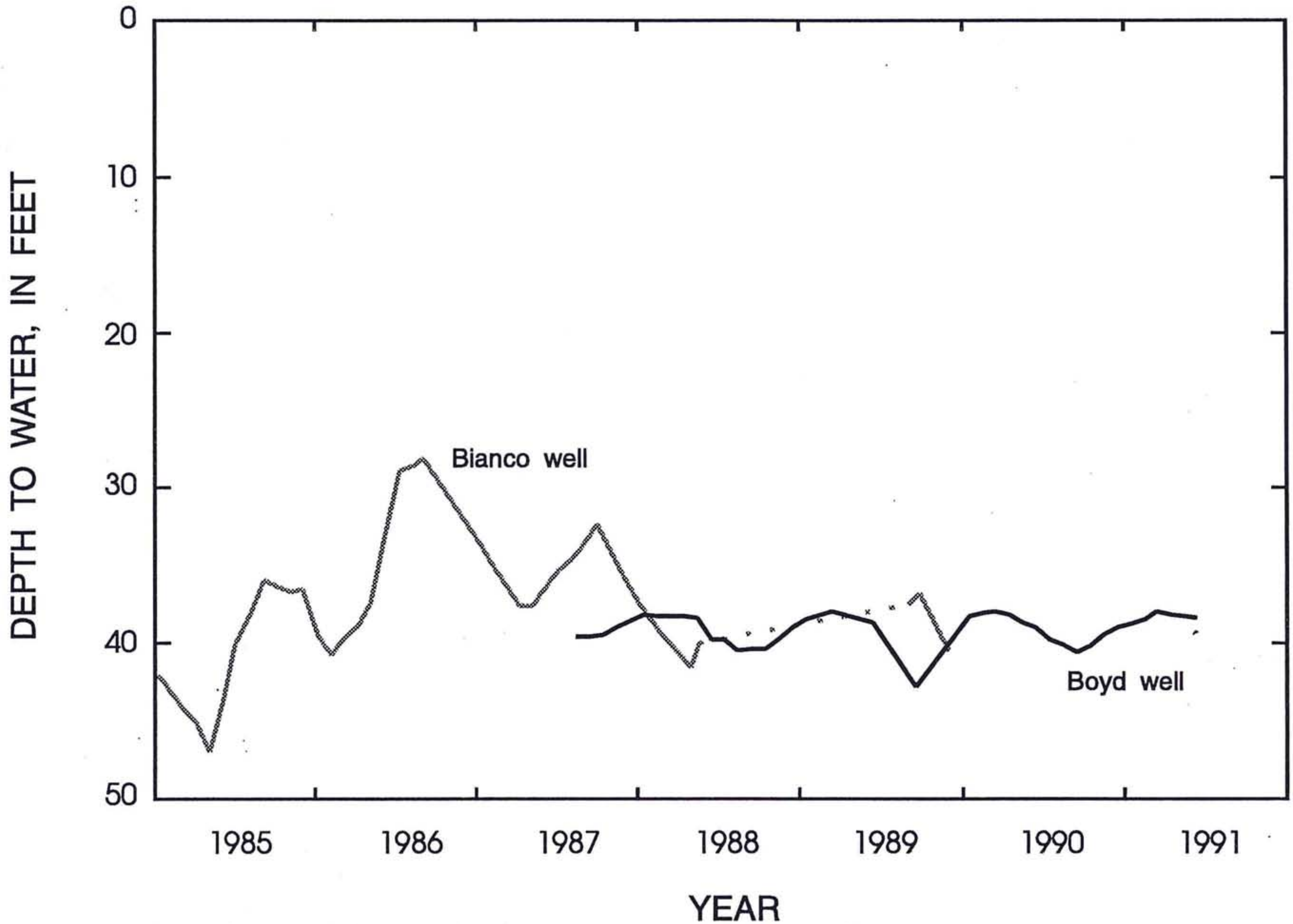

Figure 23. Water levels in the Bianco and Boyd wells, 1985-1991.

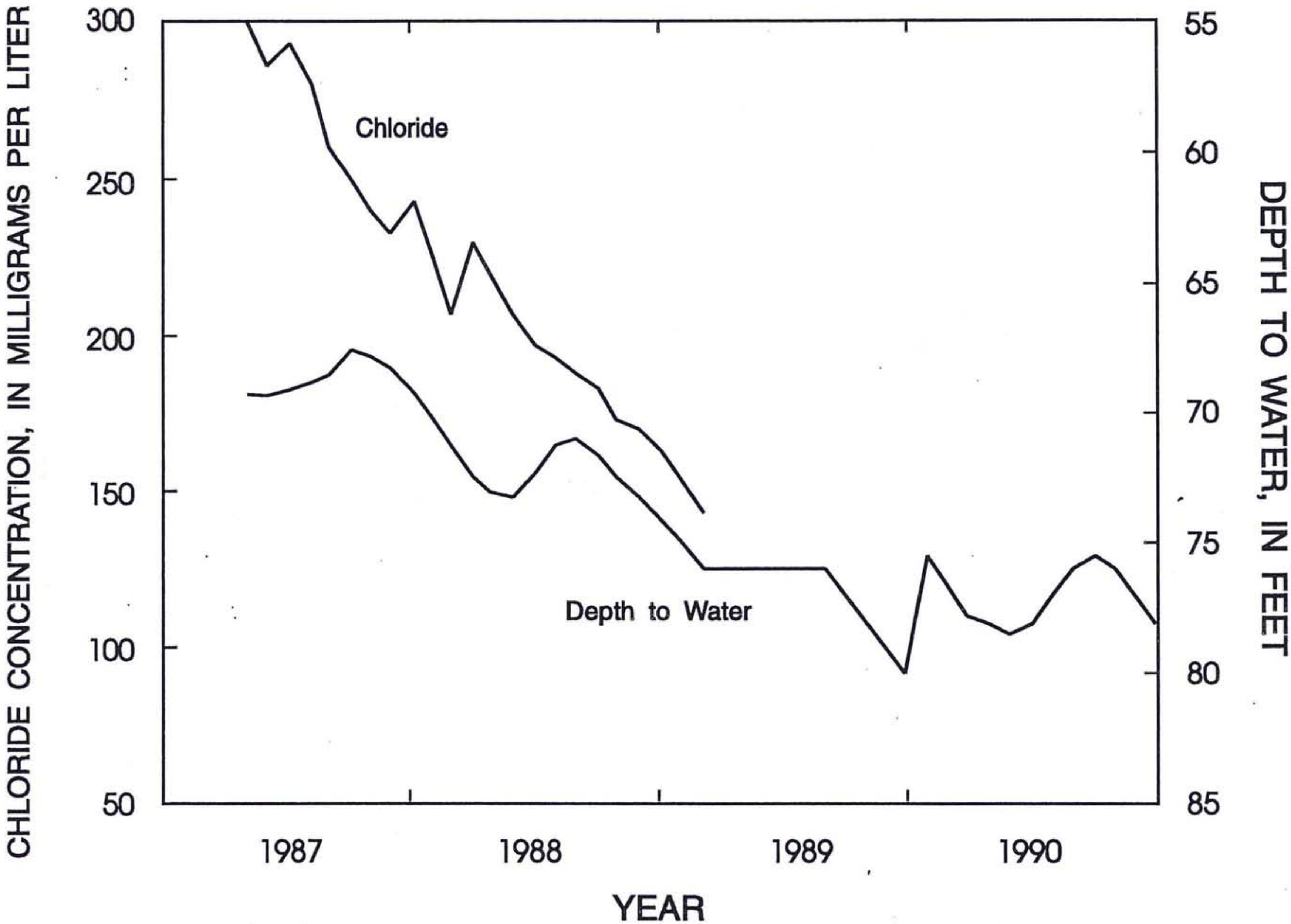

Figure 24. Water level in the Steinhardt well and chloride concentrations in water pumped from this well, 1987-1990.

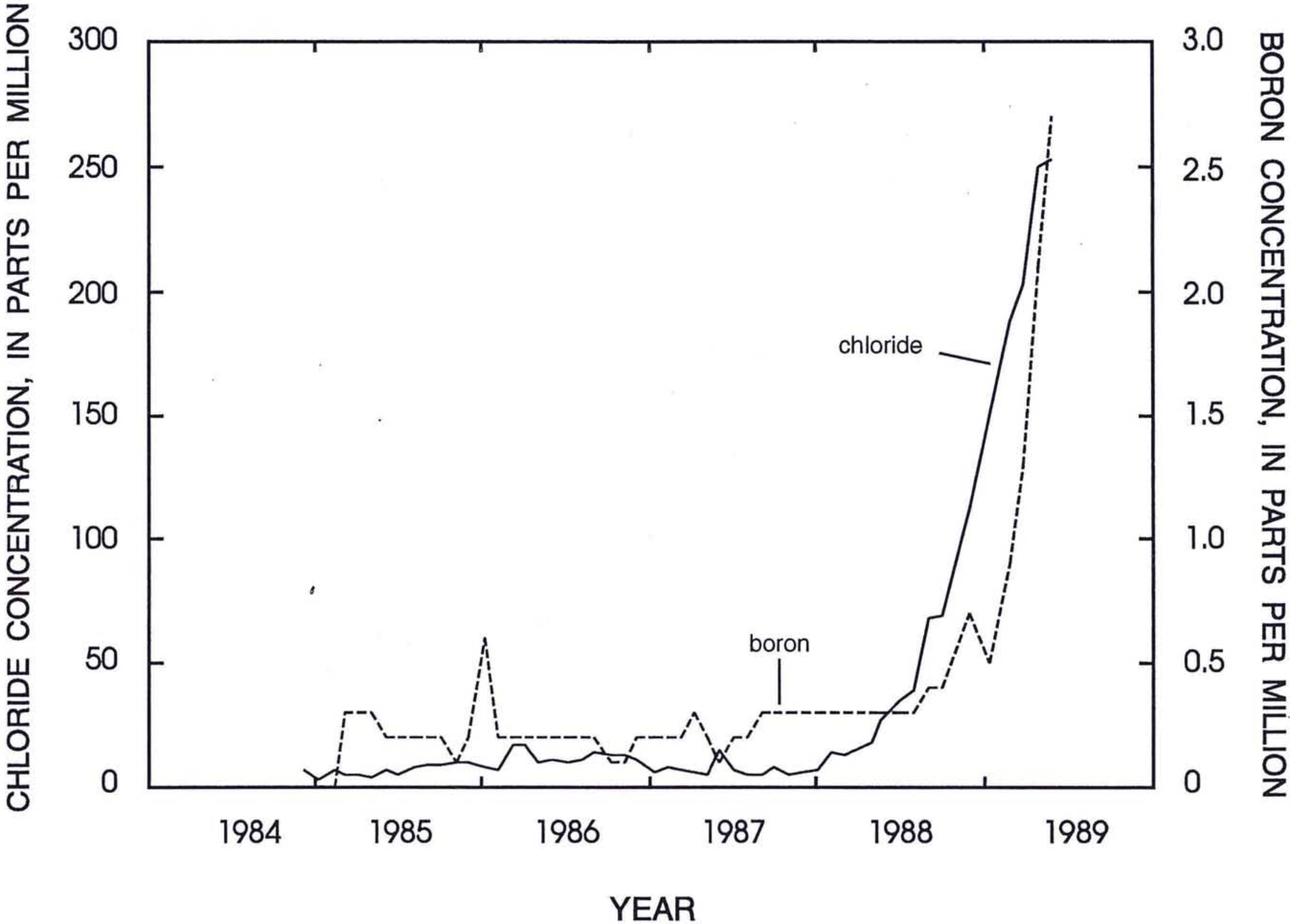

Figure 25. Concentrations of chloride and boron in water pumped from the Brown School well, December 1984 to May 1989.

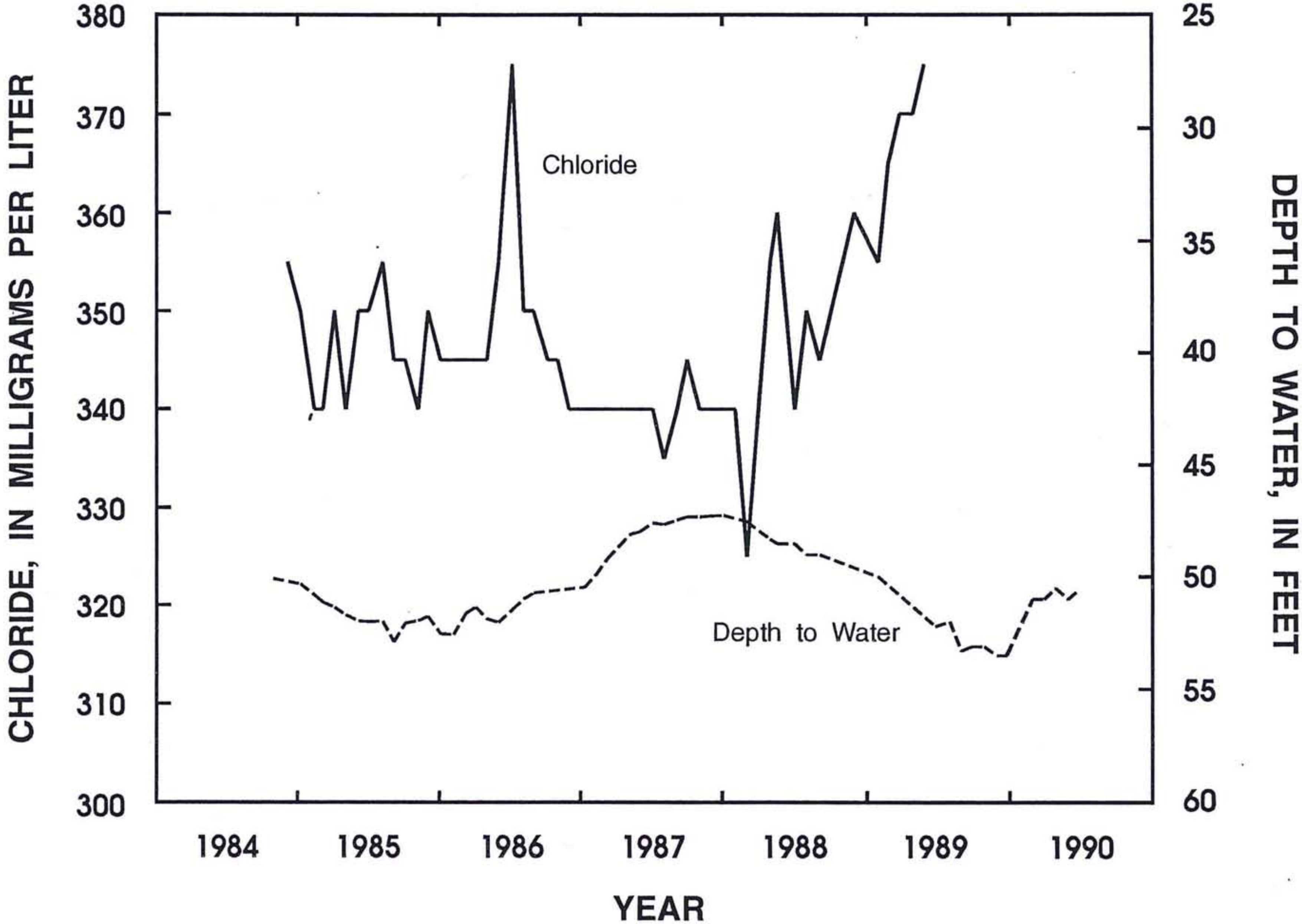

Figure 26. Water levels and concentrations of chloride in the Herz-2 (geothermal) well, 1984-1990.

Table 3. *Data for selected wells completed in the ground-water system of South Truckee Meadows and Pleasant Valley*

[nm, not measured; unk, unknown]

Well Name	Depth[1] (feet)	Temperature[2] (°C)	Chloride[3] (mg/L)	Water-level[4] Decline 1985-89 (feet)
PTR-1	110	43	10-80	25
PTR-2	435	76	nm	nm
MW-3	800	nm	nm	25
MW-4	400	nm	nm	16
Bianco	110	21	nm	~0
Boyd	56	18	16-22	~0
Steinhardt	135	nm	140-300	10
Brown School	unk	16	10-250	unk
Herz-2	155	57	340-370	~0

[1]From Van de Kamp and Goranson (1990).
[2]From Van de Kamp and Goranson (1990).
[3]From data shown in figs. 19-24.
[4]From data shown in figs. 19-24.

variations in PTR-1 and chloride changes in a nearby pumped well of unknown depth have been attributed to changes in rates of recharge of low-chloride irrigation water by infiltration from Steamboat Ditch and irrigated lands to the west (Yeamans and Broadhead, 1988). Similar, but damped, water-level changes occur in the deeper PTR-2 well. Both wells show a trend of long-term decline in water level; the decline in seasonally averaged water level in PTR-1 over the 1985-90 period amounts to about 18 feet.

STMGID monitor wells MW-3 (800-ft deep) and MW-4 (400-ft deep) are located northwest of the Pine Tree Ranch wells. Hydrographs for these wells (fig. 22) show damped seasonal fluctuations superimposed on long-term declines of 15-22 feet over the 1985-90 period. Although these wells are closer to Steamboat Ditch than PTR-1 and hence might be expected to show more seasonal fluctuation in water level, their greater depth apparently serves to dampen the seasonal response (as in the case of well PTR-2). Delineation of seasonal changes in MW-3 and MW-4 is also limited by measurement intervals greater than 1 month in some years (for example 1985 and 1989).

Wells in the South Truckee Meadows show relatively high water levels in the fall and winter and low water levels in the spring and summer. This pattern is inversely correlated with seasonal variations in pumpage from the STMGID wells, and presumably other domestic ground-water wells in the area. Rising water levels in the fall and winter probably result from a combination of reduced ground-water pumpage and recharge from the creeks and irrigation ditches which flow from about April until September and peak in mid-summer. Seasonal fluctuations in water level were observed in wells in the South Truckee Meadows during the 1950's, prior to significant ground-water withdrawal from wells (Cohen and Loeltz, 964). Hydrographs from that period show water-level rises beginning sooner (June-July) than in the current situation. Thus, the effects of ground-water pumpage may be to delay the period of water-level recovery until the fall and to cause long-term declines in average water level in the ground-water system.

The available data for shallow nonthermal wells located closer to Steamboat Creek (locations shown in figure 19) show some evidence of seasonal fluctuations, but no long-term declines since 1985. Such wells include the Bianco well northeast of the ACEC and the Boyd well southwest of the ACEC (fig. 23). Water levels in these wells are probably controlled mainly by levels in Steamboat Creek. Data for the mixed-water Steinhardt well (fig. 24), located northeast of the ACEC, show an overall decline in water level since 1987 of about 10 feet and a corresponding decrease in chloride concentration (from 300 mg/L to 140 mg/L). This suggests a decrease in the thermal-water component tapped by this well.

The Brown School well and the Herz geothermal well (Herz-2), located north of the ACEC and on the west side of Steamboat Creek and Highway 395, have both shown increases in chloride concentration beginning in the fall of 1988 (figs. 25 and 26). In the Herz-2 well, this period of increasing chloride was accompanied by a decline in water level. These changes are suggestive of thermal-fluid movement into this region from geothermal fluid injection to the south. However, produced fluid from the SB GEO wells is low in calcium (12 mg/L) and calcium concentrations in the Brown School well have also increased significantly with time (17-194 mg/L, from Goranson and others, 1991). In addition, there has been a decline in water level in the shallower Herz domestic well of about 15 feet between 1986 and late 1988. Thus, other explanations for the chloride increase, such as a decrease in the nonthermal ground-water component in shallow aquifers in this area and inflow of thermal water from sources other than the SB GEO well field, must also be considered.

Changes in Hot Springs and Wells on the Main and Low Terraces

Aside from observations of hot-spring activity described by White (1968) for the 1945-52 period, records of spring discharge and water level at the main and low terrace are available only for parts of the 1977-1990 period, as indicated in Appendix A and figures in this report. This recent record includes measurements and observations made by NDEP, BLM, GOSA, and SDSU personnel, supplemented with observations by Nehring (1980) and Donald Hudson (independent consultant), and measurements and observations reported by Yeamans (1987a). The latter data consists of estimates of the flow rates of six main-terrace springs during part of the 1986-1987 period and short-term measurements of depths to water in several spring vents associated with well tests conducted by Caithness between 1979 and 1987.

Water-level measurements by BLM and NDEP were made in 1986-1988 while water was still visible in the main-terrace spring vents. SDSU personnel measured depths to water in several springs and wells at the terraces using either an electric sounder or a graduated rule in 1988 and 1989. Locations of all spring vents discussed here and elsewhere in this report are shown in figures 4 and 19. In the case of spring 6 on the main terrace, the 1988-89 water-level measurements were facilitated by removing sinter rubble from the vent to expose the water surface. On the low terrace, the discharge of the only active spring (spring 50) was also measured by SDSU. No water-level data were collected for this study after August 1989, except for a few measurements on spring 6 made by BLM in late 1989. Significant gaps in the data exist for time periods between SDSU and BLM measurements and during much of the 1988-1989 period.

The hydrograph for spring 6 is plotted in figure 27 for the period 1986-1989. More limited records for other springs on the main terrace (for example springs 12 and 42w, fig. 5) indicate that the general pattern of change in the spring 6 record is representative of water-level variations on the main terrace. Periods when spring 6 was flowing are indicated by zero depth-to-water. More detailed plots of the hot-spring data collected and compiled during this study are included in Appendix A. Also shown in figure 27 is the hydrograph for well PTR-1 and intervals of discharge from the SB GEO and CPI well fields, for which more information is given in tables 4 and 5.

Onset of the Decline in Hot-Spring Activity

Spring 6 and numerous other main-terrace springs that formerly discharged continuously or on a regular basis ceased flowing during CPI discharge interval 1 in March-May 1986. These changes appear anomalous compared with earlier years, as discussed below. Weekly observations between September 1983 and August 1984 reported by Lyles (1985), coupled with more recent observations listed in Appendix A suggest that spring 24 discharged continuously, or on a regular basis, for about two and a half years prior to the time it stopped flowing in April

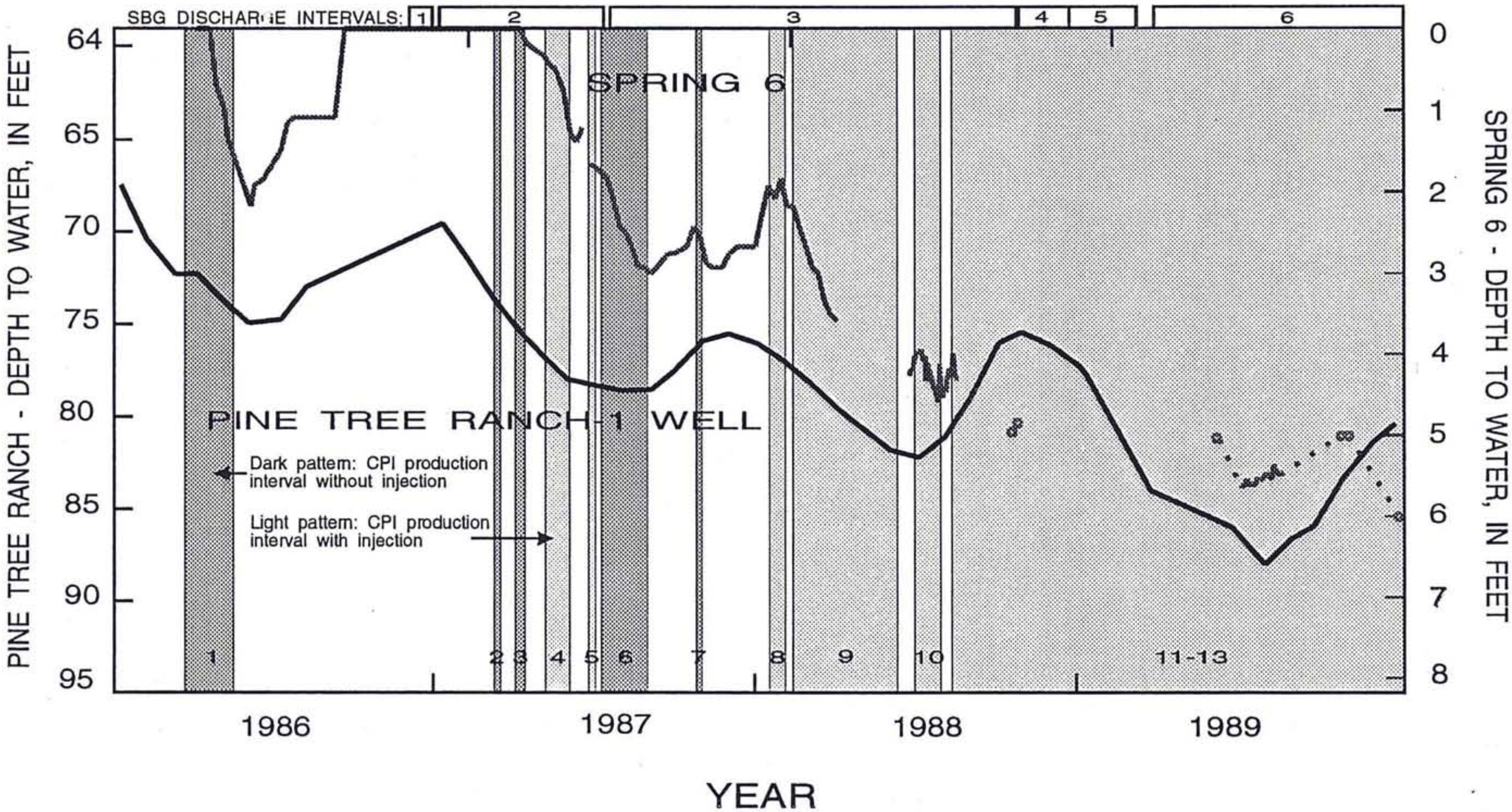

Figure 27. Water levels in spring 6 on the main terrace and the Pine Tree Ranch-1 (PTR-1) well, 1986-1989. Circles represent isolated measured water levels. Dots represent assumed trends of water levels between measurement intervals in 1989. See tables 4 and 5 for descriptions of Caithness Power Incorporated (CPI) and SB GEO (SBG) intervals.

Table 4. *Intervals of discharge from Caithness Power Incorporated production wells since 1986*

Interval	Production[1] wells	Injection well	Begin date	End date	Comments[2]
1	SB-1	None	3/21/86	5/15/86	NP=815 gal/min
2	SB-1	None	3/9/87	3/16/87	NP=620-810 gal/min
3	SB-1	None	4/2/87	4/13/87	
4	23-5	Cox I-1	5/6/87	6/3/87	No injection 5/17-19 NP=310 gal/min
5	23-5	Cox I-1	6/24/87	7/3/87	NP=310 gal/min
6	SB-1	None	7/9/87	8/29/87	NP=500 gal/min
7	83A-6	None	10/24/87	10/30/87	NP=970-2460 gal/min
8	23-5 83A-6	Cox I-1 Cox I-1	1/14/88 1/28/88	1/28/88 1/31/88	NP=340 gal/min
9	83A-6 23-5 21-5	Cox I-1	2/11/88	6/6/88	23-5, 83a-6 off 3/4-7 21-5 off 3/4-5
10	as above	Cox I-1	6/27/88	7/26/88	
11	as above	Cox I-1	8/8/88	11/25/88	23-5 off 9/15-10/17 83A-6 off 10/18-24 21-5 off 10/24-11/1
12	as above	Cox I-1	12/2/88	4/18/89	23/5 off 12/27-30 21-5 off 12/27-30
13	as above	Cox I-1	4/21/89	--[3]	

[1]Well SB-1 (Steamboat No. 1) redrilled 12/87 and renamed 21-5.
[2]Dates of production intervals and values of net production (NP) from Yeamans (1987a-1987e), Berkeley Group (1987), Bureau of Land Management (unpub. data), Thermasource (1987), B. Metcalf (Collar, 1990), and Caithness Power Incorporated monthly production reports.
[3]All wells on-line as of 8/89.

Table 5. *Intervals of discharge from SB GEO production wells since 1986*

Interval	Production wells	Injection wells	Begin date	End date	Injection rate (gal/min)[1]
1	PW-1, PW-2, PW-3	IW-3	12/2/86	12/29/86	unknown[2]
2	as above	IW-3	1/5/87	7/6/87	3321[3]
3	as above	IW-3	7/12/87	10/20/88	3158[4]
4	as above	IW-3	10/23/88	12/19/88	3218[5]
5	as above	IW-3 IW-2	12/19/88	3/4/89	756[6] 2142[6]
6	as above	IW-2	3/24/89	--[7]	

[1]Average calculated from daily average values reported by SB GEO (formerly Ormat Energy Systems, Inc.).
[2]Only two wells operating concurrently; test dates from GeothermEx, 1987.
[3]Power plant on-line; excludes July 1987 data.
[4]Power plant on-line; excludes July 1987 and October 1988 data.
[5]Power plant on-line; injection rates estimated from Nevada Division of Environmental Protection (unpub. cor.).
[6]Injection rates estimated.
[7]Wells still on-line as of 8/89.

1986. Shortly after the end of CPI discharge interval 1, most of the main-terrace springs experienced rising water levels or renewed discharge for several months. Springs 23n and 40 began to geyser in the summer of 1986 after a period of quiescence (Appendix A, Yeamans, 1986b). The record of estimated spring flow from the main terrace between June 1986 and April 1987 from Yeamans (1987a), as shown in figure 28, indicates that the combined discharge from the six monitored springs reached a peak in November 1986 of about 30 gal/min and subsequently declined to about 8 gal/min by April 1987. The overall pattern of variation in spring flow matches that observed by White (1968) of highest flow in the fall and winter, and thus appears to follow the usual seasonal trend. There is little evidence of correlation with the precipitation records for the Reno Airport or the Sky Tavern sites (fig. 28), but such short-term correlations were also not observed during the 1945-52 period.

The data from Yeamans (1987a) represents the combined discharge of springs 4, 6, 8, 10, 42, and 16se. As noted previously, however, other main-terrace springs were also flowing during this period. Yeamans (1987a) notes incidental observations of flows of 40-60 gal/min from spring 24 between October 1986 and February 1987 and eruptions from spring 40 and small flows from spring 2 during the fall of 1986. If the estimates of flow from spring 24 are accurate, the indicated total spring flow during the winter period is within the range of values reported for the 1945-52 period. This would suggest that only the estimated spring flows during the spring of 1986 and the spring of 1987 and thereafter are anomalously low. However, the inference that the long-term decline in hot-spring activity did not start until the spring of 1987 must be qualified because the accuracy of the spring discharge estimates of Yeamans (1987a) is indeterminate.

Collar (1990) describes decreases in discharge and water level in several springs during the mid-November 1986 to late February 1987 period. Although the most significant decrease in spring flow occurred in November and the information in Yeamans (1987a) indicates that well-testing and start-up operations did not begin until December, it is possible that some of the SB GEO wells were discharged in November. Detailed records of production during this period apparently do not exist. Between December 1986 and February 1987, water-levels declined in many main-terrace springs (for example, springs 4, 16, 16se, and 8nw), but other springs continued to flow.

A second period of noticeable decline in spring flow beginning in March 1987 was accompanied by full-scale production from the SB GEO field and the resumption of well testing at the CPI field. Over the 6-month period from March to August 1987, most or all of the main-terrace springs experienced generally declining water levels and subsequently became dry. Water levels in spring 8, the only spring on the main terrace to flow continuously during the 1945-52 period, remained relatively high until February 1988, when the spring was reported dry at a depth of about 1 foot (fig. 29). This designation refers to the fact that the measuring device was lowered to 1 foot below the spring orifice but failed to detect any water.

Seasonal and Long-Term Trends

Evidence of the influence of several factors can be seen in the records of seasonal and long-term change in water levels in springs such as 6 and 8. The general pattern of change

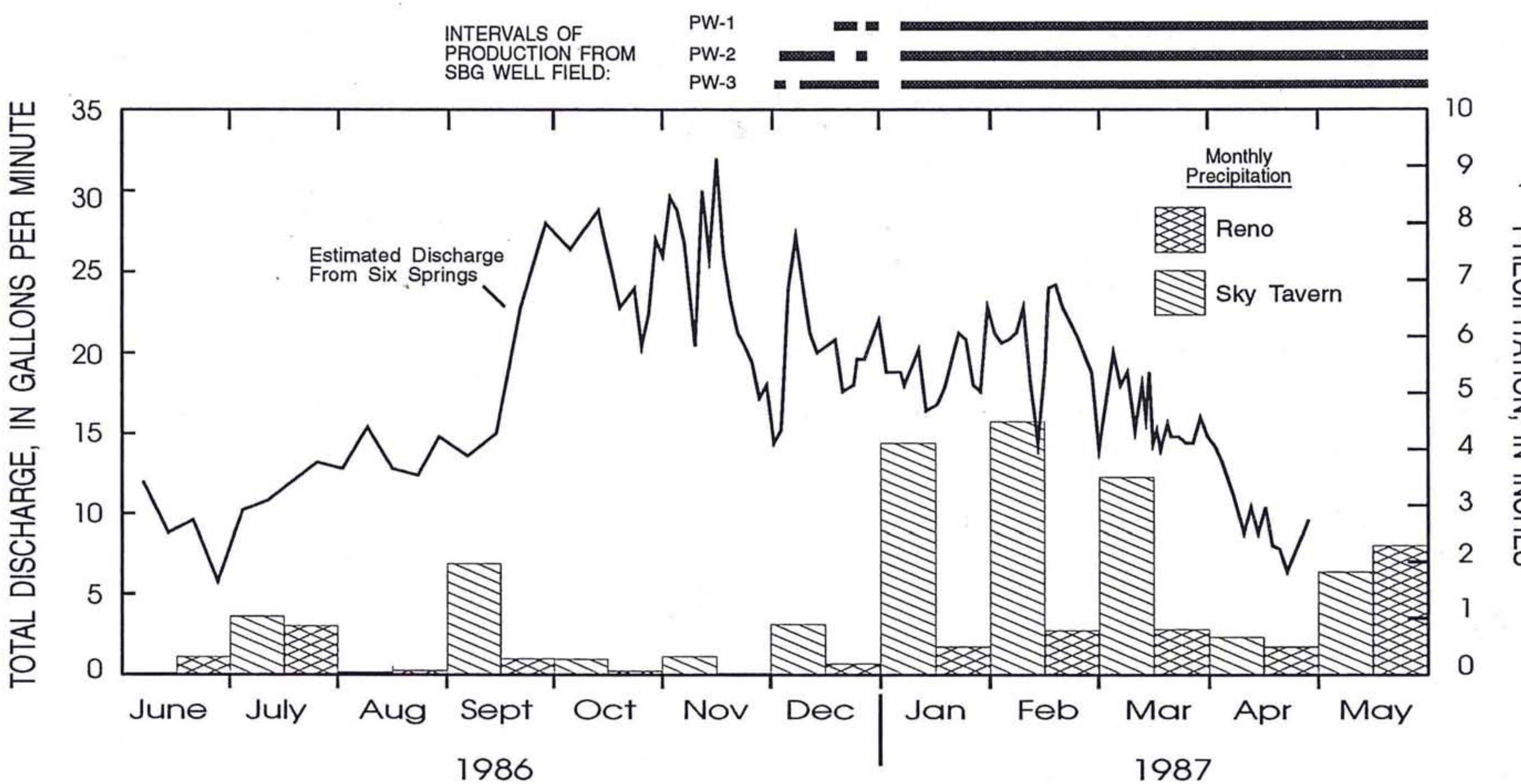

Figure 28. Visually estimated discharge from six springs on the main terrace and intervals of production from wells in the SB GEO (SBG) well field from June 1986 to April 1987 (from Yeamans, 1987a). Also shown is the monthly precipitation at the Reno Airport and Sky Tavern sites.

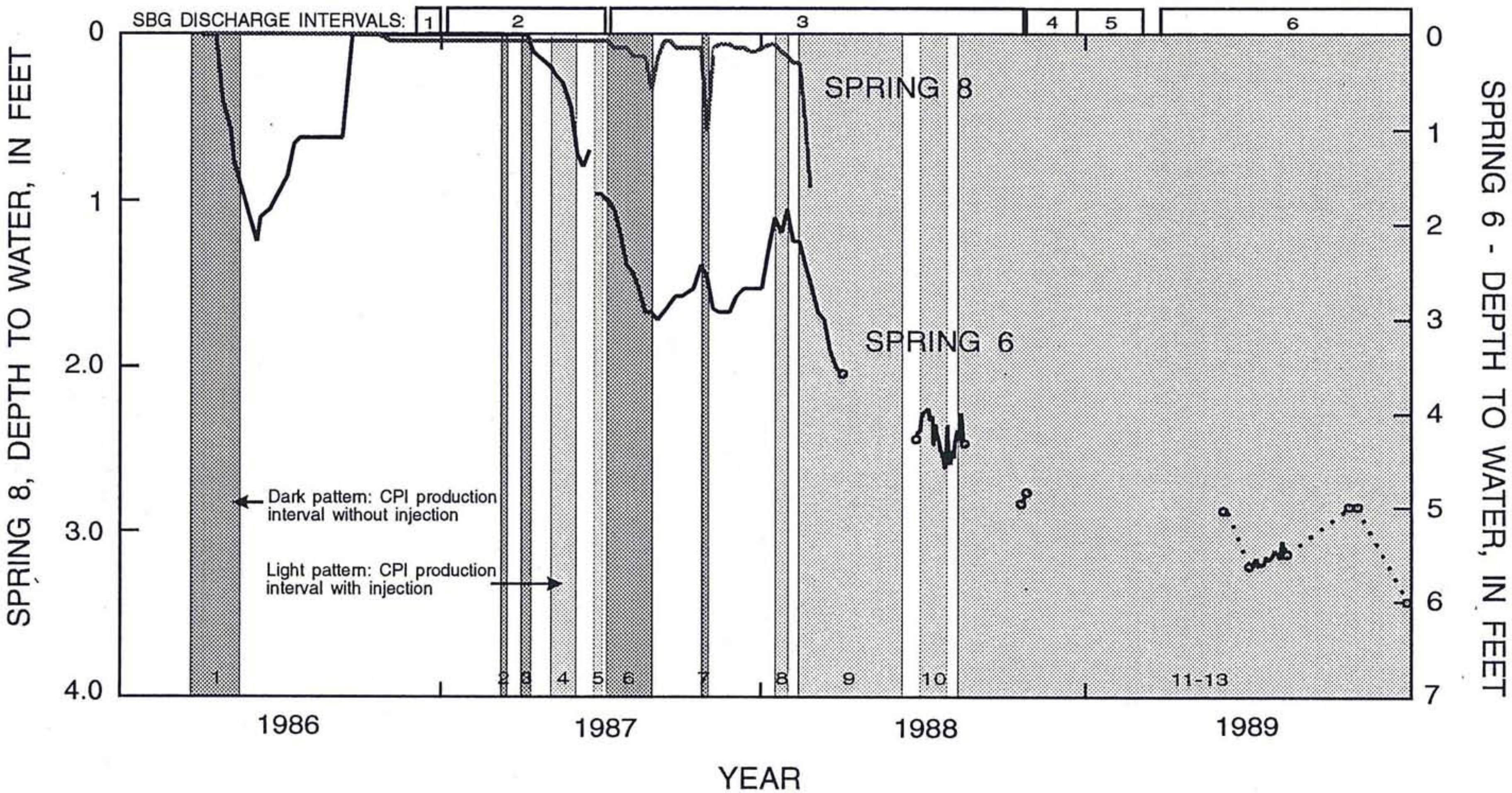

Figure 29. Water levels in spring 6 and spring 8 on the main terrace, 1986-1989. Circles represent individual measured water levels. Dots represent assumed trends of the spring 6 water levels between measurements in 1989. See tables 4 and 5 for descriptions of Caithness Power Incorporated (CPI) and SB GEO (SBG) discharge intervals.

observed in spring 6 over the 1986-1989 period is one of relatively high water levels in the winter and low water levels in the summer, superimposed on a overall decline of six feet. As such, there is a general correlation between the spring 6 hydrograph and the hydrograph for the PTR-1 well (fig. 27). This apparent seasonal pattern of water-level change in spring 6 is similar to the seasonal variation in spring flow noted by White (1968) for the 1945-1952 period (fig. 16). After 1988, the data for water-level spring 6 are too sparse to delineate a seasonal pattern, if one exists, except for the period of water-level rise in the second part of 1989. On the other hand, the data for other springs in the ACEC such as 8, 12, and 42w (figs. 5 and 29, and Appendix A) do not show any obvious seasonal cycles except perhaps during the spring 1986-spring 1987 period. The available data for these springs after mid-1987 make such determinations speculative.

Correlations can be seen between changes in water level in many springs and intervals of discharge at the geothermal well fields, as discussed in more detail below. The two periods of adequately documented water-level rise (in the fall of 1986 and 1987) are associated both with the expected seasonal recovery of the shallow ground-water system and with the cessation of well testing operations at the CPI field. However, the recovery of about 1 foot recorded in spring 6 in the fall of 1989 is noteworthy because it occurs during a period of relatively constant production at both geothermal well fields and there are corresponding recoveries in strat wells tapping the geothermal system in the Steamboat Hills (as discussed subsequently).

The long-term trend for spring 6 shows a decline in water level of about 6 feet by the end of 1989. The overall decline for other springs on the main terrace is variable, including 13 feet for spring 42w and 17 feet for spring 12 (fig. 5). There is as yet no satisfactory explanation for these differences in overall decline. Factors which may be involved include differences in water temperature and density in different spring conduits and differences in vertical permeability in the conduits and horizontal permeability in the adjacent formations. The permeability factors should affect the head loss as fluid flows upward in each conduit and laterally into the wall rock. There may also be fracture connections between different conduits at depth which allow flow from one to another. Differences in altitude between springs on the main terrace may be indicative of differences in permeability in and adjacent to each conduit. For example, the spring 6 vent is about 20 feet lower in altitude than the spring 12 vent. In general, the altitude of the piezometric surface, as delineated by spring altitudes and water levels in wells on the main terrace prior to geothermal development in the Steamboat area, sloped eastward towards Steamboat Creek with an overall drop in altitude of about 100 feet.

During this study, water-level measurements were made in well GS-8 at the base of the main terrace, and in well GS-1 and an unnamed well on the low terrace (locations in fig. 4). Other wells in these areas are either sealed shut or filled with debris. Comparison of water levels reported by White (1968) with recent measurements indicates overall declines of 4-7 feet in these wells through 1989, but only 1-3 feet between 1988 and 1989. The Byers well on the west side of the main terrace was been monitored in 1990 and 1991 by the USGS and Caithness; comparisons of depth-to-water measurements during this recent monitoring period with a measurement made in 1985 indicate a decline of about 40 feet (Colin Goranson, written communication, 1991; Donald H. Schaefer, written communication, 1991). The well is approximately 100 feet deep and reaches a maximum temperature of about 120°C. Data from White (1968) on well GS-3, drilled next to the Byers well to a depth of 686 feet, indicate that neither well penetrates the main fracture system through which high-chloride thermal water flows upward to the main-terrace hot springs.

Short-Term Fluctuations

A consistent pattern of correlation between intervals of CPI well discharge and short-term water-level fluctuations in spring 6 exists for the 1986-1988 period (fig. 27). The clearest response is that for interval 1, which involved a two month test of Steamboat No. 1 (later recompleted and renamed 21-5). The average well discharge during this period was about 815 gal/min and no fluid was reinjected (table 4). The decline in water level in spring 6 during and following CPI interval 1 was approximately 2 feet, although some additional decrease in head within the spring conduit must also have accompanied the change from flowing to non-flowing conditions. The net rate of production (production minus injection) during subsequent CPI discharge intervals was 300-500 gal/min, except for a few relatively short discharge intervals with higher net production. The production/injection rate histories for each well field are discussed further in the next section of the report. Other examples of water-level declines and recoveries associated with CPI discharge intervals include intervals 6, 7, 8, and 9. For interval 4 in May-June 1987, water levels in springs 6, 12, and 42w were declining before the test started, but the rate of decline accelerated during the test period, and water levels rose following shut-in.

Water-level data were collected daily over a two-month period in mid-1988 from springs 6, 12, and 42w (figs. 5 and 30). This period includes CPI discharge interval 10 and part of interval 11. All three springs show consistent responses of water-level decline during production and rise following shut-in, although the spring 6 response is more noisy because some measurements were made under boiling conditions. Water-level declines during interval 10 range from 0.6 feet in spring 6 to 1.84 feet in spring 42w. The relative amount of change in each spring during and following discharge interval 11 is in general correspondence with the differences in long-term water-level decline in these springs. That is, changes in springs 12 and 42w are two to three times larger than changes in spring 6. Although not shown in this report, semilog plots of these data (water-level change as a function of log time) show linear relations for both rising and falling periods, indicative of aquifer response to geothermal production (Collar, 1990).

Water levels in some of ACEC springs are affected by thermal cycling or intermittent boiling of the fluid column in the spring conduit. This condition can cause significant changes in the depth to water, as evidenced by the water-level record for spring 6 shown in figure 30. For springs with water levels shallow enough to be visible from the land surface, such a spring 8, measurements were avoided under boiling conditions. For other springs, the available water-level records may include measurements made under boiling conditions and some apparent short-term changes may reflect this anomalous condition.

Correspondence between changes in water level in spring 8 and CPI discharge intervals 6-9 are apparent in figure 29. Prior to discharge interval 6, water levels in spring 8 remained

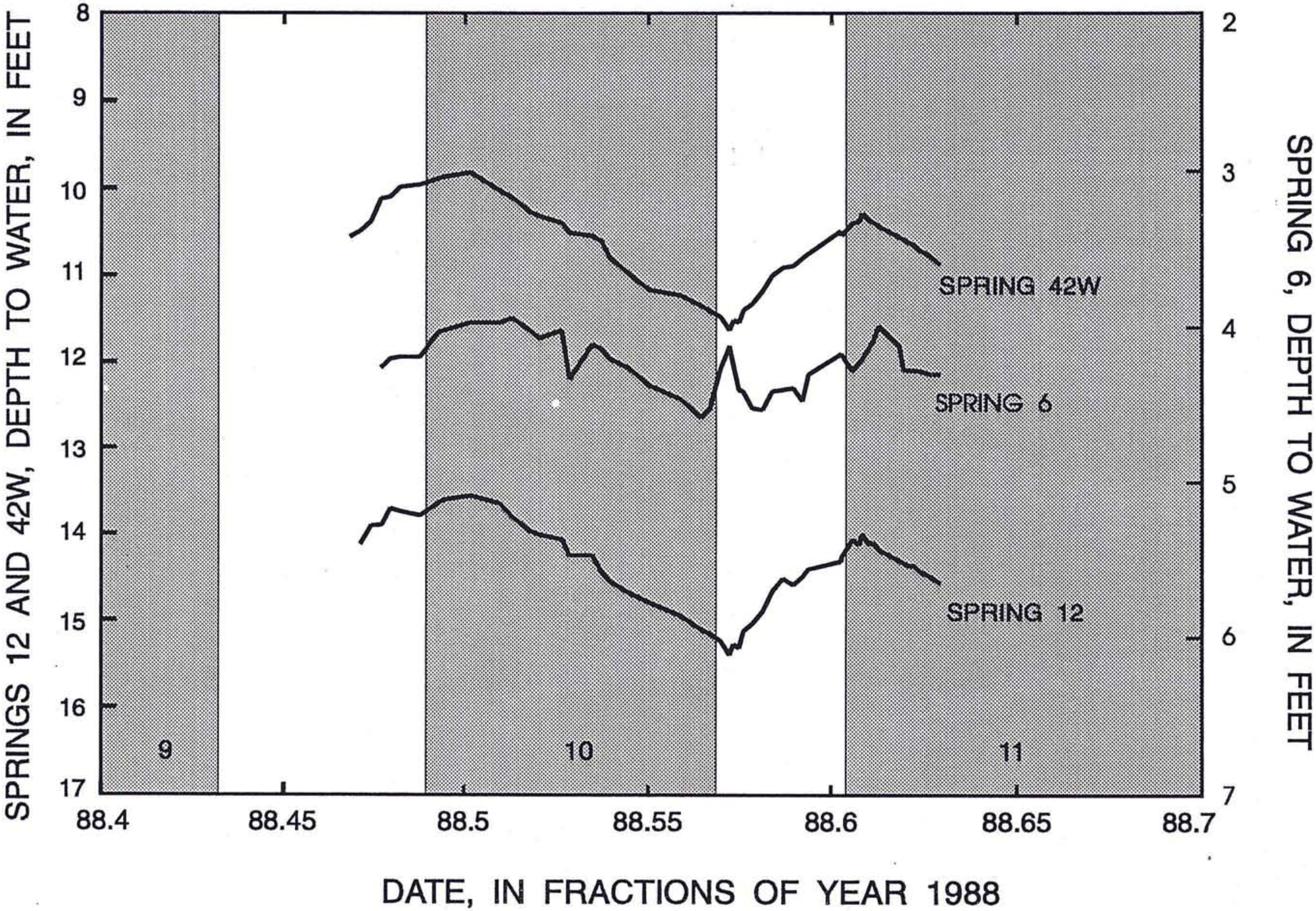

Figure 30. Water levels in springs 6, 12, and 42w on the main terrace during the summer of 1988 and periods of discharge from the CPI well field, as numbered in table 4.

near the rim and discharge occurred through a crack below the rim.

Limited thermal-water production occurs on an intermittent basis from the Steamboat Spa well on the low terrace (fig. 19). This well is 260 feet deep and most likely draws thermal water from the older alluvium overlying granodiorite bedrock in this area (Appendix D). The history of discharge from this well is only approximately known; its maximum flow is about 60 gal/min, but mineral deposition limits its ability to sustain flow. The well is reported to have discharged continuously, without pumping, throughout 1987 and up to May 1988, when the discharge declined and ceased (Collar, 1990). From May 1988 to the last week in March 1989 the well remained inactive. From June to August 1989, the well was induced to flow each weekday from morning until evening. The shapes of the hydrographs for well GS-1 and the unnamed monitor well at the low terrace (Appendix E) are similar and most likely reflect the effects of discharge from the Steamboat Spa well.

Changes in wells in the Steamboat Hills and on the High Terrace

Five production wells and one injection well have been drilled by Caithness Power, Inc. in the Steamboat Hills (fig. 19); currently only wells 23-5, 83A-6, 21-5, and Cox I-1 are in use. Unused CPI production wells 28-32 and 32-5 are shown as observation wells in figure 19 (strat 32-5 is located adjacent to unused production well 32-5). Three production wells and two injection wells were drilled for the SB GEO power plant on the high terrace; wells PW-1, PW-2, PW-3, and IW-2 are currently being utilized. Water-level or downhole-pressure data have been collected on a semi-continuous basis from numerous monitor wells in the Steamboat Hills and on the high terrace, including hydrologic observation wells (OW) completed in the SB GEO well field and stratigraphic test (strat) wells drilled for temperature gradient information in the Steamboat Hills. These strat wells were later perforated or recompleted with tubing slotted near the bottom for water-level monitoring. Well-completion information for all these wells is listed in tables 6-8; each is shown in the geologic section in figure 7. Additional information, including temperature profiles and lithologic logs for some of these wells is given in Appendix B and C.

Observation Wells

Water-level data for the wells monitored in these areas is obtained from depth-to-water measurements made from the land surface or from gas-pressure measurements made in capillary tubing. The gas-pressure measurements are made with absolute-reading or gage-reading pressure transducers, and converted to depths-to-water using the known depth of the capillary tube pressure chamber. For the strat wells with capillary tubing, we have converted the gas-pressure measurements to depths-to-water using either measured absolute pressure or gage pressure converted to absolute pressure. This yields a water level record with less variation from barometric pressure changes than would the gage-pressure measurements alone because of the relatively high barometric efficiency of these wells. As a result, however, the actual depth to water in such wells is approximately 30 feet greater than our calculations would indicate. The influence of barometric pressure on water-level changes in the strat wells is discussed in a subsequent section of this report and by Collar (1990).

For monitor wells IW-1, OW-1, and OW-2 in the SB GEO well field, both downhole

Table 6. *Caithness Power Incorporated well-completion information*

Well	Distance to spring (feet)	Approximate elevation (feet)	Depth (feet)	Casing depth (feet)	Open-hole interval Elev. (feet) (thickness)	Open-hole rock types
<u>Production</u>						
23-5	9480	5348	2422	1475	3873-2926 (947 feet)	metamorphic
83A-6	10390	5732	2540	2137	3595-3192 (403 feet)	metamorphic, granodiorite
21-5	8875	5732	2767	1292	4440-2965 (1475 feet)	metamorphic, granodiorite
<u>Injection</u>						
Cox I-1	5100	5057	3449	1764	3293-1608 (1685 feet)	granodiorite

Table 7. *SB GEO well completion information*

Well	Distance to Spring (feet)	Approximate Elevation (feet)	Depth (feet)	Casing Depth (feet)	Open Hole Interval Elev. (feet) (thickness)	Open Hole Rock Types
<u>Production</u>						
PW-1	3990	4719	626	600	4119-4093 (26 feet)	granodiorite
PW-2	4090	4734	530	495	4239-4204 (35 feet)	granodiorite
PW-3	3720	4725	566	545	4180-4159 (21 feet)	granodiorite
<u>Injection</u>						
IW-2	4220	4698	1403	730	3968-3295 (673 feet)	granodiorite
IW-3	4370	4695	517	400	4295-4178 (117 feet)	tuff breccia (89 feet) granodiorite (28 feet)

Table 8. *Selected data for stratigraphic test wells in the Steamboat Hills area*

Well	Depth feet	Formation[1] perforated	Temperature[2] °C	Change in Water Level[3] 1987-1989 in feet
strat 2	844	Kgd	171	-26
5	1680	Kgd	44	-16
6	1936	Pkm	87	-22
7	1503	Tk	84	-11
8	1940	Pkm	96	(+1)[4]
9	915	Kgd	179	-14[5]
13	1767	Pkm	177	+9
14	1630	Kgd	177	+2

[1]Pkm = Pre-Cretaceous metasedimentary rocks; Kgd = Cretaceous granodiorite; Tk = Tertiary volcanics (Kate Peak Formation).
[2]Measured temperature in perforated interval or at bottom of well.
[3]Water level decline indicated by minus, rise by plus, measured from mid 1987 to mid 1989.
[4]No data for 1987 or 1989.
[5]No data before December 1987.

pressure and wellhead pressure are measured because gas columns exist in these wells. Reported depths to water for these wells (Ormat 1987a-d, 1988a-d, and 1989a-c), based on differences between downhole and wellhead pressure, give a misleading view of reservoir drawdown because the calculated depth to the water surface in the well changes as the gas-column pressure changes. Gas pressures have changed in part because of the addition of nitrogen to the wellbore from the capillary tubing. We have instead calculated effective depths-to-water from the downhole pressure and the reported depth of the pressure transducers in wells OW-2 and IW-1. By this method, changes in the effective depth-to-water represent actual changes in reservoir pressure. The reported depth-to-water data for OW-1 are highly variable and not readily interpretable, possibly because of instrument problems (Collar, 1990; Ormat Energy Systems, Inc., written communication, 1989). They are not reported here.

Detailed hydrographs for each monitor well are included in Appendix E. In these plots a distinction is made between depth-to-water calculations based on hand-held measurements and those based on transducer measurements. In the main part of the report, less detailed hydrographs are presented for some wells considered to be representative of changes observed in the geothermal system during the 1987-1990 period. These include strats 2, 5, 9 and 13, and observation wells IW-1 and OW-2. Except for strat 13, these wells have shown long-term declines in water level of 15-26 feet over the 1987-1990 period, but with significant short-term variations that are discussed below. Water-level and well completion data for other strat wells are summarized in table 8. These wells show either steady long-term declines of 11-22 feet (strats 6 and 7), or water-level rises of 1-2 feet over the 1987-1989 period. On the basis of an additional 15 foot decline in water level in strat 7 between 1980 and 1985 (Yeamans, 1985), it appears that the declines in strats 6 and 7 are part of longer-term head declines in bedrock aquifers in and near Pleasant Valley (Collar, 1990). The small rises in strats 8 and 14 have no clear explanation.

Strat 13 is located next to CPI production well 23-5 and was completed with a slotted liner in metamorphic basement at 1,767 feet, where the measured temperature is 177°C. An overall rise in water level in strat 13 of about 9 feet was observed from 1987-1989, but there are several periods of water-level fall associated with CPI discharge intervals involving production from 23-5 and corresponding water-level rises following shut-in (fig. 31). During discharge interval 11 in 1988, well 23-5 did not discharge for a month between September and October, during which time the water level in strat 13 rose about 3 feet. This correlation indicates that a hydraulic connection exists between strat 13 and well 23-5. Other factors, however, must be responsible for the long-term rise in water level in strat 13.

Strats 2, 5, and 9 are located near the northern end of the Steamboat Hills, in the general vicinity of the Cox I-1 injection well. Strats 2 and 9, with bottom-hole temperatures of 171°C - 179°C, are completed with liners slotted at depths of 830-930 feet in the same thermal flow zone penetrated by, but cased off in, the Cox I-1 well. Strat 5 shows a linear temperature profile, but a maximum temperature of only 44°C in granitic bedrock at a depth of 1,700 feet. Fluid sampled from strat 5 was relatively dilute (C. Stewart, Caithness Power Inc., written communication, 1991); its temperature and chemistry indicate that it is completed within the non-thermal ground-water system. No fluid samples have been obtained from strats 2 and 9. In spite of differences in bottom-hole temperature and presumably fluid chemistry between strats 2 and 9 and strat 5, similar water-level changes occurred in these wells from

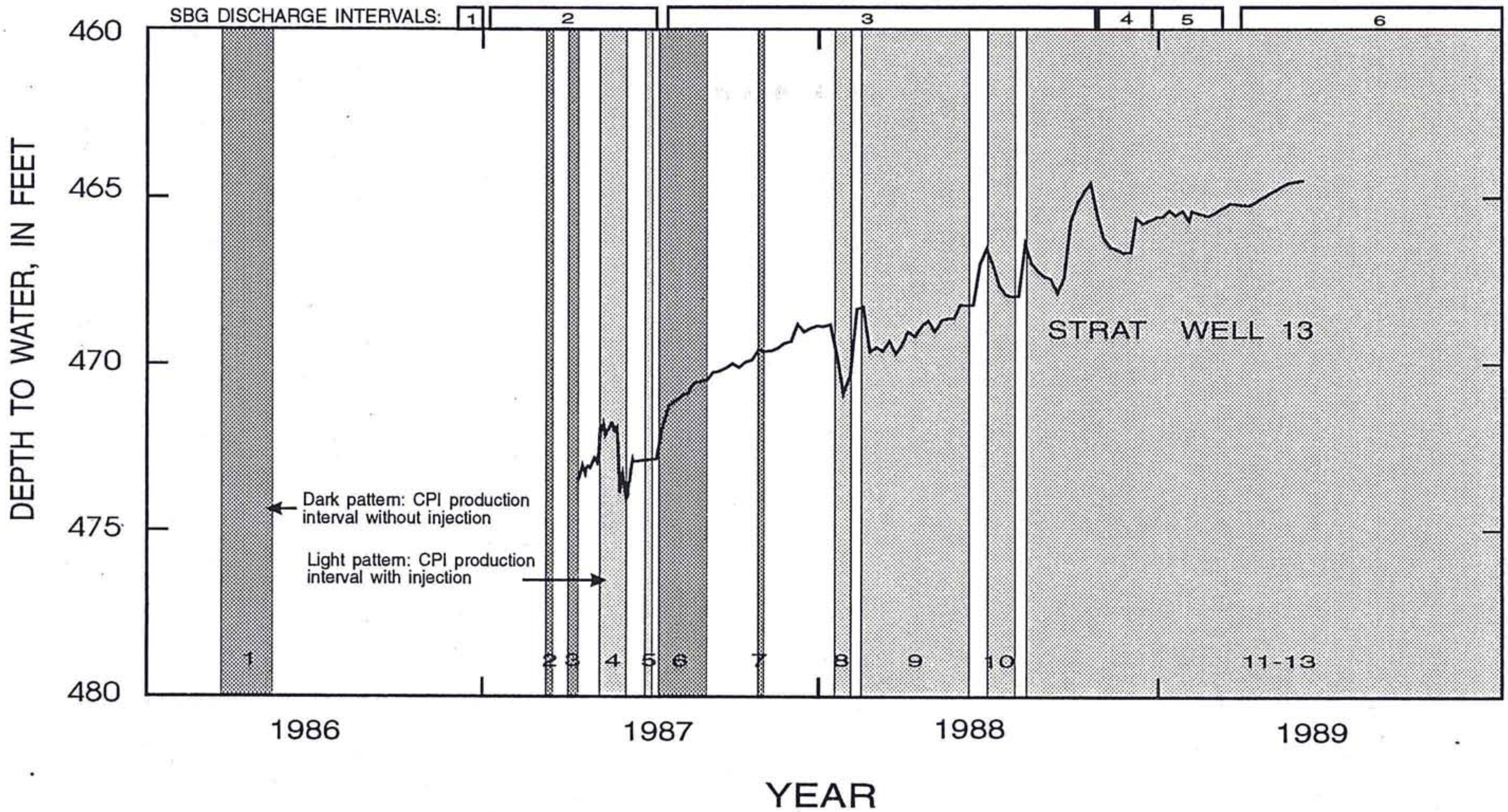

Figure 31. Water levels in strat well 13, 1986-1989. Also shown are intervals of production from the Caithness Power Incorporated (CPI) and SB GEO (SBG) well fields as numbered in tables 4 and 5.

1987 to 1990. Between the spring of 1987 and summer of 1989, water levels declined approximately 16 feet in strat 5 and 26 feet in strat 2 (fig. 32). The rate of decline in strat 9 was comparable to that in strat 2.

A period of significant water-level rise and fall was observed in strats 2, 5, and 9 during the fall of 1989 and winter of 1990 (fig. 32). Both power plants were in nearly continuous operation during this period. Water-level rises also occurred during this period in the Pine Tree Ranch-1 well and STMGID monitor wells MW-3 and MW-4 (fig. 22) and in spring 6 (fig. 33). The magnitude of the rise in each well was comparable (5-7 feet), except for wells MW-3 and MW-4 and spring 6 for which the rise was on the order of 1 foot. Precipitation during the July 1988-June 1989 period was twice that in the two previous precipitation year (fig. 15). These comparisons suggest that similar processes, such as increased recharge to the shallow ground-water system or decreased rates of ground-water pumpage may influence changes in hydraulic head at each location. This inference must be qualified, however, in view of unexplained differences in the onset and duration of the water-level rise at these locations and relatively sparse data.

An anomalous rise in water level was also detected in strat 5 beginning in July 1991, accumulating to about 34 feet by September 1991 and continuing to rise since that time. Although no corresponding water-level rises had been detected in strats 2 and 9 and PTR-1 as of October 1991, a 15-foot rise was recorded in the Woods well 0.25 miles southwest of PTR-1 between July and October. These changes may in part reflect the effects of the abnormally high precipitation in the entire region in March 1991. However, the magnitude of the rise in strat 5 is difficult to account for by this means alone. Because the tubing in strat 5 is not cemented against the surface casing or the open-hole section, it is possible that the water level in this well responds to more than one aquifer. This problem is common to other strat wells in the Steamboat Hills. Nevertheless, the general correspondence between periods of water-level rises in the ground-water system in the South Truckee Meadows and in thermal and nonthermal aquifers in the Steamboat Hills argues for a corresponding relation during periods of water level decline.

Results of numerous interference tests on CPI wells, conducted since 1979, provide some evidence of pressure communication between the CPI well field and strat wells 2, 5, and 9. The evidence is sometimes hard to interpret unambiguously because of (1) noise in the water-level records from barometric pressure and earth-tide influences, boiling conditions at the water surface (strat 9 and possibly strat 2), and instrument malfunctions; (2) inadequate measurement frequency and/or insufficient pre-test measurements; and (3) ongoing seasonal trends. Pressure monitoring data collected during a 2-week shut-down of the CPI well field in May 1990 has also proven useful in delineating and quantifying hydraulic connections between wells, as discussed below.

Pressure data collected during a 28-day test on Steamboat No.-1 in 1980 showed drawdowns and corresponding buildups of 4 feet and 6 feet in strats 2 and 9, respectively (Yeamans, 1984). No fluid was reinjected during this test. Faulder (1987) calculated a water-level decline of 1.9 feet in strat 2 during the first half of a 27-day flow test on well 23-5 (discharge interval 4 in table 4, for which all fluid was injected into Cox I-1). A total decline of about 4 feet was observed over the entire flow test. However, measurements were

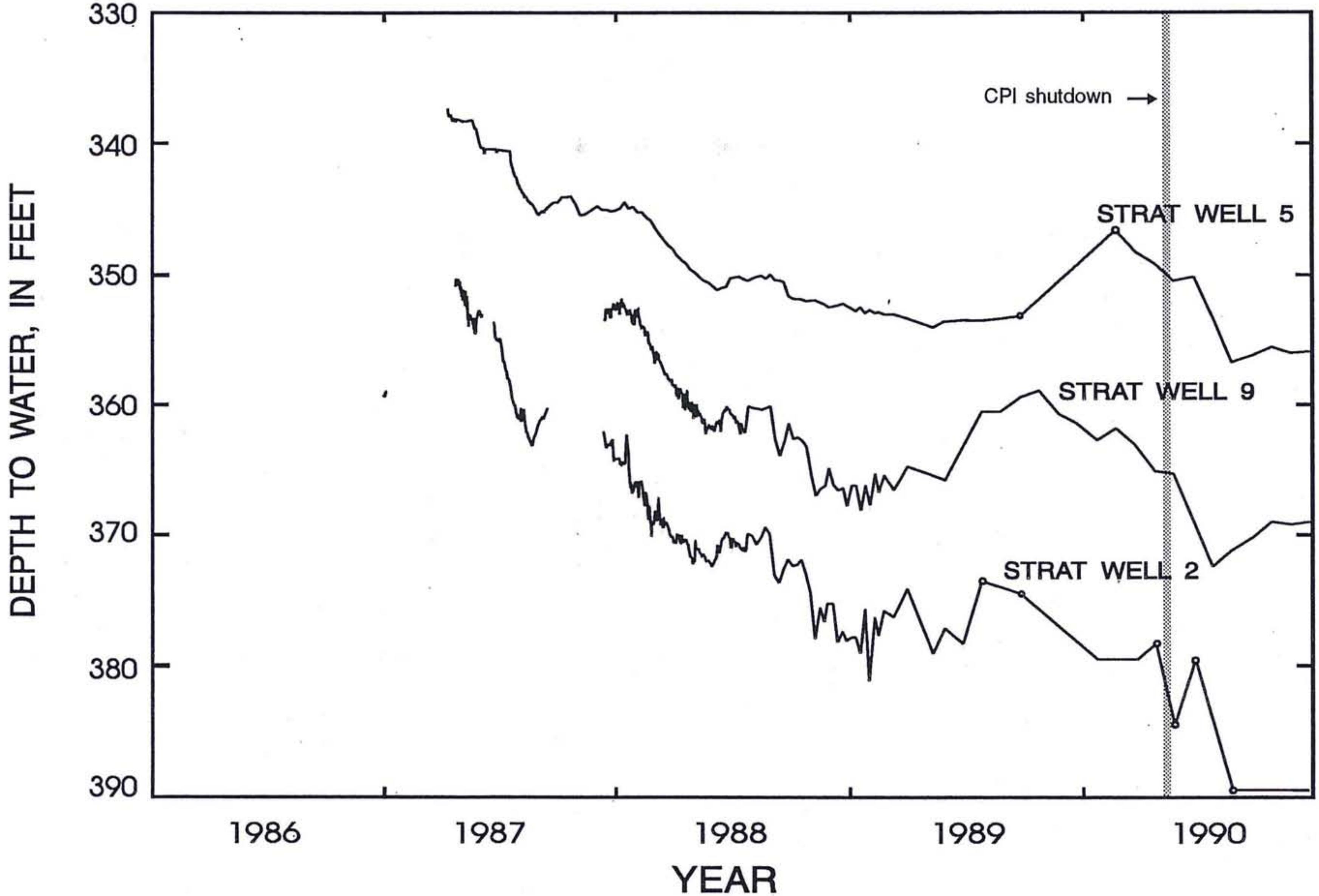

Figure 32. Water levels in strat wells 2, 5, and 9, 1986-1990. Dots represent monthly measurements made after June 1989. Water levels for strats 2 and 5 were adjusted by adding a constant to adjust to common scale (5 feet added for strat 5; 22 feet added for strat 2).

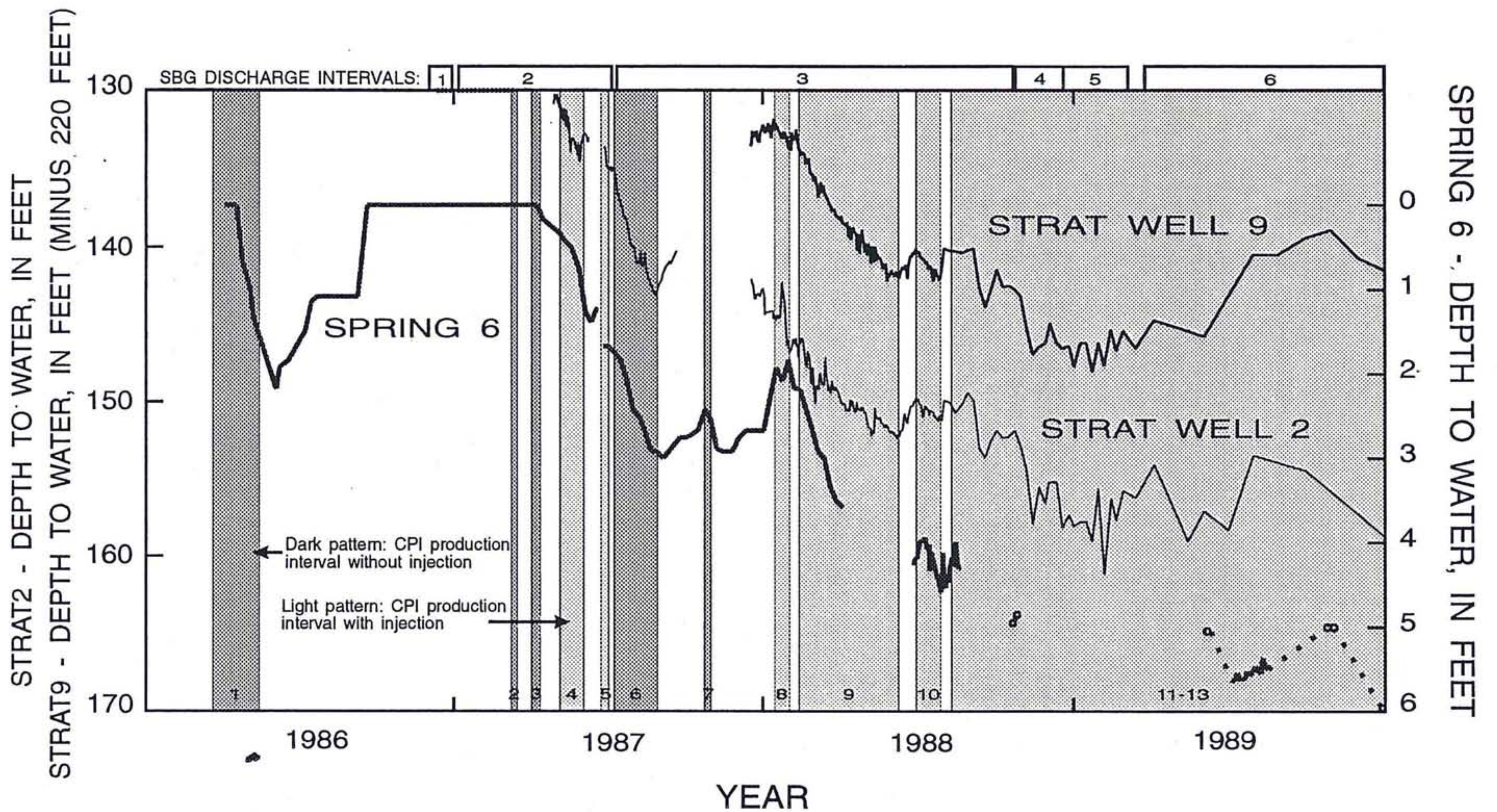

Figure 33. Water levels in spring 6 and strat wells 2 and 9, 1986-1989. For spring 6, circles represent isolated measured water levels. Dots show assumed water-level trends in 1989. CPI stands for Caithness Power Incorporated; SBG stands for SB GEO.

discontinued shortly after the end of the discharge interval so it is not known whether a corresponding pressure buildup occurred. In addition, very little pressure record was obtained prior to the start of the test, so that it is difficult to separate the seasonal trend in water level from that caused by production. No clear response in strat 9 was found during the 1987 test, although such interpretations are limited by a relatively large diurnal variation (1 psi, or 2.5 feet) that appears to reflect barometric pressure variations. Although Faulder (1987) concludes that strat 9 did not respond to injection into Cox I-1, it seems possible that the difference in response in strat 9 to this test compared with the 1980 test may reflect the effects of both drawdown from production and reservoir pressure support from reinjection. Data from subsequent discharge intervals indicate a difference in strat-well response to production with and without reinjection, as discussed below.

The data for strat 5 during the 1979, 1980, and 1987 interference tests yield conflicting indications of hydraulic communication with CPI production wells. A drawdown and recovery of approximately 1 foot was indicated from hand-held measurements during the 1979 test (Yeamans, 1984; Chevron, 1987). During the 1980 test, pressure transducer measurements indicated a decline in downhole pressure of 0.9 psi during production, but a continued decline in pressure following shut-in. Yeamans speculates that there may have been a malfunction related to a leak in the pressure line. During the 1987 test, no change in depth-to-water was observed during the first week of the 28-day test, leading Faulder (1987) to conclude that no pressure response to production was seen. However, a capillary tube and pressure chamber were installed in strat 5 about 1 week after the test began and following a short period of widely varying pressure data, the calculated depth-to-water shows a decline of about 2 feet during the remainder of the test. This is consistent with a more delayed and attenuated pressure response in strat 5 than in strats 2 and 9 that would be expected because strat 5 is not completed in the geothermal system.

Data reported at monthly intervals during 1990 from strats 2, 5, and 9 do not adequately delineate the effects of the shut-down of the CPI well field May 14-26, 1990 (fig. 32). Although a slight flattening of the downward trends in water level in strats 5 and 9 are indicated following the shut-down, the data for strat 2 may be affected by equipment problems, such as water in the gas chamber or a bad pressure gage. Fortunately, downhole pressure data collected at two-hour intervals are available during May and June 1990 for strat 9 and well 28-32. Well 28-32 is a production-diameter well north of CPI well 21-5. Although it is drilled to depth similar to the other CPI production wells, its static temperature profile (Appendix C) indicates that it reaches its maximum temperature of 209°C at a depth of 1,800 feet - some 600 feet shallower than the other production wells. The data for strat 9, contained in an unpublished report by Petty (1992), show a water-level recovery following shut-in of about 2 feet but a drawdown following restart of full production of about 10 feet. After about 14 days of full production and 50 days since partial resumption of production and injection, water levels in strat 9 begin to rise in a logarithmic fashion typical of well response to injection. Well 28-32 showed a similar response to shut-in and restart, except that pressure support from injection appears to begin about 20 days after partial production and injection resumed. The results from this test, then, establish that there is pressure communication between the CPI production **and** injection zones and the shallow thermal reservoir penetrated by strat 9 and presumably strat 2.

The water-level records for strats 2 and 9 show some similarities with that for spring 6 (fig. 33). The overall pattern of decline from 1986 through the summer of 1989 is the same for each feature, as is the pattern of rising water level in the second-half of 1989. These similarities indicate that the same stresses may be involved. Correlations between changes in water level in these wells and periods of production from the CPI wells, discussed previously for the spring 6 water-level record, are also seen in the strat-well records. In particular, water-level declines of 5-8 feet are observed during intervals 6 and 9, with indications of subsequent partial recovery. A greater rate of water-level decline during interval 6, without injection, than during interval 9, with injection, is consistent with pressure support from injection. A similar effect is seen in the strat 5 record.

These data indicate that water levels in strats 2, 5, and 9 and in hot springs at the main terrace have responded both to changes in the shallow ground-water system in and around the Steamboat Hills and to production and injection at the CPI well field. The effects of production from the SB GEO well field on these features are more difficult to delineate. A hydraulic connection between the shallow thermal zone penetrated by strats 2 and 9 and the SB GEO production reservoir is suggested (but not proven) by the presence of a low resistivity trough between these areas and by observation of water-level declines in the Towne geothermal well at the high terrace during well tests in 1979 and 1980 (Yeamans, 1984). Of possible significance in this regard is the fact that overall declines in water level in strats 2 and 9 between 1987 and mid-1989 were significantly greater than the corresponding decline in strat 5. We would expect from the differences in hydrogeologic conditions at these sites (strat 5 penetrates a non-thermal ground-water aquifer; strats 2 and 9 penetrate a shallow thermal flow zone) that strat 5 should be more responsive to changes in the shallow ground-water system than strats 2 and 9. Hence the greater water-level declines in strats 2 and 9 may be indicative of the additional effect of geothermal well production.

The records of calculated depths to water, based on measured downhole pressures in observation wells IW-1 and OW-2 in the SB GEO well field (figs. 34 and 35) show declines of 15-20 feet over the 1987-89 period. There is considerable scatter in the data for these wells, most likely reflecting equipment problems and operator measurement errors. On the basis of the records for these observation wells, there appears to be reservoir head decline both on the production side of the field (20 feet in OW-2) and on the injection side of the field (15 feet in IW-1). This may indicate limited pressure support from injection, although other factors such as declines in water levels in the surrounding ground-water system may also affect these results. Head declines measured in the SB GEO observation wells are comparable to differences in heads between the high terrace and the main terrace before development, indicating that the present drawdown of the SB GEO reservoir might not induce significant inflow of thermal water from the main terrace, even if permeable fractures existed between these two areas.

Production Wells

The SB GEO production wells are relatively shallow (500-600 feet deep) and produce water at temperatures near 170°C. The currently used injection well (IW-3) is of comparable depth, but injection well IW-2, used until March 1989, is open from 730-1,414 feet (table 7). A summary of intervals of production and injection from the SB GEO field is given in table

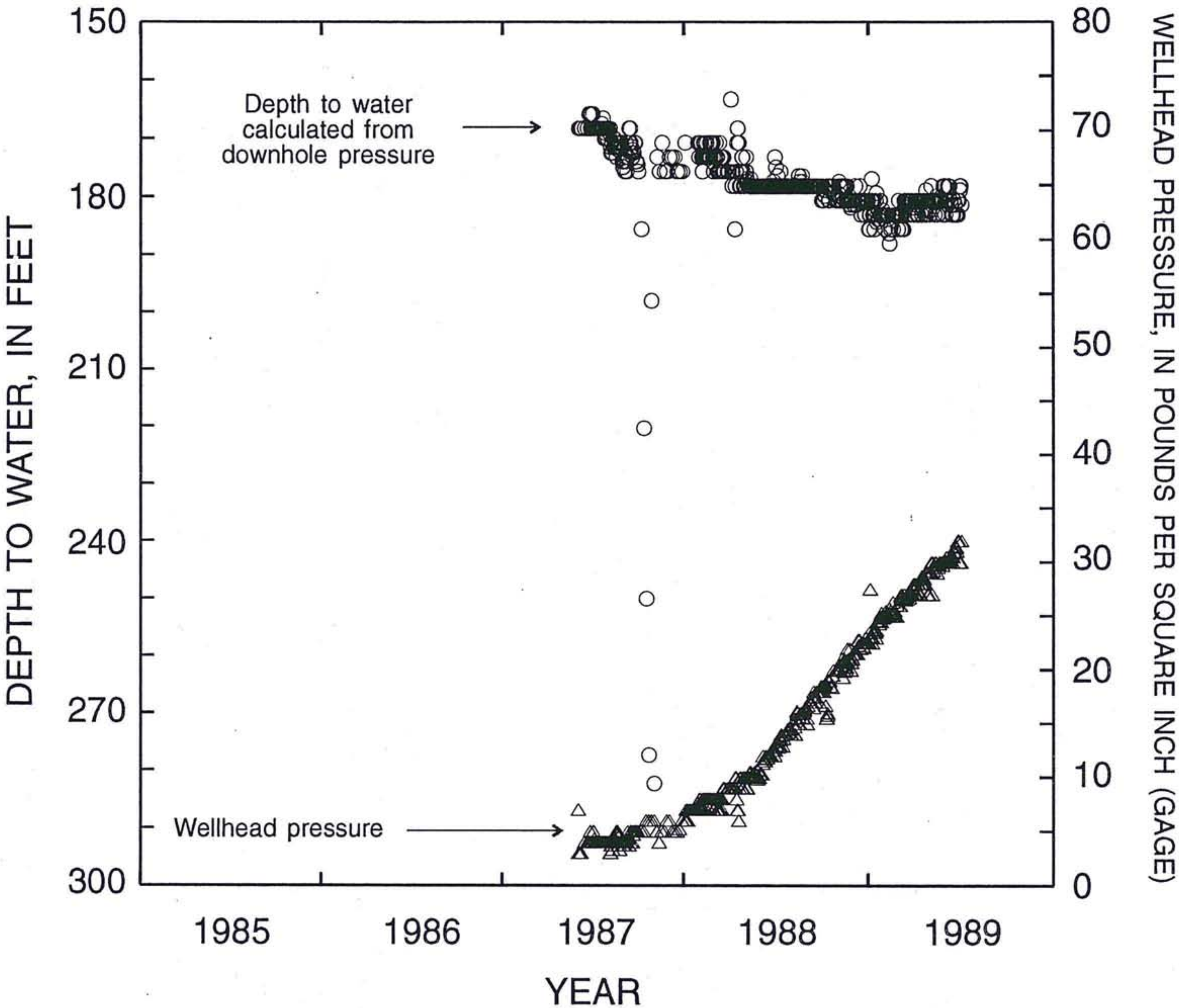

Figure 34. Depth-to-water in well IW-1, calculated from downhole-pressure and wellhead-pressure measurements, 1987-1989.

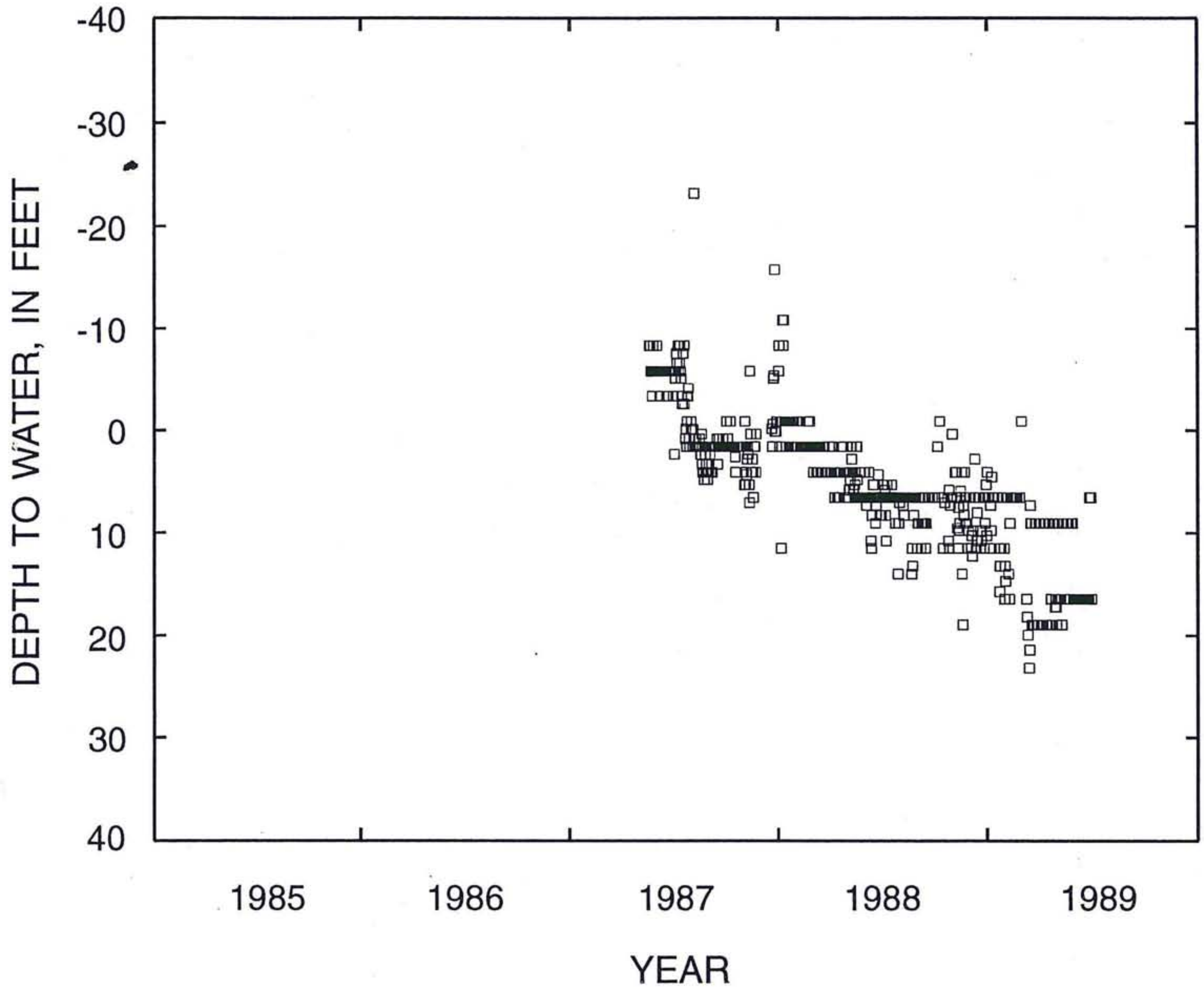

Figure 35. Depth-to-water in well OW-2, calculated from downhole-pressure measurements, 1987-1989.

5; plots of average monthly production rates are shown in figure 36. Considerable variability in production and injection rates occurred in 1987, but rates in subsequent years have been relatively constant. Although there is no net loss of mass from the fluid stream, there is a difference of about 200 gal/min between the volumetric production and injection rates because of the difference between production and injection temperatures. A more detailed plot of daily average injection rates for 1987-88 (fig. 37) shows that periods of significant change in well-field operation during 1987 were of relatively short duration. The hydrograph for spring 6 (fig. 37) shows little evidence of correlation with changes in injection rate, except for an apparent rise of about 1 foot in January 1988, following a week-long period of decreased production and injection.

Downhole pressure data for the SB GEO production wells are proprietary, and were not examined in detail during this study. Head changes of 20-40 feet (equivalent to pressure changes of about 8-15 psi) have been observed in these wells (Colin Goranson, written communication, 1991). Reservoir transmissivity values obtained from interference tests and from computer simulations of the production-well pressure data range from 17,000 to 34,000 ft^2/day (kh = 1,000 to 2,000 darcy-ft), depending on assumptions regarding injection pressure support and reservoir head decline caused by declines in water level in the shallow ground-water system (Goranson and others, 1991; C. Goranson, written communication, 1991). Reservoir pressure recovery of only about 5 psi (12 feet) was measured in the production wells during a recent shut-down of the field (C. Goranson, written communication, 1991). This indicates that the additional head decline measured in the production wells prior the shut-down may be caused by other factors, such as water-level declines in the shallow ground-water system and drawdown in the CPI reservoir.

There is no clear indication of any significant decline in production reservoir temperature, as would be expected after almost 5 years of injection at distances of about 500 feet from the production wells. Although well-head temperatures do show long-term declines on the order of 15°C, such declines can be attributed in part to declines in well-head pressure accompanying normal plant operation. Goranson and others (1991) suggest that injected fluid moves downward along steeply dipping fractures which provide pressure communication with similar structures intersected by the production wells but effectively prevent injected fluid from flowing laterally to the production wells. A similar explanation for the apparent pressure support from injection without temperature declines in production wells may apply to the CPI well field.

Construction is nearly completed for a significant addition of geothermal production adjacent to the SB GEO well field, involving new production wells sited east and southeast of the existing well field on private lands that border the northern boundary of the ACEC (JBR Consultants, 1991). Interference testing will be needed to delineate the degree of hydraulic connection between the existing SB GEO wells, additional production and injection wells drilled for this expansion, and hot springs on the main terrace. However, there presently exists no regulatory requirements for such testing.

CPI production is obtained from three wells drilled into a zone of open fractures in metamorphic and granitic bedrock at depths of 2,400-2,800 feet. Temperature profiles in these wells show high gradients down to zones of temperature reversal which mark the

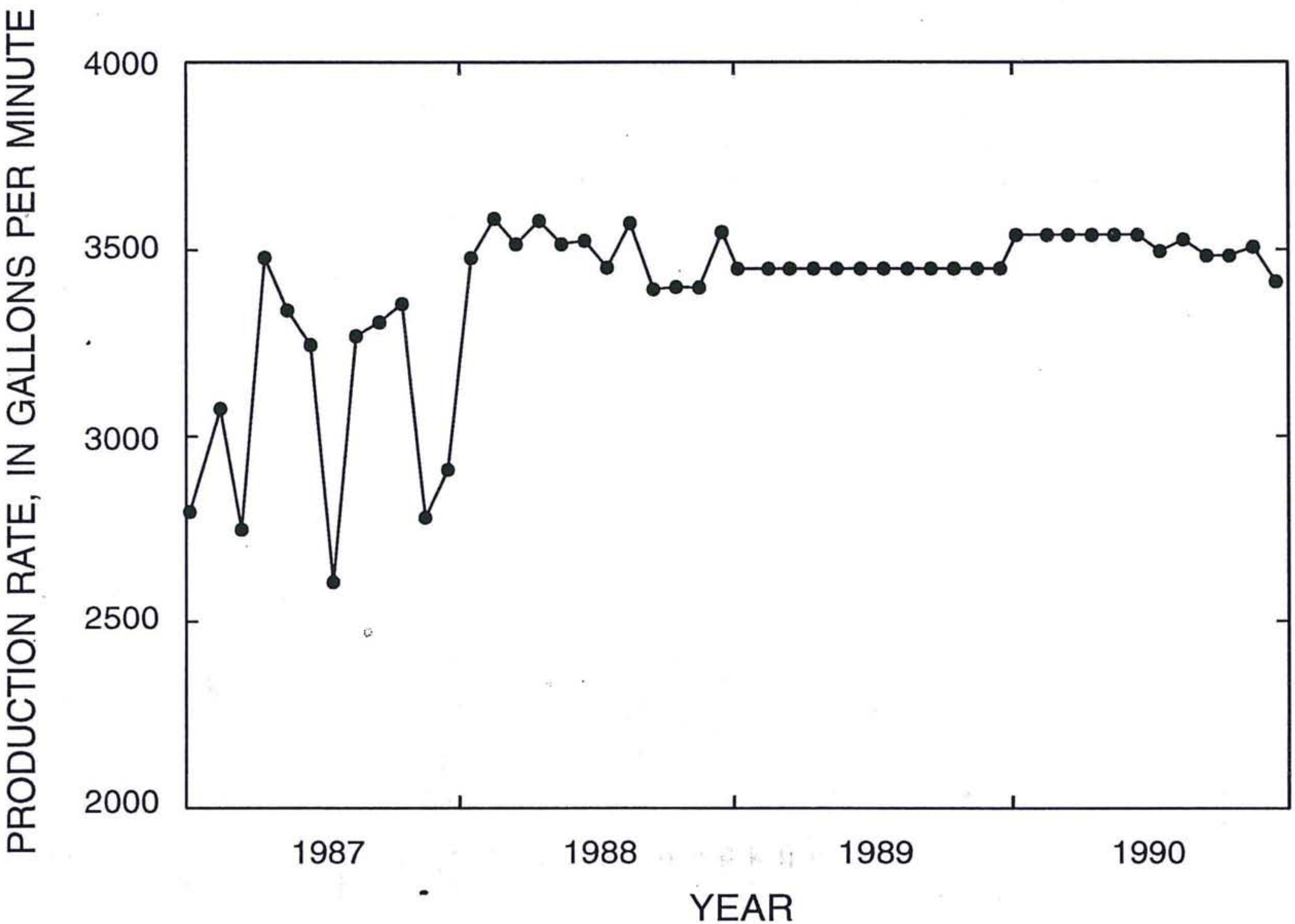

Figure 36. Monthly averaged total production rate for the SB GEO well field, 1987-1990 (from C. Goranson, written commun., 1991).

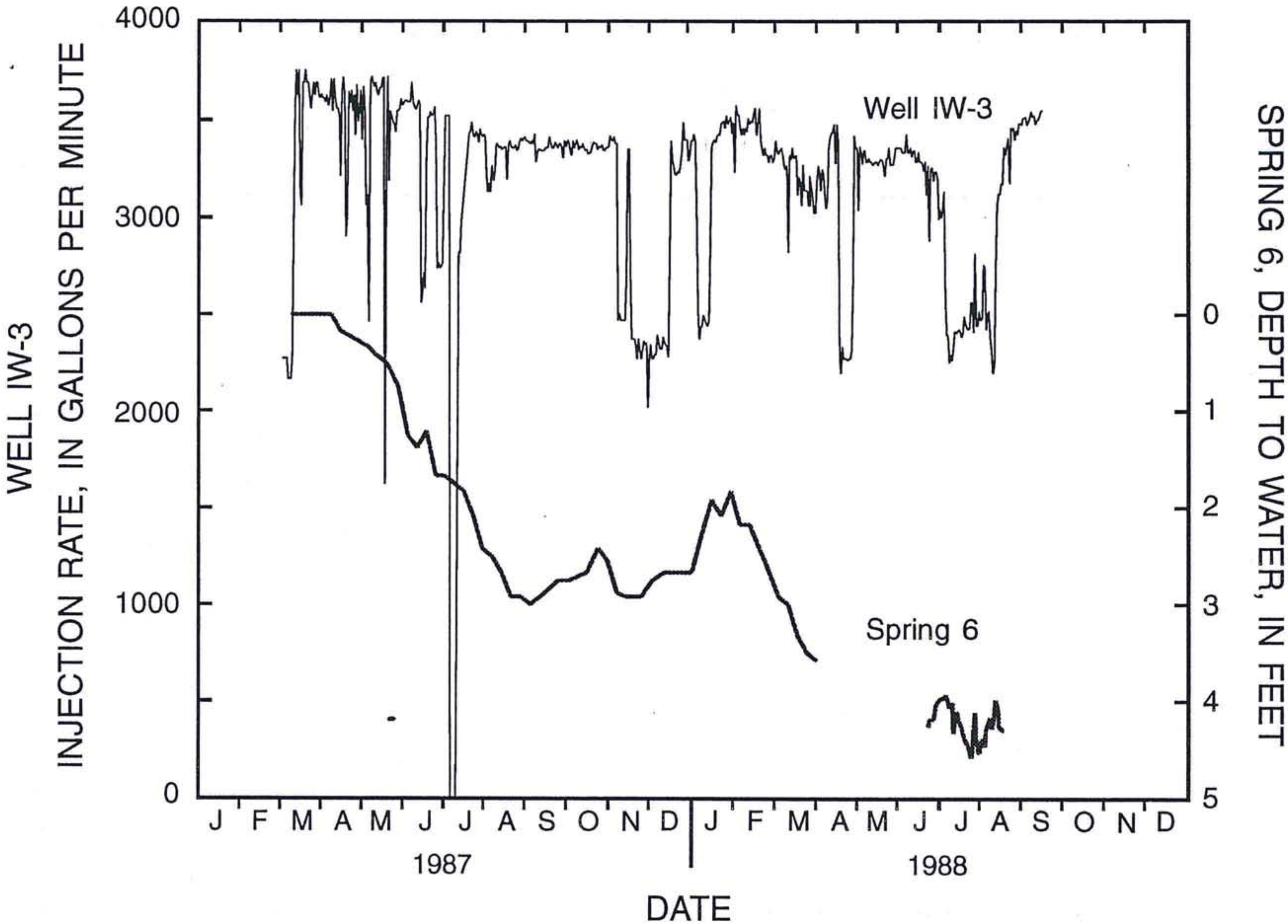

Figure 37. Daily averaged injection rate in SB GEO well IW-3 and depth to water in spring 6, 1987 - 1988 (modified from Collar, 1990).

production reservoir in the CPI well field. Measured reservoir temperatures range from 221°C in wells 21-5 and 83A-6 to 238°C in well 23-5. Other wells drilled for production, including 28-32 and 32-5 (fig. 19) remain unused because of lower permeability or formation damage. Intervals of relatively constant production from the CPI well field are listed in table 4; plots of monthly average production and injection rates following initiation of full-scale operations in 1988 are shown in figure 38. As noted previously, the difference between the total production and injection rates has remained relatively constant since 1988, reflecting the consumptive loss of about 500 gal/min of steam condensate for power-plant cooling. Periods of very low monthly average production and injection correspond with plant shut-downs for maintenance.

Direct measurements of pressure changes in production wells are few in number and of questionable reliability. Such measurements include nitrogen-line pressure readings in wells 21-5 and 83A-6 made for several hours before and after these wells were shut-in May 1990, capillary-tube pressure measurements in well 23-5 during a production test in May-June 1987, and pressure surveys run in 23-5 and 83A-6 under static (shut-in) conditions in 1987, 1988, and 1990. The gas-line pressure measurements suggest that drawdowns on the order of 4-7 psi (10-15 feet) occur within hours of initiation of production, but such interpretations are limited by large variability in these pressure measurements made under less-than ideal conditions. More reliable reservoir pressure measurements could have been made in observation wells completed and instrumented for that purpose. However, of the strat wells drilled in and near the CPI well field, only strat 32-5 (fig. 19), and possibly well 28-32, are deep enough to penetrate the production zone. Strat 32-5 has not been monitored, but could be cleaned out and used to record reservoir pressure changes (P. van de Kamp, oral communication, 1991).

Differences between repeated downhole pressure surveys in wells 23-5 and 83A-6 suggest drawdowns on the order of 20-50 feet between 1988 and 1990, whereas essentially no difference is seen between pressure profiles run in 83A-6 under static conditions in May 1990 and flowing conditions in September 1990 (Petty, 1992). The use of repeat pressure surveys to estimate reservoir drawdown in limited by the accuracy of the downhole pressure tool and by differences in fluid-column temperatures and densities between surveys.

More reliable indications of reservoir drawdown are provided by pressure measurements made with high-quality pressure gauges in unused production wells during interference tests conducted before full-scale operations began at the CPI field. In particular, tests conducted in March-May 1986, March-May 1987, and May-June 1987 involved production from one well and pressure monitoring in other unused production wells. Dates and production rates for these tests, only the latter of which involved injection in Cox I-1, are listed in table 4. Each test yielded calculated reservoir transmissivity and storage coefficients near 9,000 ft^2/day and 10^{-3}, respectively (table 9). Full pressure support from reinjection (net production = 310 gal/min) was assumed in calculating reservoir parameters for the May-June 1987 test. The drawdown trends in wells 21-5 and strat 2 during the May-June 1987 test can reasonably be extrapolated to conditions of higher flow rates and longer production times. From these test results, reservoir drawdown estimates of 10-15 feet can be calculated for full-scale production and injection (net production = 500 gal/min) over two years operation. Although considerably larger drawdown (190 feet) was measured in production well 23-5 during the first two weeks

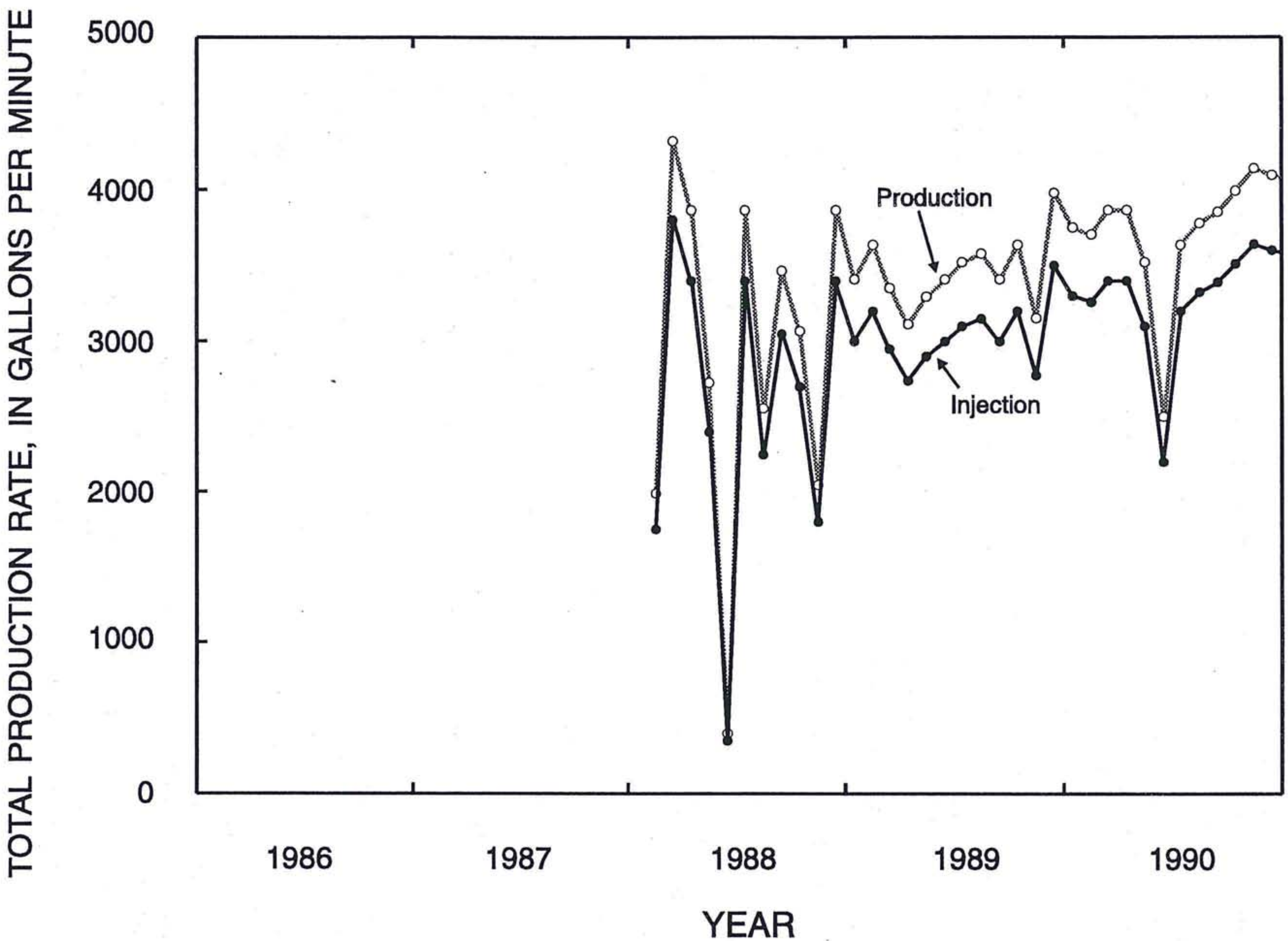

Figure 38. Monthly averaged production and injection rates for the Caithness Power Incorporated well field, 1988-1990.

Table 9. *Reservoir parameters determined for the geothermal system in the Steamboat Hills area from well test analyses and spring hydrographs*

Well(s) and Year of Test	Injection[1]	Transmissivity[2] (feet²/day)	Storage Coefficient[3]	Observation Well	Source(s)
Steamboat No. 1, 1980	no	3270	$9.0x10^{-4}$	strat 2	Collar (1990)[4]
Steamboat No. 1, March-May, 1986	no	8500	$(1.2x10^{-3})$	23-5?	Berkeley Group (1987)
Steamboat No. 1, March-May, 1987	no	6800	$(1.2x10^{-3})$	--[5]	Berkeley Group (1987)
23-5/Cox I-1 May-June, 1987	yes	7930 9500, 8800	nd $7.8x10^{-4}$	strat 2 21-5	Faulder (1987) Goranson (1989) Faulder (1987)
Steamboat No. 1, 1987	no	1250-2140	$9.0x10^{-4}$	strat 2	Collar (1990)
21-5, 23-5[6] 83A-6, 1988	yes	1340-2400	$2.5x10^{-3}$	strat 9	Collar (1990)
21-5, 23-5[7] 83A-6, 1988	yes	3050	$2.8x10^{-3}$	spring 12, spring 42w	Collar (1990)

[1]Full pressure support from injection into Cox I-1 assumed where indicated.
[2]Based on values of net production and fluid properties at 200°C.
[3]Values in parentheses were calculated from reported values of cH, using $S=\rho g \phi cH$ with density at 200°C.
[4]Determined from Theis curve match of data from Yeamans (1984).
[5]Strats 2, 6, 7, 8, 9, and Caithness Power Incorporated (CPI) wells SB-1, 28-32, and 23-5 (T and S values are averages for area between SB-1 and Cox I-1).
[6]Strat 9 analysis for data from CPI production interval 9.
[7]For spring water-level data during CPI production intervals 10 and 11.

of the May-June 1987 test, this is most likely attributable to the effects of boiling and two-phase flow in the vicinity of the well during production. This well is normally operated at wellhead pressures high enough to prevent reservoir boiling (C. Goranson, oral communication, 1991). The two years of CPI operation covers the 1988-1989 period after which all the main-terrace springs were dry.

The estimate of reservoir drawdown noted above is based on assumptions of uniformly high transmissivity over a large reservoir area (radial flow in an infinite, homogeneous porous media), and full pressure support from injection. The latter assumption allows the use of the difference between volumetric production and injection rates in calculating the stress on the reservoir. If injection pressure support is only partial, the calculated reservoir transmissivity from the interference test in 1987 would need to be larger to match the drawdown observed during this test. The same estimate of 10-15 feet of drawdown during full-scale production would apply in either case. Faulder (1987) concluded that pressure support (in well SB-1) is provided by injection in Cox I-1 because similar transmissivity values are indicated for the May-June 1987 interference test with injection as for previous tests that did not involve injection.

For the high transmissivities indicated from such tests, breakthrough of cooler injection fluid in the production wells should have been observed after several years of operation, if there were good communication between Cox I-1 and the producing wells through a permeable zone of limited vertical extent between these areas. The fact that significant cooling has not yet been observed from wellhead measurements may indicate that pressure communication is provided through steeply dipping fractures that allow cooler injection fluid to move downward rather than laterally toward the production wells. Under pre-development conditions, fluid chemistry in the injection zone was similar to that in the production zone, but temperatures were significantly different (160°C versus 225°C). Several factors, including (1) higher temperatures (~175°C) in the shallow thermal zone penetrated by strat wells 2 and 9 above the injection reservoir and (2) pressure data collected during and after the May 1990 shut-down which show a delayed response in strat 9 to injection, indicate that hydraulic connections between the injection zone, the shallow thermal zone, and perhaps the CPI production reservoir are somewhat indirect.

The calculated drawdown estimates noted above also assume that the reservoir acts as an open system, either because it is very large in extent or because it is recharged. Results from short-term tests indicate full recovery of water levels when production wells are shut in, as expected in an open system. But these results do not preclude the effects of low-permeability boundaries causing greater water-level declines during extended periods of production. We have only the gas-pressure measurements from the production wells and the pressure measurements on strat 9 and 28-32 during the 1990 shut down to suggest that reservoir pressures would fully recover following shut down, and hence that boundaries have effectively not yet been reached.

From the information discussed above, it is clear that the amount of drawdown in the production reservoir and the degree of pressure support from injection are as yet only approximately known. The best estimates we can make are that there is significant pressure support from injection and that drawdown in the production well field is still relatively small as of 1990

(10-15 feet). This level of reservoir drawdown has most likely caused water level declines of a few feet in the shallow thermal zone tapped by strat wells 2 and 9. Additional drawdown is expected to occur if more fluid is produced according to current plans for expansion of CPI generating capacity.

Changes in Thermal-Water Discharge

Measurements of chloride flux in Steamboat Creek during the 1988-89 period yield estimates of the total rate of discharge of thermal water from the Steamboat geothermal system that can be compared with previous estimates to indicate recent changes. Thermal-water discharge into Steamboat Creek is calculated from the increase in chloride flux between Rhodes Road south of the low terrace and Huffaker Hills (fig. 13), assuming a chloride concentration of 820 mg/L for thermal water from the Steamboat system. Our results are presented in table 2, along with those of White (1968). More detailed results of our measurements are included in Appendix G.

We obtained chloride and streamflow data at three different times, under differing conditions of streamflow diversion for irrigation. The most reliable results are for the March 1989 measurements when no such diversions were taking place; the calculated thermal-water discharge at that time was 663 gal/min. White (1968) calculated a discharge of 810 gal/min from springs and seepage into the creek in the spring of 1955. This suggests that the rate of thermal-water discharge to Steamboat Creek has declined, although the difference between these estimates (18 percent) may result in large part from measurement error. The total thermal-water discharge from the Steamboat geothermal system in 1955 was estimated as 1,110 gal/min, by adding in the average discharge of hot springs on the main and low terrace (65 gal/min) and wells on or near the terraces (300 gal/min). If it is assumed that the flow from these wells represents thermal water that would have flowed from hot springs or seeped directly into Steamboat Creek had the wells not been in operation, then the present-day thermal-water discharge would only be about 60 percent of what it was in 1955.

Most (~70 percent) of the well discharge in 1955 occurred from the Reno Resort wells, located approximately 0.25 miles north of the main terrace (fig. 19). White (1968) speculates that these wells were capturing thermal water that formerly flowed from springs close to these wells and springs in the northern part of the main terrace. He based this speculation on his observations of effects of well production on springs close to these wells and comparisons with unpublished descriptions of spring activity in 1916 by L.H. Taylor of the U.S. Geological Survey. Taylor estimated the total spring flow from the main terrace at 180 gal/min in October 1916, part of which occurred from springs in the northern part of the main terrace. White's measurements of total spring flow in the month of October during the 1945-1952 period averaged 45 gal/min.

Water-level elevations reported for the Reno wells and the Mt. Rose Resort well during White's study were near the elevation of Steamboat Creek and hence significantly lower than the elevations of the principal hot springs at the main terrace to south. Hence, it is reasonable to assume that under undisturbed conditions thermal water flowed eastward **and** northward in the subsurface from the main terrace toward Steamboat Creek, and that the Reno and Mt. Rose Resort wells captured thermal water that would have flowed to the creek. The calculated total thermal water discharge into Steamboat Creek in 1981-82, 1,300 gal/min (Shump, 1985), when there was no substantial discharge from geothermal wells, lends further support to the contention that the natural discharge from the Steamboat system was formerly 1,110 gal/min or larger. Observations of spring activity during the 1970's and early 1980's, while showing no evidence of flow from vents in the northern part of the main terrace and in the vicinity of the abandoned Reno wells, are too limited to conclude that the cessation of discharge from the Reno wells did not result in reactivation of some hot springs.

These considerations indicate that the total thermal-water discharge from the Steamboat geothermal system has declined significantly in recent years. Collar (1990) suggested that the decline is caused by the net production of fluid from the CPI well field, because if this production (380 gal/min under 90°C conditions - table 2) is added to the calculated seepage into the creek, the indicated total discharge (1,050 gal/min) would be remarkably close to the estimate of White (1968). Production from the SB GEO well field is ignored in this argument because all the produced fluid is reinjected. The complication here is that at neither well field is there a net loss of chloride from the geothermal system, and chloride inputs to Steamboat Creek are what is actually being measured. Thus, for well field operations to be causing the apparent decrease in discharge of thermal water, there would need to be changes in the rates and directions of thermal-water flow through the well field areas. Drawdowns induced in each field by development could result in such changes, by effectively capturing some or all of the natural thermal-water throughflow. Furthermore, any chloride injected in the Cox I-1 well that does not flow toward the production wells would not yet be expected to reach Steamboat Creek because of poor pressure communication with the hot springs and slow rates of ground-water movement.

An alternative explanation for the apparent decline in discharge from the geothermal system is that thermal water from the main terrace is being diverted northward into the shallow ground-water system. This might be expected to accompany the declines in water levels in the South Truckee Meadows resulting from the drought and increased pumpage of ground-water. Increases in chloride in wells tapping aquifers with mixtures of thermal and non-thermal ground water (for example, PTR-1) may reflect both an increase in the thermal component and a decrease in the non-thermal component. However, because patterns and rates of flow of thermal and non-thermal ground water in the South Truckee Meadows are not adequately known, it is impossible to assess the degree to which thermal water that formerly flowed into Steamboat Creek is now being diverted into, and retained in, the ground-water system in the South Truckee Meadows.

FACTORS AFFECTING HOT-SPRING ACTIVITY

The systematic decline in hot-spring activity at the main terrace since 1986 appears to be unprecedented in this century. Spring flow ceased in 1987 and since that time measured water levels in spring vents declined 1 to 17 feet. During the 1945-52 period, variations in spring flow from the main terrace were observed, with total flow covering a range from about 30 gal/min to 90 gal/min but never dropping below 30 gal/min. Numerous factors were identified by White (1968) as contributing to the changes in spring activity during his period of study, including variations in barometric pressure, earth tides, and precipitation, and earthquakes. He considered that the first three were minor factors, causing relatively short-term, small amplitude changes in spring activity, and that the longer-term, larger magnitude changes were due to variations in precipitation and consequent ground-water recharge. These same factors, along with fluid production from geothermal and domestic ground-water wells, should have affected spring activity during our study.

Three scales of variation in spring flow and water level were considered to be of significance in our 1986-1989 period of observation: (1) short-term changes over periods of hours to weeks, (2) seasonal changes, and (3) long-term changes. The long-term changes involve cessation of flow and declines in water level that as yet show no signs of significant reversal. Seasonal changes, anticipated from the results of the 1945-52 observations, are poorly documented during the 1986-90 period because of the difficulties in making measurements in the spring vents and the complicating effects of other influences. Short-term variations in spring activity were the most useful in this study for delineating cause-and-effect relations with periods of geothermal well discharge.

Short-Term Variations

For this discussion, short-term variations in spring activity (flow and water level) are those occurring over time periods of hours to weeks. Factors that could influence these changes include barometric pressure, earth tides, earthquakes, local storms, and geothermal well discharge. Of these, earth tides and earthquakes are considered relatively minor, causing variations in water level on the order of 0.1 feet. Their effects are discussed by White (1968) and Collar (1990).

Barometric Pressure

Barometric pressure effects on spring flow and water level were considered by White (1968) to account for most of the day-to-day changes he observed. Barometric efficiency (BE) of an aquifer (BE) refers to the ratio of water-level change in a well or spring tapping the aquifer to the corresponding change in barometric pressure causing the water-level change. Equations relating BE to the compressibility and porosity of the aquifer and the compressibility of the fluid are presented by Collar (1990). White (1968) calculated barometric efficiencies of 0.2 to 1.18 for different vents on the main terrace. A BE greater than 1.0 is possible where water in the spring vent is at or near the boiling point. Spring vents highest in altitude on the main terrace were more strongly affected by barometric pressure changes than were vents at lower altitude. White (1968) considered this relation to reflect the effects of restrictive (lower permeability) fissures connecting the lower altitude vents with the higher altitude vents. A similar relation between barometric efficiency and altitude of vents on the low terrace was considered by White (1968) to indicate that the main and low terraces act as distinct subsystems that are interconnected at relatively great depth (several hundred feet). Differences in rock compressibility and porosity, as related to mineral deposition, may be partly responsible for the differences in BE between different vents. It is interesting to note, however, that a general correspondence between vent altitude on the main terrace and magnitude of water-level decline over the 1986-1989 period has been observed in this study, especially if one includes the data for well GS-8. Possible explanations for this relation are discussed below.

Water-level measurements in spring vents on the main terrace collected by SDSU personnel during this study also show influences of barometric pressure changes. During October 19-25, 1988, measurements were made in springs 6, 12, 42w, and 62 three to four times per day using an electric sounder or a graduated rule (spring 6). The data for springs 6 and 12 (figs. 39 and 40) show that most of the daily fluctuation in water level in these springs is due to barometric pressure changes (as measured at the Reno Airport). Barometric efficiencies, calculated by linear regression, are 0.42 for spring 6 and 0.45 for spring 12. The correlation coefficient for the spring 12 data set (0.44) was significantly lower that for the spring 6 data set (0.79), indicating that random errors and/or other influences (for example earth tides) affected the data for spring 12. From these results, and those of White (1968), it appears that water-level changes in the main-terrace springs induced by barometric pressure fluctuations have historically been no greater that about 0.5 feet and are commonly smaller (for example, 0.1 ft in spring 6). The larger changes result from barometric pressure changes accompanying storm fronts. Although such changes can occur over time scales of hours to weeks, they are unlikely to have been of significance in terms of either the long-term declines in water level at the main terrace or the short-term variations of 0.5-2.0 feet observed during intervals of geothermal well discharge.

Barometric pressure changes have a somewhat larger affect on the water-level records for strat wells 2 and 9. During the May 1987 interference test on CPI well 23-5, diurnal pressure changes as large as 0.2 psi and 1.0 psi were measured in the capillary tubing in strat 2 and strat 9, respectively (Faulder, 1987). These pressure measurements were apparently made with absolute-pressure-reading gages. The long-term water-level records for these wells also show significant variability related to barometric pressure changes, particularly after July 1988 when gage-pressure transducer readings were initiated. Barometric efficiencies estimated for each well are greater than 1.0; this must be related to the fact that the upper part of the fluid column in these wells is boiling. The appearance of the detailed hydrographs for these wells suggests that water-level variations of 0.25-0.5 feet may be caused by changes in barometric pressure.

Precipitation

White (1968) observed that precipitation of as much as 0.5 inches per storm had no detectable effects on the hot-spring system, whereas storms of 1 inch or more generally had clearly observable effects within periods of 1-2 days. No attempt was made in our study to correlate spring hydrographs with daily precipitation records because our interest was in

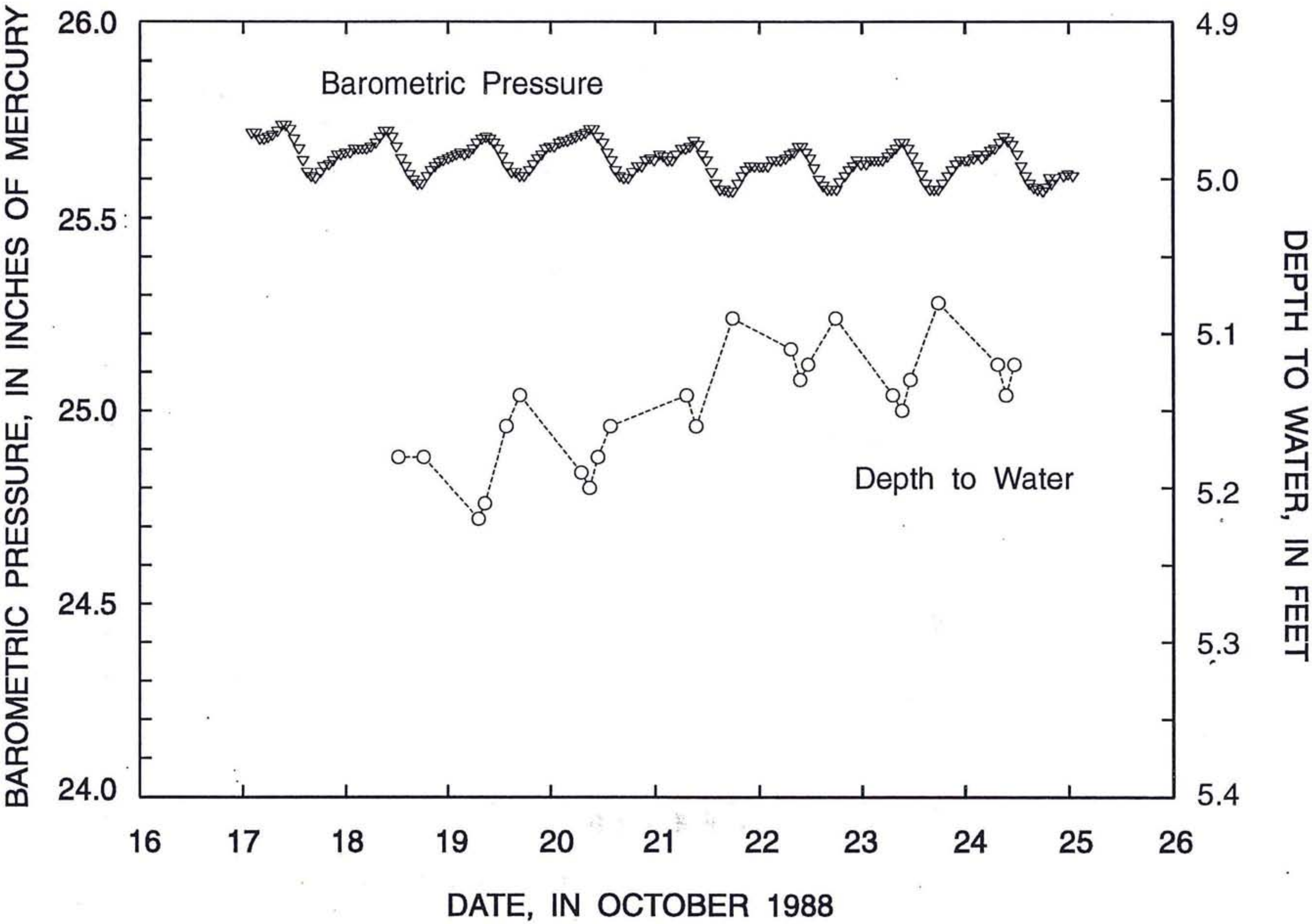

Figure 39. Depth to water in spring 6 and barometric pressure measured at the Reno Airport, in October 1988.

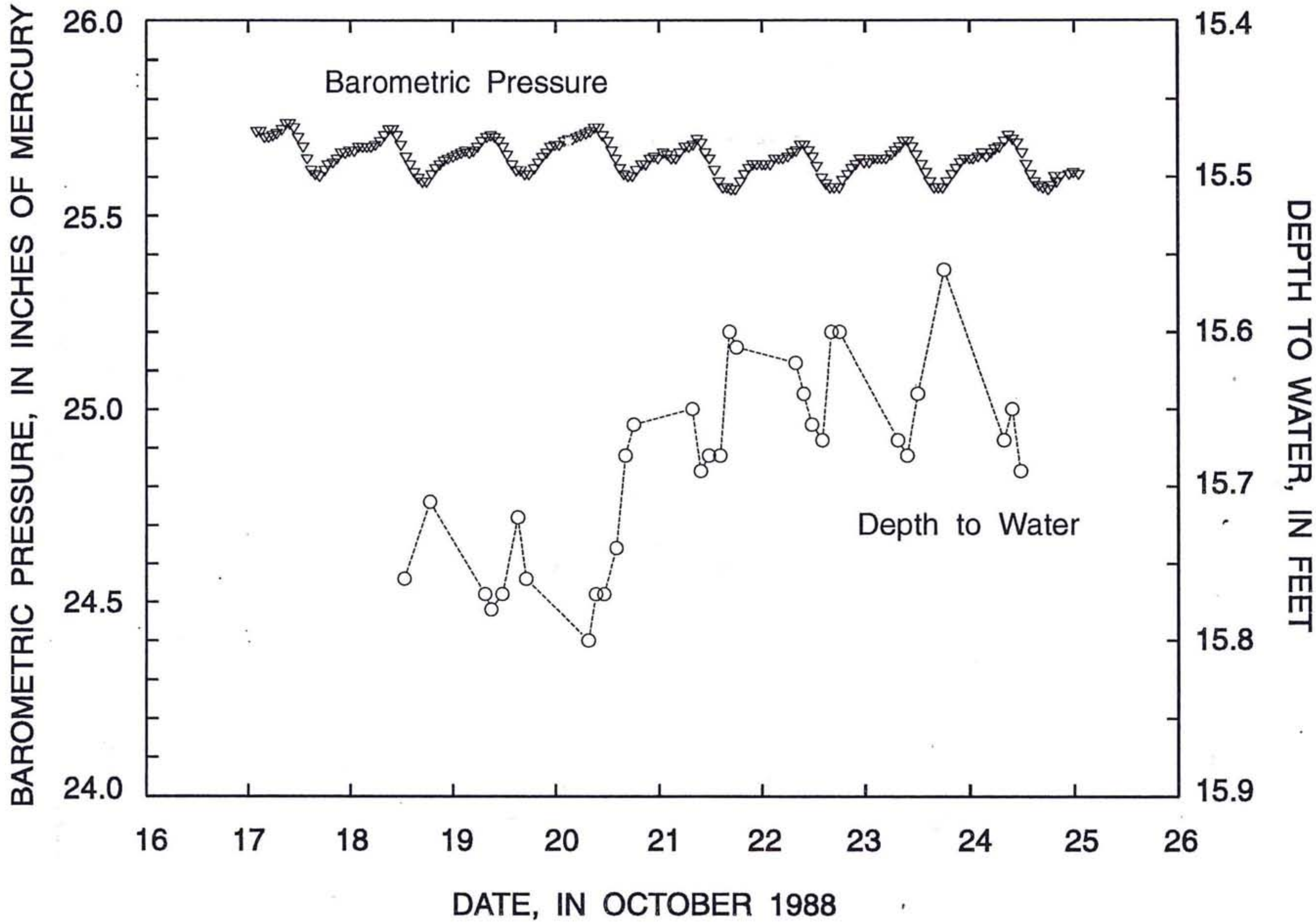

Figure 40. Depth to water in spring 12 and barometric pressure measured at the Reno Airport, in October 1988.

stresses that caused longer-term changes in the hot springs. In addition, we noted in previous sections of the report that correlations are not commonly observed between spring activity and monthly or even seasonally averaged precipitation (figs. 16 and 28).

Geothermal Well Production

Short-term changes in hot-spring activity delineated during the 1986-1989 period include declines and rises in water level in several springs associated with CPI discharge interval 1 in 1986, declines and rises in springs 6, 12, and 42w associated with CPI intervals 9-11 in 1988, and similar changes in spring 6 during 1987. As noted previously, determinations of cause-and-effect relations for some of these changes is complicated by the influence of seasonal changes in the ground-water system, as indicated by the hydrograph for the Pine Tree Ranch-1 well (fig. 27). The 1986 data show a rapid rise in water level in spring 6 that occurs within three weeks of cessation of CPI discharge interval 1 and more than a month before water levels in PTR-1 begin their seasonal rise. The rate of ground-water production from the STMGID wells, which should have exerted a significant influence on heads in the shallow ground-water system, remained at relatively high levels during the summer of 1986. This suggests that production from the CPI well field had a significant effect on the temporary decline in spring activity in 1986.

Apparently no water-level data for strat wells 2, 5, and 9 were collected during 1986. Such data would have facilitated the interpretation of the cause(s) of the terrace-wide changes in the hot springs during that year. Water-level data for these wells during 1987-89 are well correlated with the spring 6 record, particularly over the period which includes CPI discharge intervals 4-9 (fig. 33). Data collected from the May 1990 CPI well field shut-down and from earlier periods of well testing before 1988 show convincing evidence of hydraulic connections between these strat wells and the CPI production and injection wells. Hence, the correspondence between short-term changes in water level in these strat wells and water levels in spring 6 during CPI discharge intervals argues for a similar hydraulic connection between the main-terrace springs and the CPI well field.

Monitoring data collected in springs 6, 12, and 42w and strats 2 and 9 during the summer of 1988 (figs. 30 and 33) are particularly useful in quantifying the effects of CPI well field operations on hot-spring activity. As noted previously, there is a consistent pattern of change in each spring (decline during production, and rise during shut-in) and a general correspondence between differences in short-term change and long-term water-level declines in these springs. Furthermore, corresponding changes in water level occurred in strats 2 and 9 during the summer of 1988. Taken together, these data indicate that CPI production can cause water-level declines of at least 1-2 feet at the main terrace and in the shallow thermal-water flow zone penetrated by strats 2 and 9.

Evidence that short-term changes in hot-spring activity have occurred in response to production from the SB GEO well field consists mainly of a decline in the total visually estimated flow of the main-terrace springs in November 1986; cessation in flow of two springs (4 and 16se) in December 1986; and declines in water level in several spring vents in January and February 1987, following the onset of well tests in December 1986 and full-scale operations in January 1987. Only for one period (January 1988) is there a clear correlation between a change in SB GEO production and water level in spring 6 (fig. 37).

Seasonal Variations

Seasonal variations in hot-spring activity similar to those observed during 1945-52 would be expected to occur during the 1986-89 period. A pattern of relatively high discharge and water level in the winter months and low discharge and water level in the summer months, superimposed on a long-term decline, is generally consistent with hydrographs for spring 6 and strat wells 2 and 9. Modest rises in water level in spring 6 and in strat wells 2, 5, and 9 in the fall of 1989 lend support to the contention that changes in water level in the shallow ground-water system in the Steamboat Hills and South Truckee Meadows have significantly influenced hot-spring activity. Yeamans' (1987a) record of estimated flow from six main-terrace springs between June 1986 and April 1987 shows an increase from 10 gal/min to 30 gal/min from summer to winter and a subsequent decline that reflects this seasonal pattern, but could also be influenced by CPI well testing. No clear pattern of seasonal change is seen in the hydrograph for springs 8, 12, and 42w, however, and water levels in the other main-terrace springs fell too deep to measure during the spring of 1987 so that patterns of seasonal change could not be evaluated.

Changes in precipitation and related changes in rates of recharge to the ground-water and geothermal systems must have been the primary influences on hot-spring flow during the 1945-52 period of detailed observation. Both seasonal variations and long-term changes in spring flow were observed. Although the correlation between quarterly averaged spring flow and precipitation is not strong, there was a consistent seasonal pattern to the spring-flow variations that must in some way be related to variations in water-level in the shallow ground-water system surrounding the main terrace. The general mechanism for such effects should involve a lowering of head in the thermal reservoir beneath the main terrace during periods of low ground-water level and a rise in head beneath the terrace during periods of high ground-water level. White (1968) diagrams a conceptual model for a hot-spring conduit placed above the level of discharge for the surrounding ground-water system that would allow for such effects from both changes in head in the thermal reservoir (causing changes in the rate of upflow) and changes in head in the ground-water system surrounding the conduit (causing changes in the rate of lateral leakage of thermal water from the upflow conduit). Because the main-terrace spring vents are at altitudes approximately 100 feet higher than the areas of seepage into Steamboat Creek, and because hot-spring discharge rates (~60 gal/min before 1987) were much less than thermal-water seepage rates into Steamboat Creek (~600 gal/min), hot-spring discharge should have been relatively sensitive to head changes in the underlying thermal reservoir and to water-level changes in the surrounding ground-water system. During periods of relatively low streamflow or low water table, more thermal water would tend to leak laterally away from the spring conduits and flow in the subsurface eastward and northward toward eventual discharge in Steamboat Creek. During wetter periods, more thermal water should discharge at the springs.

Ground-water withdrawals for domestic consumption in the South Truckee Meadows have enhanced the seasonal variation in water levels in this area and therefore should have added to the effect that changes in the shallow ground-water system have on hot-spring activity at the main terrace. Declines in water level in the shallow ground-water system in the South Truckee Meadows in response to ground-water pumpage had begun by 1985. Although Yeamans' (1987a) estimates of spring flow in 1986-1987 suggest that hot-spring activity did not begin its systematic decline until the spring of 1987, the accuracy of these estimates is uncertain and therefore comparisons with measurements of total spring flow during the 1945-1952 period are questionable. This issue is of importance because the similarity in the hydrographs for the PTR-1 well and spring 6 indicates that the hot springs may respond relatively rapidly to changes in water level in ground-water system. If, in fact, the hot-spring decline in hot-spring activity did not start until 1987, it would be difficult to explain the apparent lag between this decline and the long-term decline in the shallow ground-water system. Clearly, actual measurements of total spring flow in 1986 and in previous years would have been of great value in resolving this issue.

Long-Term Changes

Drought-related changes in recharge to both the geothermal system and the shallow ground-water system are unlikely to be solely responsible for the decline in hot-spring activity. As Collar (1990) points out, the almost complete cessation in hot-spring flow at the main terrace in 1987 occurred before the severity of the current drought had reached levels comparable to those during the 1945-1952 study period. Hence, lower precipitation and associated ground-water recharge alone could not be responsible for the loss of spring flow. Drought-related changes in recharge to the geothermal system over periods of several years are even less likely to have direct effects on hot-spring activity. Overall head differences driving water flow from recharge to discharge areas are on the order of 1,000-2,000 feet and overall flow paths probably approach 5-10 miles in length. Thus, changes in head within the recharge area (the Carson Range) should be damped out before reaching the discharge area, except in the unlikely event that rock permeabilities were uniformly high (similar to those estimated for the geothermal reservoirs). Similar conditions of relatively constant spring flow were described by Mifflin (1968) and Eakin (1966) for large-scale ground-water flow systems in Nevada.

Water-level measurements in observation wells show declines in the South Truckee Meadows ranging from 14-21 feet over the 1985-89 period in wells PTR-1, MW-3, and MW-4. These wells are located north and northeast of the main terrace; their water levels are affected by pumpage of ground water for various consumptive uses, recharge from creeks draining the Carson Range, and leakage from irrigation ditches. Other wells located near Steamboat Creek and away from centers of pumpage have shown essentially no long-term declines. Wells in the northern part of the Steamboat Hills (strats 2, 5, and 9) have shown declines of 16-26 feet over the 1987-89 period. Such declines are equal to or larger than declines in water level in the hot spring vents during this time (1-17 feet). With the existing data, however, there is no way to determine directly how much of the main-terrace water-level decline is due to declines in water level in the surrounding ground-water system.

Water levels in spring 6 and in various observation wells (including PTR-1, MW-3, MW-4, and strats 2, 5, and 9) rose in the fall of 1989, following a period of relatively high precipitation in the winter of 1989. Production from the geothermal well fields was relatively continuous but not constant during this period of rising water levels. It is likely that the water-level rise of 1 foot in spring 6 was related to rises in ground-water levels in the South Truckee Meadows and Steamboat Hills. Additional data collected from existing monitoring wells and from a monitoring well completed at the main terrace during periods of rising water level would help clarify these relations.

Evidence of the influence of geothermal well production on hot-spring activity consists of (1) correlations between short-term changes in water level in spring vents and periods of production from the CPI and SB GEO well fields, and (2) similar correlations between the spring 6, 12, and 42w hydrographs and the hydrographs for strat wells 2 and 9. The significance of (2) depends on the evidence discussed previously from CPI interference tests and 1990 CPI well-field shut-down that these strat wells are in hydraulic communication with the CPI production reservoir. The shallow thermal-water flow zone penetrated by strat wells 2 and 9 exhibits temperature and hydraulic head characteristics that are consistent with a hydraulic connection between this zone and the reservoir underlying the hot springs. Although it could be argued that a continuous zone of lateral flow between these strat wells and the main terrace may be an oversimplification, there is no known geologic or structural evidence to show that these wells and the CPI production wells are not in some way hydraulically connected with the hot springs.

The degree of correlation between intervals of CPI production and water-level changes at the main terrace is, in our view, too great to be explained away as due to the normal seasonal changes in spring activity. We infer from the magnitude of the water-level changes that specific intervals of CPI production have resulted in declines of 1-2 feet in the hot spring vents. Full-scale production for extended periods could presumably have a somewhat larger effect, depending on the delay that may be involved for injection pressure support to be manifested. There is less evidence from such correlations that production and injection from the SB GEO well field has had a discernable effect on hot-spring activity. This partly reflects the absence of interference tests at times when water levels were being measured at the main terrace.

Water-level declines of 1-2 feet at the main terrace from CPI production are reasonable, given the measurements of 2-10 feet of water-level change in strat 9 and well 28-32 associated with the May 1990 shut-in and subsequent start-up. The available information from the CPI well field indicates drawdowns of 10-15 feet after two years of full-scale production with injection support. Assuming that a hydraulic connection existed, the drawdown at the main terrace (2 miles away) would amount to a few feet under conditions of radial flow in a homogenous reservoir with transmissivity and storage coefficients equal to those determined for the CPI well field (9,000 ft^2/day and 0.001, respectively). An areally restricted connecting zone would tend to cause drawdowns of more than this amount at the main terrace for the same transmissivity, whereas a lower transmissivity applied to the radial flow case would yield less drawdown. Such calculations also indicate that the effects of geothermal production should begin to occur at the main terrace after times of 5-10 days, as actually observed. There is some indication from CPI well tests involving strat wells 2 and 9 and springs 12 and 42w as observation wells (table 9) that transmissivity may be lower outside the CPI well field. However, because the geometric and hydrologic characteristics of permeable regions between the CPI well field and the main terrace are largely unknown, these drawdown calculations are useful only to suggest that declines in hot-spring water levels of a few feet resulting from CPI production are hydrologically reasonable.

The SB GEO well field is much closer to the main terrace than is the CPI well field and has experienced 15-20 feet of drawdown. However, the current SB GEO well field may be less directly connected to the hot springs. This inference is based on the more limited evidence of correlations between SB GEO discharge intervals and changes in hot-spring water levels and the higher heads in the SB GEO reservoir than beneath the main terrace under pre-development conditions.

The available information indicates that 1-3 feet of water-level decline at the main terrace is likely to have been caused by long-term drawdown in the CPI reservoir. This estimate is based on the range of results obtained from actual measurements of changes in spring water levels associated with various CPI production intervals, pressure measurements in observation wells during and following the May 1990 shut-in, and calculations of reservoir drawdown after several years of full-scale production based on the results of various well tests. More accurate quantification of this influence would require completion of observation wells in the production reservoir and in the feed zone beneath the main terrace and some form of interference testing, most reasonably associated with a regularly scheduled field shut-down and restart. If the estimate of 1-3 feet of head decline from CPI production is correct, then the remainder of the declines observed at the main terrace should be attributable to water-level declines in the ground-water system, and to a much smaller extent to production from the SB GEO well field.

The effect of a given change in head beneath the main terrace on water levels in the hot-spring vents can only be speculated on at this time. Water-level declines in individual vents for which measurements have been made range from 1 to 17 feet between 1987 and 1989. As noted previously, the relative changes in water level in springs 6, 12, and 42w (~0.5-2.0 feet) were roughly the same during mid-1988 (CPI discharge intervals 9-11) as the overall declines since 1987 (6-17 feet). These differences are also generally consistent with the observation that spring vents at higher altitude on the main terrace exhibit larger changes in water level than do spring vents at lower altitude. This may be related to differences between the resistance of the spring conduits to upward flow and lateral leakage. Springs at higher altitudes should be those with less resistance to upward flow and perhaps more resistance to lateral leakage. Wells drilled on the main terrace, for example GS-4, GS-5, and the Rodeo well, had higher water-level altitudes than did the hot springs in the 1945-52 period, presumably because they provided relatively low vertical- and high lateral-resistance taps to deeper fractures.

Assuming that flow is taking place within and between different spring conduits, even though the hot springs no longer flow at the surface, the resistance to flow would still influence the water level in each vent. Under these conditions, the higher altitude (lower conduit resistance) springs should exhibit the greatest change in water level from a given change in head in the underlying source reservoir. Furthermore, the water-level changes in such vents should be closer to, or better representations of, the head changes in the source reservoir. This indicates that for the purposes of evaluating the effects of different stresses on hot- spring activity, the head change beneath the ACEC between 1987 and 1989 was probably close to 17 feet.

The only wells on the main terrace for which recent water-level measurements could be obtained are GS-8 on the far eastern (low altitude) side of the terrace and the Byers well on the far western (high altitude) side (fig. 4). The measurements for GS-8 show a water-level decline of about 1 foot between 1988 and 1989 and 7 feet since the 1950's. Similar measurements for the Byers well show a decline of about 40 feet between 1985 and 1991, on the basis of a depth to water of 5 feet in 1985 (from C. Goranson, oral communication, 1991). The Byers well, which is about 100 feet deep with a bottom-hole temperature of 120°C, most likely does not penetrate the principal fracture system supplying thermal water to the main-terrace springs (based on thermal, chemical, and lithologic data for the adjacent GS-3 well described by White, 1968). Thus, the decline in water level in this well since 1985 may be indicative of the declines in water level in the shallow ground-water system surrounding the terrace. However, water-level measurements in Byers well are also affected at times by thermal cycling and boiling (D.H. Schaefer, written communication, 1991). Well GS-8 appears to tap thermal water flowing eastward in alluvium toward Steamboat Creek from the conduit system in bedrock beneath the main terrace. Changes in water level in GS-8 may be partly controlled by the water levels in Steamboat Creek.

The depth to water measured in TH-1, a core hole recently completed north of the ACEC hot springs for the proposed expansion near the SB GEO well field (referred to as the Steamboat #2 and #3 Geothermal Projects in JBR Consultants Group, 1991), was 33 feet (C. Goranson, oral communication, 1991). Although this well appears to tap vertical fractures that may be connected with the conduit system supplying the main-terrace springs, it would be questionable to use the depth to water in this well as a measure of the change in head beneath the main terrace because there was a significant pre-development gradient in head northward between the ACEC and the Reno and Mt. Rose Resort wells.

High-chloride thermal water began discharging at the main terrace adjacent to well GS-5 in the summer of 1991. This discharge appears to originate from a shallow casing break in GS-5. It is most likely that such flow does not indicate a recovery of hot-spring water levels, but rather the effects of relatively light two-phase fluid flowing up the well casing and leaking out near the surface. A similar situation was apparently responsible for high wellhead pressures measured in several of the GS series wells on the main terrace during drilling (White, 1968; D.White, oral communication, 1991).

MONITORING PROGRAM

Hydrologic monitoring in the Steamboat area is done by the geothermal operators to (1) observe, assess, and correct adverse effects on the springs and geysers in the Area of Critical Environmental Concern (ACEC) (Chevron Resources, 1987) and (2) to detect adverse impacts to ground-water quality in alluvial aquifers surrounding the Steamboat Hills. Both Caithness Power Incorporated (CPI) and SB GEO are required to furnish quarterly reports on monitoring results to the Nevada Division of Environmental Protection (NDEP) under permits NEV50018 (for SB GEO) and NEV70007 (CPI). Currently, CPI reports on all aspects of the monitoring activities, including water-level measurements in observation wells, chemical sampling of observation wells, and measurements of stage and chloride concentration in Steamboat Creek; SB GEO reports separately on pressure measurements in three observation wells in their well field and water level and fluid chemistry for seven wells in the South Truckee Meadows. Sites considered part of the monitoring program are listed in table 10, along with parameters recorded and measurement frequency at each site (site locations shown in plate 2 and fig. 19). Not listed are production and injection wells at each facility, for which records of daily measurements of flow and wellhead temperature, and wellhead pressure and downhole pressure (SB GEO wells only) are furnished. Caithness is required to monitor springs 12 and 42w according to the NDEP permit and to make visual observations of other spring activity. However, such monitoring has been restricted by declines in water level in the spring vents and refusal of private land owners to give permission for access to many of the springs on the main terrace (outside the ACEC) and the low terrace. Data collected by CPI on hot-spring activity has been significantly augmented since mid-1986 by measurements and observations made by BLM, NDEP, and SDSU personnel, and other private individuals (Appendix A).

Stream-Water Quality and Stage

CPI monitored stream stage (using a staff gage) in Steamboat Creek at Rhodes Road and at Virginia City Highway (State Highway 341) and in Steamboat, Chandler, and Crane irrigation ditches near the Virginia City and Mt Rose Highways (plate 3) at monthly intervals during 1987-89. Water samples at these locations were collected and analyzed for chloride concentration. None of the staff-gage readings have been calibrated to stream discharge, so there is as yet no streamflow data corresponding to the chloride concentration data.

Review of CPI records for the time period May 1987 to September 1988 (Yeamans, 1987e-f, 1988a-c) reveals significant variations in chloride concentration. These variations probably reflect dilution of the thermal-water component derived from seepage by nonthermal water inputs from upstream sources. These data cannot be interpreted in terms of the locations and rates of thermal-water inputs to Steamboat Creek until rating curves are developed from actual discharge measurements at the staff-gage sites.

Water Levels and Fluid Measures in Wells

Pressure measurements in strat wells 2 and 9 are potentially most useful in delineating possible effects of geothermal well-field operations on shallow thermal aquifers beneath the Steamboat Hills. Indeed, the stated purpose of monitoring these wells is to observe changes

Table 10. *Current monitoring sites for Caithness Power Incorporated (CPI) and SB GEO (SBG) geothermal developments (excluding production and injection wells and points denied access by land owner)*

Type of feature: TW, Thermal Well; W, Nonthermal Well; DW, Domestic Well; S, Spring; SW, Surface Water.
Parameters: WL, Water Level; Q, Discharge Rate; T, Temperature; C, Chemistry.
Frequency: (w:m), weekly monitoring for the first year, monthly thereafter; (m:q), monthly monitoring for the first year, quarterly thereafter; (m:q&y), Monthly monitoring for the first year, quarterly and yearly thereafter; (m:q4:y), Monthly monitoring for the first year, quarterly for the following 4 years, yearly thereafter; (y), yearly.

Monitoring Site	Type of feature	Parameters (frequency)
Caithness Power Incorporated		
Strat. Well 2	TW	WL(w:m), T(y)
Strat. Well 5	W	as above
Strat. Well 6	W	as above
Strat. Well 7	W	as above
Strat. Well 9	TW	as above
Strat. Well 13	TW	as above
Strat. Well 14	TW	as above
STMGID Well[1]	DW	WL, T, C(m:q)
Woods Well	DW	as above
Tangen Well	DW	as above
MacKay Well[1]	TW	as above
Curti Barn Well	TW	as above
Curti Domestic Well	DW	as above
Pine Tree Ranch Well 2	TW	as above
1055 Lavender Well[1]	TW	as above
Steinhardt Well	TW	as above
Boyd Well[1]	DW	as above
Rogers Well[1]	DW	as above
Jeppson Well[1]	DW	as above
Seep	S	Q, T, C(m:q)
Spring 12[2]	S	Q[4], Wl, T, C(m:q)
Spring 42[2]	S	Q[4], Wl, T(m:q), C(m:q&y)
Other main terrace spring[3]	S	Visual observations
Steamboat Creek at Rhodes Road	SW	Q, T, C(m:q)
Steamboat Creek at Virginia City Hwy	SW	as above

Table 10. Current monitoring sites for Caithness Power Incorporated (CPI) and SB GEO (SBG) geothermal developments--continued

Monitoring Site	Type of feature	Parameters (frequency)
Steamboat Ditch	SW	as above
Chandler Ditch	SW	as above
Crane Ditch	SW	as above
Steamboat Spa[3]	SW	as above
SB GEO (formerly Ormat Energy Systems Inc.)		
Brown School Well	DW	WL[2], T, C(m:q4:y)
Herz Domestic Well	DW	as above
Herz Well #2	TW	as above
Bianco Well	DW	as above
Pine Tree Rch Well 1[1]	TW	as above
Flame Well	TW	as above
Peigh Well	DW	as above
OW-1	TW	WL (weekly average)
OW-2	TW	WL (weekly average)
IW-1	TW	WL (weekly average)

[1]Separate wells were used for water level measurement and water chemistry sample. STMGID stands for South Truckee Meadows General Improvement District.
[2]Only where possible to obtain sample or measurement.
[3]Access to springs 4, 6, 8, 10, and 16se was denied, as was access to low terrace springs and wells.
[4]Visually estimated.

in head in the Steamboat geothermal system due to CPI well discharge and injection before such changes are observed at the main terrace and to determine if CPI well-field operations are affecting the hydrology in the vicinity of the main-terrace springs (Chevron Resources, 1987). Pressure data collected from strats 2 and 9 before July 1988 were obtained from absolute-reading transducers; gage-pressure transducers were used after that time and are currently being used. Data from the gage-pressure transducers show relatively large fluctuations in response to barometric pressure changes that, along with a reduction in measurement frequency, make it more difficult to delineate and interpret short-term changes. Even when a correction is applied by adding the observed barometric pressure at the Reno Airport, the resultant hydrographs show more variability after July 1988 than before (see for example fig. 32). Better water-level information could be obtained from these wells if records of local barometric pressure were used to filter the fluid pressure data.

Strat 9 is completed with 2.88-inch liner perforated from 905-915 feet. Attempts were made to cement the liner from the top, but the outcome of the cementing operations, in terms of the thickness of cemented liner, is unknown. Strat 2 is completed with 2.88-inch liner slotted from 795-835 feet. There is apparently no cement in the water-filled annulus below the depth of the surface casing (156 feet). Sections of the formation outside the liner at 250 feet and 430 feet have been gun perforated. Thus, for strat 2, and to a lesser extent strat 9, measured pressures could respond to hydrologic changes in more than one zone. This is obviously not an ideal situation for interpretive purposes.

Strat 5 is completed with 2.88-inch tubing (open but unslotted), to 1,687 feet. Water-level data for strat well 5 are determined from depth-to-water measurements made from the land surface, except for brief periods in 1987 when downhole pressure transducers were used. A float-activated recording system is currently in place in strat 5 for continuous water-level monitoring. Because of its location and depth, water levels in this well could be expected to respond both to changes in the shallow ground-water system and to changes in bedrock aquifers. As noted previously, interpretations of data from different interference tests lead to varying interpretations of the influence of geothermal well production on water-levels in strat 5. We currently do not know the depth or depths at which the 1,700 ft-deep liner in strat 5 is perforated or slotted.

Both downhole- and wellhead-pressure data are collected on the SB GEO production, injection, and monitor wells. Only the data for monitor wells IW-1, OW-1, and OW-2 are reported to NDEP. Problems with the pressure data for these wells, and the corresponding calculated depth-to-water data were discussed previously. The existing data for these wells are useful mainly for providing a measure of the overall decline in downhole pressure in the existing SB GEO production zone. The proposed expansion for the Steamboat #2 and #3 Geothermal Projects can be expected to cause additional reservoir drawdown that may affect heads beneath the main terrace. Consideration should be given by BLM and NDEP for monitoring such effects in a well such at TH-1 near the northern boundary of the ACEC.

A clear need exists at present for means of monitoring fluid pressures in the CPI reservoir and beneath the ACEC part of the main terrace. The addition of monitoring wells at these locations would offer opportunities to conduct interference test(s) at the CPI well field that could better quantify the degree of hydraulic communication between these areas and to observe increases in head beneath the main terrace that may accompany a return to higher precipitation conditions in the Steamboat area. Such monitoring would also make it possible to assess the success of any mitigation measures that might be attempted to increase heads and water levels at the main terrace, such as injection into the shallow thermal zone penetrated by the Cox I-1 and strat 9 wells, as discussed below. Because of environmental problems associated with drilling a monitor well in the ACEC, attempts should first be made to gain access to or recomplete an existing well on the main terrace (for example the Rodeo well and wells GS-4 and GS-5) that currently is either sealed near the surface with mineral deposits or are filled in with rubble. A recent attempt to drive a well point into the spring 42w vent for access to make water-level measurements proved unsuccessful (Schaefer, 1991).

Water-level and temperature data were collected from the Byers well from October 1990 to July 1991, and have recently been resumed. These data show a decline in water level of about 2 feet over this period, with barometrically induced fluctuations of about ± 0.2 feet. Although water-level changes in this well may not adequately reflect pressure changes in the hot-spring conduits and underlying source reservoir, water-level data collected from the Byers well would provide useful control for interpreting similar data from a monitor well drilled into the principal fracture system beneath the main terrace. This well should be monitored with a pressure transducer rather than a float because thermal fluctuations may cause large changes in fluid level in this well.

There currently exists no adequate means for monitoring changes in reservoir pressure in the CPI well field. The production wells cannot easily be instrumented for this purpose and the currently monitored strat wells are not completed into the deep reservoir. Strat 32-5, however, is completed into the production reservoir in the vicinity of unused production well 32-5. Temperature and lithologic data for strat 32-5 indicate that, if it were cleaned out, it could serve as an adequate monitor of reservoir drawdown. There is, however, no previous pressure record for this well. Alternatively, well 28-32 could be monitored on a continuous basis. Well 28-32 has been shown to be connected with the other production wells and the Cox I-1 injector, but exhibits its maximum downhole pressure at a depth some 600 feet shallower than the CPI production wells.

CONCLUSIONS AND SUGGESTED ADDITIONAL DATA COLLECTION

Conclusions

The principal conclusions of this study are listed below.

1. A systematic decline in hot-spring activity became apparent in and adjacent to the Area of Critical Environmental Concern (ACEC), located on the main silica terrace at Steamboat Springs, in early 1987, but may have started earlier. By mid-1989, all springs had ceased flowing and measured water-level declines in spring vents in the ACEC ranged from 1 to 17 feet. The total decline in head in the reservoir supplying thermal water to the springs was probably close to 17 feet in 1989, when the spring water levels could no longer be measured.

2. These changes were accompanied by successive years of below-normal precipitation in the Steamboat region beginning with the July 1986-June 1987 precipitation year. Lower precipitation and associated decreases in recharge to the ground-water and geothermal systems are unlikely to be the only factors responsible for the decline in hot-spring activity because similar periods of drought in the past did not cause such drastic reductions in spring flow.

3. Drought conditions and increased pumpage of ground water for domestic consumption in parts of the South Truckee Meadows north and northwest of the main terrace have resulted in long-term declines in water level in alluvial aquifers. Most of this pumpage occurs from wells operated by the South Truckee Meadows General Improvement District (STMGID). Between 1985 and 1989, the decline in annually averaged water-level in two cold-water observation wells and a warm-water (43°C) observation well located in these areas ranged from 14 to 21 feet. These wells also show seasonal variations in water level that reflect cycles of recharge and pumpage of ground water.

4. Water-level declines of 14-26 feet were measured between 1987 and 1989 in strat wells 2, 5, and 9 in the northern part of the Steamboat Hills. Strat wells 2 and 9 are drilled into permeable zones containing thermal water at temperatures near 175°C, whereas strat well 5 is completed in the nonthermal ground-water system. Similarities between both long-term declines and seasonal changes in water level in these strat wells and changes observed in wells in the South Truckee Meadows indicate that water level changes in these strat wells are due in large part to variations in ground-water withdrawals and recharge to the ground-water system.

5. Data collected during numerous interference tests show that strat wells 2 and 9 and well 28-32 are hydraulically connected with the Caithness Power Incorporated (CPI) production and injection wells, but that only a few feet of the long-term water-level decline in these wells can be attributed to CPI well-field operations.

6. Most (about 80-95 percent) of the long-term decline in water level in the ACEC springs may be due to the effects of declines in water level in the shallow ground-water system. These percentages were calculated (and then rounded off) by subtracting the effects of CPI well-

field operations noted below (1-3 feet) from the estimated total head decline in the ACEC in 1989 (17 feet). The only direct indications of the effects of changes in water level in the ground-water system on hot-spring activity are the seasonal and annual variations in spring flow delineated during the 1945-1952 period, the general correspondence between the water level record for spring 6 and the Pine Tree Ranch-1 well during the 1986-1989 period, and the period of rising water level in spring 6, strat wells 2, 5, and 9, and the Pine Tree Ranch-1 well in late 1989.

7. Water-level declines in the ACEC springs of 1-3 feet due to production from the Caithness well field are indicated by correlations between short-term changes in spring water level and periods of production from the CPI well field, similarities between short-term responses observed in the hydrographs for several hot springs and strat wells 2 and 9, and theoretical calculations of reservoir drawdown after several years of production. This effect represents about 5-20 percent of the estimated total head decline beneath the ACEC in 1989.

8. Under full-scale production with pressure support from injection, drawdown in the CPI production reservoir is estimated to be about 10-15 feet. There are indications of greater drawdown in the immediate vicinity of the production wells. Both the long-term drawdown in the production reservoir and the resultant decrease in head beneath the ACEC need to be better quantified by reservoir testing involving pressure measurements in observation wells completed in the production reservoir and in the reservoir feeding the ACEC hot springs. Theoretical calculations suggest that if there were a high-transmissivity connection between the CPI well field and the main terrace, water-level declines of a few feet at the main terrace could result from well-field drawdown of 10-15 feet.

9. The location and characteristics of the apparent hydraulic connection between the CPI production reservoir and the ACEC hot springs are uncertain. Such a connection could be provided through a shallow thermal-water flow zone evidenced in several wells in the northern part of the Steamboat Hills at depths near 1,000 feet. Such a zone could be fed by upflow of thermal water from the deeper production reservoir along steeply dipping faults. The injection zone in Cox I-1 may not be in direct hydraulic connection with this shallow thermal aquifer, but may influence production-induced pressure changes in this zone by providing pressure support through the deeper reservoir to the CPI production wells.

10. Although head declines of 15-20 feet have been observed in the SB GEO well field, there is only limited evidence for an influence of SB GEO operations on the ACEC hot springs. This may reflect lower permeability or fault-related anisotropic conditions between these two areas and higher heads at the high terrace than at the main terrace under pre-development conditions. It is likely, however, that the proposed expansion of geothermal production to the southeast of the SB GEO well field will have a more significant effect on the ACEC springs.

Additional Data Collection

The findings of this study represent the best interpretation that can be made at this time as to the influence of various factors on the recent decline in hot-spring activity at Steamboat. The available data do not prove that a given stress has caused a certain amount of water-level decline in the hot springs. Indeed, because there is no monitoring point into the reservoir beneath the main terrace that feeds the hot springs, there is no accurate measure of the change in head or pressure beneath the main-terrace ACEC. The estimates given here of the effects of geothermal well production and water-level declines in the shallow ground-water system should best be considered as indicative of the relative effects of these factors. Such a delineation may suffice for decision-making purposes. We can, however, suggest several steps to provide better measures of these effects and of additional effects from future changes in climate, ground-water pumpage, and geothermal well production. These suggestions are listed below.

1. An observation well is needed within the ACEC to monitor pressure changes in the reservoir feeding the hot springs. Initial attempts should be made to gain access to an existing well in the ACEC, possibly GS-4, GS-5, or the Rodeo well; if those efforts are unsuccessful, then a new well should be drilled. Such a well should then be instrumented for continuous pressure measurement using a transducer. Similar measurements should be obtained in the Byers well at the west side of main terrace.

2. Well TH-1, drilled north of the ACEC for the Steamboat #2 and #3 Geothermal Projects, should be instrumented for use as an observation well to delineate the effects of future geothermal production north of the ACEC. This use will be limited, however, by the close proximity of a new production well. At a minimum, detailed information on production schedules and rates for all the geothermal wells north of the ACEC should be obtained.

3. Pressure monitoring should be done in a well completed in the CPI production reservoir. Unused production well 28-32 could be used for that purpose, as could well 32-5 if it could first be cleaned out.

4. An interference test should be conducted at the CPI well field to provide better information with which to quantify the effects of production and injection on pressures beneath the main terrace. Several types of test are possible, including (a) a field-wide shut-down for a period of at least two weeks during the spring or summer, when ground-water levels should be in decline; (b) flow tests on a new production well; and (c) temporary diversion of part of the injection stream into strat 9.

5. Testing involving injection into strat well 9 might permit better evaluation of possible hydraulic connections between strat wells 2 and 9, the main terrace, and the CPI production reservoir. However, before attempting to use strat well 9 for this purpose by diverting some of the injection stream from Cox I-1, the physical status of strat 9 would need to be thoroughly investigated. Also, there is no way to accurately predict beforehand what effects injection in strat well 9 would have on the ground-water system in the South Truckee Meadows or on the SB GEO well field. Consequently, these areas would have to be monitored to detect adverse effects.

6. Utilization of absolute-reading pressure gages on the gas lines in the strat wells should be considered to eliminate some of the variability caused by barometric pressure variations. Alternatively, the pressure records could be filtered for barometric (and earth tide) effects utilizing barometric data obtained with a separate transducer on site. Increasing the measurement frequency in strat wells 2, 5, and 9 would also make it possible to better delineate seasonal variations.

7. More easily interpretable pressure records could be obtained from these wells if the annulus in strats 2 and 9 were cemented to isolate the shallow thermal aquifer near the bottom of the well. However, the cost and possibility of well failure associated with such efforts must be weighed against the anticipated benefits prior to a decision being reached about these wells.

8. Measurements of both chloride concentration and stream discharge (not only stage) in Steamboat Creek at Rhodes Road, Virginia City Highway, and Huffaker Hills should be made on an annual or biannual basis (spring and fall) to determine rates of inflow of thermal water. If a suitable monitor well in the ACEC can be established, regular chloride and temperature measurements should also be made in the well.

Should these suggestions be carried out, additional information useful in understanding various hydrologic aspects of the Steamboat area would be obtained. Such an increased understanding will assist in future management of the hydrologic and biologic resources of the ACEC. Until some or all of these measures are accomplished, it would be difficult to specify mitigation measures to correct adverse effects of geothermal production. Mitigation measures that would involve changes in reinjection locations or curtailment of production are unlikely to be effective in returning the hot springs to their former flowing conditions because other factors, such as continued ground-water pumpage and expansion of the geothermal production on private lands north of the ACEC, are likely to have significant negative effects on the ACEC springs.

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APPENDIX A. HOT-SPRING OBSERVATIONS IN TABULAR AND GRAPHICAL FORM

Records of hot spring and geyser activity data for the main terrace have been compiled, in chronological order, from five sources: Nancy Nehring, formerly of the U.S. Geological Survey and now in private business (NN); the Geyser Observation and Study Association (GOSA); Donald Hudson, an independent geological consultant (DH); the Bureau of Land Management (BLM); and the Nevada Division of Environmental Protection (NDEP). Nehring (1980) recorded observations of hot spring activity on 7 June 1977 as part of a fluid geochemistry study of the Steamboat Springs Geothermal System. GOSA (unpubl. data) began recording observations on spring and geyser activity, on an infrequent basis, in late 1983. Their intent was to understand geyser activity documented at Steamboat Springs by White (1968). GOSA began recording more detailed observations when a noticeable and widespread decline in spring and geyser activity occurred in early-mid 1986. Hudson (unpubl. data) began recording observations of spring and geyser activity, including estimates of depth to water, in late 1985. These observations were recorded, on an infrequent basis, as a result of a personal interest in understanding the relationship between metalliferous precipitate deposition and spring/geyser activity. The observations were generally centered on springs north of 6 and south of 17. Estimates of depth to water in spring vents made by Hudson and GOSA are followed by (est.). The BLM began recording observations of spring and geyser activity in mid-1986, in an effort to determine the effects of geothermal fluid withdrawal and injection on thermal features at the Main Terrace. With the same objectives, the NDEP began observations in mid-1987. The data compiled by NDEP and BLM have not been published but are on file in the agency offices in Reno and Carson, respectively. The dates of geothermal production and injection at Steamboat Springs are also listed, in chronological order, with the spring and geyser observations. The locations of the wells and springs are shown on Plate 2 and figure 4.

The data below are presented here in tabular and graphical form for several reasons:

1) They provide evidence of recent geyser activity at Steamboat Springs.

2) They allow (a) a qualitative assessment of hot spring and geyser activity with time, in light of the factors which affect such activity, and (b) a comparison with previous observations (White, 1968).

3) They provide an independent check of observations recorded as part of monitoring efforts by geothermal power plant developers and operators.

On a given date, observations from a particular source (shown in parentheses) follow the designated spring number. The spring numbering system and nomenclature are from White (1968). In some cases numbers have been assigned to spring vents which either were not active or were not recognized during White's (1968) study (for example, 24n and 24ne or springs with numbers greater than 100). The wording of the observations remains in a form as close as possible to the original field, or tabulated, source notes. However, most water levels in spring vents reported in inches, centimeters or meters have been converted to feet, to the nearest 1/100th of a foot, so that changes in water levels may be more easily discerned. For this reason, the data appear to be more precise than they actually are. All temperature measurements in degrees fahrenheit have been converted to degrees celsius.

Some interpretation of the wording may be necessary. For example, a "dry" spring [vent] is one in which standing water is no longer visible or where depth to water measurements are no longer possible. Depending on the morphology of a vent, the amount of rock debris it contains, or the eyesight of the observer, a spring may be noted as dry by one observer and not so by another. Note that a "steaming" spring implies that the spring is dry. In addition, water temperature and/or electrical conductivity measurements (the latter in microseimens/cm at 25°C) imply that the spring [vent] contains standing water, unless the spring is noted as discharging. A "flowing" spring is a discharging one. Some springs may discharge through openings or cracks in the siliceous sinter which are below the rim of a vent. Hence they contain standing water, but at the same time may be noted as discharging (for example, springs 8, 12, 15, 16 and 42).

Water level measurements reported by BLM and NDEP were recorded using graduated rulers. Differences in depth to water measurements, sometimes recorded for the same spring on the same day, may be due to daily fluctuations of water levels in hot spring vents (White, 1968; this study), differences in precision and accuracy of the measurements or the use of different reference points by different observers. In some instances (for example, springs 4 and 6) the BLM and NDEP measurements were from the same reference point; in other cases (e.g. spring 12) the reference points differ by 0.27 feet.

Hydrographs shown for springs on the main terrace (p. A-48 to A-65) were copied from Collar (1990), along with captions used by Collar. They are included here graphical record of changes in water level than are provided in the main part of the report.

7 JUNE 1977 (NN)
Main Terrace

1-1n: marshy seep to southeast
2: dry; several small seeps to east, three small springs to south, 95°C
2nw: flowing, 8 lpm (est.); 75.5°C
3: flowing, 2 lpm (est.); 60°C
4: flowing, 4 lpm (est.); 76.5°C
5: flowing, 8 lpm (est.), 95°C; spring in trench to south flowing, 10 lpm (est.); 87°C
6: flowing, 1 lpm (est.); 97°C
7: 78°C; pool between 6 and 7, 57°C
8: flowing, 0.25 lpm (est.); 91°C
8nw: almost dry, 91°C
9: almost dry
10: 85°C; vent between 9 and 10, 63°C
11: flowing, 0.25 lpm (est.); 75°C
12: 95°C
12sw: dry
13: almost dry
13w-14: dry
14w-15sw: dry
15: lightly steaming
15w: a little water at 1.2m (4ft.) depth

16-16se: dry
17: flowing, 0.25 lpm (est.); 86°C
18: several small seeps, 4 lpm (est.); 90°C
19: seep, 0.25 lpm (est.); 77°C
19n-20: marshy seeps
21-21s: dry
21w: dry
21n: flowing, 4 lpm (est.); 70.5°C
22: dry
23: flowing, 20 lpm (est.), 95°C; some water flowing along "fault" as spring 24 (description sounds like this is 24)
23n: inflow from 23?
24: 97°C (see 23)
24w: dry
24e: dry
27: flowing, 4 lpm (est.), 87°C; nearby flowing spring, 20 lpm (est.), 78°C
34: stagnant
34n: dry
35: steaming
35n: steaming
37: dry
38: 84°C; pool to south
39-36: water level at about 4.5m (15ft.) depth
40: steaming
41s: steaming
42: water level at about 0.9m (3ft.) depth
42w: same as 42
43: 63°C

Low Terrace

25: flowing, 0.25 lpm (est.); 93°C
25s: flowing, 2 lpm (est.); 76°C
25ss: flowing, 1 lpm (est.); 88°C
26: flowing, 2 lpm (est.); 95.5°C
26nw: flowing, 1 lpm (est.); 92.5°C
29: dry
30: dry
30s: dry
30n: dry
31: dry
31s: dry
31n: dry
32e: dry
32se: dry
33: cool water in stone/concrete basin
44: marshy seep

44e: dry?
44ne: flowing, 4 lpm (est.), 45°C; several seeps nearby
50: flowing, 8 lpm (est.); 53°C
50n: dry
54: marshy seep

10 SEP 1983 (GOSA)
6: discharging, 97°C
7: 63°C
8: 93°C
10: rise in water level in vent followed by small eruption and discharge
24: discharging
24sw: erupting every 15 min., with some water landing as great as 20 ft. from vent

25 NOV 1983 (GOSA)
10: small eruptions
16: boiling at north end
23n: geysering to 3-4ft., every 4-5 min., lasting 40 sec.
24: discharging
24sw: water level rises to within 3ft. of ground surface, then surges, erupting to 5ft. above ground

3 MAR 1984 (GOSA)
4: water level 0.33ft. (est.) below rim, splashing; no discharge
6: water level at vent rim, splashing, 96°C; a few discharging seeps and small vents uphill from 6
7: standing water, 68°C
8: discharge from crack in vent cone, 87°C
10: erupting, water level 3in. below rim between eruptions
12: heavy boiling, 18in. high
13: water boiling heavily, 3-4in. above rim
16se: water jetting, boiling to 1ft.
23n: erupting to 2-3ft. every 2 min. for 15 sec.; area south of 23n has 4 small springs which are splashing and overflowing
24: discharging
24e: water level down 0.25ft. (est.), 77°C
24sw: water splashing 3ft. below vent rim
40: series of eruptions to 8-12ft., lasting 5-10 min., followed by 6-9 min. of quiesence; individual eruptions within series lasting 30 sec., occuring every 40 sec.

23 JUN 1984 (GOSA)
2: discharging, 56°C
4: 94°C
6: 98°C
12: steady boiling, slight discharge
16,16se: both vents erupting steadily to a height 3-5ft.
23n: inactive as geyser due to inundation by discharge from 24

24: discharging
40: weak eruptions
42: discharges great amount of water, while jetting/boiling up to 2ft.; eruption lasts 10sec, occuring every 8-10 min.

22 SEP 1984 (GOSA)
24: discharging
42: erupting to 8ft.
42w: erupting in unison with 42 to 15ft.; erupted to 15-20ft.

29 SEP 1984 (GOSA)
24: discharging
42w: geyser eruptions lasting 1min.

21 OCT 1984 (GOSA)
8: discharging from crack in vent cone
12: water level down 0.33ft. (est.), slight discharge
23?: eruptions below ground surface, 1-2 ft. above static water level, lasting 20-30 sec, every 40-50 sec.
24: heavy discharge
24sw: water level down 3ft. (est.), heavy boiling
40: water splashing 2 ft. above ground surface from eruptions at 3ft. depth; 4-8 eruptions in a series, each separated by about 30 sec.; water level falls out of sight for 8-10 min. between series
42: water level down 0.33ft. (est.) at south end, periodic overflows in center of vent, jetting/boiling 6-8in. high at north end; erupted to 1ft.
42w: water level down 0.50-0.83ft. (est.)
remark: three, very small, spring vents have formed approximately 8 ft. south of those uphill from 6 noted on 3 March

27 OCT 1984 (GOSA)
10: erupting
12: 97°C
12sw: 92°C
24: discharging
42: no water visible (after eruption of 42w)
42w: eruption lasting 1 min.

9 DEC 1984 (GOSA)
8: discharging from crack in vent cone
14: overflowing, 96°C
16,16se: drained, steaming
23n: drained, dormant
24: discharging
24sw: audible water at depth
24w: constant geysering to 18in.
40: eruptions to 5ft., every 2 min., lasting 60 sec.
42: jetting/boiling in center of vent to 18in.

42w: water level down 0.50ft. (est.)

6 APR 1985: injection into well OW-1 begins

7 APR 1985: injection into well OW-1 ends

8 JUNE 1985 (GOSA)
10: active
24: discharging
26: erupting to ≈30cm
40: subterranean eruptions
42: active
106: considerable overflow

16 JUNE 1985 (GOSA)
24: discharging
42: active, 98°C
42w: 98°C

4 JULY 1985 (GOSA)
10: active
24: discharging
40: subterranean eruptions
42: active

6 SEP 1985: discharging of well PW-1 begins; injection into well IW-1

9 SEP 1985: discharging of well PW-1 ends

10,11 SEP 1985 (GOSA)
10: active
24: discharging
42: active

21 SEP 1985 (GOSA)
13: ≈94-96°C
24: discharging
42: active
42w: 98°C, induced eruptions

28 SEP 1985 (GOSA)
10: active
12sw: standing water in vent, ≈76-78°C
13: standing water, ≈95-97°C
24: discharging
42: induced eruptions
42w: induced eruptions

102: full and noisily bubbling

14 OCT 1985 (GOSA)
10: erupting
13: standing water, 96C
14-16: ≈93-97°C
24: discharging
42: active, induced eruption

19 OCT 1985 (GOSA)
10: erupting
24: discharging
42: active
42w: induced eruptions
106: considerable overflow

26 OCT 1985: discharging of well 23-5 begins; no injection

29 OCT 1985: discharging of well 23-5 ends

14 NOV 1985 (DH)
39: erupting to 3ft.
41: erupting to 3ft.

30 NOV 1985 (GOSA)
10: erupting
24: discharging
24sw: erupting to ≈1/2m
39: erupting to ≈1/2 m
40: dormant
41s: erupting to ≈1m
42: active
102: erupting to ≈1/2m
106: no discharge, standing water

14 DEC 1985 (DH)
39: not quite as active as 14 November
41: not quite as active as 14 November

21 DEC 1985: intermittent discharging of well PW-2 begins; injection into PW-1

28 DEC 1985 (GOSA)
1e: splashing to ≈10-15cm
10: erupting
19n: splashing to ≈10cm
24: discharging
26: erupting to ≈30cm

39: erupting to ≈1m
40: no activity
41s: erupting to ≈1m
42: active
101: active
102: dormant

31 DEC 1985: intermittent discharging of well PW-2 ends

2 JAN 1986: discharging of well PW-2 begins; injection into wells PW-1 and IW-2 (not concurrently)

3 JAN 1986: discharging of well PW-2 ends

8 FEB 1986 (GOSA)
10: erupting
11n: active
13w: increased bubbling and overflow
14: water visible
14w: active
19n: active
24: discharging
27: considerable discharge
39: decreased activity, erupting to ≈1/2m
40: no activity
41: splashing in small vent in debris filled hole
41s: decreased discharge, erupting to ≈1m
101: full, bubbling
102: no activity
103: evidence of discharge
106: no discharge or activity
110: splashing to ≈20cm

11 FEB 1986 (DH)
39: erupting slightly
40: erupting slightly, little discharge
remarks: water level in 14 related to 12, 12sw, 13, 15, 16 and 42; short-lived outflow south of 3e

23 FEB 1986 (GOSA,DH)
1w: bubbling and splashing
1e: dormant
10: erupting
13: induced eruption
24: discharging
39: erupting to ≈1/2m, barely discharging
41: splashing and bubbling

41s: erupting to ≈1m
42: active
42w: induced eruptions
101: full, bubbling
103: moderate overflow
109: active
110: water higher, splashing to ≈20cm

21 MAR 1986: discharging of well Steamboat No. 1 (21-5) begins; no injection

22 MAR 1986 (GOSA)
10: active
24: discharging
36ne: splashing to ≈1/2m
39: minor activity, occasional splashes to 1/2m
40: no activity
41s: dormant, no overflow, water level dropped
42: active
103: steady overflow
105: active, splashes to 1m
106: water visible deep in vent
109: erupting
110: has water, but quiet
111: newly active vent?

4 APR 1986 (GOSA)
4: steady discharge, boiling
6: steady discharge, boiling
8: slight, steady discharge
8nw: water level down 0.66ft. (est.), stable
10: erupting
11: steady discharge
12: reduced discharge compared to previous [GOSA] observations; splashing to 1/2m
12sw: small, steady discharge
16: steady overflow, occasional spouting
24: steady discharge, decreased overflow
25,26: same as previous visit
36ne: dry
39: occasional splash to vent rim
40: no activity
41s: water level down 1.64ft. (est.), north vent active
42: 96-97°C
42w: induced eruptions
103: dry
104: dry
105: dry
106: dry

110: dry
111: dry

12 APR 1986 (DH)
6: flowing
9: flowing
14: flowing
24: standing water, no discharge
42: flowing
remarks: activity greatly reduced; few springs flowing

19 APR 1986 (GOSA)
4: steady discharge
6: no overflow
8: slight, steady discharge
8nw: water level down ≈0.82ft. (est.)
10: erupting
11: water level down 0.13ft.
11n: dry
12: some overflow
12sw: water level ≈0.16ft. (est.) below overflow
16: steady discharge, occasional spouting
19n: overflowing as usual
24: dry
27: overflowing as usual
34: overflowing as usual
39: no activity, dry
41s: no activity, dry
42: water level down 0.13ft. (est.)
42w: induced eruptions
103: dry
104: dry
105: dry
106: dry
110: dry
111: dry

26 APR 1986 (GOSA)
2: 44°C
2nw: water level just below overflow
3: steady overflow, 61°C
4: completely dry, but damp; audible water at depth
6: water level ≈0.67ft. below overflow, 92°C
8: unchanged from previous observations
8nw: water level down ≈2.83ft., 73°C
10: erupting, 91°C
11: water level ≈0.23ft. from vent rim, occasional bubbling

11n: dry
12: water level down 0.03ft., no splashing, 95°C
12sw: water level down 0.83ft.
13: unchanged from previous observations, higher discharge?; 97°C
13nw: overflowing
15s: 92°C
16: water level down ≈0.03ft. (est.), no overflow
16se: 90°C
19n: no overflow
24: dry
27,28: unchanged from previous observations, moderate discharge
34: no overflow
39: dry, audible water at depth
41s: dry
42: water level down ≈0.83ft., no splashing or overflow
42w: water level down ≈0.83ft.
103: dry
104: dry
105: dry
106: dry
110: dry
111: dry

3 MAY 1986 (DH)
6: flowing
42: flowing
remark: few, if any, springs flowing

5 MAY 1986 (GOSA)
4: dry
6: water level down 0.98ft. (est.)
8: slight, steady discharge
8nw: water level down 3.28ft. (est.)
10: smaller eruptions
11: water level down 0.66ft. (est.)
12: water level down 0.07ft. (est.)
12sw: water level 0.82ft. (est.) down
16: water level down 0.07ft. (est.)
24: dry
39: dry
41s: dry
42,42w: water level down 0.82ft. (est.)
103: dry
104: dry
105: dry

106: dry
110: dry
111: dry

9 MAY 1986 (GOSA)
2: dry
3: slight discharge, 63°C
4: dry
6: water level down ≈1.33ft. (est.) below overflow, 97°C
7: water level down ≈1.31ft. (est.) from high water mark
8: unchanged from previous observations
8nw: water level down ≈3.28ft. (est.), 78°C
10: erupting
11: water level down ≈0..83ft. (est.) from vent rim
12: water level down ≈0.23ft. (est.), 96°C
12sw: water level down ≈1.31ft. (est.)
13: standing water, 98°C
13nw: overflowing, 72°C
15-16: water level down ≈0.46ft. (est.), no overflow
19n: dry
24: dry
24e: audible water at depth
27,28: only discharging springs in northern area
34: dry
39: audible water at depth
41s: dry
42: water level down ≈0.82ft. (est.), no splashing or overflow
42w: water level down ≈0.98ft. (est.)
43: water level down ≈3.50ft. (est.)

15 MAY 1986: discharging of well Steamboat No. 1 (21-5) ends

18 MAY 1986 (DH)
39: audible water at depth
40: steaming
41: steaming
remark: little other activity than above observations

22 MAY 1986 (DH)
8nw: water visible 2-3 feet (est.) down
9: water visible
12: water level nearly to overflowing
13: water level nearly to overflowing
14: water level nearly to overflowing
15,16: water level nearly to discharge opening in sinter
24: dry
24w: steaming here and nearby

39: audible water at depth here and nearby
41: audible water at depth here and nearby
42: good flow (i.e. discharge)

26 MAY 1986 (DH)
8: starting to flow from under sinter
remark: not much change in springs since 22 May

1 JUNE 1986 (DH)
8: flowing
10: geysering as usual, with intermittent overflow
12: water level 0.25ft. (est.) from overflowing, seeping from crack in sinter
13w: slightly flowing
15,16: water level 0.08-0.17ft. (est.) below discharge opening in sinter
15w: water bubbling
39: audible water at depth
41: steaming
42: overflowing a little bit
42w: not flowing

4 JUNE 1986 (GOSA)
4: water level down ≈1ft. (est.), 93°C
6: water level down ≈2.17ft. (est.), 93°C
7: standing water in vent
8: discharging from crack in vent cone, 91°C
10: erupting
11: water level down ≈0.17ft. (est.)
12: trickle of discharge, some splashing, 97°C
12sw: water level down 0.58ft. (est.), 81°C
13: standing water, 93°C
13w: standing water, 75°C
15s: standing water, 90°C
16: water level down ≈0.08ft. (est.), 91°C
16se: overflowing (during eruption?)
23: dry
42: some seeping discharge
42w: water level down ≈0.58ft. (est.), 97°C

8 JUNE 1986 (GOSA,DH)
2: dry
3: unchanged from previous [GOSA] observation
4: water level ≈1ft. (est.) down, 80°C
6: water level 1.92ft. (est.) down, 96°C
7: standing water in vent
8: discharging from crack in vent cone, 90°C
8nw: water level 3.17ft. (est.) down
10: active

11: water level down ≈0.08ft. (est.)
12: some discharge
13: water level down 0.83ft. (est.), 98°C
13w: slightly flowing, 76°C
15: slightly flowing
16: slightly flowing
19n: full, bubbling, slight overflow
24: dry, steaming
24w: steaming
37: steaming
39: audible water at depth
41: steaming
41s: steaming
42: some discharge

19 JUNE 1986 (GOSA)
4: full, slight trickle of overflow, 68°C
6: water level down 1.83ft. (est.), 96°C
7: standing water, no change from previous observation
8: no change from previous [GOSA] observations
8nw: water level down 3ft. (est.)
10: active
11: water level down 0.08ft. (est.)
12: overflowing
12sw: water level down ≈0.50ft. (est.), 81°C
14,15,16: unchanged from previous [GOSA] observation
19n: overflowing
24: dry
34: trickle of overflow
39: occasional splashes of water seen at depth
40: dry, dormant
42: water level a few centimeters below rim, 98°C
42w: water level a few centimeters below rim, 97°C

23 JUNE 1986 (BLM)
4: discharging
42: discharging

8 JULY 1986 (BLM)
4: full, steady discharge
6: water level down 1.48ft. from rim
8: full, bubbling
8nw: water level down 2.95ft.
10: erupting
11: steady discharge
12: small amount of discharge
12sw: water level down 0.26ft. from vent rim

16: steady discharge, no eruptions 24n,24ne: small amount of flow
39: no visible water; splashing to land surface from at depth
41s: dry
42: small pulsating geyser, partial overflow

12 JULY 1986 (DH)
8: flowing
10: active
11: south vent not flowing, north vent overflowing
12: "leaking" water (i.e. slight flow)
13,13w: algae in vent
14: standing water in vent
15w: standing water in vent
23: flowing
23n: water boiling about 2ft. (est.) down
24: standing water about 0.08ft. (est.) deep
24w: steaming
39: water splashes to nearly land surface from below

17 JULY 1986 (DH)
24: water level slightly higher than 12 July
remark: not much change in springs from 12 July

18 JULY 1986 (BLM)
4: higher discharge than 8 July
6: water level down about 1.15ft. from rim
8: full, bubbling
8nw: water level down 2.46ft.
10: steady boiling eruption and 2-3 minute discharge
11: steady discharge
12: slightly greater discharge than 8 July
12sw: water level down 0.26ft. from rim
16: slightly greater discharge than 8 July
24n,24ne: more discharge than on 8 July
39: no visible water; splashing to land surface from at depth
41s: dry, steaming
42: steady overflow; pulsating geyser

25 JULY 1986 (BLM)
4: steady discharge
6: water level up slightly (≈0.07ft.) from 18 July
8: water level at vent rim, some discharge from crack in vent cone
8nw: water level same as 18 July
10: erupting
11: steady discharge
12: steady boiling, not discharging
12sw: water level down 0.05ft.

16: steady discharge
24n: steady discharge
24ne: steady discharge with eruptions to 1ft.
39: water visible and splashing at 2ft. depth
41s: dry
42: steady overflow with more intense pulsations

8 AUG 1986 (BLM)
4: steady discharge
6: water level same as 25 July
8: full, some discharge from crack
8nw: water level same as 25 July
10: erupting
11: steady discharge
12: steady boiling of water over vent rim
12sw: full, with some outflow
16: steady discharge
23n: 15 sec. eruptions to 1.5-2ft. every 1.5-2 min.; abundant outflow
24ne: bubbling, but not erupting
39: water splashing at 2ft. depth
41s: dry, but audible water at depth
42: steady overflow

17 AUG 1986 (DH)
8: flowing
8nw: water level has risen ≈1ft. (est.) since 22 May
10: geysering like normal
11: so. vent flowing, no. vent flowing slightly
12: slight flow
12sw: barely flowing
14: slight flow in north vent
15w: slight flow; south of here: several pools
16se: strong flow
24: overflowing, no vigorous activity
24e: not flowing, but boiling in vent
39: cannot see water
42: overflowing in center of vent with vigorous boiling

25 AUG 1986 (BLM)
4: steady discharge
6: water level same as 8 August
8: full, some discharge from crack
8nw: water level same as 8 August
10: wet spring apron indicating eruptions
11: steady discharge
12: full, steady boiling, but no overflow
12sw: full, with some outflow

16: steady discharge
23n: water level down 0.66ft.
24: water in fissures
24n,24ne: steady flow
39: water splashing at 2ft. depth
41s: audible water at depth
42: water level high, steady discharge and bubbling

8 SEPT 1986 (BLM)
4: very full, steady discharge
6: water level same as 25 August; small springs to west discharging
8: full, some discharge from crack
8nw: water level same as 25 August
10: erupting
11: steady discharge
12: full, steady boiling, but no overflow
12sw: full, with some outflow
remark: 13, 13w, 14, 15, 15w and 16se full of water and some springs discharging
16: steady discharge
23n: almost dry
24: flowing heavily
24n: erupting to 1ft.; all springs in area full and flowing
39: water splashing at 2ft. depth
40: 30-45 sec. eruptions to 3-5ft., every 2 min.
41s: boiling water visible
42: water level high, steady discharge and bubbling

17 SEPT 1986 (GOSA)
4: overflowing
6: overflowing, 93°C
8nw: water level down ≈2.5ft. (est.)
10: active
11: discharging
12: slight overflow, 92°C
13: standing water, 91°C
15,16: discharge from north end
17s: sputtering discharge
23n: erupting
24: considerable, continuous discharge
24e: water level down ≈0.33ft. (est.)
36ne: water visible
40: erupting to >10ft.
41s: water visible, splashing in bottom of north vent
42: considerable discharge, 96°C
42w: water level down ≈0.08-0.17ft. (est.)
103: water visible, down ≈0.08ft. (est.)

20 SEPT 1986 (GOSA)
10: erupting
23: stops sputtering for ≈8-12 sec. after eruption of 23n
23n: erupting
39: water visible 4-5ft. (est.) down, heavy steam
40: erupting
41s: water visible ≈3ft. (est.) down in no. vent, considerable splashing
42: active
42w: induced eruptions, 97°C

22 SEPT 1986 (BLM)
4: very full; steady, slightly greater discharge than 8 September
6: full and discharging
8: full and discharging from crack
8nw: water level same as 8 September
10: erupting
11: steady discharge
12: full, steady boiling, no overflow
12sw: full, with some outflow
16: steady discharge
24: discharging
24n,24ne: discharging
36: water visible
39: water splashing at 2ft. depth
40: 10-12ft. high eruptions occur approximately every 30sec. and last 10-15 sec.; about every 10 min. eruptions cease for 1.5-2 min. then begin again
41s: boiling water visible
42: bubbling rapidly, same as 8 Sept, but contains foam in portions of vent (see 42w, 20 Sept.)

6 OCT 1986 (BLM)
4: steady discharge
6: discharging
8: discharging from crack
8nw: water level same as 22 September
10: erupting
11: steady discharge
12: full, steady boiling, no overflow
12sw: full, with some outflow
16: steady discharge
23n: 2ft. eruptions every 3-4 min., lasting about 15 sec.
24,24n,24ne: somewhat greater outflow than 22 September
39: splashing water at 2ft. depth
40: eruptions same as 22 September
41s: water level slightly higher than 22 Sept.; occasional splashes of water onto ground surface
42: steady bubbling and discharge

18 OCT 1986 (DH)
8: flowing
8nw: water level about 1.50ft. (est.) below rim
10: active
11e: flowing
11s: flowing
14,15,16: flowing
16se: flowing
23: geysering to 3ft. for a few minutes followed by heavy outflow
23n: few minutes after cessation of 23, geysers to 3ft. with heavy overflow for several minutes; alternates with 23
24: strong flow
24e: slight flow
36: rapid boiling at vent bottom
39: boiling, but not erupting
40: geysering
41s: rapid boiling at vent bottom

20 OCT 1986 (BLM)
4: steady discharge
6: discharging
8: discharging from crack
8nw: water level 0.66ft. down
10: erupting
11: steady discharge
12: boiling heavily, steady outflow
12sw: steady flow
16: steady discharge
24,24n,24ne: discharging
39: splashing water at 2ft. depth
40: erupting, abundant overflow
41s: water level 0.33ft. down; no splashing onto land surface
42: steady bubbling and discharge

25 OCT 1986 (GOSA)
10: erupting
14-16: water level dropped about 1.5in. around 1400 hrs.
17s: steady discharge
23n: erupting
24: erupting
24e: 94°C
40: erupting
41s: activity in north vent
42w: induced eruptions
112: overflow from three areas
113: erupting
114n: water level down 0.50ft. (est.), 77°C

4 NOV 1986 (BLM)
4: steady discharge
6: slightly more discharge than 20 October
8: steady bubbling, water level almost to vent rim, discharging from crack in vent cone
8nw: water level down 0.33ft.
10: active
11: steady discharge
12: boiling heavily, steady outflow
12sw: steady flow
16: steady discharge
23n: erupting to 3ft. every 2-3 min., lasting 10 sec.
24,24n,24ne: heavy flow
39: splashing water at 2ft. depth
40: erupting as during previous (BLM) observations
41s: water level down about 0.33ft.; heavy bubbling and occasional splashing onto land surface
42: discharging and rapidly boiling
43: full, with steady discharge

8 NOV 1986 (GOSA)
10: erupting
11n: 68°C
12: quiet, full, 97°C; occasional spouting
13: 93°C
23n: erupting
42: induced eruptions
42w: induced eruptions

16 NOV 1986 (DH)
4: active?
8: flowing
8nw: water level about 0.08ft. (est.) from vent rim
10: active
11s: flowing
11e: flowing
11n: standing water in vent
12: flowing
13w: flowing
14: flowing
15,16: not flowing, standing water in vent
16se: flowing
23,23n: no change from 18 October
24: high flow; geysering at south end to 1ft.
24e: not flowing
24sw: much boiling 2-4ft. (est.) down
36: rapid boiling at vent bottom
39: boiling, not erupting; number of small springs along fissure ≈50ft. southeast of 39
40: geysering up to 10ft., lasting 30 sec.-3 min.

41s: rapid boiling at vent bottom

22 NOV 1986 (GOSA)
10: erupting
23n: erupting
40: erupting
42w: induced eruption
101: active, splashing
107: splashing over rim

23 NOV 1986 (BLM)
4: water level down 0.50ft. from vent rim, no outflow
6: discharging
8: water level almost to rim, discharging from crack
8nw: full, no outflow; layer of foam on water surface ("soaped" by GOSA?)
10: erupting
11: steady discharge
12: boiling heavily, steady outflow
12sw: steady flow
16: water level down 0.33ft.
24: flowing strong
24n,24ne: good outflow
39: splashing water at slightly less than 2ft. depth
40: erupts intermittently to 5-6ft. every 15 sec., lasting about 2 min.; repeats cycle after 3-4 min. of quiet
41s: water level down 0.67ft.; audible, but not visible; no splashing onto land surface
42: discharging and boiling rapidly; contains foam (see 42w, 22 Nov.)

2 DEC 1986: discharging of wells PW-1, PW-2 and PW-3 begins (not concurrently); injection into well IW-3

14 DEC 1986 (DH)
2: slight flow
3: slight flow
6: good flow
8: slight flow
8nw: barely overflowing; several seeps to west
9: water level about 0.67ft. (est.) from vent rim in fissure east of 9
10: flowing
11s: flowing
11e: slight flow
11n: standing water in vent
12: water level just below vent rim; west spring apron very wet suggesting intermittent overflow
12sw: slight flow
14: water level down 0.5ft. (est.) below vent rim
15,15w,16,16se: water level up to 1ft. (est.) below rim for this group of springs
23: alternating between flowing and geysering

23n: strong flow, geysering up to 18in.
24: heavy flow; geysering and splashing out of vent/fissure
24e: water level 0.67ft. (est.) below rim; slight flow from area between 24 and 24e
24sw: audible water at depth
36: rapid boiling, water just visible
39: heavy steaming; wet ground to east suggestive of geysering?
40: boiling; little water splashing onto land surface
41s: water level barely visible, down 0.5ft. (est.) since 16 November
42: moderate flow

16 DEC 1986 (BLM)
4: water level down 0.83ft. from vent rim, no outflow
6: discharging
8: water level almost to rim, discharging from crack
8nw: slight overflow, bubbling steadily
10: initially full, bubbling and overflowing; erupts for 5-7 min., water level drops below vent bottom rapidly, then the vent begins to refill after 20 min. to overflowing and the cycle repeats
11: steady discharge
12: boiling heavily, steady outflow
12sw: steady flow
16: water level down 0.83ft.
23n: geysering to 4-5ft.
24,24n,24ne: heavy flow
39: splashing water at slightly less than 2ft. depth 40: audible water at depth; no eruptions observed
41s: audible water at depth, no splashing onto land surface
42: discharging and boiling rapdily

29 DEC 1986: discharging of wells PW-1, PW-2 and PW-3 ends

5 JAN 1987: discharging of wells PW-1, PW-2 and PW-3 begins; injection into well IW-3

7 JAN 1987 (BLM)
4: water level down 0.67ft. from rim, no outflow
6: discharging
8: water level almost to rim, discharging from crack
8nw: full, bubbling steadily, but no overflow
10: erupting as on 16 December
11: steady discharge
12: boiling heavily, steady outflow
12sw: steady flow
16: water level down 0.67ft. below rim
23n: erupting to 1-2ft.
24,24n,24ne: heavy flow
39: water not visible, audible at depth; steaming
40: dry, no audible water
41s: dry, no audible water

42: steady outflow, increased boiling

10 JAN 1987 (GOSA)
10: active
42w: induced eruptions

17 JAN 1987 (DH)
4: water level down 0.67ft. (est.)
6: flowing
8: flowing
8nw: water level down 0.50ft. (est.)
8w: standing water in vent
11s: flowing
11e: standing water in vent
11n: standing water in vent
12: strong flow
12sw: trace of flow
14: dry
15: dry
15w: dry
16: dry
16se: dry
22s: ≈75ft. south of 22, water level 3ft. (est.) down
23: moderate flow
23n: geysering steadily to 6-8in.
24: strong flow, no geysering; flow from fissure between 24 and 24e
42: boiling, leaking from north end of vent
42w: water level 0.17ft. (est.) below vent rim

20 JAN 1987 (BLM)
4: water level down 1.00ft. from rim, no outflow
6: discharging
8: water level almost to rim, discharging from crack
8nw: water level down 0.50ft. below rim
10: erupting
11: steady discharge
12: boiling heavily, steady outflow
12sw: steady flow
16: dry, steaming
23n: steady bubbling, erupting to 1-1 and 1/2ft.
24,24n,24ne: heavy flow
39: audible water at depth
40: dry
41s: dry
42: rapid boiling, with good outflow

21 FEB 1987 (GOSA)
10: erupting
12: spouting at 1056 hrs.
42w: induced eruptions
101: active

22 FEB 1987 (DH)
4: water level 0.33ft. (est.) below rim
6: flowing
8: flowing
8nw: water level 0.67ft. (est.) below rim
8w: dry
10: pulsing
11s: flowing
11e: slight flow
11n: standing water in vent
12: strong boiling, moderate flow
13: dry
13w: dry
14: dry; strong boiling in vent between 14 and 15w
15,16,16se: water level 1ft. (est.) below rim
23: moderate flow
23n: continuous geyser to about 6in. 24: strong flow; fissure between 24 and 24e is dry
24e: water level 1ft. (est.) below rim
24sw: strong boiling around vent
36: strong boiling
39: audible water at depth, steaming
40: dry
41s: dry
42: strong boiling

25 FEB 1987 (BLM)
4: water level down 0.67ft. from rim, no outflow
6: discharging
8: water level almost to rim, discharging from crack
8nw: water level 0.75ft. below rim
10: steady bubbling, no outflow; no eruptions observed
11: steady discharge
12: boiling heavily, steady outflow
12sw: bubbling, steady outflow
16: dry
23n: steady bubbling, with good outflow; no geysering
24,24n,24ne: somewhat decreased flow since 20 January
39: audible water at depth, steaming
40: dry
41s: dry
42: rapid bubbling, with some outflow; some "suds" (i.e. soap suds?-see 42w, 21 February)

9 MAR 1987: discharging of well Steamboat No. 1 (21-5) begins; no injection

10 MAR 1987 (BLM)
4: water level 0.33ft. down from rim, no outflow
6: full and discharging
8: water level almost to rim, discharging from crack
8nw: water level down 1.00ft. from rim
10: bubbling, but not fluctuating; no outflow
12: boiling heavily, steady outflow
12sw: water level down about 0.33ft. from rim, no outflow
16: dry
24,24n,24ne: steady outflow
39: audible water at depth, steaming
40: dry
41s: dry
42: bubbling, with some outflow

13 MAR 1987 (BLM)
4: water level down 0.54ft. from rim, no outflow
6: full and discharging
8: water level almost to rim, discharging from crack
8nw: water level 1.17ft. down from rim
10: bubbling, fluctuating; no outflow
11: steady discharge
12: boiling heavily, steady outflow
12sw: water level down 0.33ft. from rim, no outflow
16: dry
23n: steady bubbling and outflow; erupting to 1ft.
24,24n,24ne: dry; no visible water or outflow
39: no audible water at depth, steaming
40: dry
41s: dry
42: bubbling, fluctuating, with some outflow

15 MAR 1987 (DH)
6: flowing
8: flowing
8nw: water level down 2.50ft. (est.) below rim
10: active
15w: standing water in vent, about 0.50-0.67ft. (est.) down
18: flowing
23n: geysering to about 4in.
24: dry
24sw: audible water at depth
36: no water visible
39: audible water at depth
42: boiling, but not overflowing; leaking from crack at northeast end of vent

remarks: few, if any, other springs flowing

16 MAR 1987: discharging of well Steamboat No. 1 (21-5) ends

17 MAR 1987 (BLM)
4: water level down 1.17ft. below rim
6: full and discharging slightly more than 13 March
8: water level almost to rim, discharging from crack
8nw: water level down 1.25ft. from rim
10: fluctuating; ground to east wet suggesting recent discharge
11: steady discharge
12: somewhat greater outflow than 13 March
12sw: water level 0.5ft. below rim
16: dry
23n: steady geysering, outflow slightly less than 13 March
24,24n,24ne: dry
39: no audible water at depth
40: dry
41s: dry
42: bubbling, fluctuating, with some outflow

24 MAR 1987 (BLM)
4: water level down 1.67ft. below rim
6: full and discharging
8: water level almost to rim, discharging from crack
8nw: water level 1.42ft. below rim
10: fluctuating water level
11: steady discharge
12: outflow greatly reduced since 17 March
12sw: water level down 0.50ft. below rim
16: dry
23n: steady geysering
24,24n,24ne: dry
39: no audible water at depth
40: dry
41s: dry
42: boiling rapidly, discharge greater than 17 March

2 APR 1987: discharging of well Steamboat No. 1 (21-5) begins; no injection

9 APR 1987 (DH)
23n: not flowing or geysering
remarks: no noticeable change in springs observed on 15 March

10 APR 1987 (BLM)
4: water level 2.08ft. below rim
6: full and discharging

8: water level almost to rim, discharging from crack
8nw: water level 2.17ft. below rim
10: water level initially 20in. below rim; level rose over a 20 min. period to 13in. below rim and maintained this level for at least 30 min.; no discharge observed
11: water level 0.42ft. below vent rim; no discharge
12: water level 0.17ft. below rim, no discharge
12sw: water level 0.58ft. below rim
16: dry
23n: water level steady, 0.83ft. below rim; no geysering
24,24n,24ne: dry
39: no audible water at depth
40: dry
41s: dry
42: discharging, boiling rapidly

13 APR 1987: discharging of well Steamboat No. 1 (21-5) ends

16 APR 1987 (BLM)
4: dry
6: water level 0.17ft. below rim, no discharge
8: water level almost to rim, discharging from crack
8nw: water level 2.50ft. below vent rim
10: bubbling; water level steady, 8in. below rim
11: water level 0.42ft. below rim, no discharge
12: water level 0.25ft. below rim
12sw: dry
16: dry
23n: audible water at depth
24,24n,24ne: dry
39: no audible water at depth
40: dry
41s: dry
42: water level 0.42ft. below rim

19 APR 1987 (DH)
2: dry
3: dry
4: dry
6: very slight overflow
8: slight flow
8nw: water level 2.50ft. (est.) below rim
10: geysering as usual
11s: water level 0.33ft. (est.) below rim
11e: dry
11n: dry
12: water level 0.67ft. (est.) below rim
14: dry

15: dry
15w: dry
16: dry
23n: audible water at depth
24: dry
24w: dry, steaming
24sw: steaming
36: steaming
42: water level 0.33-0.50ft. (est.) below rim; slight flow from crack at north end

26 APR 1987 (DH)
remark: activity overall unchanged from 19 April

28 APR 1987 (NDEP)
2: dry
3: discharging
4: water visible at depth, below large rock in vent
6: water level about 0.33ft. (est.) below lip (rim)
8: discharging through crack/hole in vent
8nw: water level down ≈2.5ft. (est.)
10: geysering at irregular intervals
12: not flowing; water level below rim
16: water visible ≈2ft. (est.) down
23n: audible water at depth
24: dry
42: water level 0.67ft. (est.) below rim, flowing from crack

1 MAY 1987 (NDEP)
2: 1/2in. deep water in vent
3: discharging
4: water level 2.08ft. down
6: water level 0.17ft. below rim
7: water visible ≈2ft. (est.) down
8: flowing
8nw: depth to water-2.42ft.
10: wet ground surface suggests geysering
12: depth to water-0.40ft., no flow
42: depth to water-0.33ft.; flowing

2 MAY 1987 (GOSA)
4: dry
6: water level down ≈0.17ft. (est.)
8: increased discharge
8nw: water level down ≈1.50ft. (est.)
10: erupting
12: water level down ≈0.25ft. (est.)
12sw: water level down ≈0.50ft. (est.)

13w: dry
14-16: water level down ≈0.25ft. (est.)
19: discharging
23n: erupting
24: dry
40: steaming
42w: induced eruptions
113: discharging
117: discharging

3 MAY 1987 (DH)
remark: no noticeable change in activity from 26 April

5 MAY 1987 (NDEP)
2: no water in vent
3: discharging, 63°C; EC-3500
4: water level 2.08ft. down, boiling below large rock
6: water level 0.17ft. below rim, 93°C; EC-3500
7: depth to water-1.17ft. (new reference point), 70°C; EC-3500
8: discharging, 86°C; water level 0.04ft. below rim, EC-3500
8nw: depth to water-2.56ft.
10: ground surface wet, suggests geysering; 89°C, EC-3250
12: depth to water-0.67ft., 94°C; EC-3600
13: depth to water-1.38ft.
16: depth to water-2.00ft.
23n: water level 1.29ft. down in south vent
24: dry
42: depth to water-0.42ft., 96°C; slight decrease in flow from crack, EC-3600
43: depth to water-2.46ft.

6 MAY 1987: discharging of well 23-5 begins; injection into well Cox I-1

6 MAY 1987 (BLM,NDEP)
2: dry
3: discharging, 63°C; EC-3600
4: water level 2.08ft. below rim (BLM and NDEP)
6: depth to water-0.31ft.(NDEP), 0.33ft.(BLM); 93°C, EC-3500
7: depth to water-1.25ft., 70°C; EC-3700
8: discharging from crack, 86°C, EC-3500; depth to water-0.04ft.(NDEP)
8nw: depth to water-2.56ft.(NDEP), 2.58ft.(BLM)
10: water level 12in. below rim; water level rises and overflows for about 1 min., falls out of sight and returns to 12in. below rim after 5 min.; cycle lasts 25-30 min.
11: water level down 0.54ft., no discharge
12: depth to water-0.71ft.(NDEP), 0.67ft.(BLM), 94°C; EC-3700
12sw: bubbling water, 0.83ft. below rim
13: depth to water-1.38ft.
16: depth to water-2.13ft.(NDEP), 1.92ft.(BLM)

23n: water boiling 0.92ft. below rim(BLM), 1.29ft.(NDEP); no outflow, occasionally splashes onto land surface
24,24n,24ne: dry
39: no audible water at depth
40: dry
41s: dry
42: depth to water-0.48ft.(NDEP), 0.67ft.(BLM), 96°C; flowing, EC-3700
43: depth to water-2.50ft.

8 MAY 1987 (NDEP)
2: dry
3: discharging, 63°C; EC-3600
4: water level 2.00ft. down
6: depth to water-0.33ft., 93°C; EC-3500
7: depth to water-1.31ft., 70°C; EC-3750
8: discharging, 88°C; depth to water-0.04ft., EC-3500
8nw: depth to water-2.54ft.
10: geysering, 89°C
12: depth to water-0.73ft., 94°C; EC-3750
13: depth to water-1.38ft.
16: depth to water-1.96ft.
23n: water level 1.33ft. down
24: dry
42: depth to water-0.5ft., 96°C; flowing, EC-3750
43: depth to water-2.40ft.

9 MAY 1987 (DH)
8: flowing
42: water level down about 0.17ft. (est.) since 3 May; flow from north end of vent about half of 3 May
remark: no other noticeable change in springs from 3 May

11 MAY 1987 (NDEP)
2: dry
3: discharging, 63°C; EC-3600
4: water level down 2.08ft., boiling below large rock
6: depth to water-0.38ft., 94°C; EC-3600
7: depth to water-1.29ft., 70°C; EC-3750
8: discharging, 87°C; depth to water-0.0.06ft.
8nw: depth to water-2.63ft.
10: 90°C, ground surface wet
12: depth to water-0.75ft., 94°C; EC-3750
13: depth to water-1.42ft.
16: depth to water-2.00ft.
23n: boiling hard; water level down 1.58ft. in north vent
24: dry
42: depth to water-0.42ft., 96°C; flowing, EC-3750

43: depth to water-2.46ft.

12 MAY 1987 (BLM)
4: water level 2.08ft. below rim
6: water level 0.42ft. below rim
8: water level almost to rim, discharging from crack
8nw: water level 2.50ft. from vent rim
10: active as on 6 May
11: water level 0.54ft. below rim
12: water level 0.67ft. down from rim
12sw: water level 0.92ft. below rim
16: water level 1.92ft. below rim
23n: water level 1.08ft. below rim; no splashing or geysering
24,24n,24ne: dry
39: no audible water at depth
40: dry
41s: dry
42: water level 0.67ft. below rim; good outflow from cracks at northeast end of vent

15 MAY 1987 (NDEP)
2: dry
3: discharging, 63°C
4: water level down more than 2.33ft. (not visible), audible at depth
6: depth to water-0.54ft., 94°C;
7: depth to water-1.46ft., 71°C;
8: discharging, 87°C; depth to water-0.04ft.
8nw: depth to water-2.67ft.
10: geysering, 88°C
12: depth to water-0.88ft., 94°C
13: depth to water-1.50ft.
16: depth to water-2.00ft.
23n: water only visible in north vent
24: dry
42: depth to water-0.42ft., 96°C; flowing
43: depth to water-2.67ft.

20 MAY 1987 (BLM)
4: audible water at depth
6: water level 0.50ft. below rim
8: water level almost to rim, discharging from crack
8nw: water level 2.67ft. below rim
10: active
11: water level 0.63ft. below rim
12: steady boiling, water level 1.33ft. down from rim
12sw: water level 1.17ft. below rim
16: water level 1.92ft. below rim
23n: audible water at depth, ≈1.58ft. below rim

24,24n,24ne: dry
39: no audible water at depth
40: dry
41s: dry
42: water level 0.75ft. below rim, outflow declined since 12 May

22 MAY 1987 (NDEP)
2: dry
3: discharging, 62°C
4: audible water at depth
6: depth to water-0.63ft., 94°C; EC-3400
7: depth to water-1.46ft., 66°C; EC-3500
8: discharging, 87°C; depth to water-0.04ft., EC-3200
8nw: depth to water-2.75ft.
10: geysering, 88°C
12: depth to water-1.79ft., 95°C; EC-3500
13: depth to water-2.38ft.
16: depth to water-2.33ft.
23n: audible water at depth
24: dry
42: depth to water-0.81ft., 95°C; not discharging, EC-3500
43: depth to water-2.88ft.

29 MAY 1987 (BLM,NDEP)
2: dry
3: discharging, 60°C; EC-3600
4: dry
6: depth to water-0.83ft.(NDEP), 0.75ft.(BLM); 94°C, EC-3500
7: depth to water-2.50ft., 73°C; EC-3600
8: depth to water-0.04ft.(NDEP); steady discharge from crack, 86°C, EC-3200
8nw: depth to water-2.83ft.(NDEP), 2.75ft.(BLM)
10: pulsing-water level 15in. below rim at bottom, discharging at top, of cycle
11: dry
12: depth to water-1.96ft.(NDEP), 2.00ft.(BLM); EC-3600
12sw: water level 1.17ft. below rim
13: depth to water-2.58ft.
16: water level visible, 2.58ft. down, only when surface disturbed(NDEP), cannot measure water level(BLM)
23n: water level 1.58ft. below rim(BLM), not visible(NDEP); no geysering or discharge
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: depth to water-1.00ft.(NDEP), 1.17ft.(BLM); 94°C, EC-3400
43: depth to water-3.08ft.

3 JUNE 1987: discharging of well 23-5 ends

5 JUNE 1987 (BLM,NDEP)
2: dry
3: discharging, 59°C; EC-3450
4: dry
6: depth to water-1.29ft.(NDEP), 1.25ft.(BLM); 92°C, EC-3400
7: depth to water-1.83ft., 94°C
8: depth to water-0.04ft.(NDEP); steady discharge from crack, 82°C, EC-3200
8nw: depth to water-2.92ft.(NDEP), 2.92ft.(BLM)
10: pulsing; water level 15in. below rim at bottom, discharging at top, of cycle
11: dry
12: depth to water-2.08ft.(NDEP), 2.08ft.(BLM)
12sw: water level 1.33ft. below rim
13: depth to water-2.63ft.
16: depth to water-2.75ft.(NDEP), cannot measure water level(BLM) due to overhanging sinter
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: depth to water-1.17ft.(NDEP), 1.17ft.(BLM); 94°C, EC-3400
43: depth to water-3.50ft. (different reference)

12 JUNE 1987 (BLM,NDEP)
2: dry
3: discharging, 61°C; EC-3400
4: dry
6: depth to water-1.38ft.(NDEP), 1.38ft.(BLM); 94°C, EC-3100
7: depth to water-1.92ft.
8: depth to water-0.04ft.(NDEP); discharging from crack, 87°C, EC-3200
8nw: depth to water-2.92ft.(NDEP), 2.92ft.(BLM)
10: pulsing; water level 17in. below rim at bottom, discharging at top, of cycle
11: dry
12: depth to water-2.08ft.(NDEP), 2.00ft.(BLM)
12sw: water level 1.25ft. below rim
13: depth to water-2.63ft.
16: depth to water-2.58ft.(NDEP), cannot measure water level (BLM)
23n: water level 1.58ft. below rim (BLM)
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: depth to water-1.17ft.(NDEP), 1.17ft.(BLM); 95°C, EC-3300
43: depth to water-3.50ft.

14 JUNE 1987 (DH)
6: water level down 0.67ft. (est.)
8: flowing

8nw: water level down 2ft. (est.)
10: geysering; water level falls >2ft. at bottom of cycle
11: dry
12: water level down 1.50ft. (est.)
13: water level down 2.00ft. (est.)
15: dry
16: dry
23n: audible water at depth
39: audible water at depth
42: water level 1.00ft. (est.) below rim; not flowing

19 JUNE 1987 (BLM,NDEP)
2: dry
3: discharging, 62°C; EC-3300
4: dry, vent half filled with rock debris
6: depth to water-1.17ft.(NDEP), 1.21ft.(BLM); 94°C, EC-3300
7: depth to water-1.88ft.
8: depth to water-0.10ft.(NDEP); steady discharge from crack, 86°C, EC-3000
8nw: depth to water-2.83ft.(NDEP), 2.83ft.(BLM)
10: pulsing; water level 17in. below rim at bottom, discharging at top, of cycle
11: dry
12: depth to water-1.96ft.(NDEP), 1.75ft.(BLM); 94°C, EC-3400
12sw: water level 0.42ft. below rim
13: depth to water-2.50ft.
16: depth to water-2.33ft.(NDEP), cannot measure water level (BLM)
23n: dry, audible water at depth
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: depth to water-0.88ft.(NDEP), 0.92ft.(BLM); 94°C, EC-3300
43: depth to water-3.25ft.

24 JUNE 1987: discharging of well 23-5 begins; injection into well Cox I-1

26 JUNE 1987 (BLM,NDEP)
2: dry
3: decrease in discharge since 19 June
4: dry
6: depth to water-1.54ft.(NDEP), 1.67ft.(BLM)
7: depth to water-1.92ft.
8: depth to water-0.08ft.(NDEP); steady discharge from crack
8nw: depth to water-3.00ft.(NDEP), 3.00ft.(BLM)
10: pulsing; water level 24in. below rim at bottom, discharging at top, of cycle
11: dry
12: depth to water-2.38ft.(NDEP), 2.17ft.(BLM)
12sw: water level 0.92ft. below rim

13: depth to water-2.88ft.
16: depth to water-2.58ft.(NDEP), dry(BLM)
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: depth to water-1.17ft.(NDEP), 1.25ft.(BLM)
43: depth to water-3.58ft.

28 JUNE 1987 (GOSA)
3: some overflow
4: dry
6: water level down ≈1.50ft. (est.)
7: dry
8: discharging
8nw: water level down ≈4ft. down (est.)
10: active; ≈8in.-1ft. down at start of cycle
11: dry
12: water level down ≈3ft. (est.)
13: water level down ≈4ft. (est.)
14-16: dry
23n: dry
24: dry
39: steaming
40: steaming
41s: steaming
42,42w: water level down ≈1ft. (est.)
43: standing water in vent bottom
102: steaming

2 JULY 1987 (BLM)
4: dry
6: water level 1.67ft. below rim
8: full, steady discharge from crack
8nw: water level 3.08ft. below rim
10: water level 24in. below rim at bottom, discharging at top, of cycle
11: dry
12: water level 2.83ft. below rim
12sw: dry
16: dry
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: water level 1.75ft. below rim

3 JULY 1987: discharging of well 23-5 ends

7 JULY 1987: discharging of wells PW-1, PW-2 and PW-3 ends

9 JULY 1987: discharging of well Steamboat No. 1 (21-5) begins; no injection

10 JULY 1987 (BLM)
4: dry
6: water level 1.75ft. below rim
8: full, steady discharge
8nw: water level 3.33ft. below rim
10: geysering; water level 24in. below rim at bottom, discharging at top, of cycle
11: dry
12: audible water at depth
12sw: dry
16: dry
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: water level 2.08ft. below rim

11 JULY 1987: discharging of wells PW-1, PW-2 and PW-3 begins; injection into IW-3

13 JULY 1987 (NDEP)
2: dry
3: decrease in discharge since 26 June
4: dry
6: depth to water-1.79ft.
7: dry, audible water at depth
8: depth to water-0.10ft.
8nw: depth to water-3.54ft.
10: geysering; 92°C, EC-3000
12: dry
13: dry
16: depth to water-3.42ft.
23n: steaming
24: dry
42: water barely visible at south end
43: depth to water-3.83ft.

17 JULY 1987 (BLM)
4: dry
6: water level 1.83ft. below rim

8: slow, steady discharge from crack; water level 1in. below rim
8nw: water level 3.75ft. below rim
10: pulsing; water level 30in. below rim at bottom, slight discharge at top, of cycle
11: dry
12: dry
12sw: dry
16: dry
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: audible water at depth

18 JULY 1987 (DH)
4: dry
6: water level 1.50ft. (est.) below rim
8: flowing
10: active
12: water level visible 2-3ft. (est.) below rim
15: dry
16: dry
23n: audible water at depth
24sw: audible water at depth
39: audible water at depth
42: audible water at depth

24 JULY 1987 (BLM)
4: dry
6: water level 2.08ft. below rim
8: water level 0.08ft. below rim, steady discharge from crack
8nw: water level 4.25ft. below rim
10: dry
11: dry
12: dry
12sw: dry
16: dry
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: small amount of water visible about 5ft. (est.) below rim

31 JULY 1987 (BLM,NDEP)
2: dry
3: dry

4: dry
6: depth to water-2.67ft.(NDEP), 2.42ft.(BLM)
7: dry
8: depth to water-0.08ft.(NDEP), 0.08ft.(BLM); steady discharge from crack
8nw: water level visible at depth
10: water level 20in. below rim, boiling violently
11: dry
12: dry
12sw: dry
13: dry
16: dry
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: audible water at depth(NDEP), dry(BLM)
43: dry

7 AUG 1987 (BLM)
4: dry
6: water level 2.50ft. below rim
8: water level 0.13ft. below rim; steady discharge
8nw: dry
10: water level 26in. below rim, boiling violently
11: dry
12: dry
12sw: dry
16: dry
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: dry

14 AUG 1987 (BLM)
4: dry
6: water level 2.67ft. below vent rim
8: water level 0.13ft. below rim; steady discharge
8nw: dry
10: water level 28in. below rim, boiling
11: dry
12: dry
12sw: dry

16: dry
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: dry

15 AUG 1987 (DH)
4: dry
6: water level 3.50ft. (est.) below rim
7: dry
8: flowing
8nw: dry
10: water level 1.50ft. (est.) below rim during boiling
11: dry
12: dry
12sw: dry
13: dry
14: dry
15: dry
16: dry
23n: dry
36: steaming
39: dry
40: steaming
41s: steaming
42: dry

21 AUG 1987(BLM)
4: dry
6: water level 2.92ft. below vent rim
8: water level 0.13ft. below rim, steady discharge
8nw: dry
10: water level 28in. below rim, boiling
11: dry
12: dry
12sw: dry
16: dry
23n: dry
24,24n,24ne: dry
39: dry
40: dry
41s: dry
42: dry

NOTE: Beginning at approximately this time period, hot spring observations by the Nevada Division of Environmental Protection (NDEP), Donald Hudson (DH) and the Geyser Observation and Study Association (GOSA) occur infrequently. Furthermore, Bureau of Land Management (BLM) observations continue to be on a more or less weekly basis, focusing on springs 4, 6, 8, 8nw, 10, 11, 12, 12sw, 16, 23n, 24 (and 24n, 24ne), 39, 40, 41s and 42. From this period onward, the condition of only those springs which are observed by the BLM to be active (i.e. not dry) will be described. Observations by NDEP, DH and GOSA will continue as above.

28 AUG 1987 (BLM)
6: water level 2.92ft. below rim
8: water level 0.33ft. below rim, no outflow from crack in vent cone
10: water level 30in. below rim, boiling

29 AUG 1987: discharging of well Steamboat No. 1 (21-5) ends

31 AUG 1987 (NDEP)
2: dry
3: dry
4: dry
6: audible water at depth
7: dry
8: depth to water-0.25ft., flowing from crack?
8nw: dry
10: audible water at depth
12: dry
13: dry
16: dry
23n: dry
24: dry
42: audible water at depth
43: dry

4 SEPT 1987 (BLM)
6: water level 3.00ft. below rim
8: water level 0.13ft. below rim, good outflow from crack
10: water level 31in. below rim, boiling

11 SEPT 1987 (BLM)
6: water level 2.92ft. below rim
8: water level 0.04ft. below rim, outflow from crack
10: water level 27in. below rim, boiling

18 SEPT 1987 (BLM)
6: water level 2.83ft. below rim
8: water level 0.04ft. below rim, outflow from crack
10: dry

24 SEPT 1987 (BLM)
6: water level 2.75ft. below rim
8: water level 0.08ft. below rim, outflow from crack
10: dry

27 SEPT 1987 (DH)
4: dry
6: water level 2.50ft. (est.) below rim
8: flowing
8nw: dry
10: dry
11: dry
12: dry
13: dry
13w: dry
14: dry?
15: dry
15w: dry
16: dry
23: dry
23n: dry
24: dry
24sw: dry
42: dry

2 OCT 1987 (BLM,NDEP)
2: dry
3: dry
4: dry
6: depth to water-2.50ft.(NDEP), 2.75ft.(BLM)
7: dry
8: depth to water-0.10ft.(NDEP), 0.08ft.(BLM); flowing from crack
8nw: dry
10: audible water at depth
12: dry
13: dry
16: dry
23n: dry
24: dry
42: dry
43: dry

15 OCT 1987 (BLM)
6: water level 2.67ft. below rim
8: water level 0.08-0.17ft. below rim, slight increase in flow from crack
10: dry
42: steaming

18 OCT 1987 (DH)
4: dry
6: water level ≈3ft. (est.) below rim
8: slight flow
8nw: dry
10: dry
11: dry
12: dry
13: dry
13w: dry
14: dry
15: dry
15w: dry
16: dry
23: dry
23n: dry
24: dry
42: dry

23 OCT 1987 (BLM)
6: water level 2.42ft. below rim
8: water level 0.08ft. below rim, flowing from crack
10: water level 30in. below rim
42: water level 4.00ft. (est.) below rim

24 OCT 1987: discharging of well 83A-6 begins; no injection

30 OCT 1987: discharging of well 83A-6 ends

30 OCT 1987 (BLM)
6: water level 2.54ft. below rim
8: water level 0.58ft. below rim, no flow
10: dry
42: dry

6 NOV 1987 (BLM,NDEP)
2: dry
3: dry
4: dry
6: depth to water-3.00ft.(NDEP), 2.88ft.(BLM)
7: dry
8: depth to water-0.10ft.(NDEP), 0.08ft.(BLM); flowing from crack
8nw: dry
10: water visible 19in. below rim before dropping out of sight(NDEP), dry(BLM)
12: audible water at depth
13: dry
16: dry

23n: dry
24: dry
42: dry
43: dry

13 NOV 1987 (BLM)
6: water level 2.92ft. below rim
8: water level 0.06ft. below rim, discharging

24 NOV 1987 (BLM)
6: water level 2.92ft. below rim
8: water level 0.06ft. below rim, discharging

2 DEC 1987 (BLM)
6: water level 2.75ft. below rim
8: water level 0.08ft. below rim, discharging
10: water splashing onto rocks 22in. below rim at top of eruptive cycle
42: audible water at depth

8 DEC 1987 (NDEP)
2: dry
3: dry
4: dry
6: depth to water-2.42ft.
7: dry
8: depth to water-0.08ft., flowing from crack
8nw: dry
10: dry
12: audible water at depth
13: dry
16: dry
23n: dry
24: dry
42: audible water at depth
43: dry

11 DEC 1987 (BLM)
6: water level 2.67ft. below rim
8: water level 0.08ft. below rim, discharging
10: dry
42: audible water at depth

18 DEC 1987 (BLM)
6: water level 2.67ft. below rim
8: water level 0.10ft. below rim, discharging
42: audible water at depth

23 DEC 1987 (BLM)
6: water level 2.67ft. below rim
8: water level 0.10ft. below rim, discharging
42: dry

31 DEC 1987 (BLM)
6: water level 2.67ft. below rim
8: water level 0.08ft. below rim, discharging

8 JAN 1988 (BLM)
6: water level 2.25ft. below rim
8: water level 0.06ft. below rim, discharging

12 JAN 1988 (NDEP)
2: dry
3: dry
4: dry
6: depth to water-2.00ft.
7: dry
8: depth to water-0.06ft.
8nw: dry
10: boiling water visible 1ft. from surface
12: audible water at depth
13: dry
16: dry
23n: dry
24: dry
42: audible water at depth
43: dry

14 JAN 1988: discharging of well 23-5 begins: injection into well Cox I-1

15 JAN 1988 (BLM)
6: water level 1.92ft. below rim
8: water level 0.06ft. below rim, discharging
10: dry

17 JAN 1988 (DH)
4: dry
6: water level about 2.50ft. (est.) below rim
8: flowing
11: audible water at depth
remark: all other springs dry

22 JAN 1988 (BLM)
6: water level 2.08ft. below rim
8: water level 0.10ft. below rim, flowing

28 JAN 1988: discharging of well 83A-6 begins; injection into well Cox I-1; discharging of well 23-5 ends?

29 JAN 1988 (BLM)
6: water level 1.83ft. below rim
8: water level 0.10ft. below rim, flowing
42: audible water at depth

31 JAN 1988: discharging of well 83A-6 ends

5 FEB 1988 (BLM)
6: water level 2.17ft. below rim
8: water level 0.17ft. below rim, flowing
10: audible water at depth
42: audible water at depth

11 FEB 1988: discharging of wells 21-5, 23-5 and 83A-6 begins; injection into well Cox I-1

12 FEB 1988 (BLM,NDEP)
2: dry
3: dry
4: dry
6: depth to water-2.08ft.(NDEP), 2.17ft.(BLM)
7: dry
8: depth to water-0.17ft.(NDEP), 0.17ft.(BLM); discharging
8nw: dry
10: audible water at depth(NDEP), dry(BLM)
12: dry
13: dry
16: dry
23n: dry
24: dry
42: audible water at depth
43: dry

19 FEB 1988 (BLM)
6: water level 2.42ft. below rim
8: water level 0.58ft. below rim, no discharge from crack

21 FEB 1988 (DH)
4: dry
6: water level ≈3ft. (est.) down
8: water level about 1in. (est.) below crack in vent cone [which is 1-2in. below rim]
10: dry
39: steaming
40: steaming
41s: steaming

42: steaming
remark: all other springs dry

24 FEB 1988 (BLM)
6: water level 2.58ft. below rim
8: water level 0.92ft. below rim

4 MAR 1988 (BLM)
6: water level 2.92ft. from rim
8: dry

11 MAR 1988 (BLM)
6: water level 3.00ft. below rim

15 MAR 1988 (NDEP)
2: dry
3: dry
4: dry
6: depth to water-3.00ft.
7: dry
8: dry
8nw: dry
10: audible water at depth
12: dry
13: dry
16: dry
23n: dry
24: dry
42: audible water at depth
43: dry

18 MAR 1988 (BLM)
6: water level 3.33ft. below rim

20 MAR 1988 (DH)
6: audible water at depth
8: dry
10: dry
remark: all springs dry

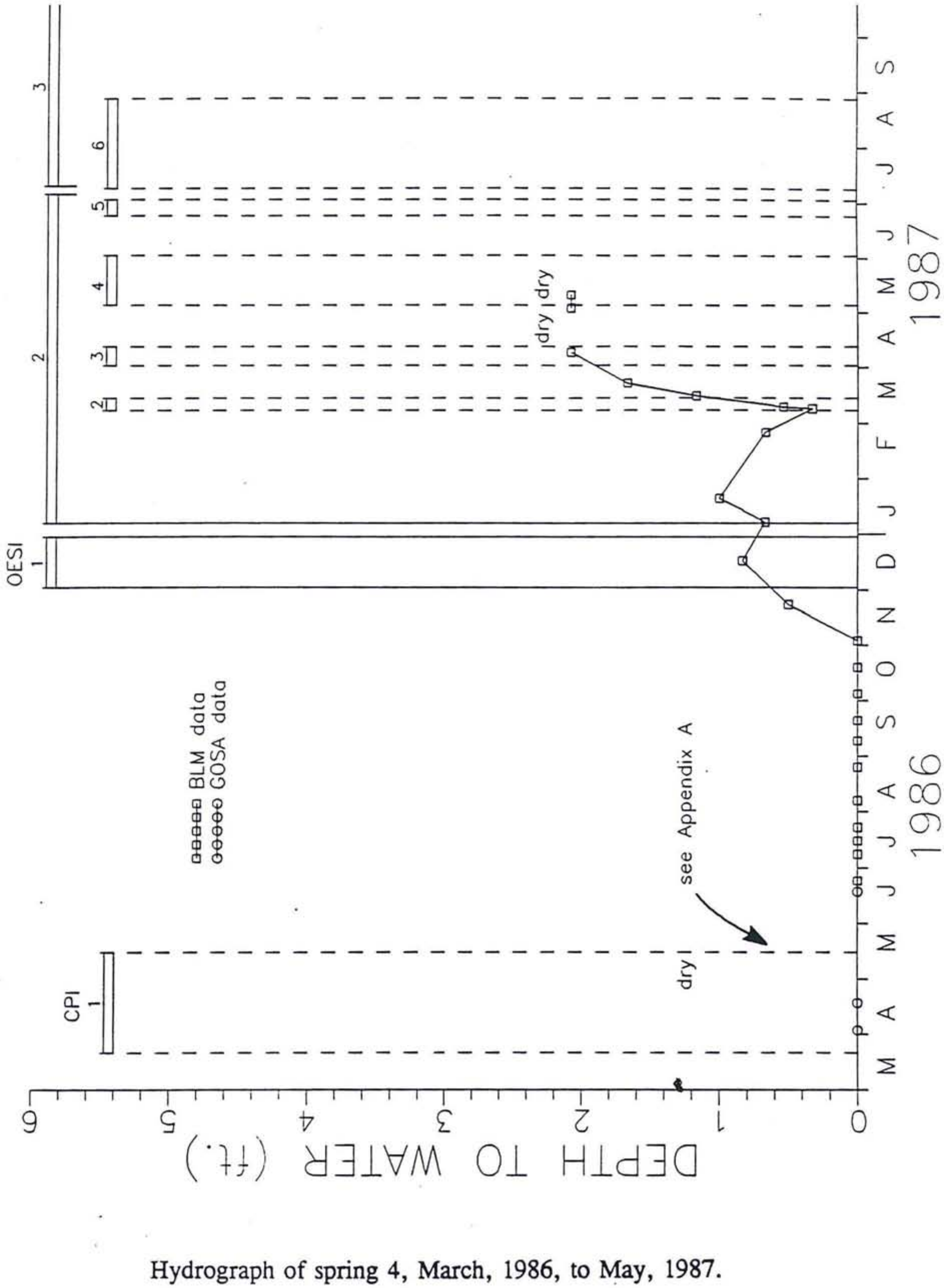
25 MAR 1988 (BLM)
6: water level 3.50ft. below rim

1 APR 1988 (BLM)
6: water level 3.58ft. below rim

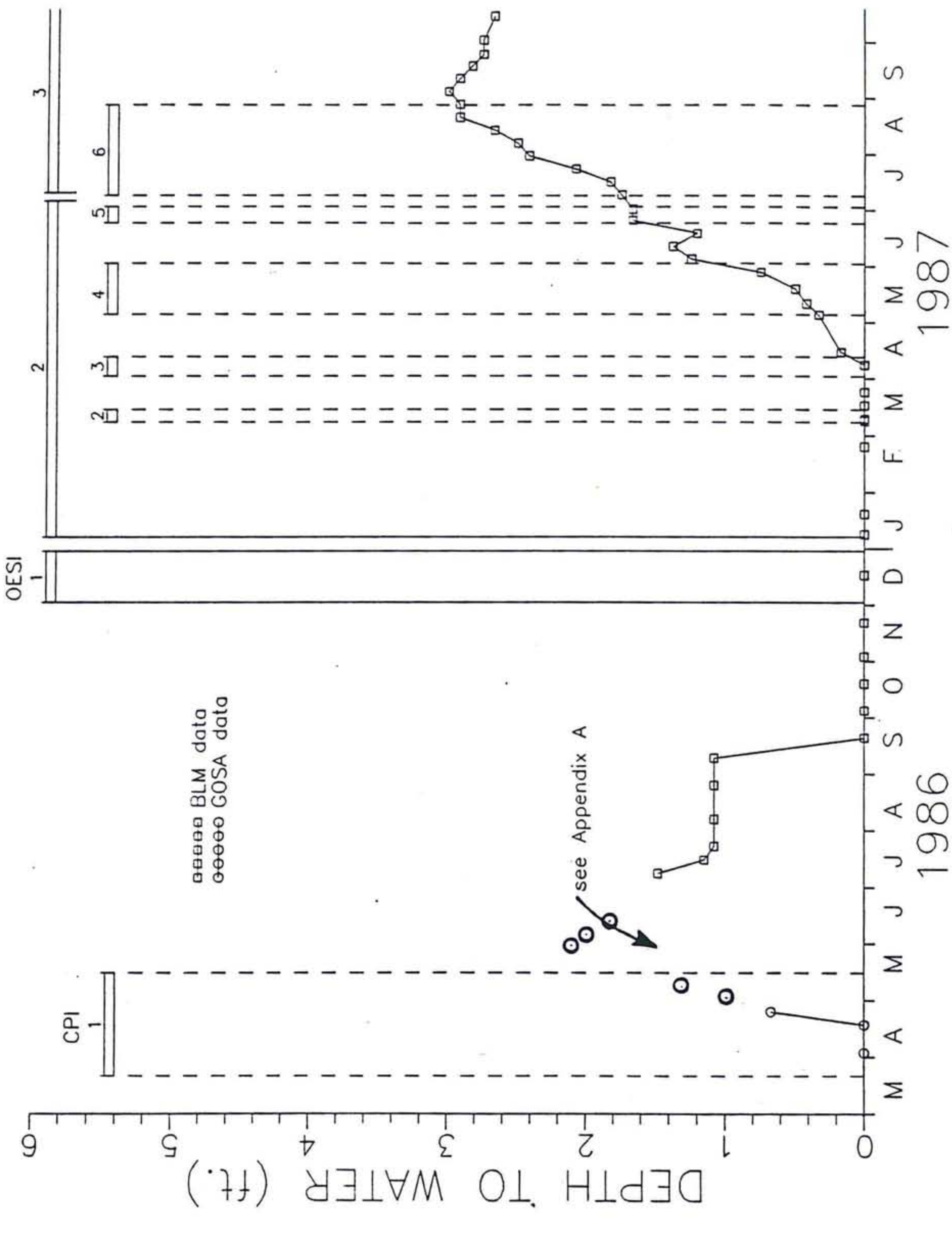
7 APR 1988 (BLM)
6: audible water at depth

22 APR 1988 (BLM)
6: dry

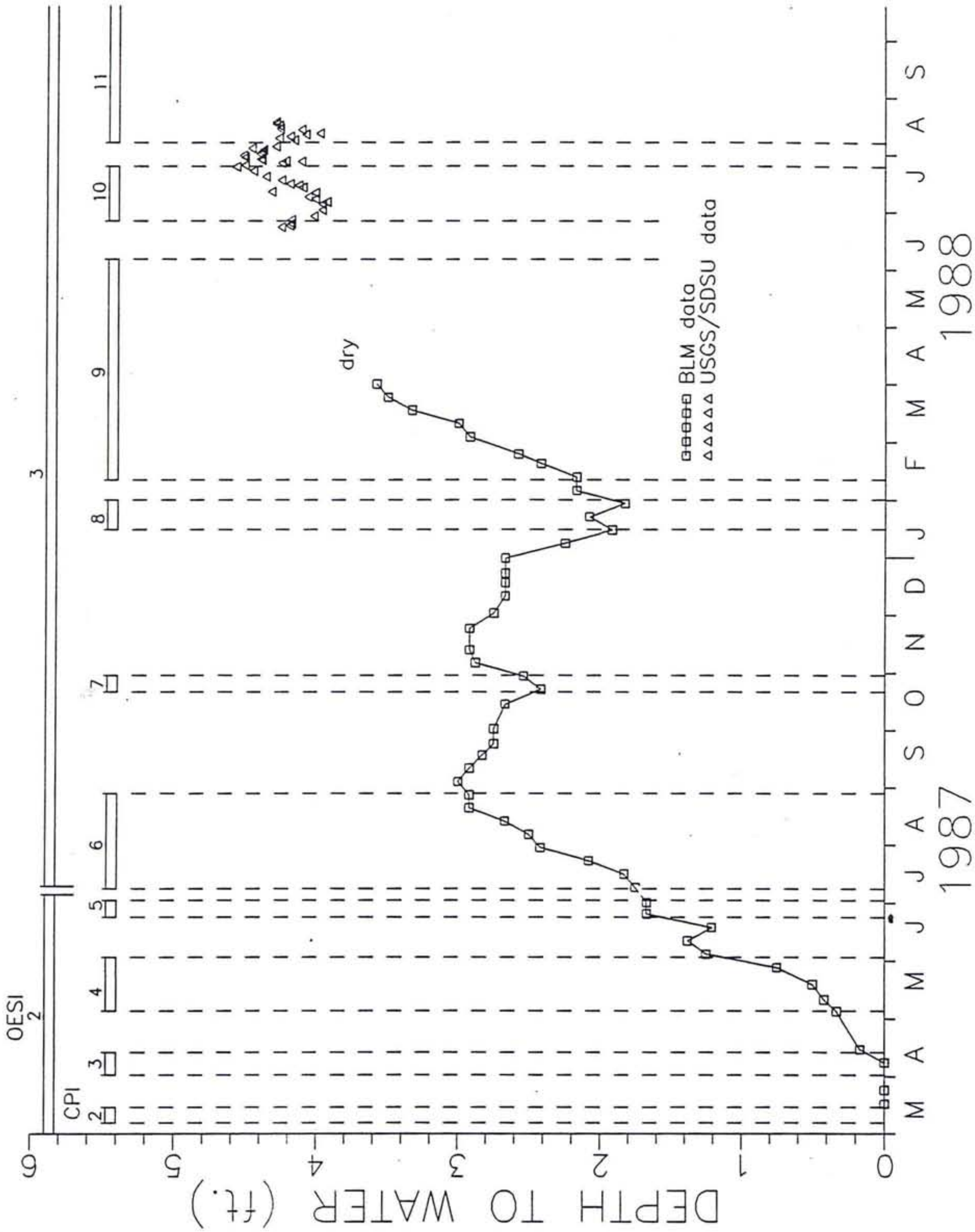
NOTE: From this time period until 20 June 1988 weekly to bi-weekly hot spring observations by BLM personnel indicate that all the hot springs are dry. On 20 June 1988, San Diego State University personnel began collecting water level measurements in several hot spring vents utilizing either a graduated rule or an electric-line water level probe. Additional dates of geothermal production and injection are contained in the accompanying text.



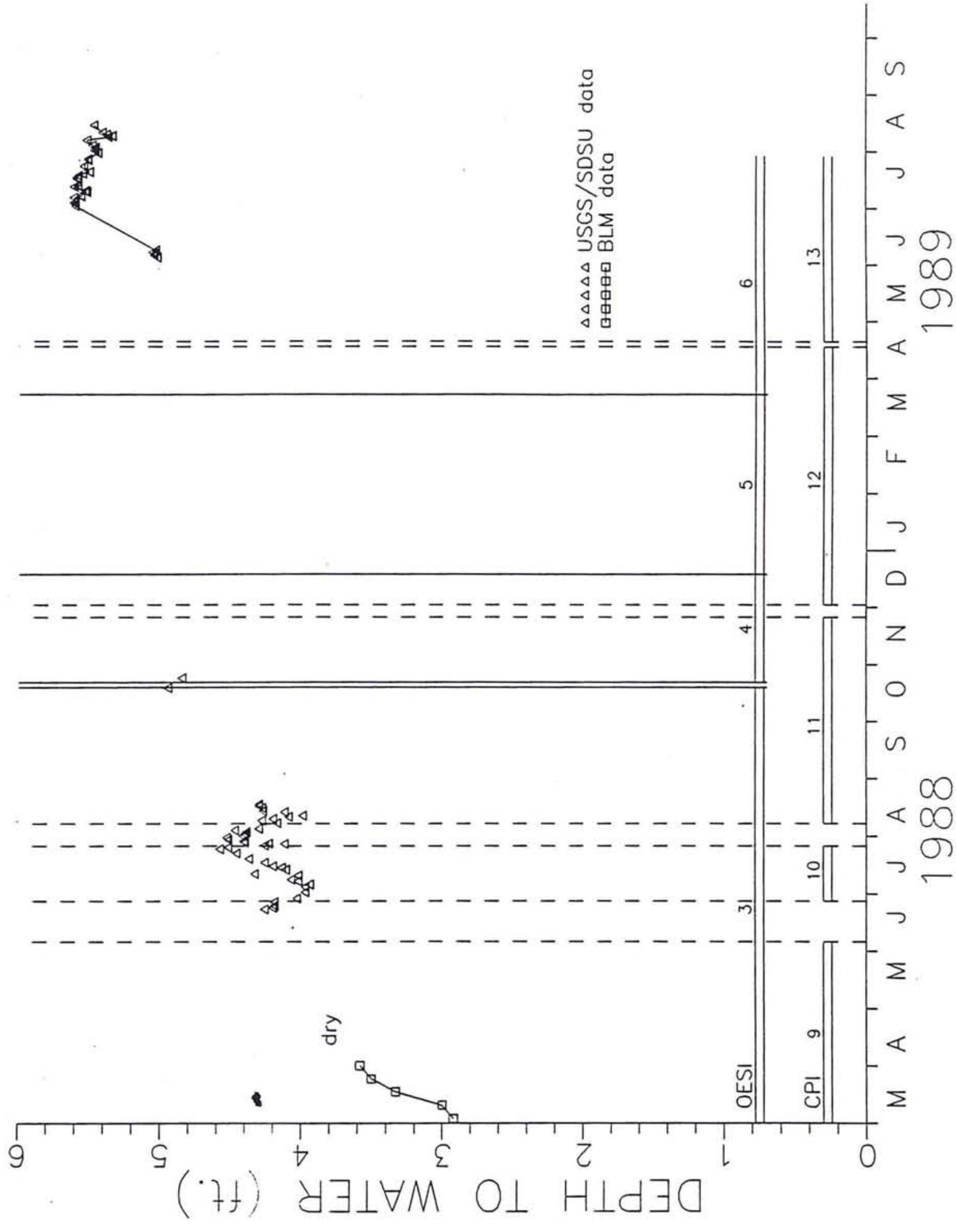
Hydrograph of spring 4, March, 1986, to May, 1987.



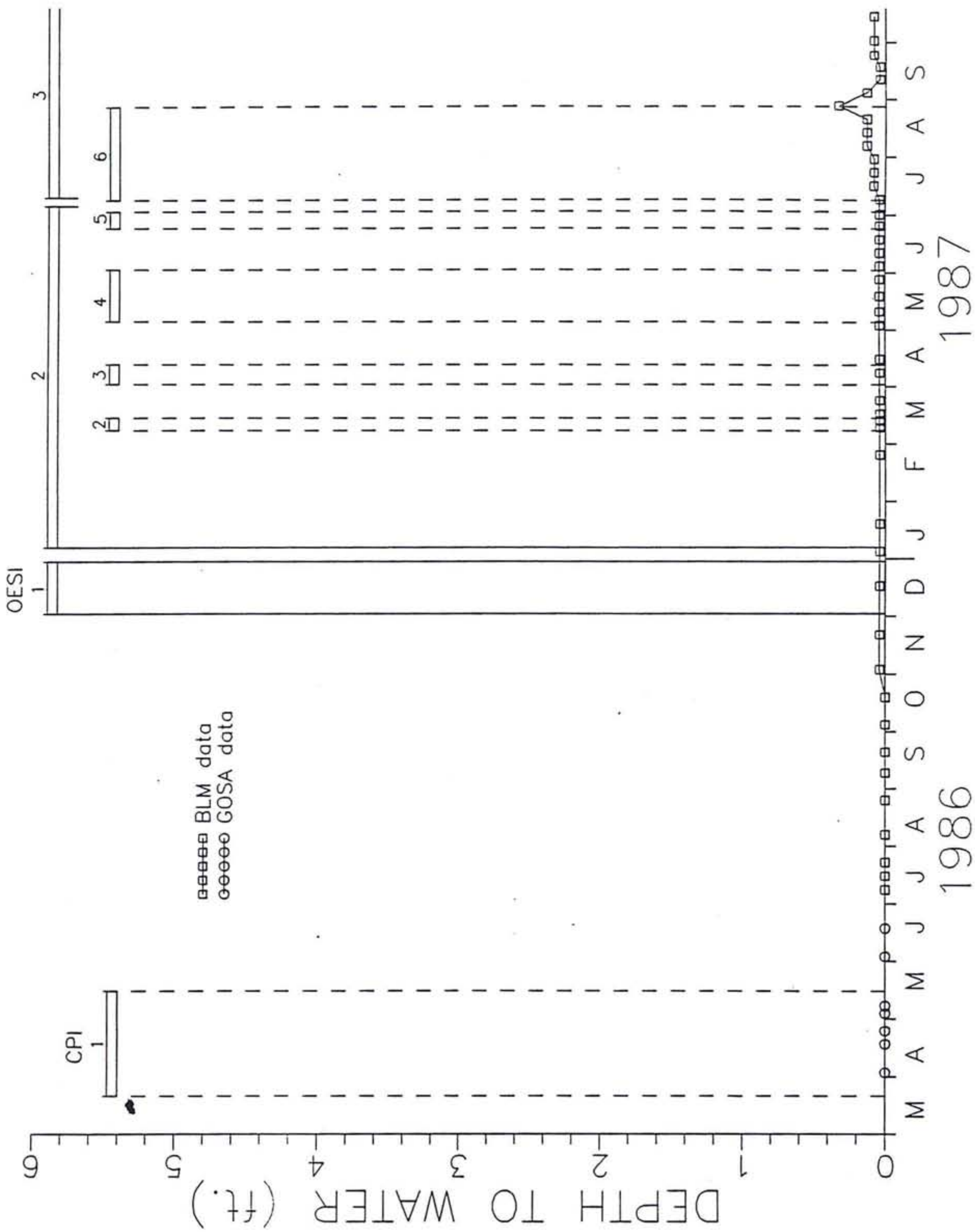
Hydrograph of spring 6, March, 1986, to August, 1989.



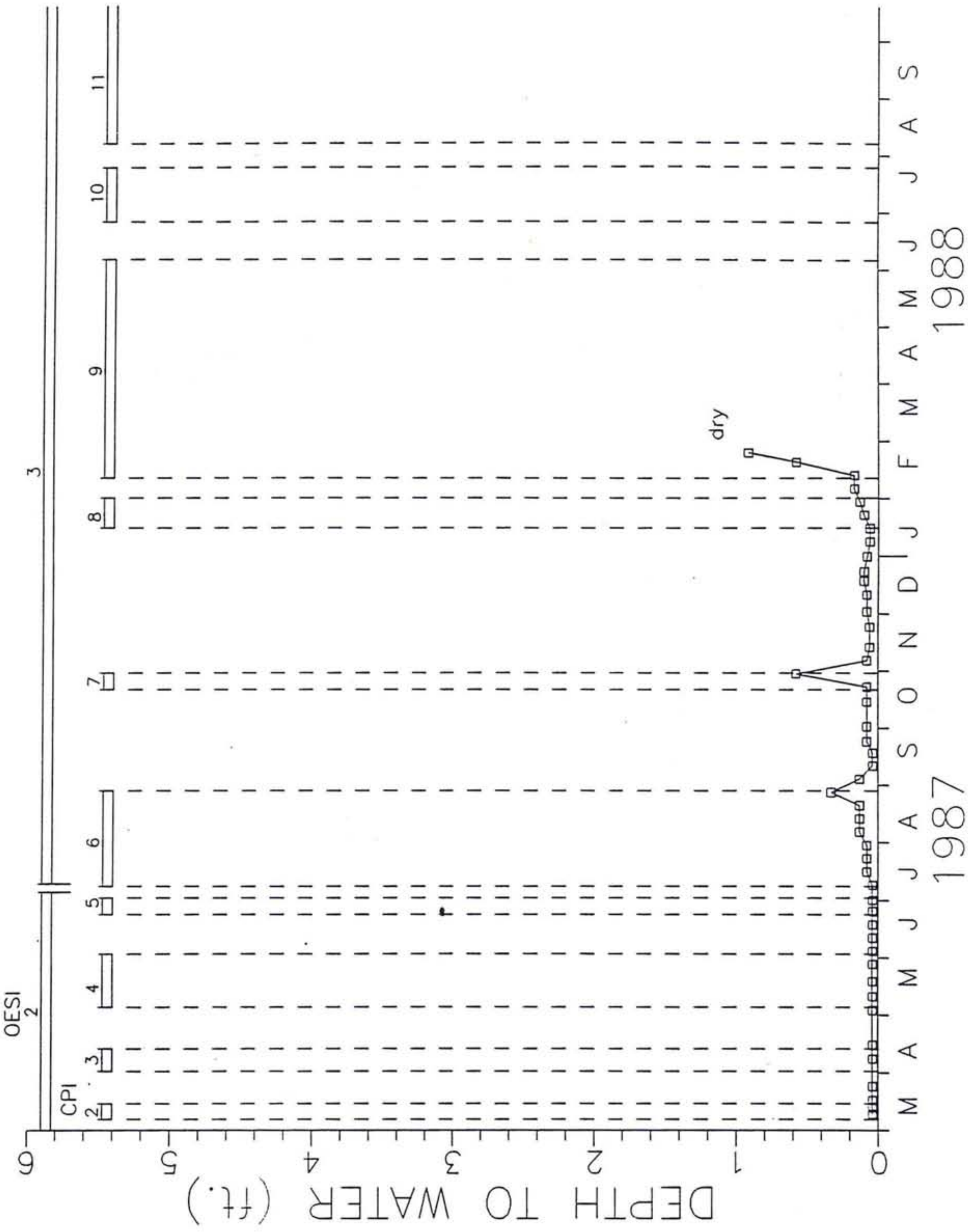
(cont'd) Hydrograph of spring 6, March, 1986, to August, 1989.



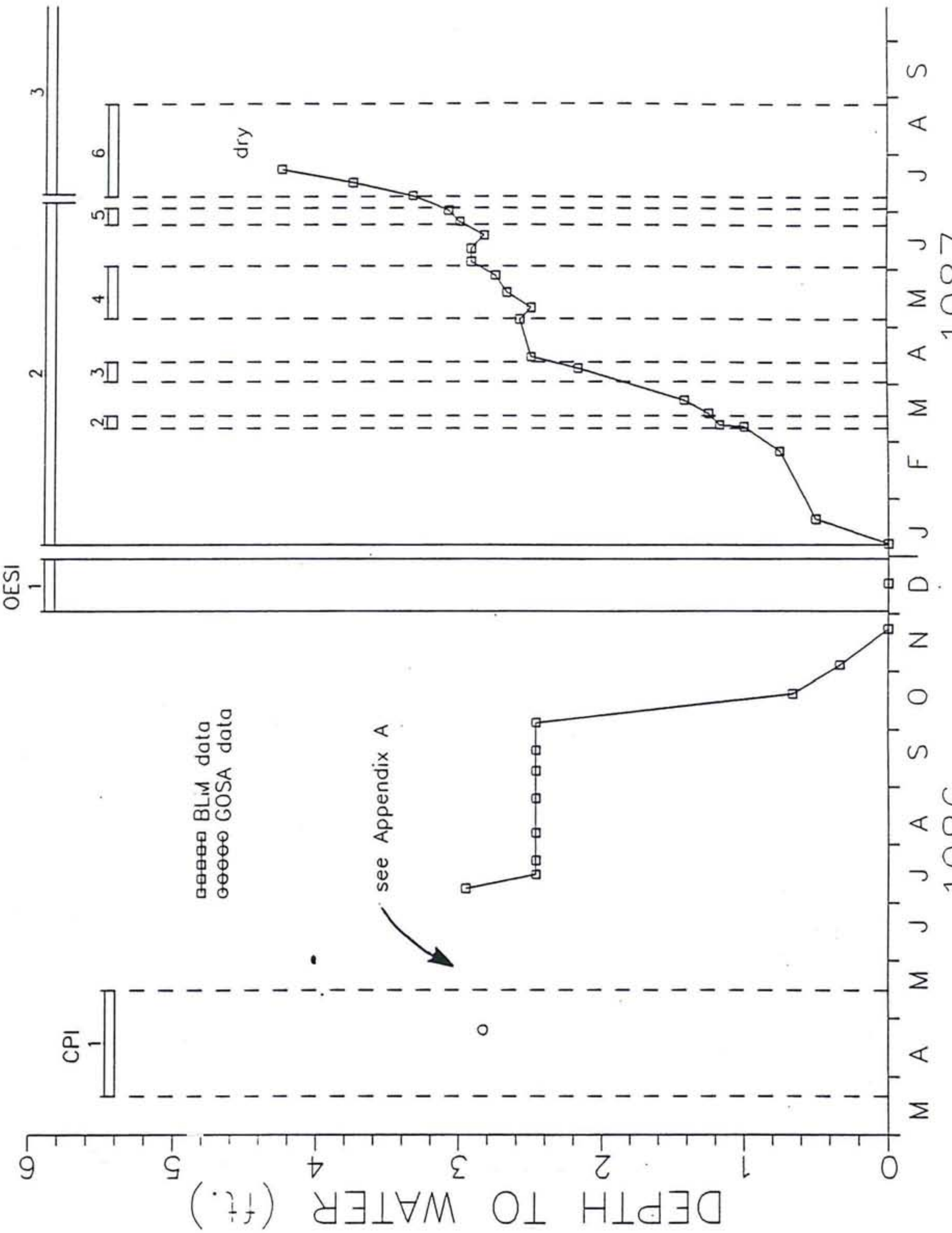
(cont'd) Hydrograph of spring 6, March, 1986, to August, 1989.



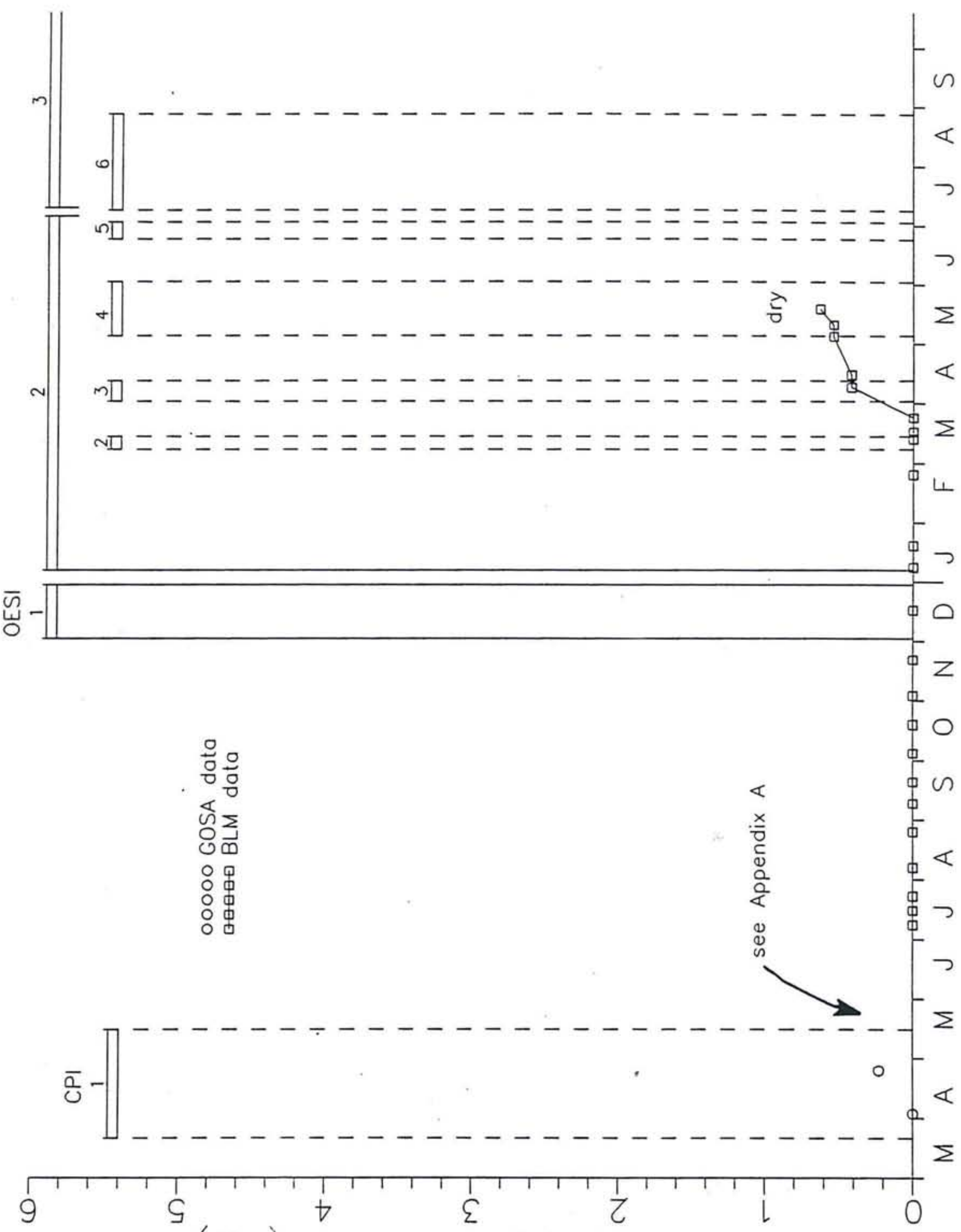
Hydrograph of spring 8, March, 1986, to February, 1988.



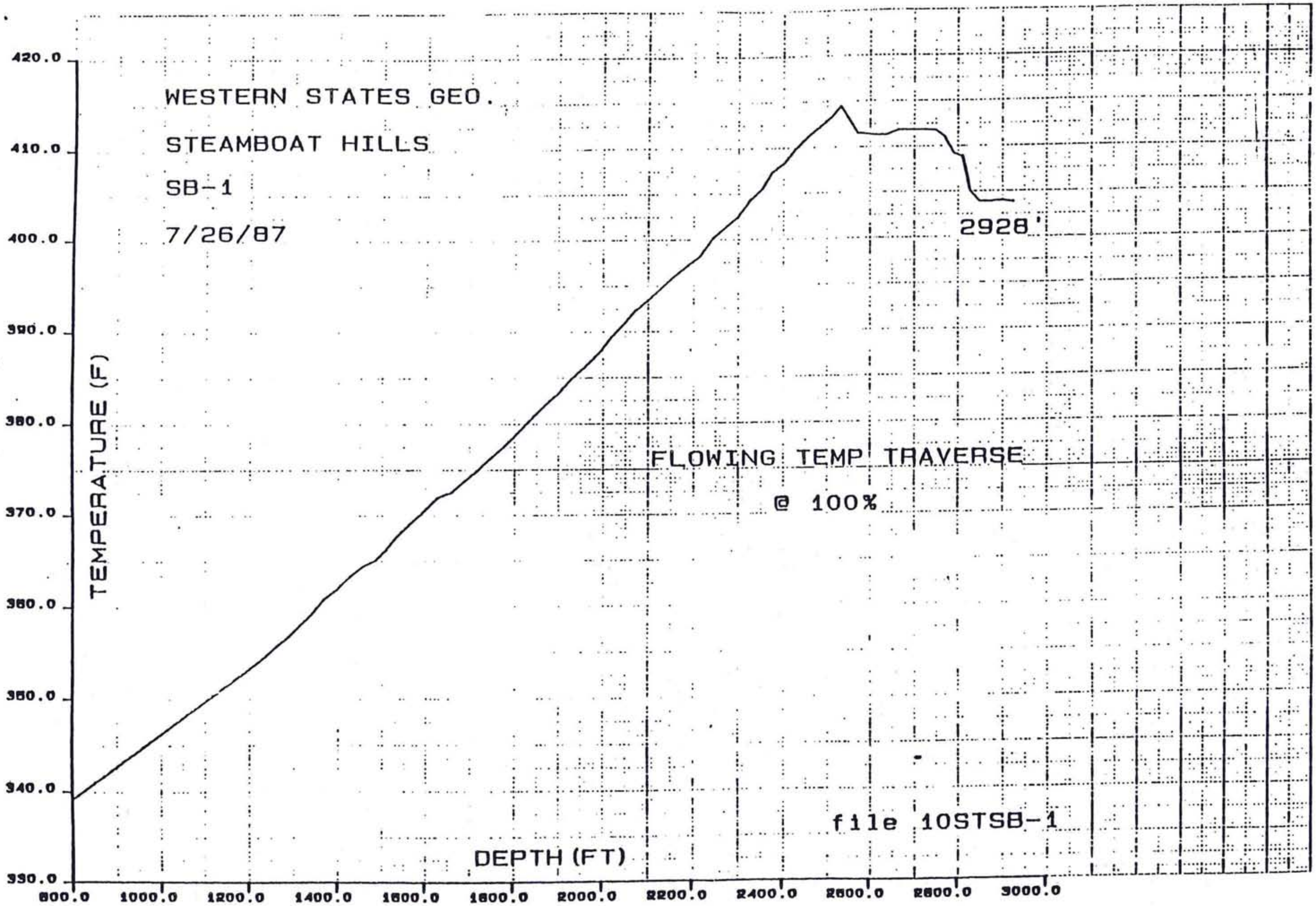
(cont'd) Hydrograph of spring 8, March, 1986, to February, 1988.



Hydrograph of spring 8nw, March, 1986, to July, 1987.



Hydrograph of spring 11, March, 1986, to May, 1987.


WESTERN STATES GEO.
STEAMBOAT HILLS
SB-1
7/26/87
2928'
FLOWING TEMP TRAVERSE
@ 100%
TEMPERATURE (F)
DEPTH (FT)
file 10STSB-1
420.0
410.0
400.0
390.0
380.0
370.0
360.0
350.0
340.0
330.0
800.0
1000.0
1200.0
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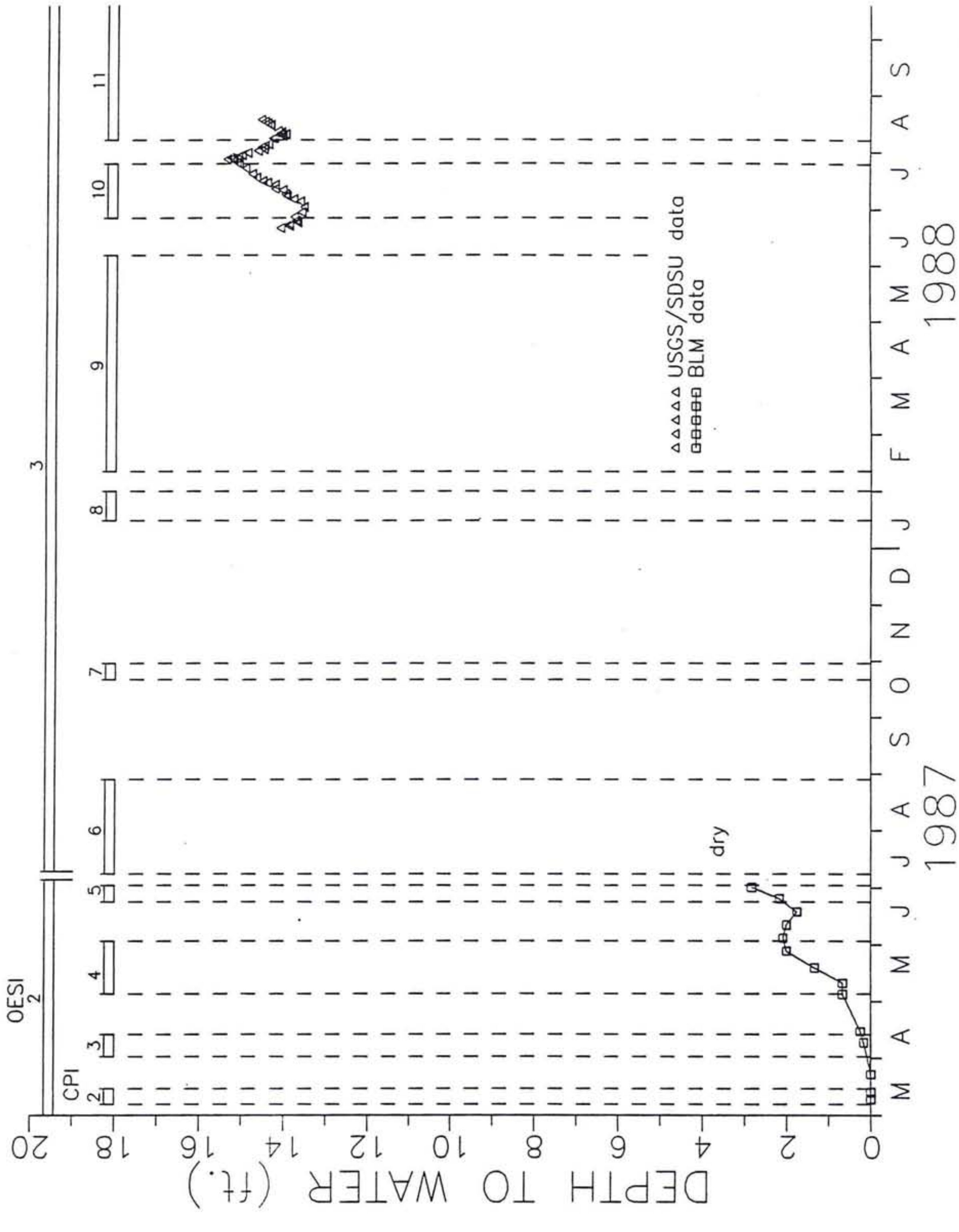
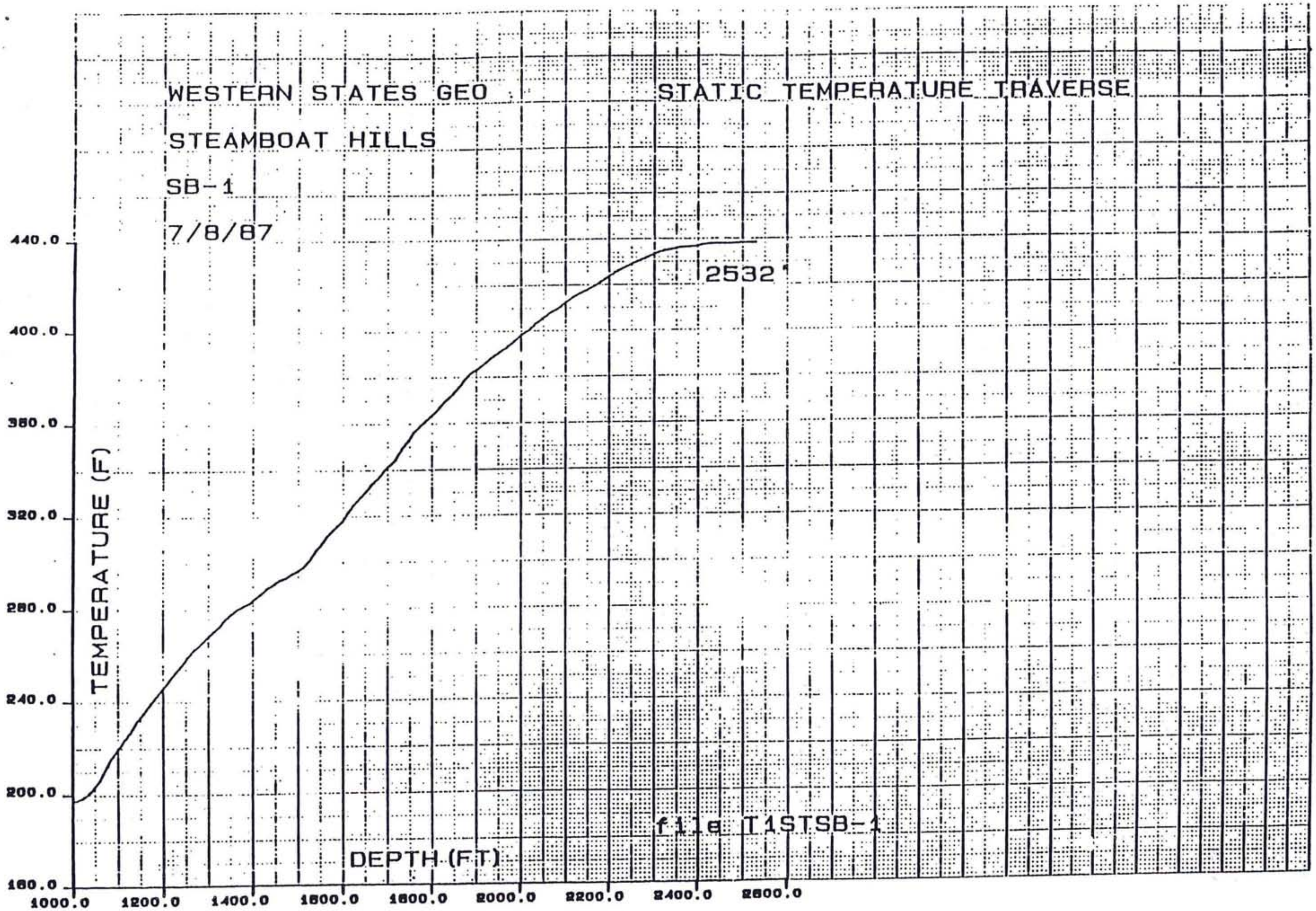
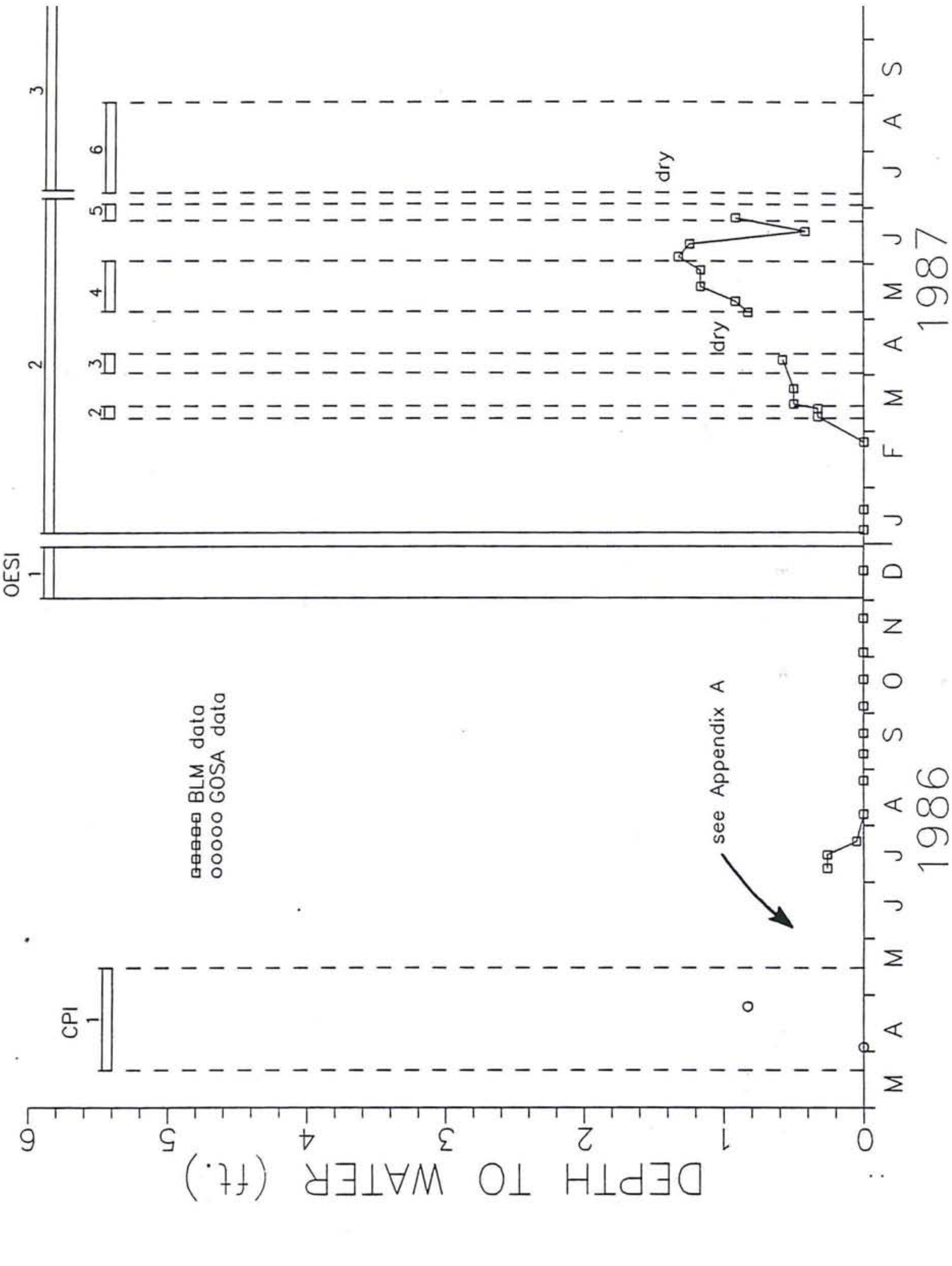
2600.0
2800.0
3000.0

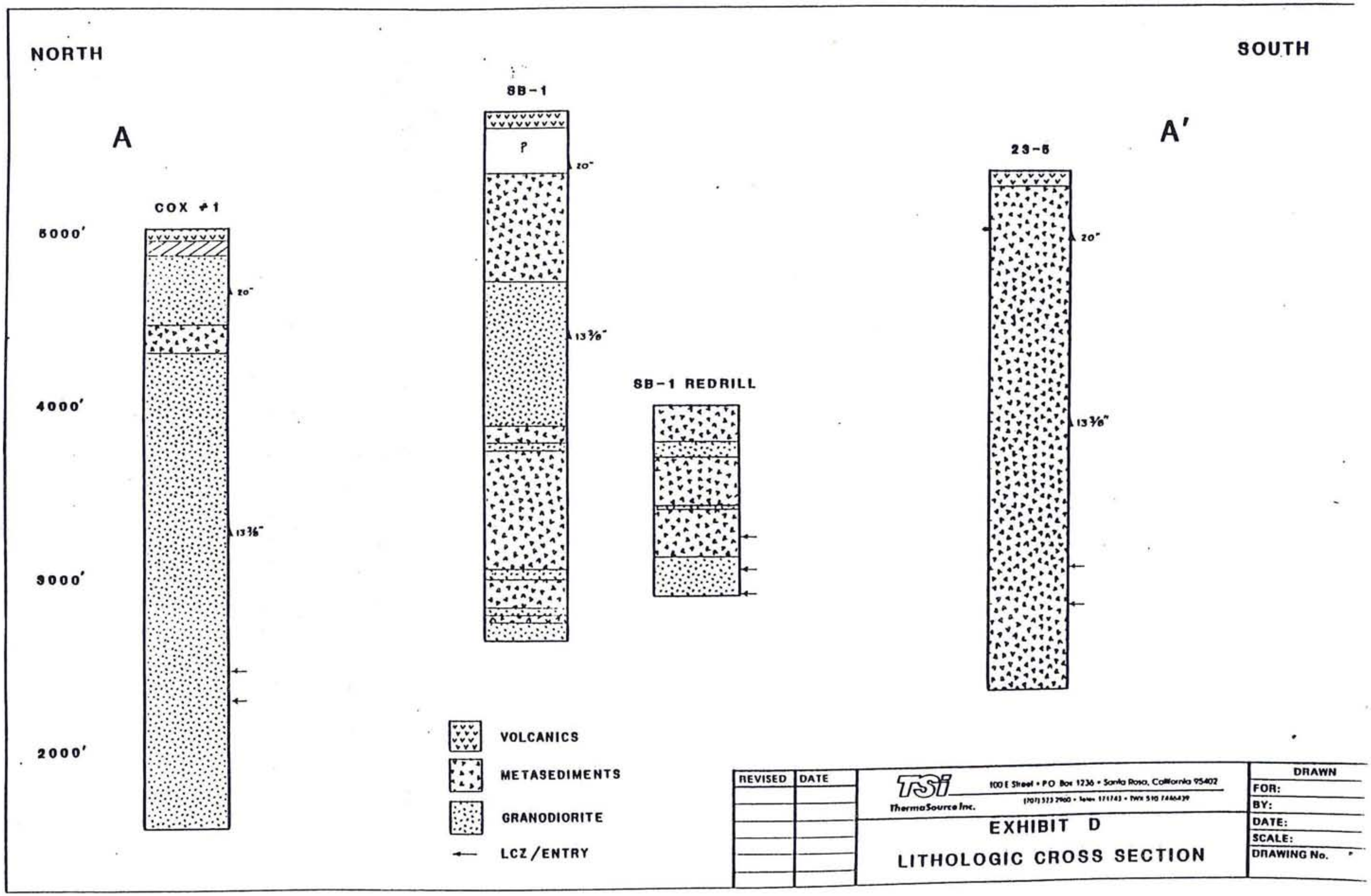


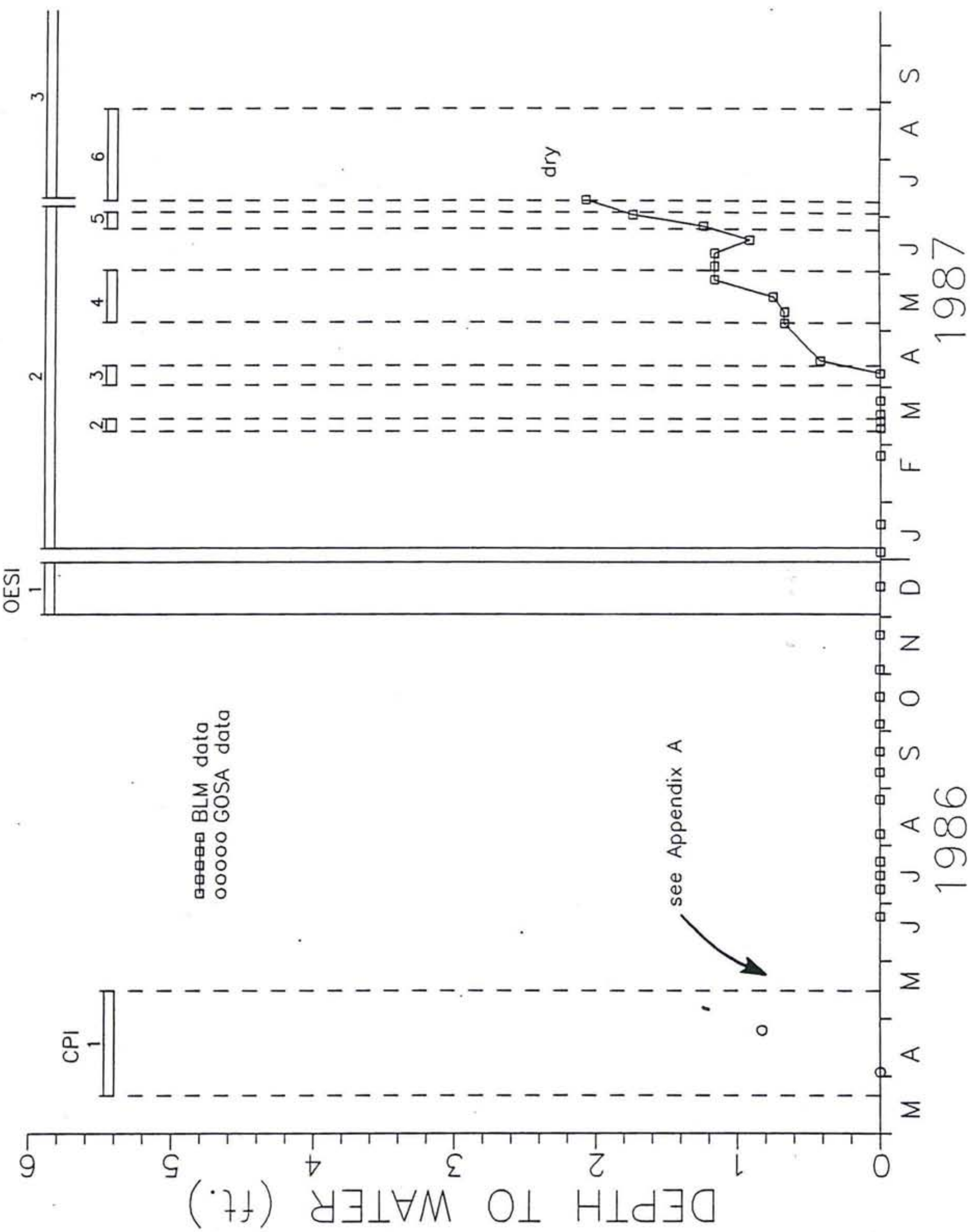
(cont'd) Hydrograph of spring 12, March, 1986, to August, 1989.


WESTERN STATES GEO
STATIC TEMPERATURE TRAVERSE
STEAMBOAT HILLS
SB-1
7/8/87
2532'
TEMPERATURE (F)
440.0
400.0
360.0
320.0
280.0
240.0
200.0
160.0
file T1STSB-1
DEPTH (FT)
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0
2600.0

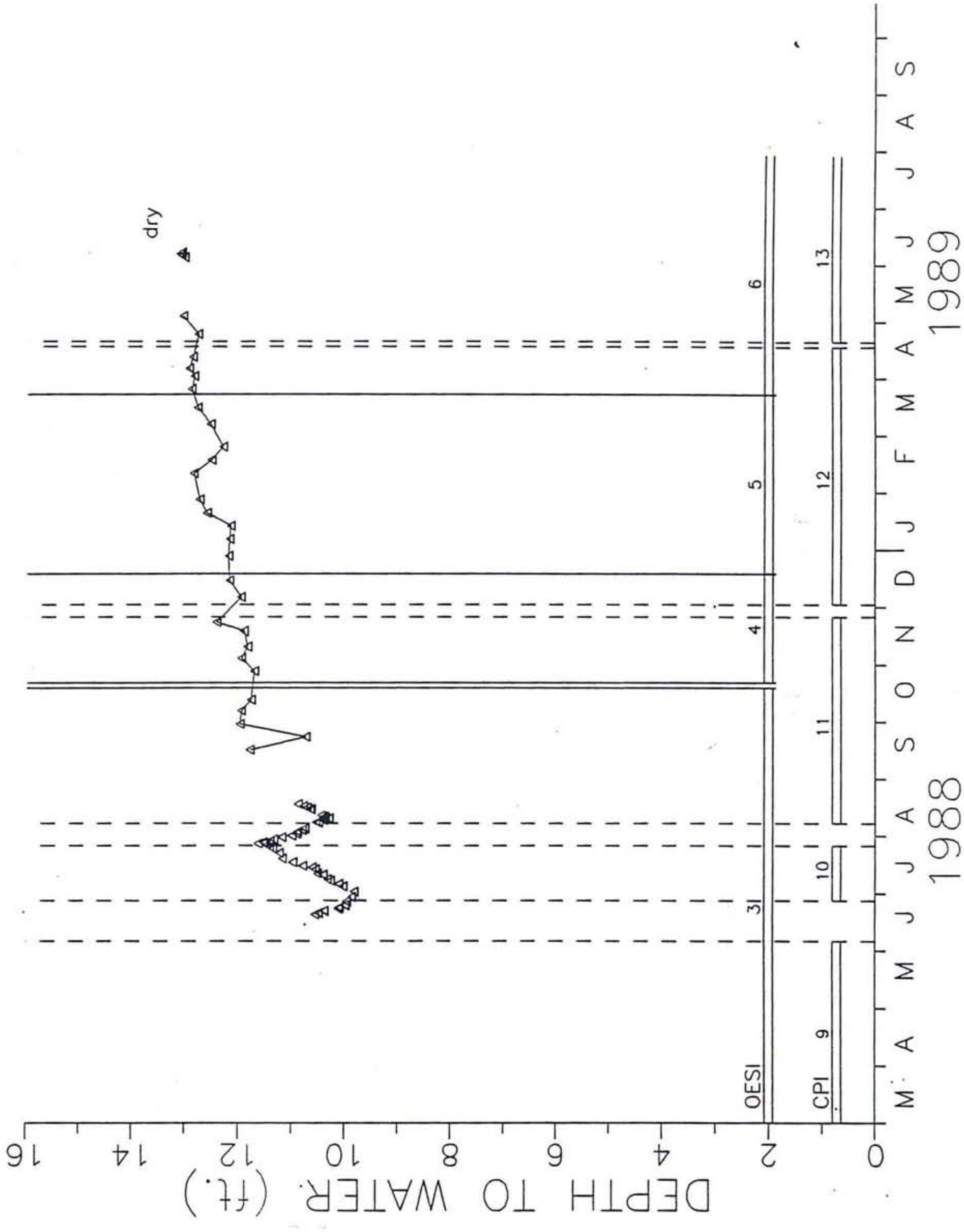


Hydrograph of spring 12sw, March, 1986, to June, 1987.

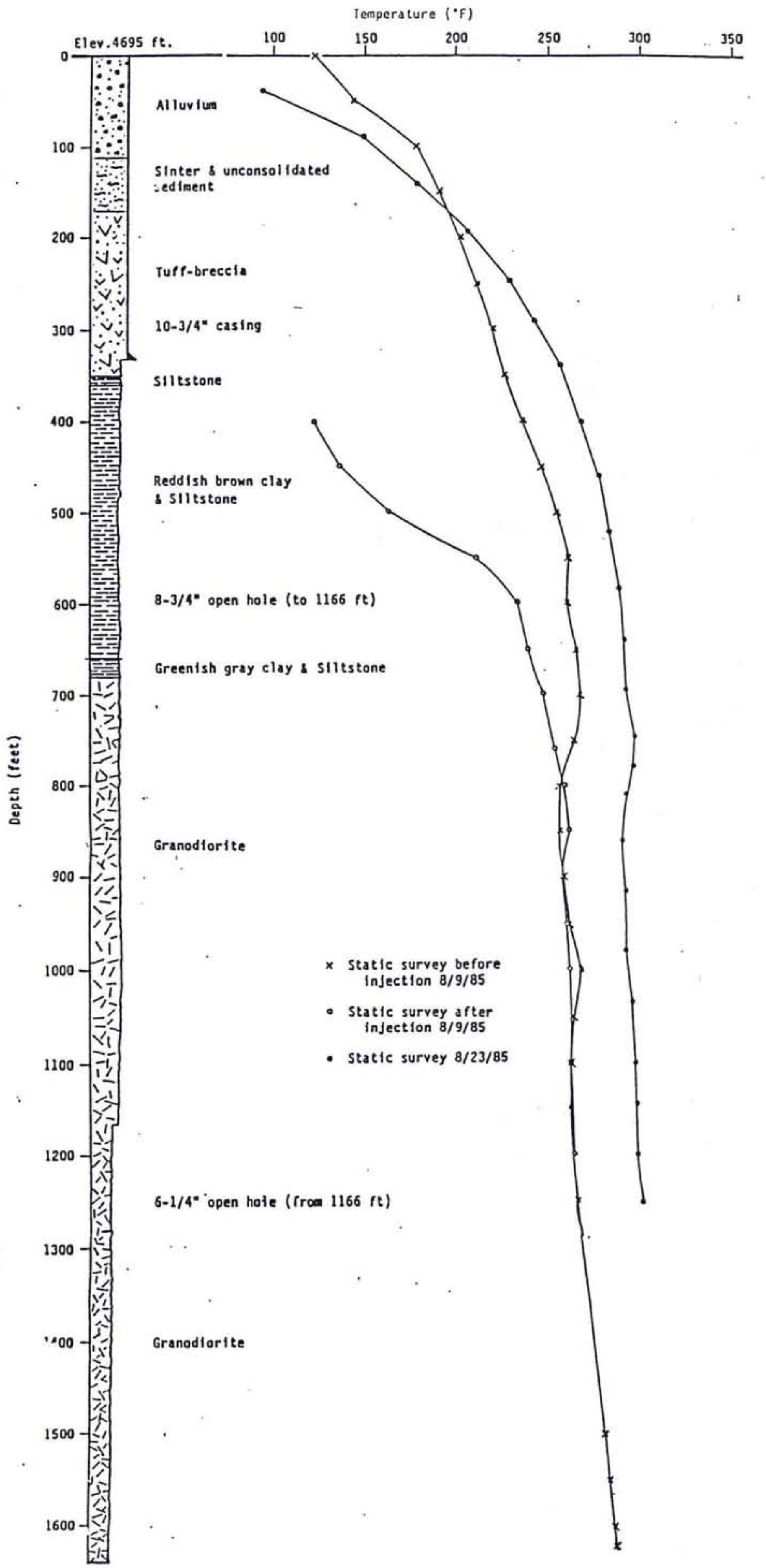

NORTH
SOUTH
A
A′
COX #1
SB-1
SB-1 REDRILL
23-5
5000′
4000′
3000′
2000′
20"
13 3/8"
?
VOLCANICS
METASEDIMENTS
GRANODIORITE
LCZ/ENTRY
REVISED
DATE
TSi ThermaSource Inc.
100 E Street • P.O. Box 1236 • Santa Rosa, California 95402
EXHIBIT D
LITHOLOGIC CROSS SECTION
DRAWN
FOR:
BY:
DATE:
SCALE:
DRAWING No.



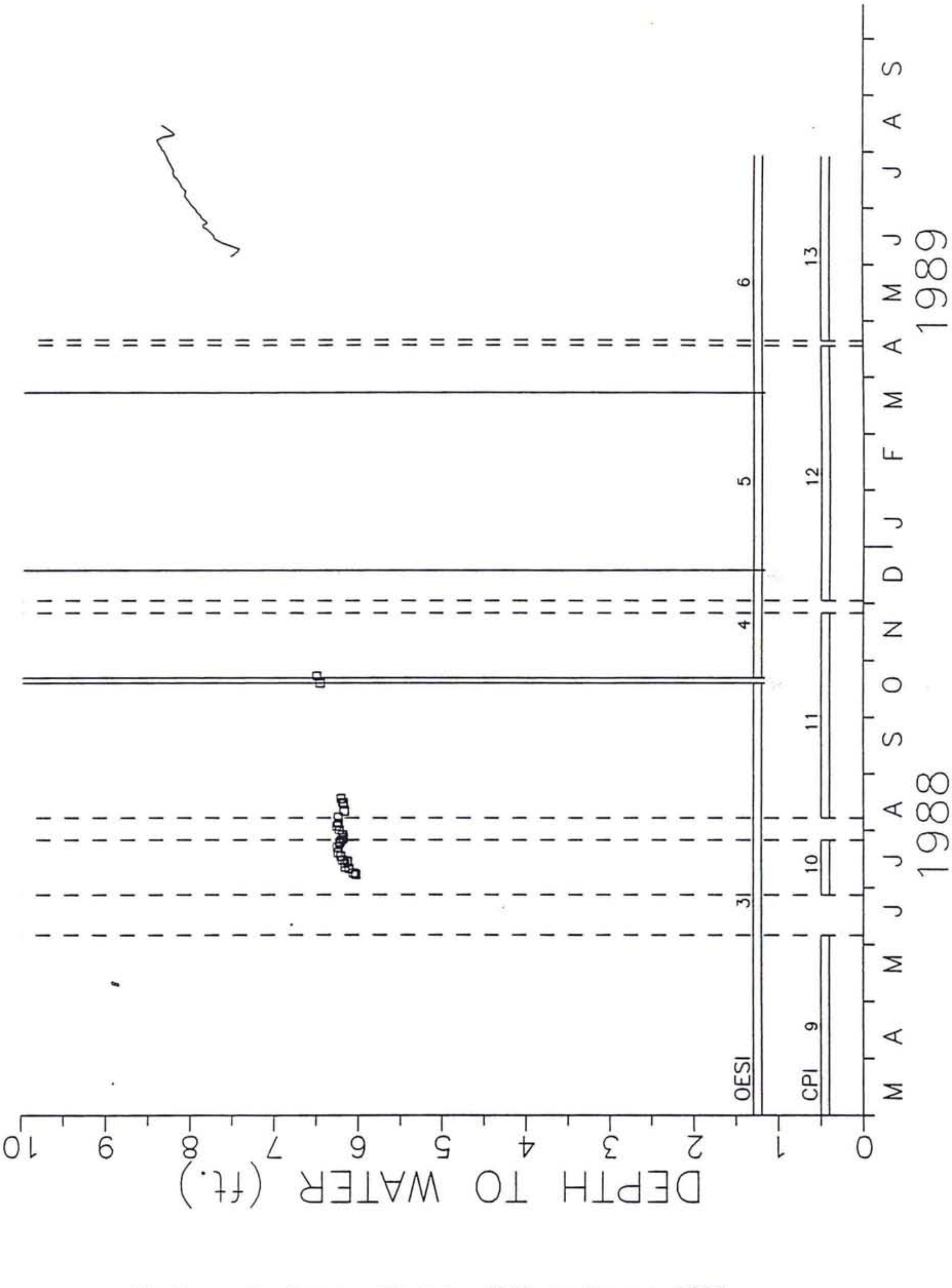
Hydrograph of spring 42, March, 1986, to July, 1987.



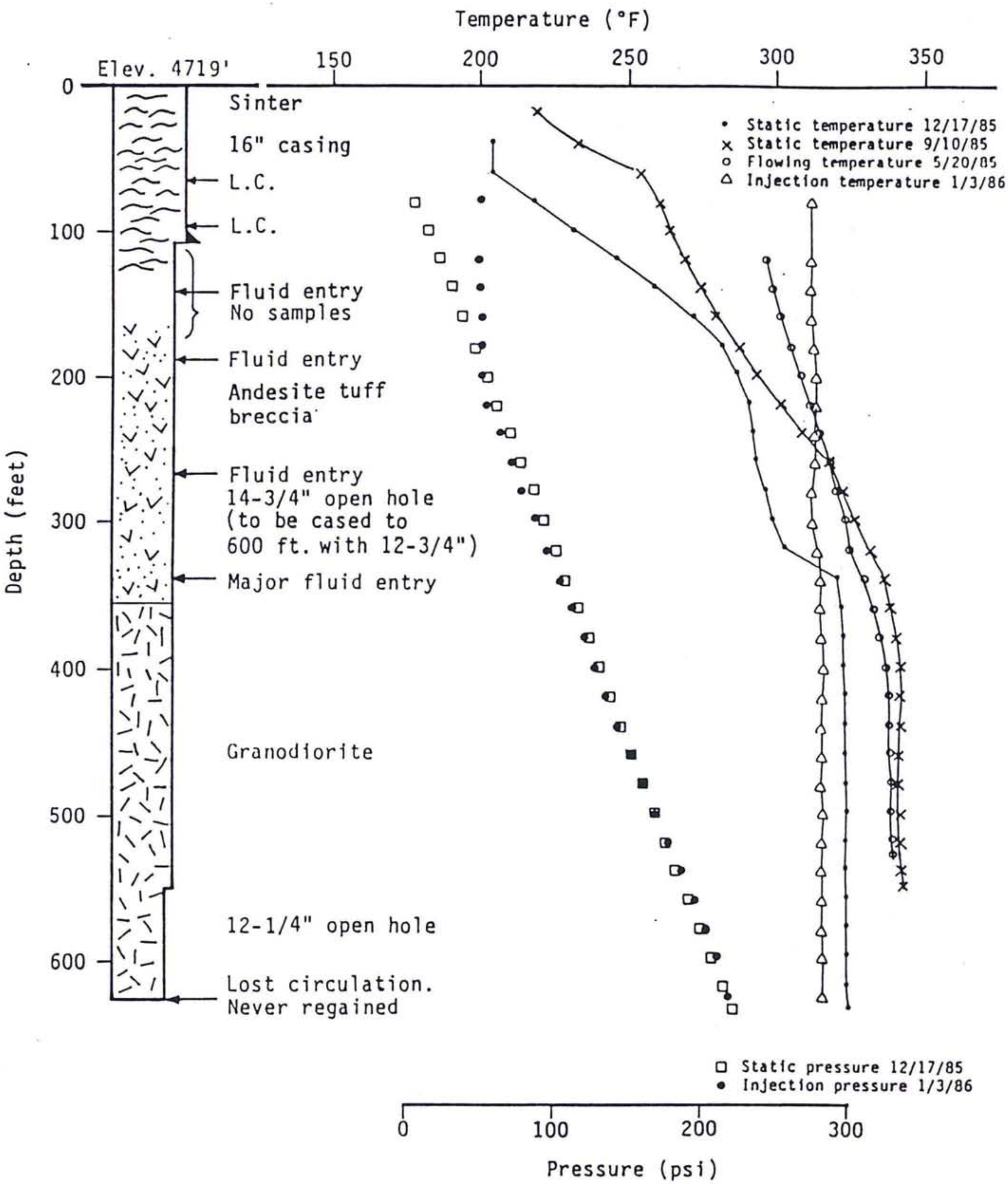
(cont'd) Hydrograph of spring 42w, July, 1987, to June, 1989.



Completion diagram, lithology and temperature profiles, well IW-1



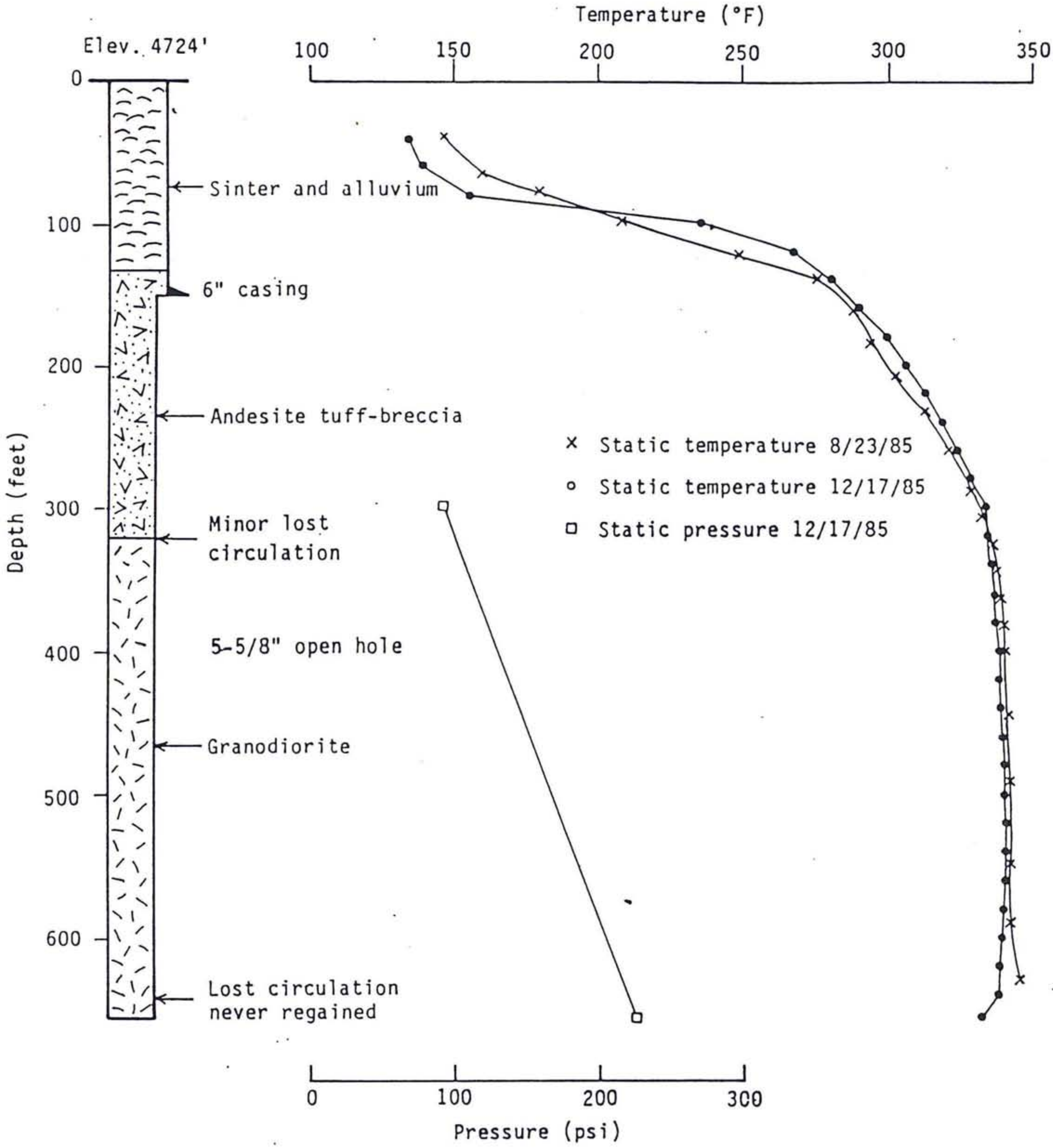
Hydrograph of spring 62, July, 1988, to August, 1989.



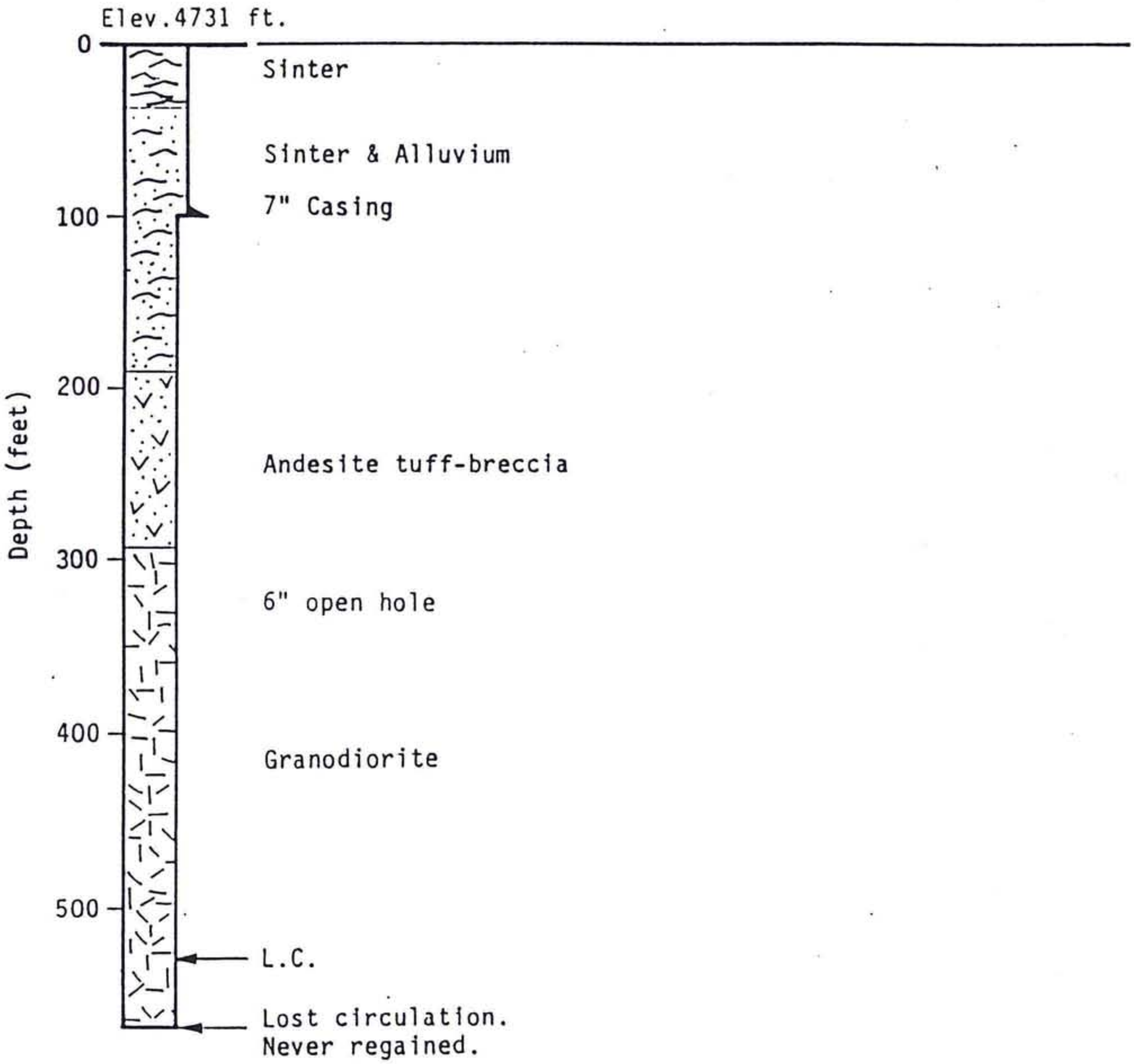
Completion diagram, lithology and temperature/pressure profiles, well PW-1

APPENDIX B. SB GEO WELL-FIELD DATA

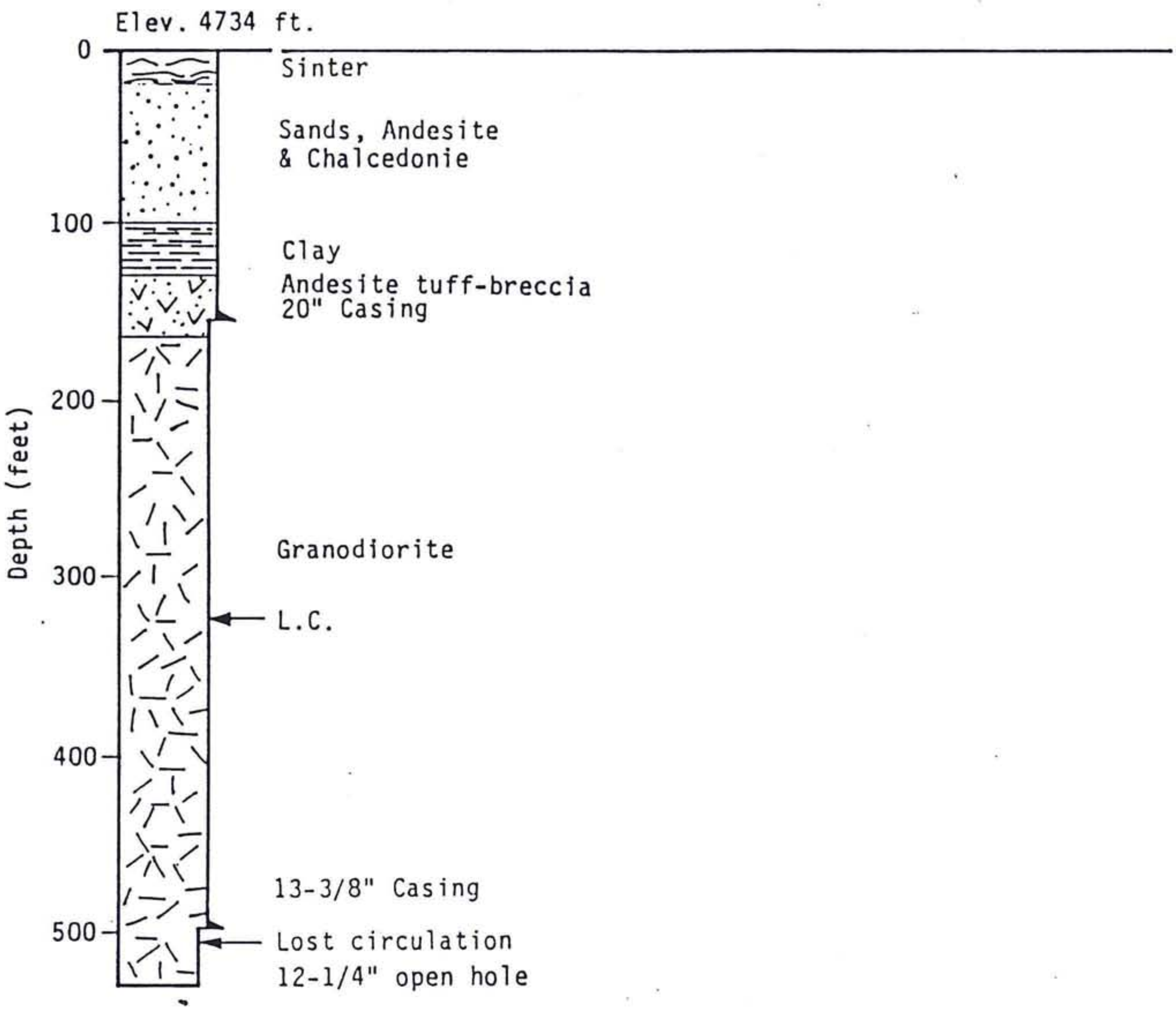
This appendix contains copies of data for the SB GEO well field. The material was obtained from the files of the Nevada Division of Environmental Protection (Reno office) and the Bureau of Land Management (Carson City and Reno offices), and from an unpublished report by GeothermEx (1986).



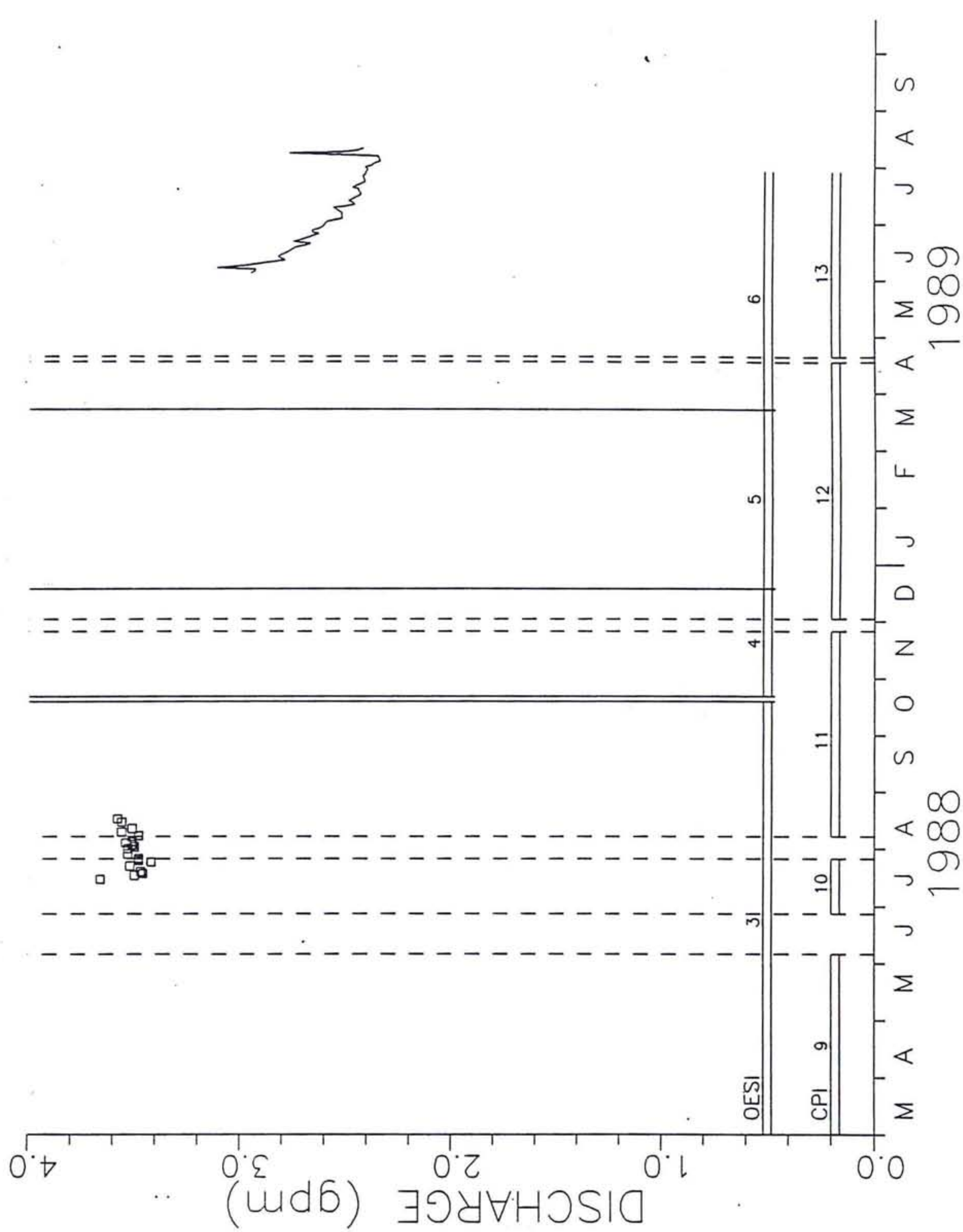
Completion diagram, lithology and temperature/pressure profiles, well OW-1



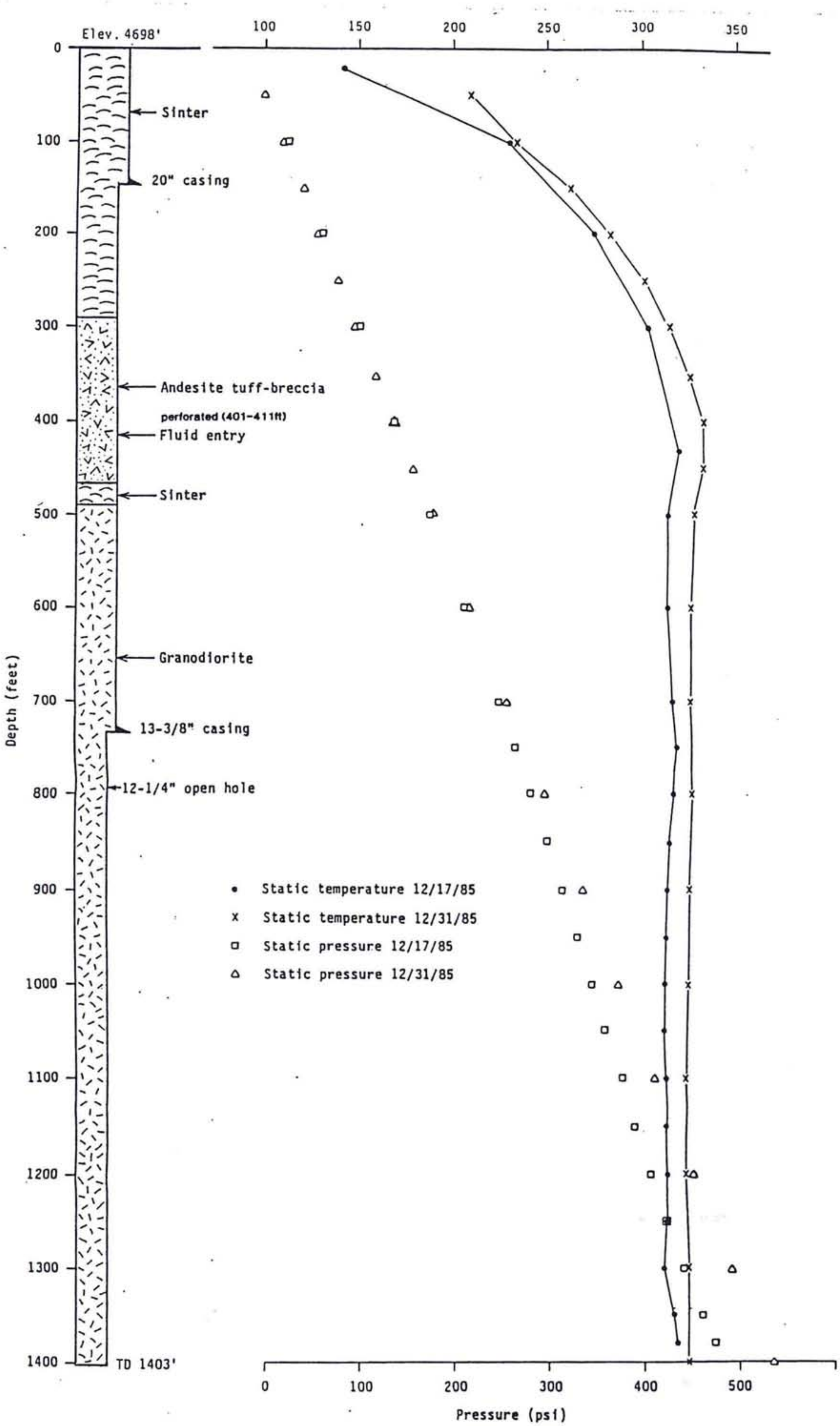
Completion diagram and lithology, well OW-2



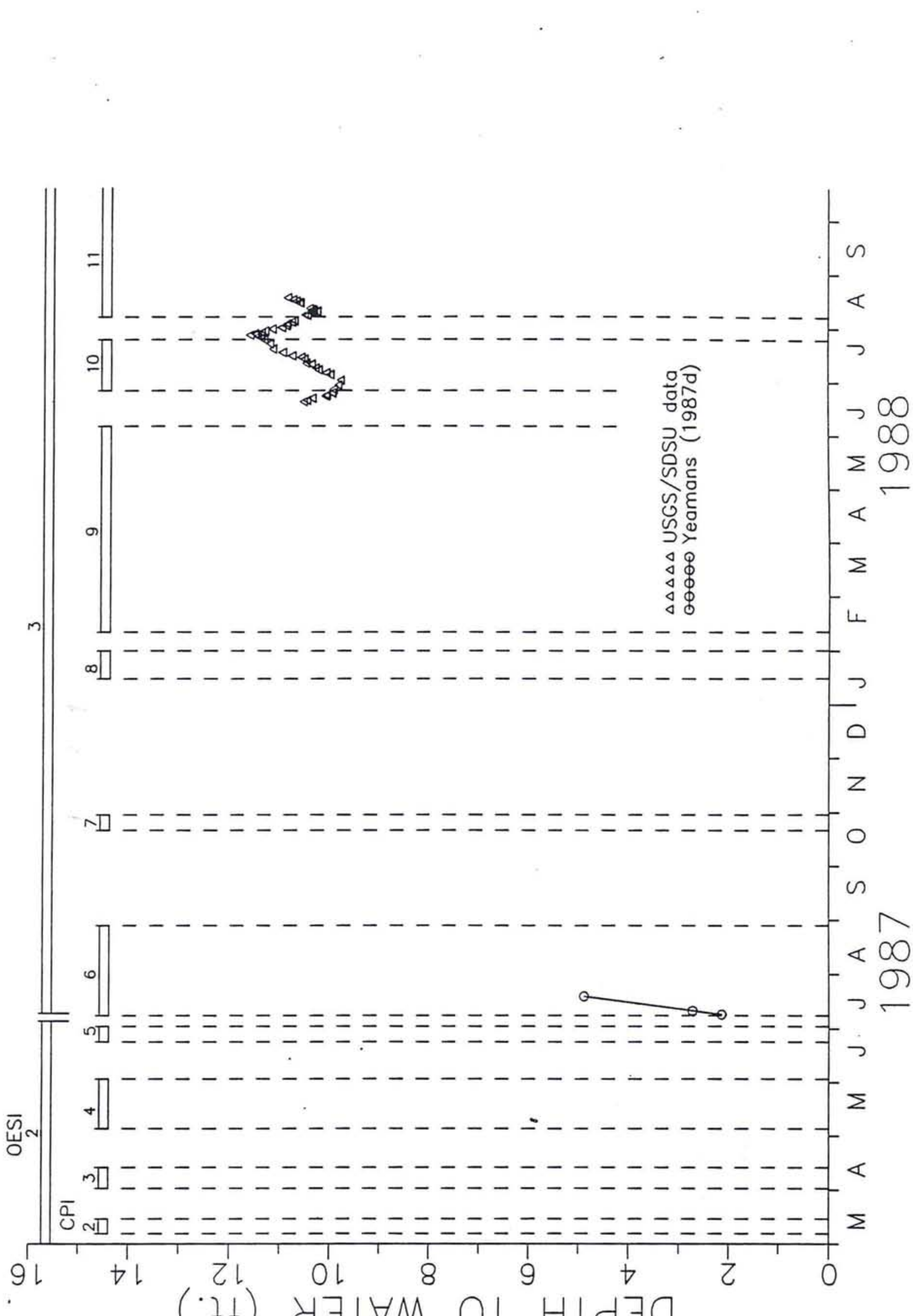
Completion diagram and lithology, well PW-2



Hydrograph of spring 50, July, 1988, to August, 1989.



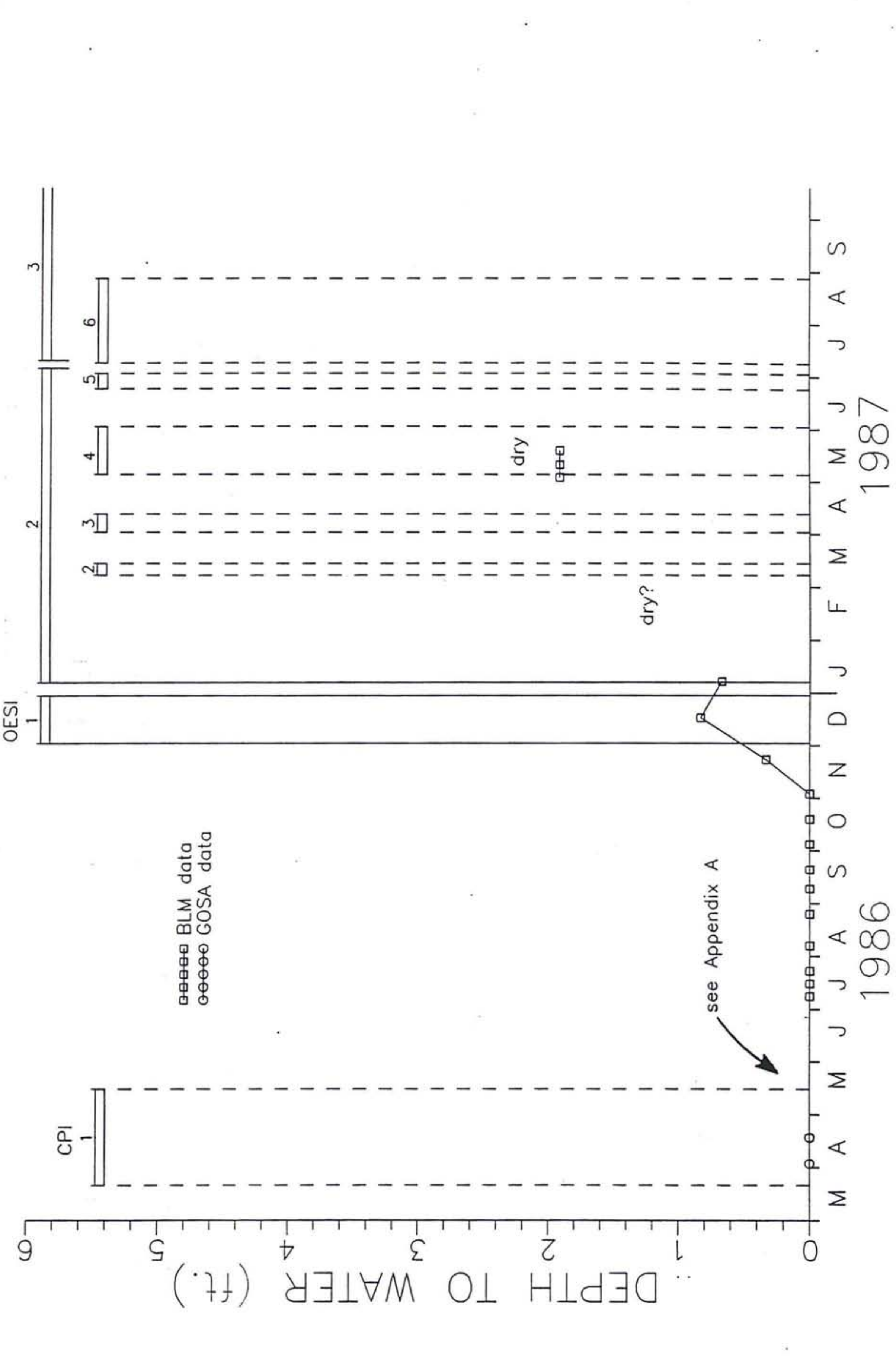
Completion diagram, lithology and temperature/pressure profiles, well IW-2



Hydrograph of spring 42w, July, 1987, to June, 1989.

APPENDIX C. CAITHNESS POWER INCORPORATED WELL-FIELD AND STRATIGRAPHIC TEST-WELL DATA

This appendix contains copies of data from the Caithness Power Incorporated well field and associated stratigraphic test wells (strat wells). The material was obtained from the files of the Bureau of Land Management (Carson City and Reno offices) and from an unpublished report by Thermasource (1987).



Hydrograph of spring 16, March, 1986, to May, 1987.

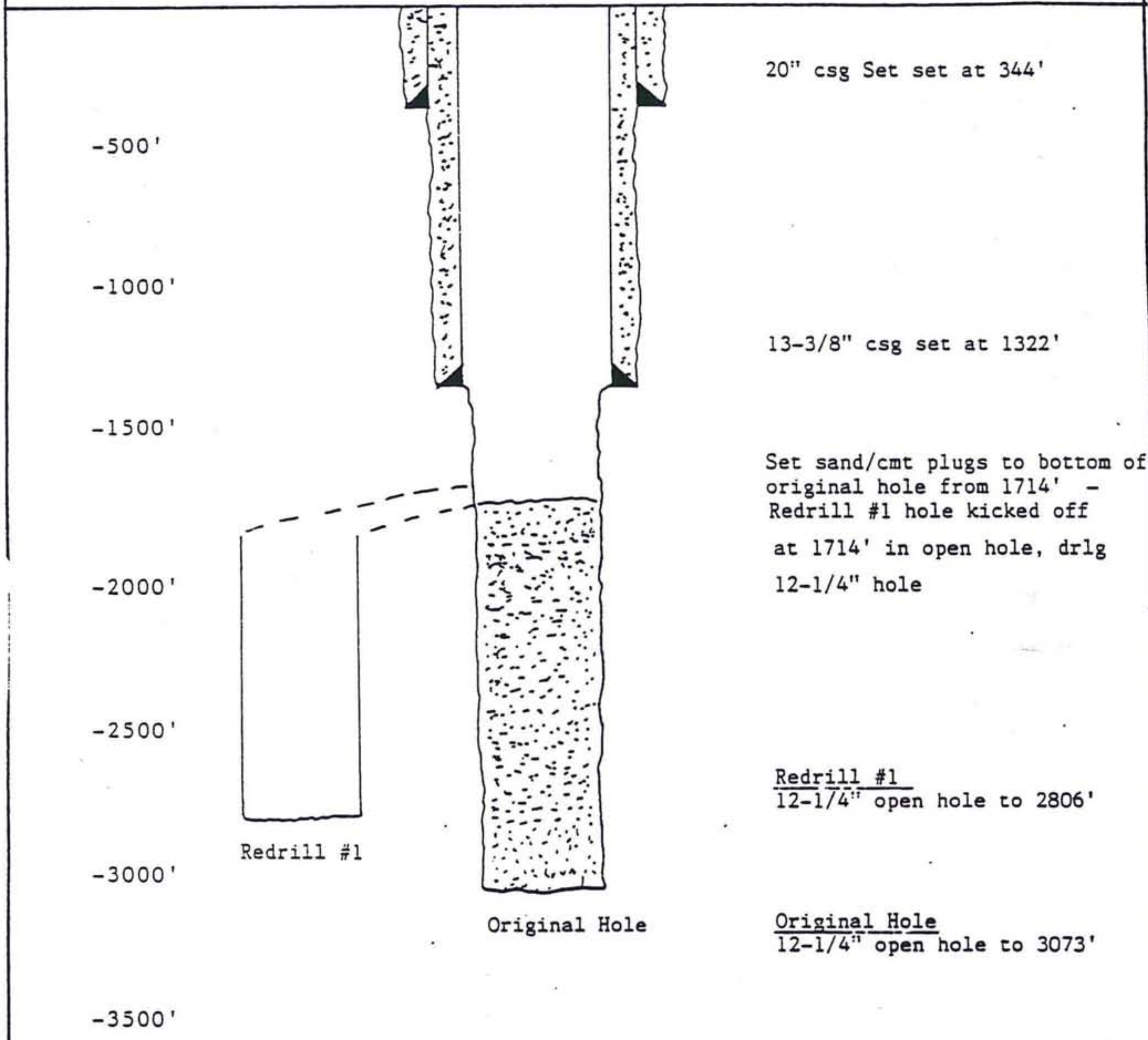
All depths based on kelly bushing elevation = ground level + 30'

Ground elevation 5732'

Original hole spudded 6/5/79, T.D. 7/16/79 to 3073' w/ P. Bawden Drlg Co.

Workover 11/6/87 - 11/12/87 Sargent Drlg Co.

Workover/Redrill #1 11/30/87 - 12/17/87 to 2806' w/ Veco Drlg Co.



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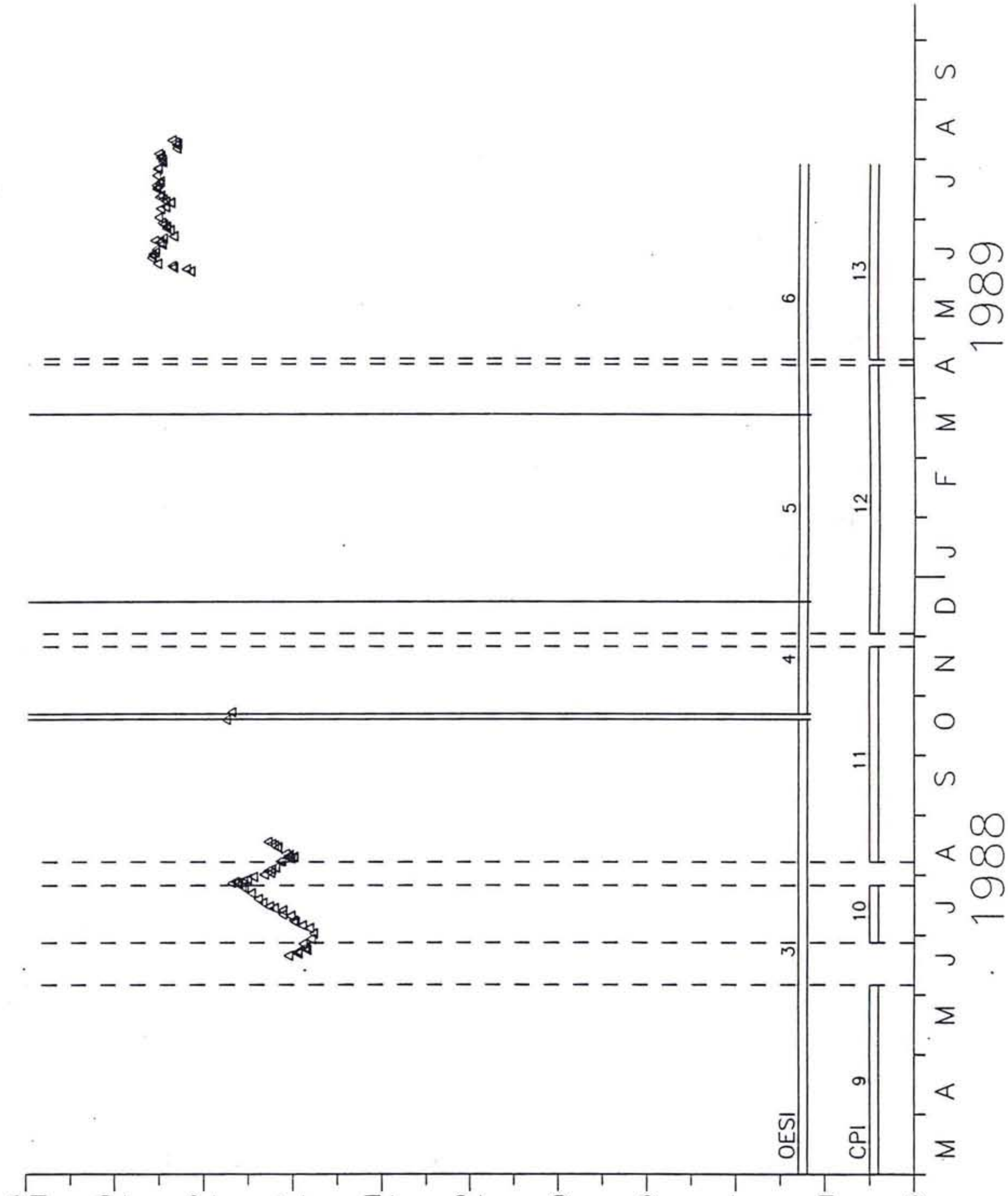
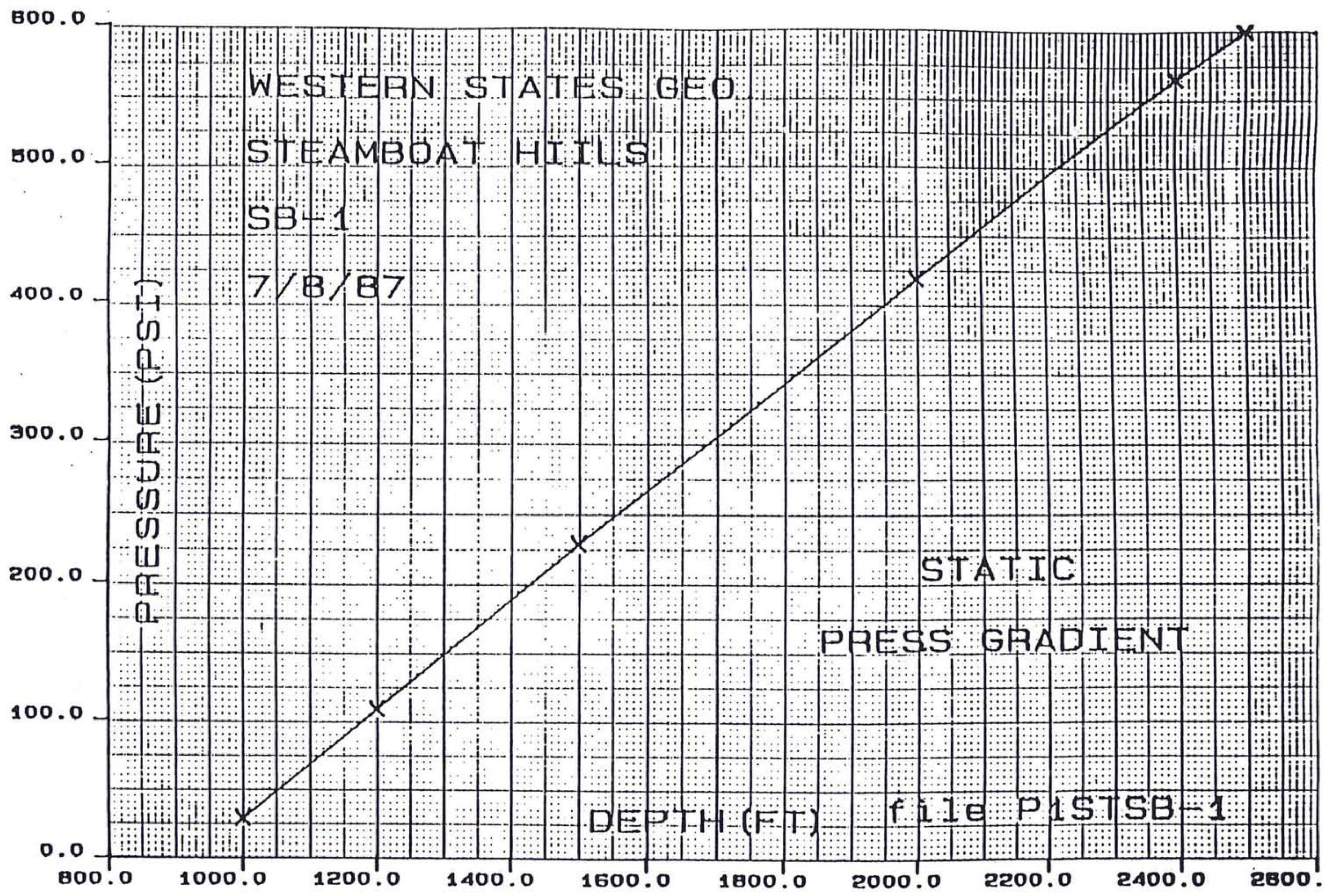
DRAWN
FOR:
BY:
DATE: 12/19/87
SCALE:
DRAWING No.

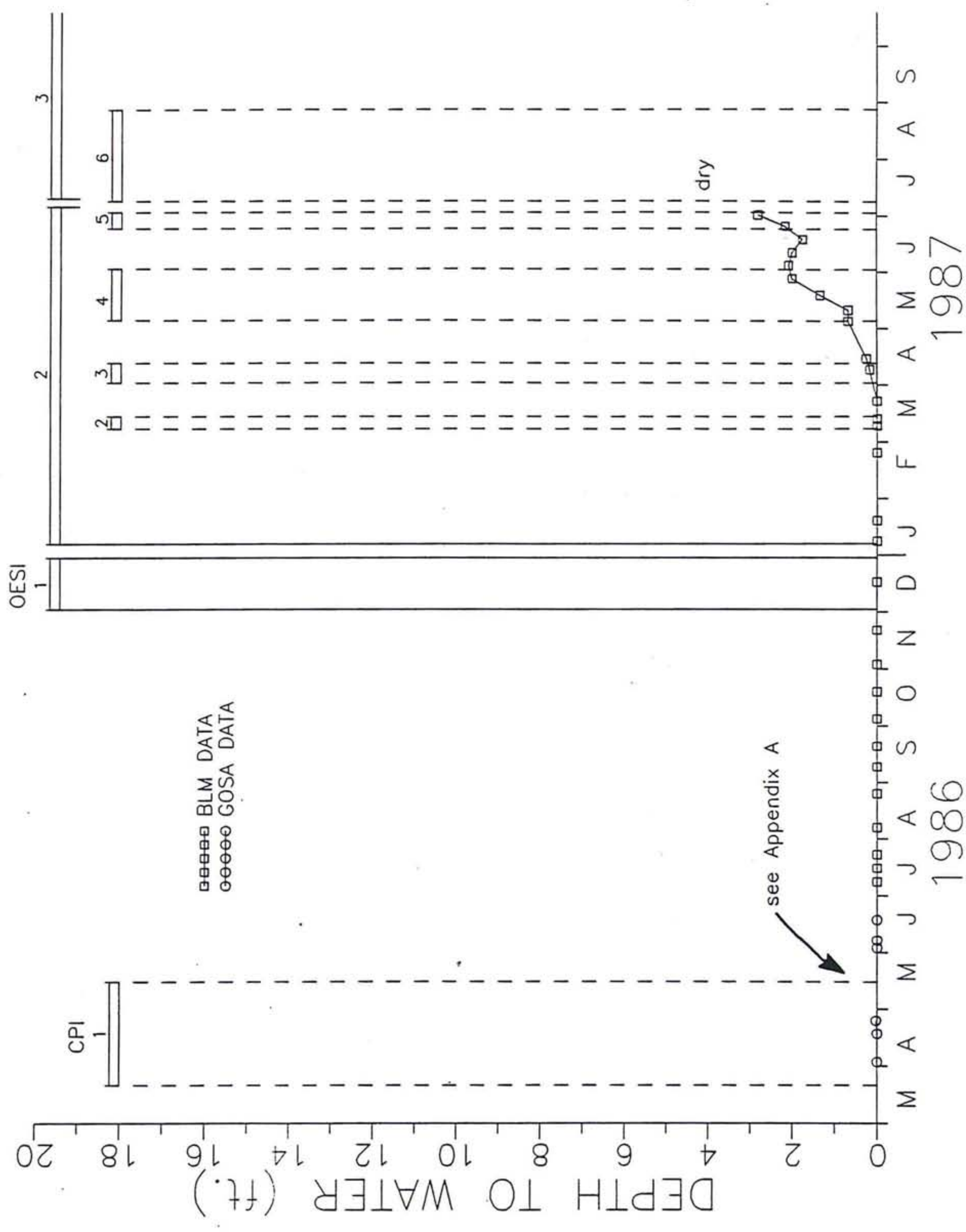
SS STEAMBOAT 1, ORIGINAL HOLE & REDRILL #1 WELL SCHEMATIC



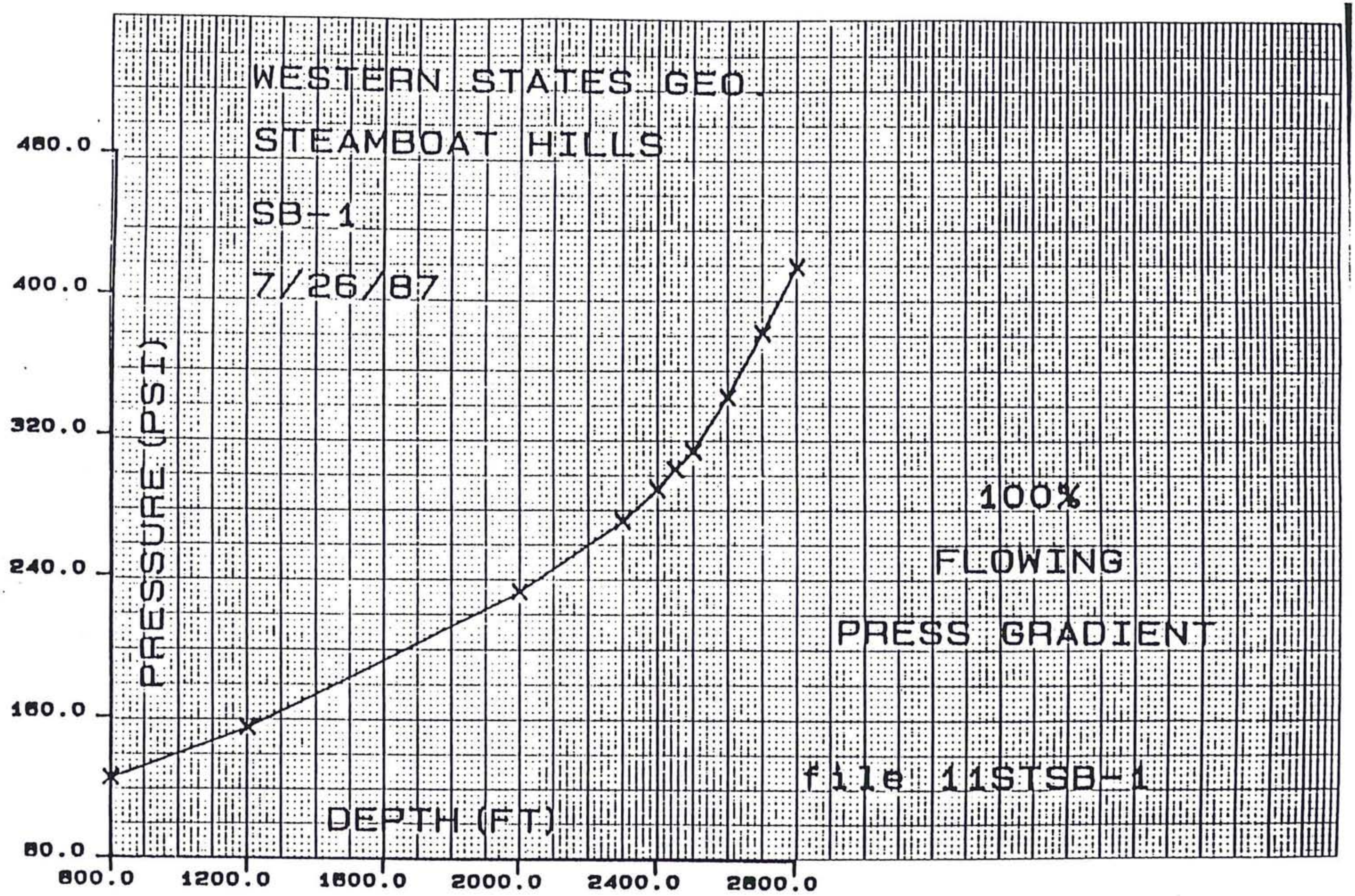
(cont'd) Hydrograph of spring 12, March, 1986, to August, 1989.



WESTERN STATES GEO
STEAMBOAT HIILS
SB-1
7/8/87
STATIC
PRESS GRADIENT
PRESSURE (PSI)
DEPTH (FT)
file P1STSB-1
600.0
500.0
400.0
300.0
200.0
100.0
0.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0
2600.



Hydrograph of spring 12, March, 1986, to August, 1989.

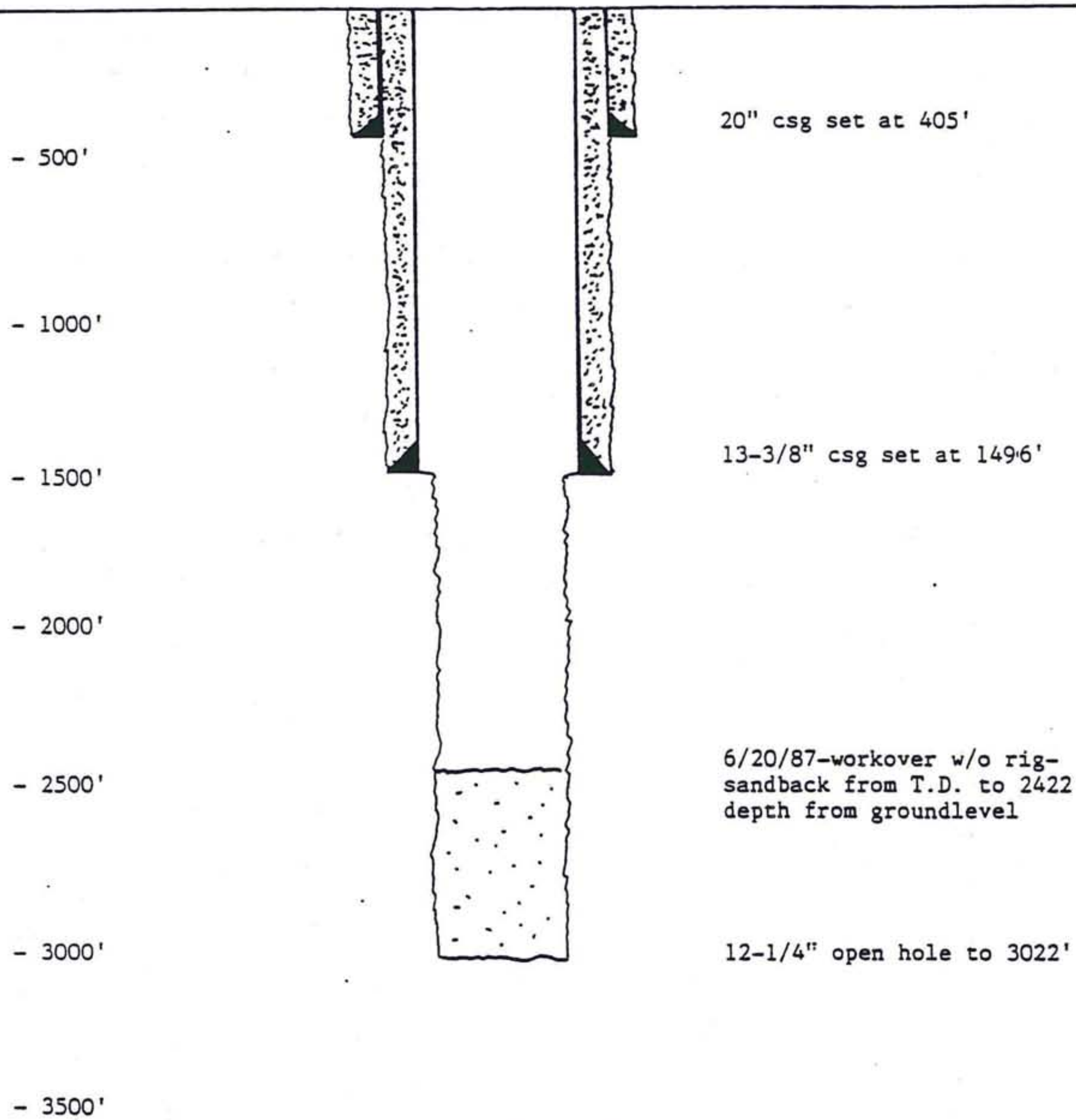

WESTERN STATES GEO.
STEAMBOAT HILLS
SB-1
7/26/87
100%
FLOWING
PRESS GRADIENT
file 11STSB-1
PRESSURE (PSI)
DEPTH (FT)
80.0
160.0
240.0
320.0
400.0
480.0
800.0
1200.0
1600.0
2000.0
2400.0
2800.0

All depths based on kelly bushing elevation = ground level + 21'

Ground elevation 5347'

Well spudded 7/9/85, T.D. 8//11/85

H & W Drlg #2



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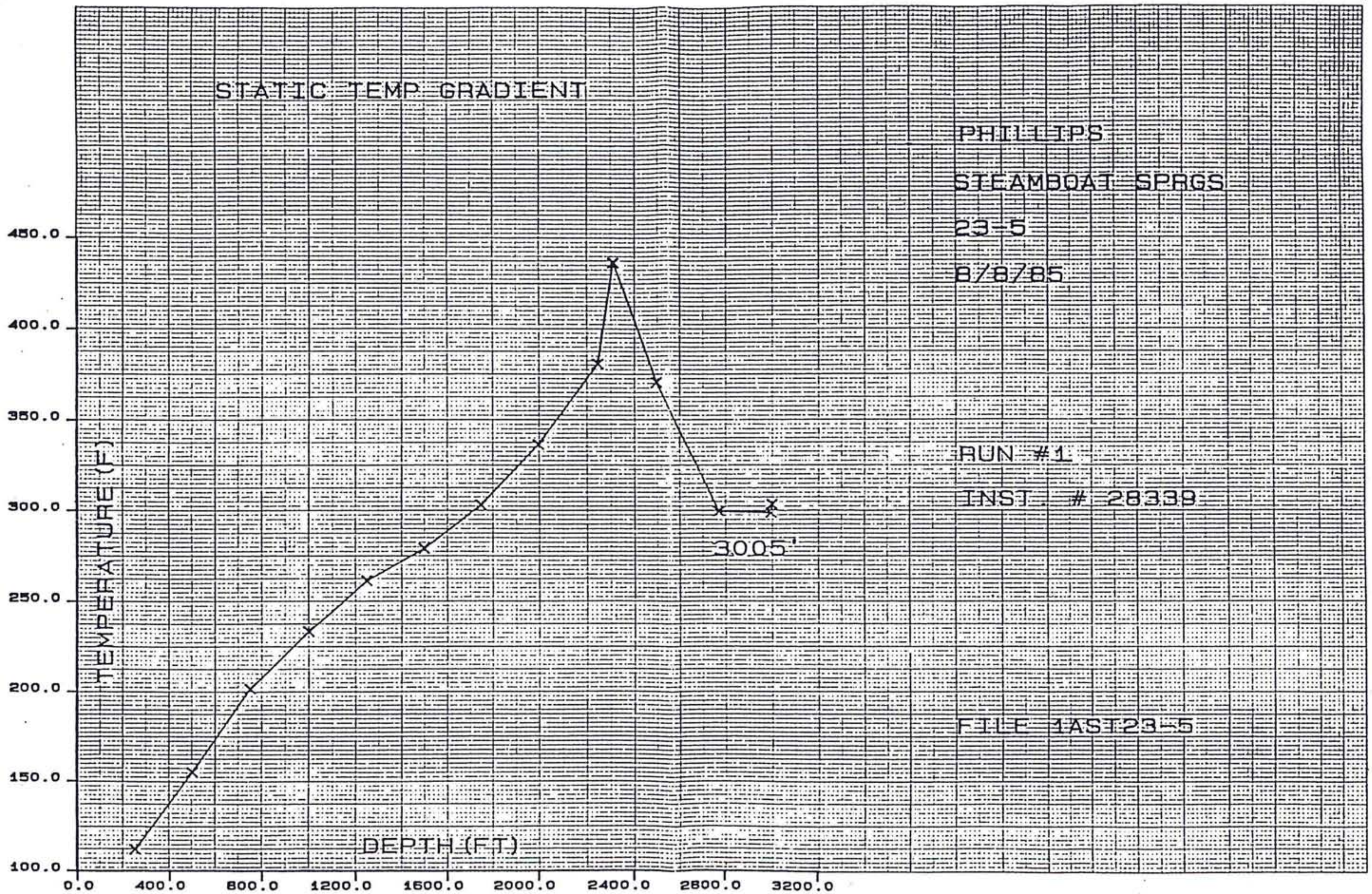
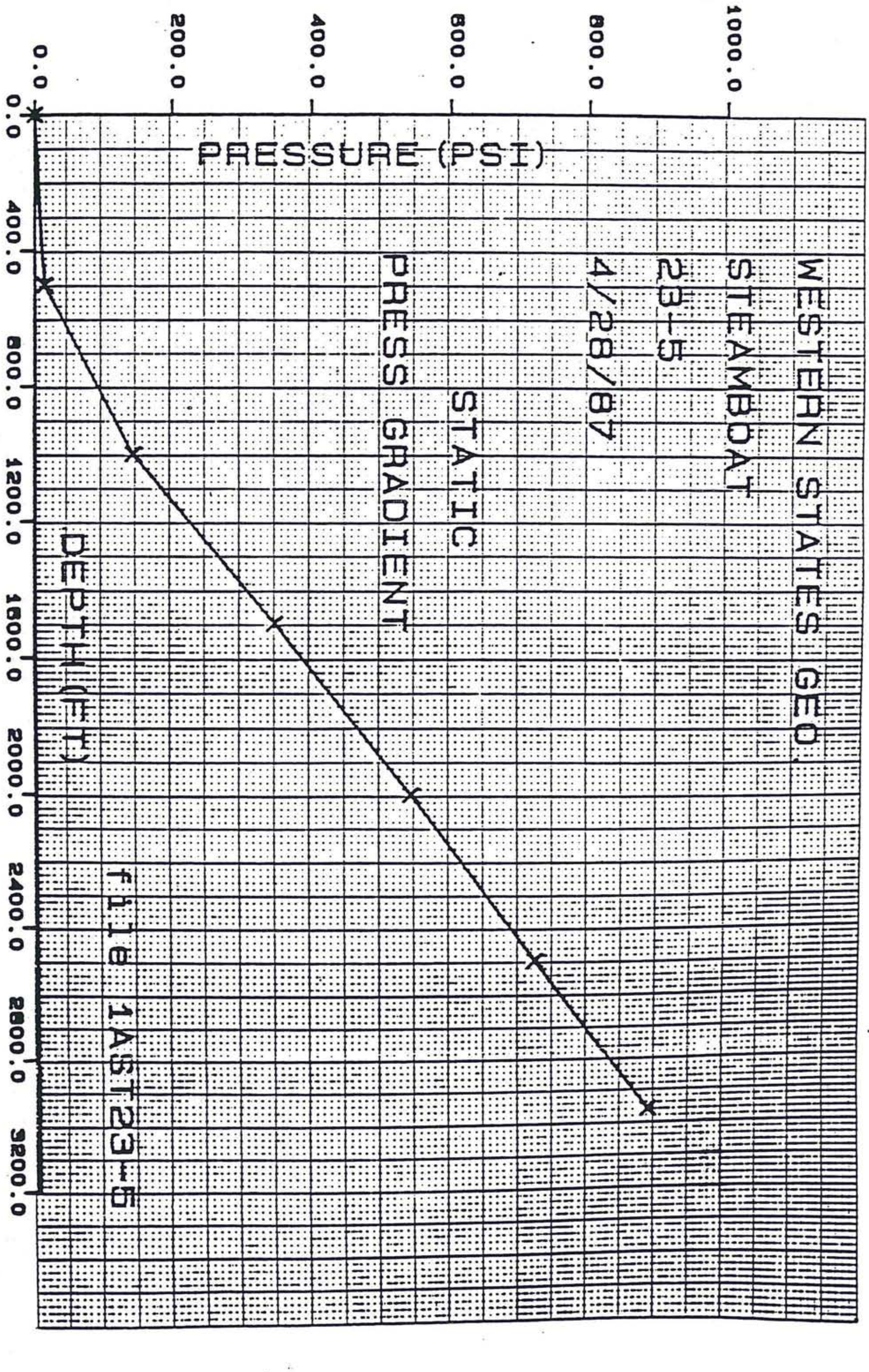
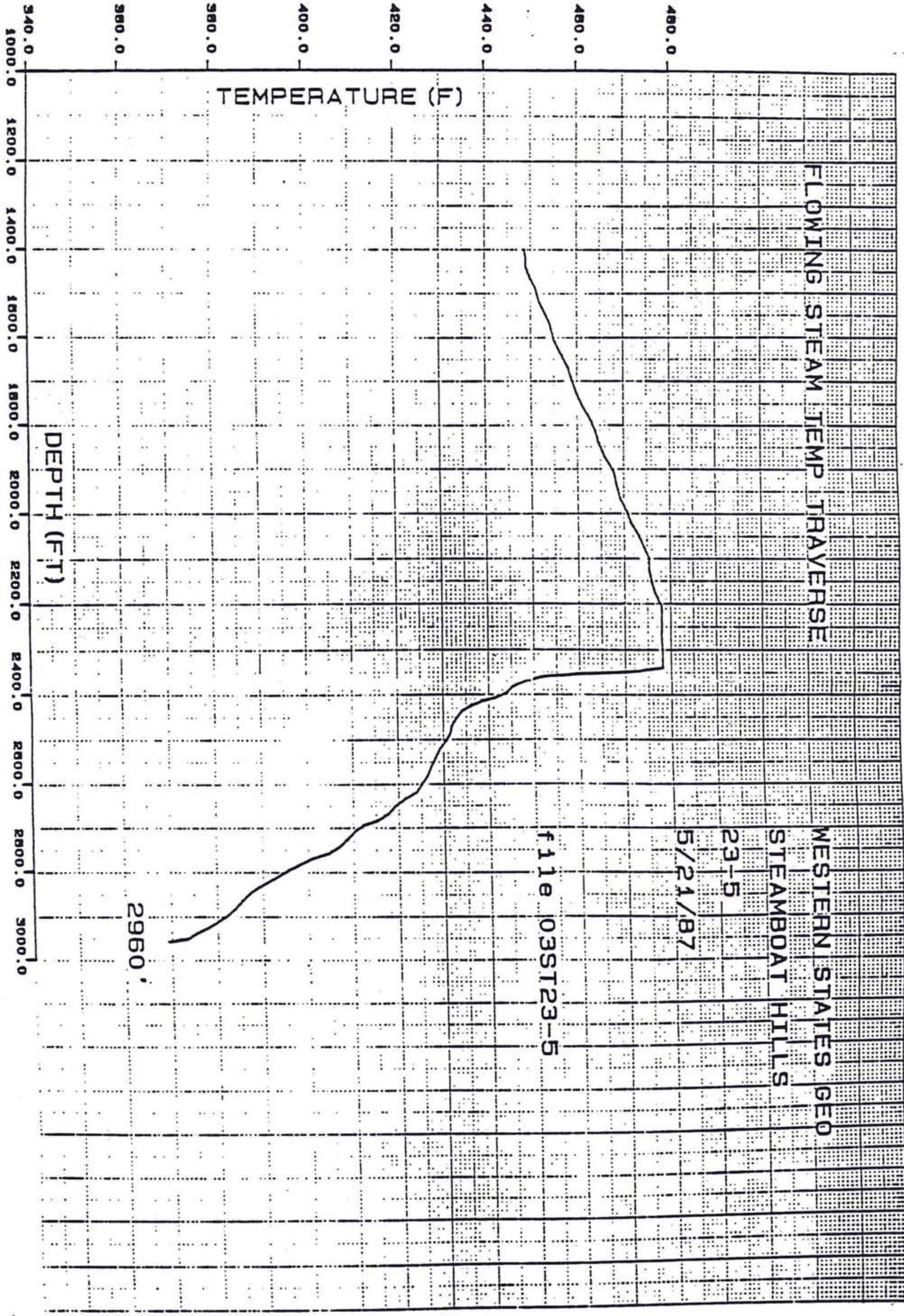
SS 23 - 5 WELL SCHEMATIC	DRAWN FOR: BY: DATE: SCALE: DRAWING No.


STATIC TEMP GRADIENT
PHILLIPS
STEAMBOAT SPRGS
23-5
8/8/85
RUN #1
INST. # 28339
FILE 1AST23-5
3005'
TEMPERATURE (F)
DEPTH (FT)
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
0.0
400.0
800.0
1200.0
1600.0
2000.0
2400.0
2800.0
3200.0



WESTERN STATES GEO
STEAMBOAT
23-5
4/28/87
STATIC
PRESS GRADIENT
PRESSURE (PSI)
0.0
200.0
400.0
600.0
800.0
1000.0
DEPTH (FT)
0.0
400.0
800.0
1200.0
1600.0
2000.0
2400.0
2800.0
3200.0
file 1AST23-5


FLOWING STEAM TEMP TRAVERSE
WESTERN STATES GEO
STEAMBOAT HILLS
23-5
5/21/87
f11e 03ST23-5
TEMPERATURE (F)
DEPTH (FT)
2960'
340.0
360.0
380.0
400.0
420.0
440.0
460.0
480.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
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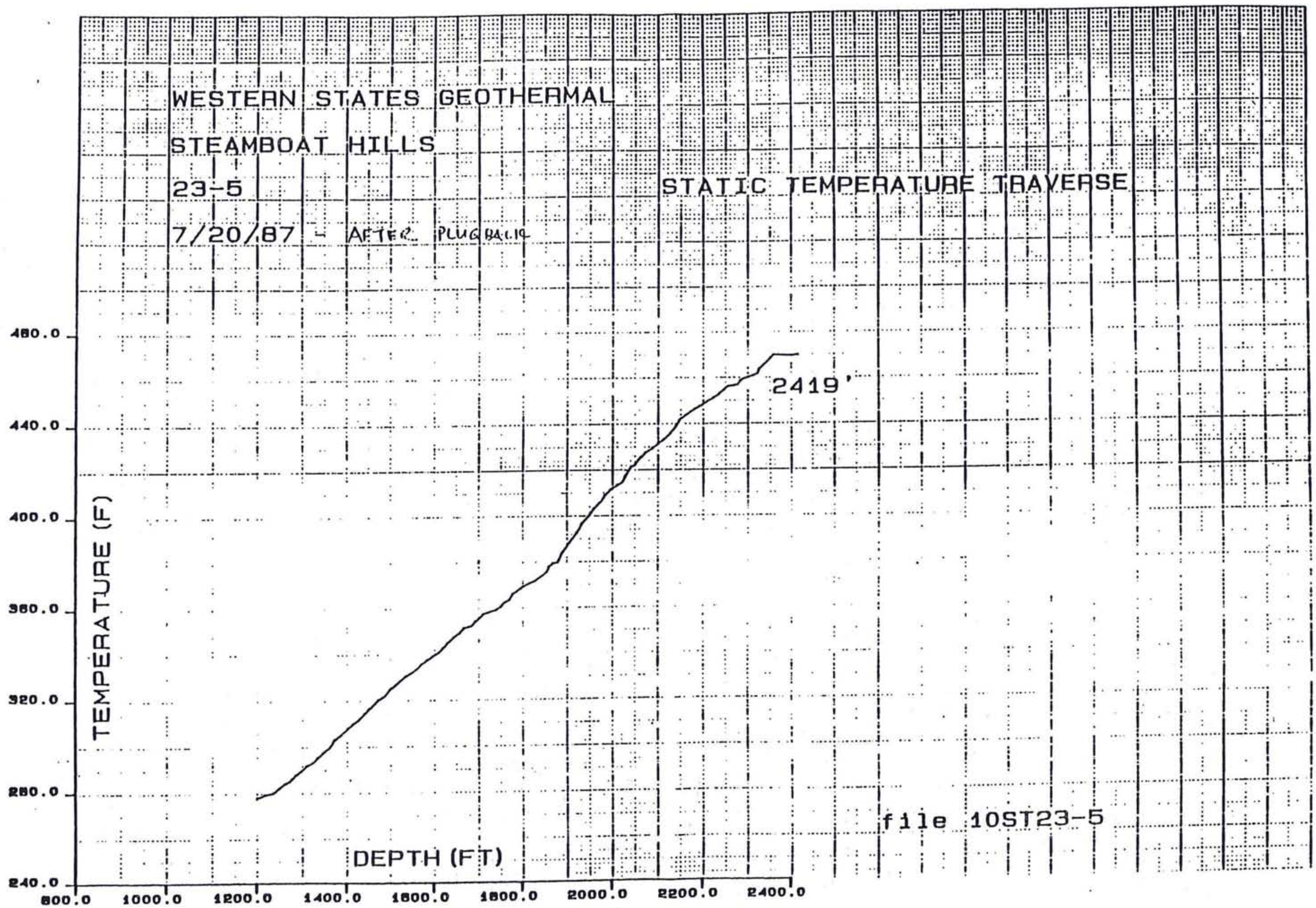
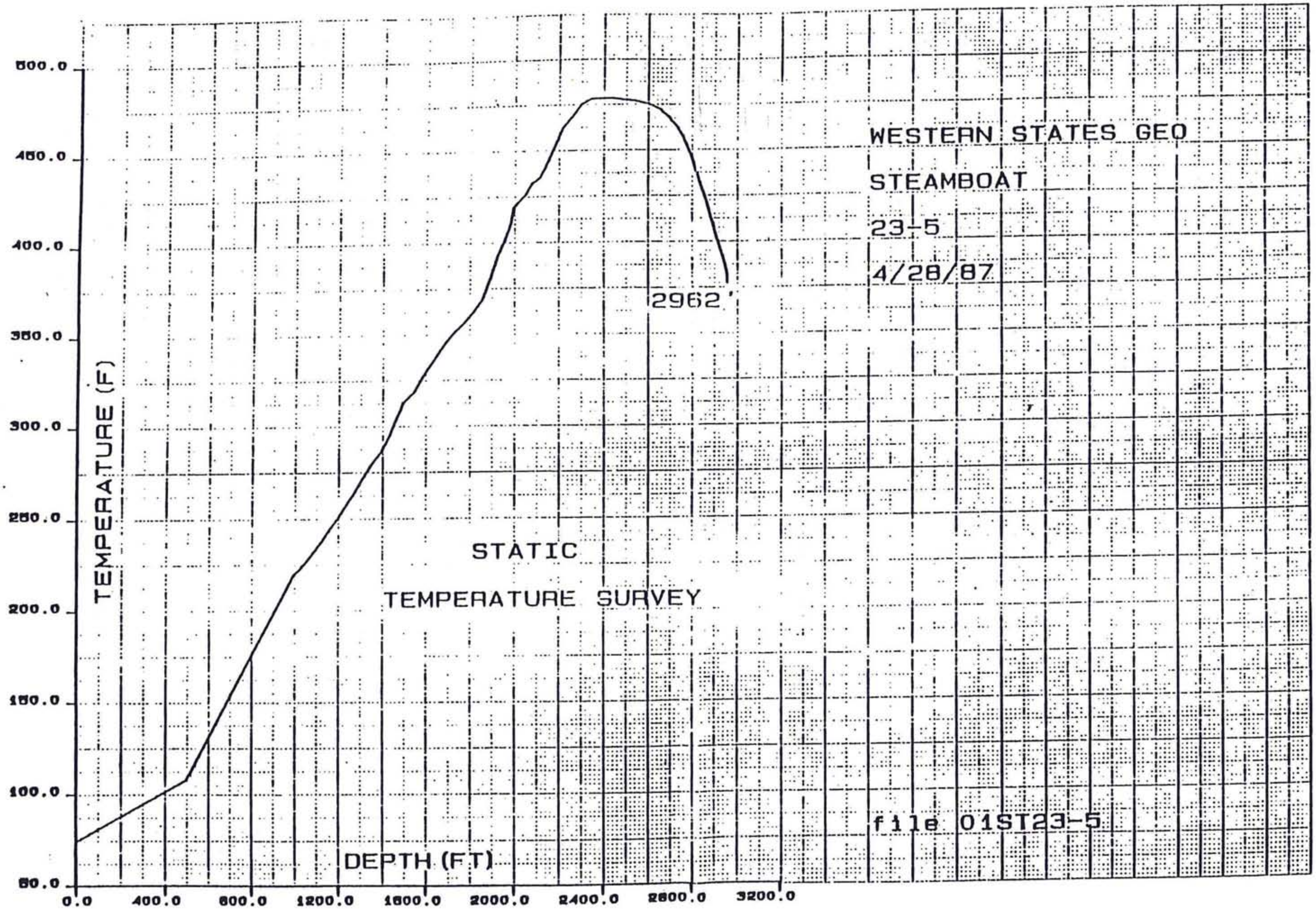
2600.0
2800.0
3000.0


WESTERN STATES GEOTHERMAL
STEAMBOAT HILLS
23-5
7/20/87 - AFTER PLUGBACK
STATIC TEMPERATURE TRAVERSE
2419'
TEMPERATURE (F)
DEPTH (FT)
file 10ST23-5
480.0
440.0
400.0
360.0
320.0
280.0
240.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0

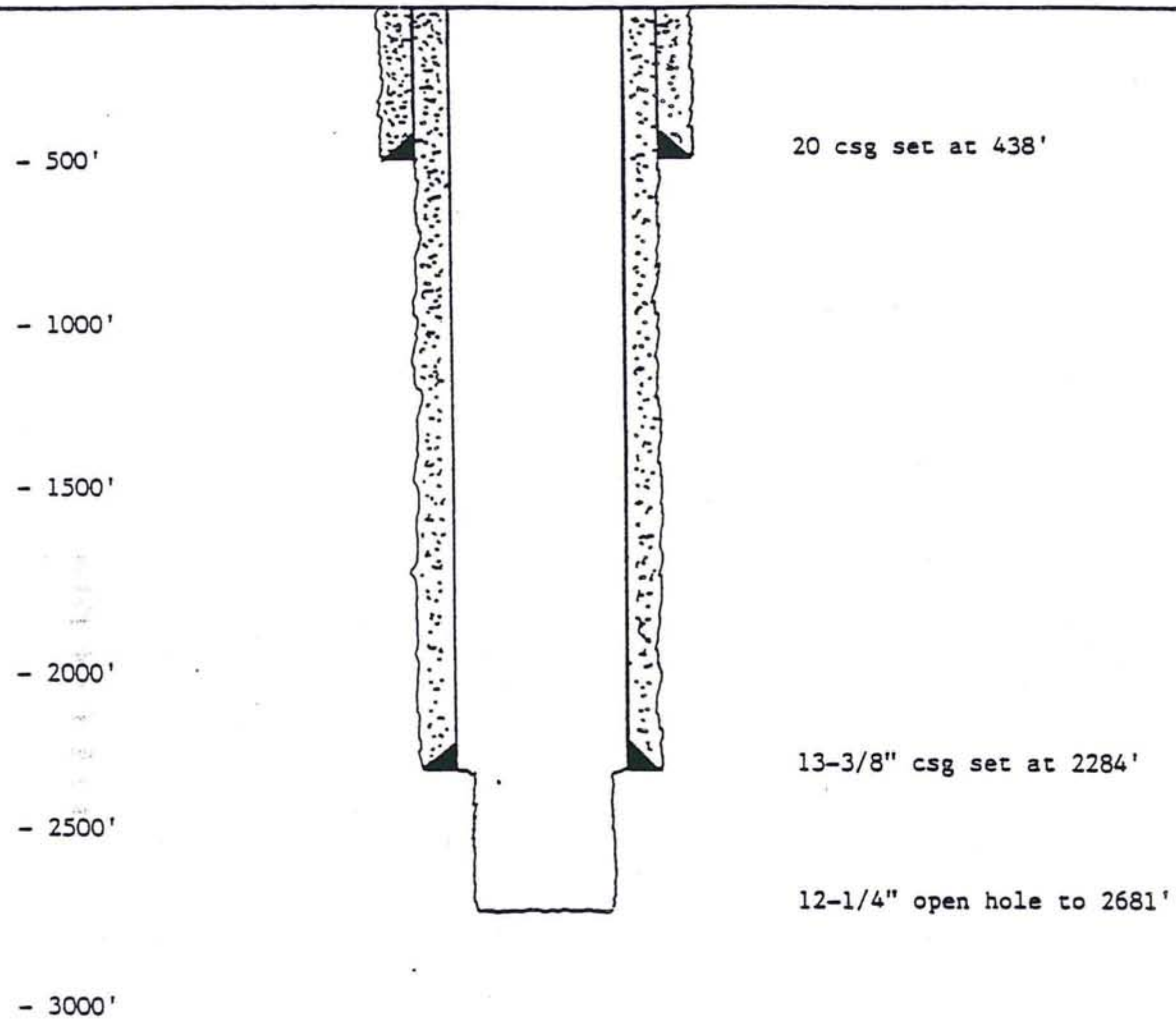

WESTERN STATES GEO
STEAMBOAT
23-5
4/28/87
2962'
STATIC
TEMPERATURE SURVEY
file 01ST23-5
TEMPERATURE (F)
DEPTH (FT)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
400.0
800.0
1200.0
1600.0
2000.0
2400.0
2800.0
3200.0

All depths based on kelly bushing elevation = ground level + 30'

Ground level 5732'

Well spudded, 9/23/87, T.D. 10/14/87

Veco Drlg Rig 10



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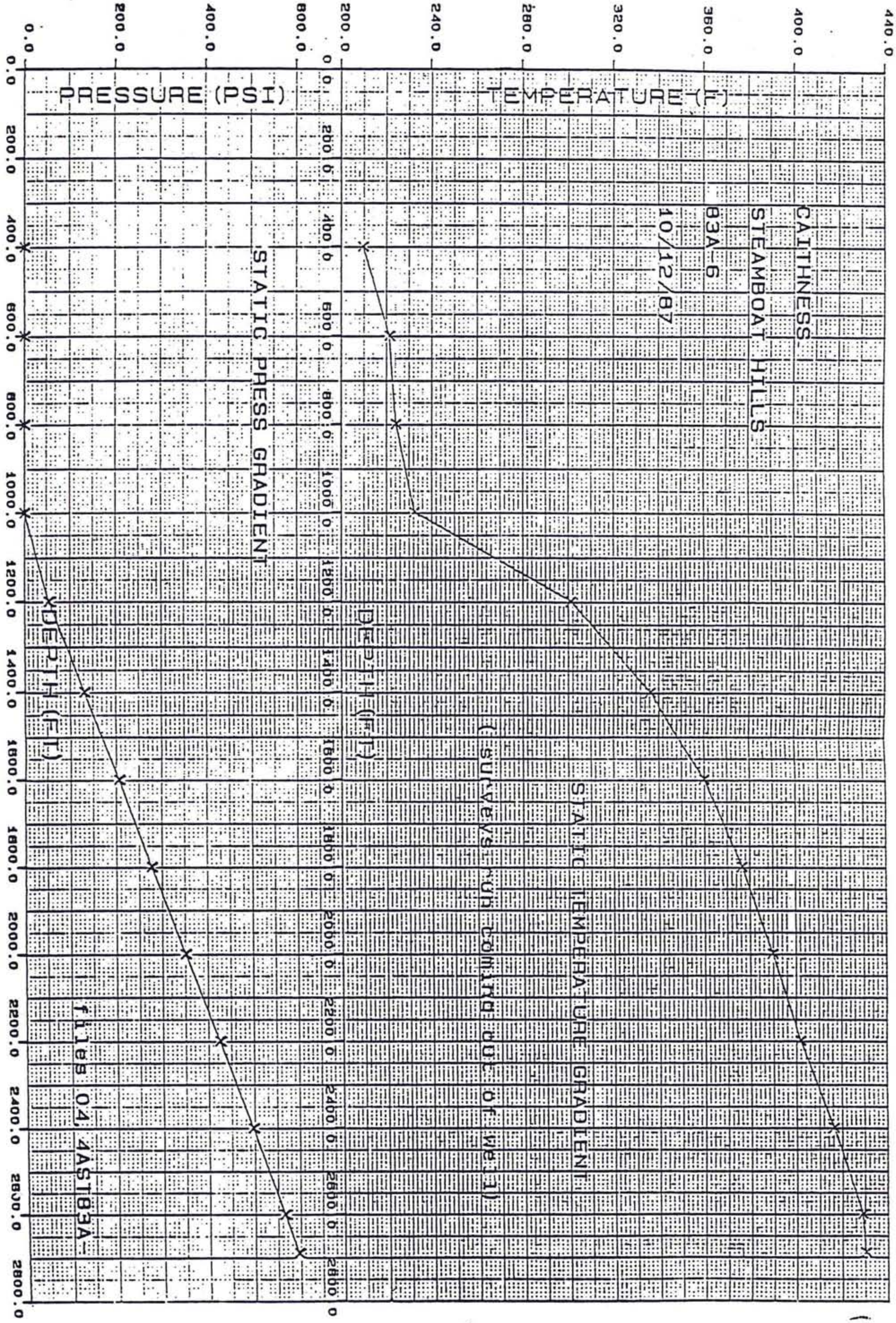
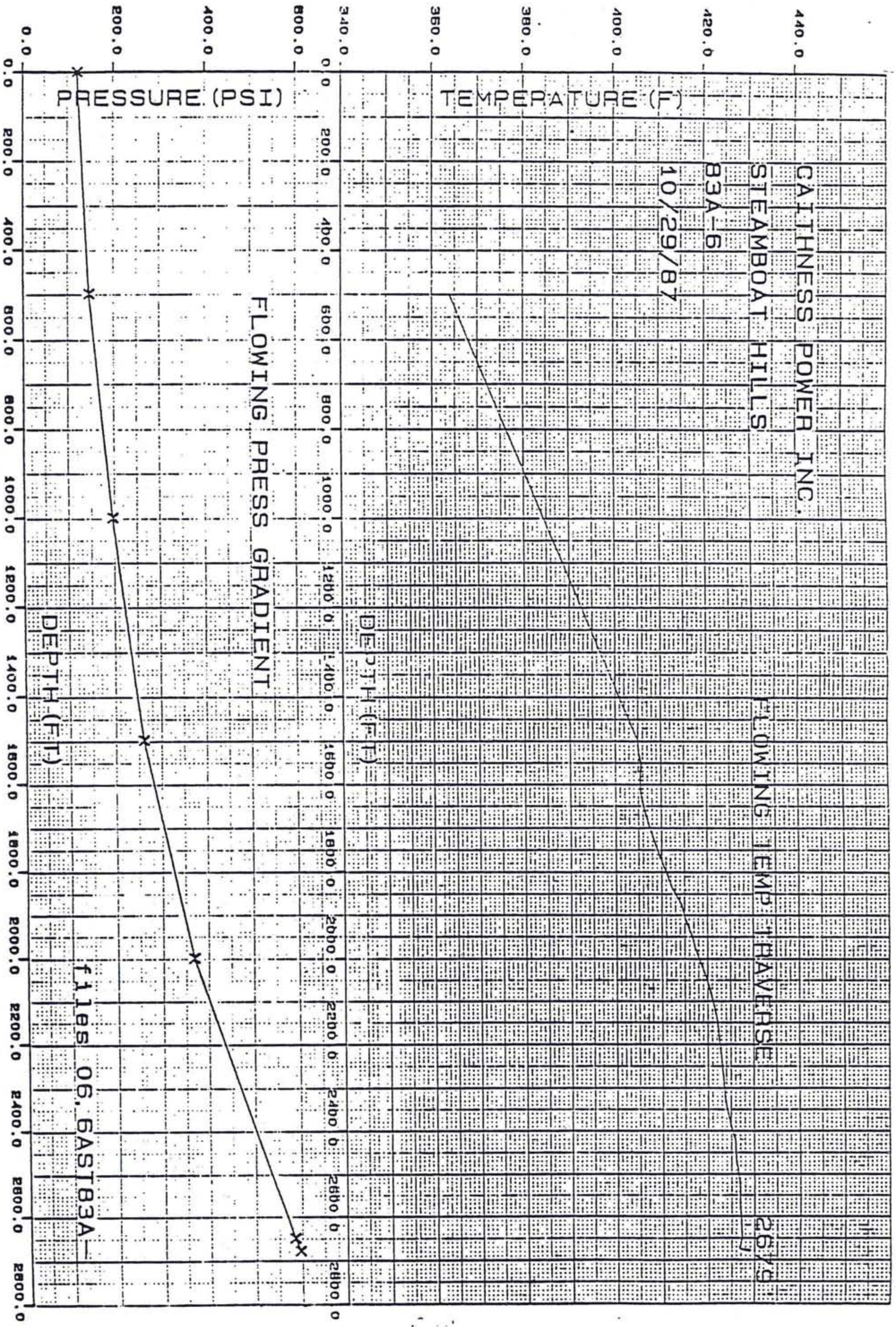
SS 83A - 6 WELL SCHEMATIC

DRAWN
FOR:
BY:
DATE:
SCALE:
DRAWING No.


CAITHNESS
STEAMBOAT HILLS
83A-6
10/12/87
PRESSURE (PSI)
TEMPERATURE (F)
STATIC PRESS GRADIENT
STATIC TEMPERATURE GRADIENT
DEPTH (FT)
DEPTH (FT)
files 04, 4AST83A-

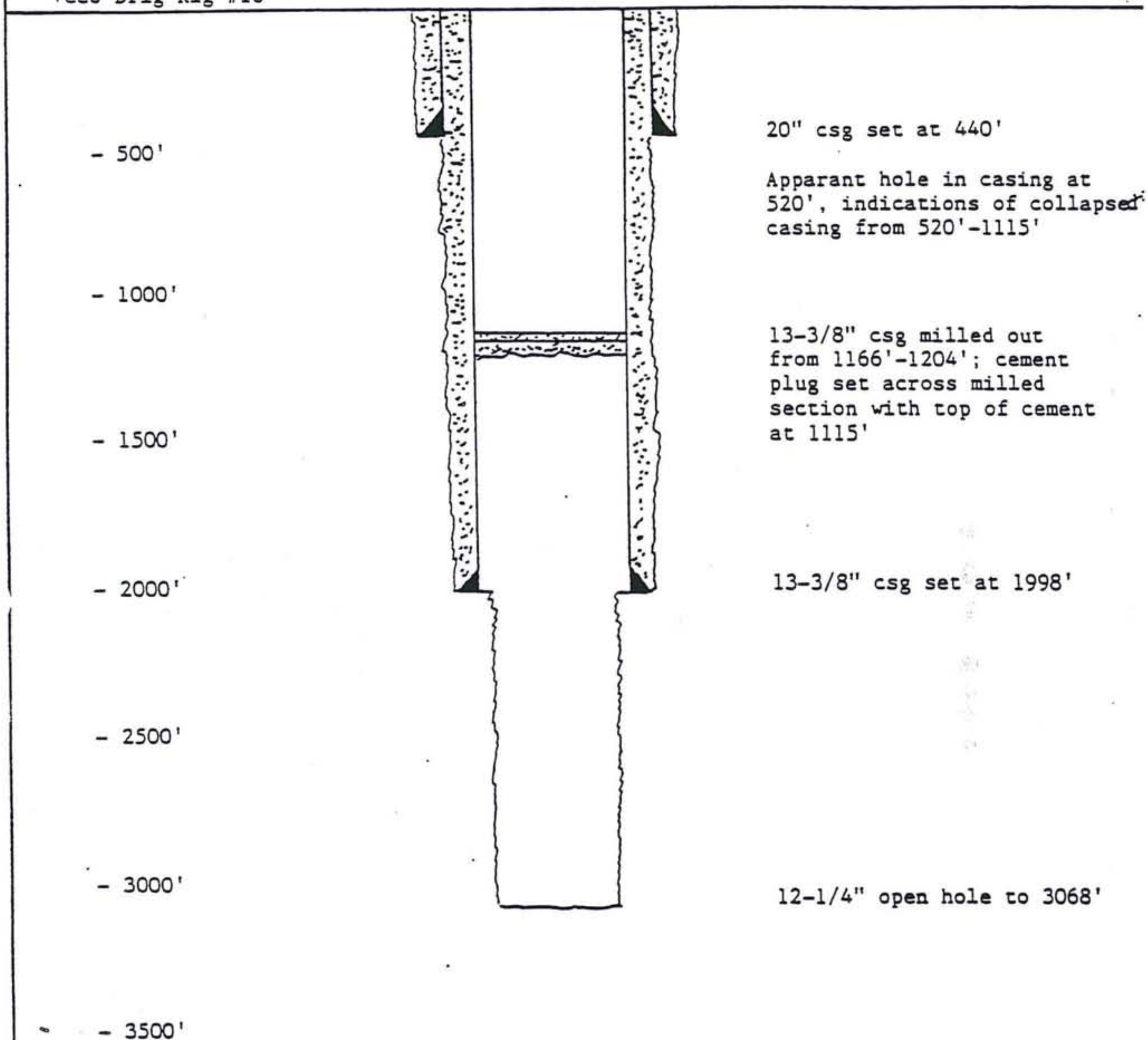

CAITHNESS POWER INC.
STEAMBOAT HILLS
83A-6
10/29/87
TEMPERATURE (F)
FLOWING TEMP TRAVERSE
2670
PRESSURE (PSI)
FLOWING PRESS GRADIENT
DEPTH (FT)
files 06.6AST83A
340.0
360.0
380.0
400.0
420.0
440.0
0.0
200.0
400.0
600.0
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0
2600.0
2800.0

All depths based on kelly bushing elevation = ground level + 30'

Ground elevation 5732'

Well spudded 7/11/87, T.D. 8/29/87

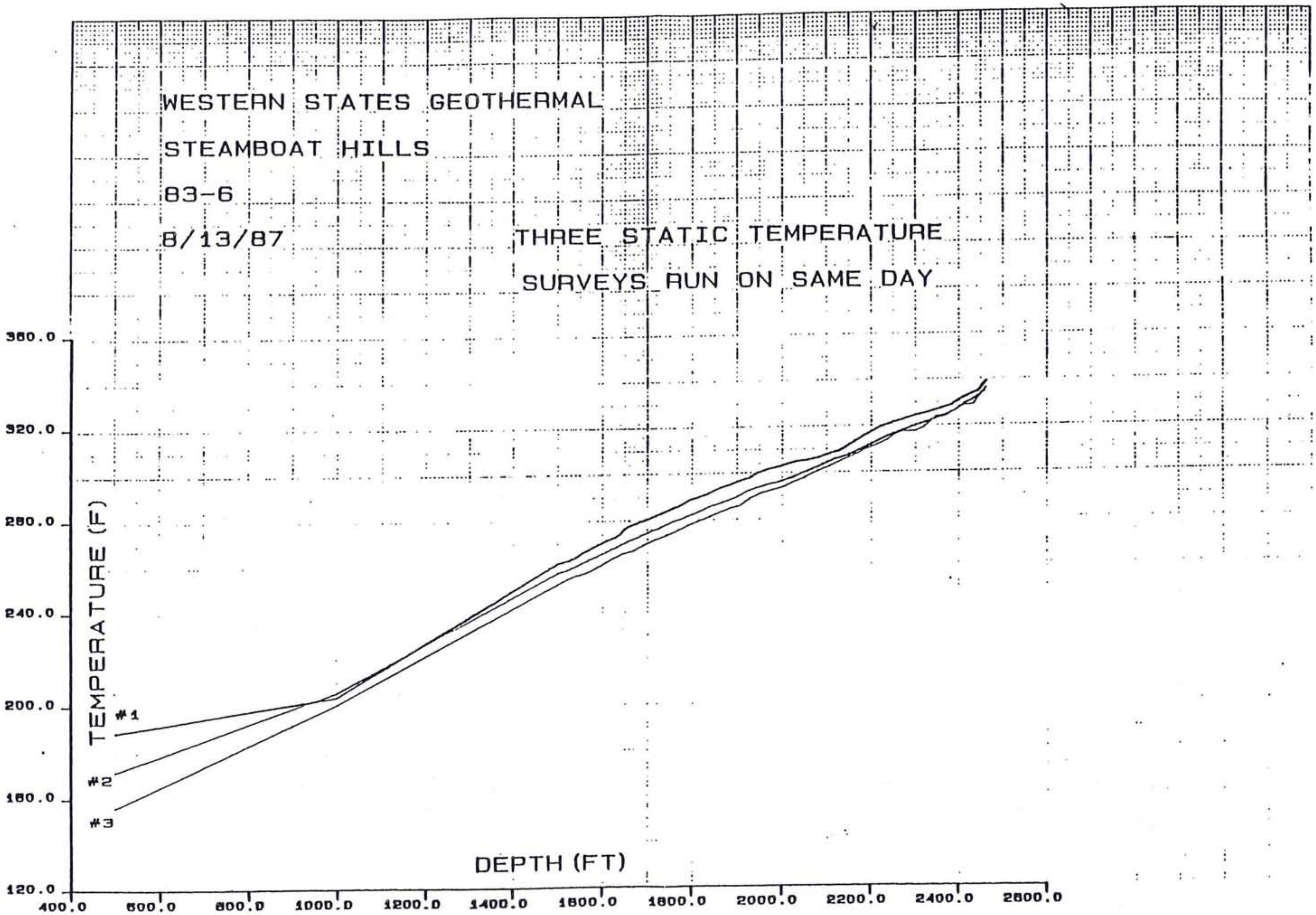
Veco Drlg Rig #10



TSi ThermaSource Inc. P.O. Box 1236 · Santa Rosa, California 95402 · (707) 523-2960

SS 83-6 WELL SCHEMATIC

DRAWN
FOR:
BY:
DATE:
SCALE:
DRAWING No.

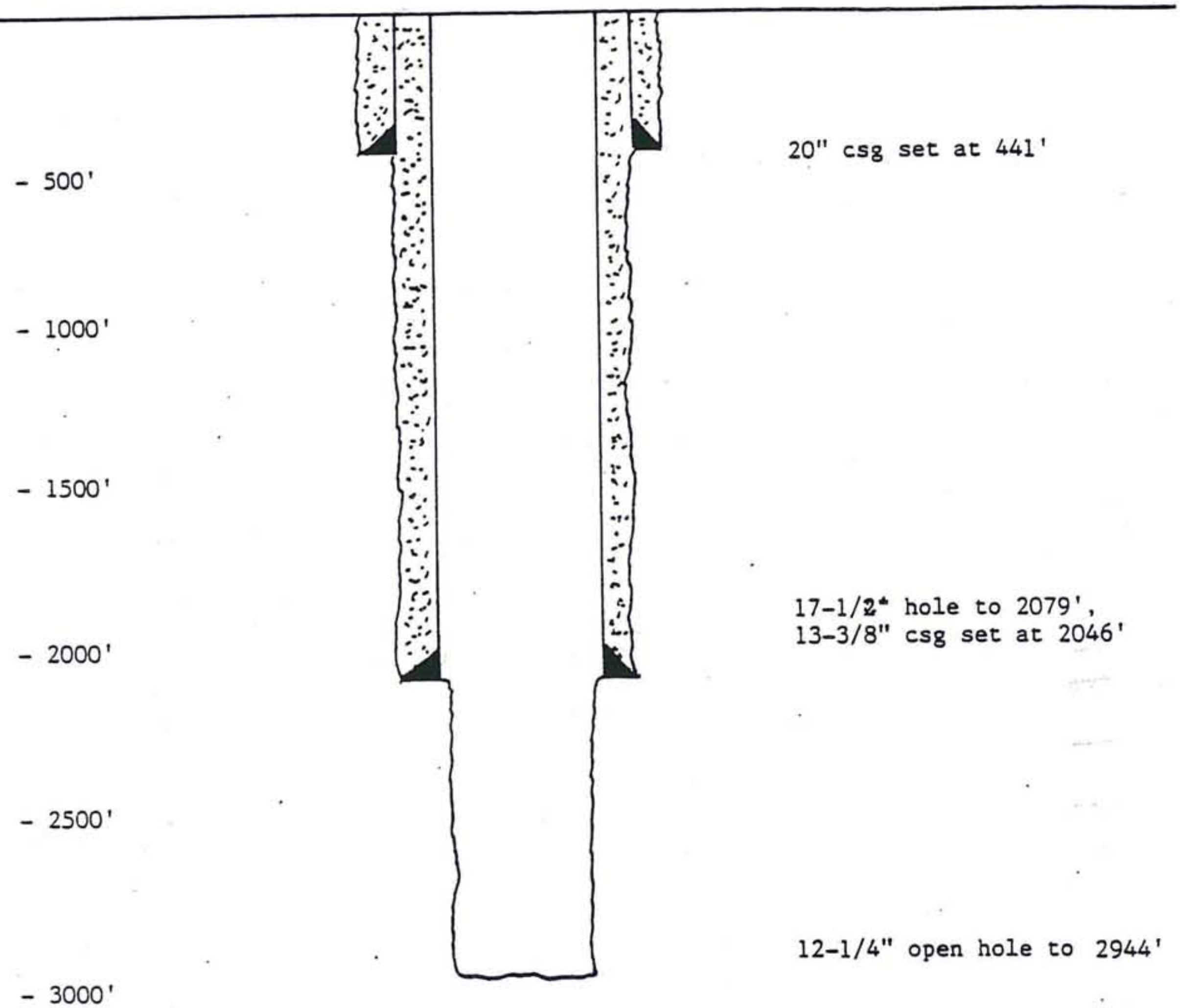

WESTERN STATES GEOTHERMAL
STEAMBOAT HILLS
83-6
8/13/87
THREE STATIC TEMPERATURE
SURVEYS RUN ON SAME DAY
TEMPERATURE (F)
DEPTH (FT)
#1
#2
#3
360.0
320.0
280.0
240.0
200.0
160.0
120.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0
2600.0

All depths based on kelly bushing elevation = ground level + 30'

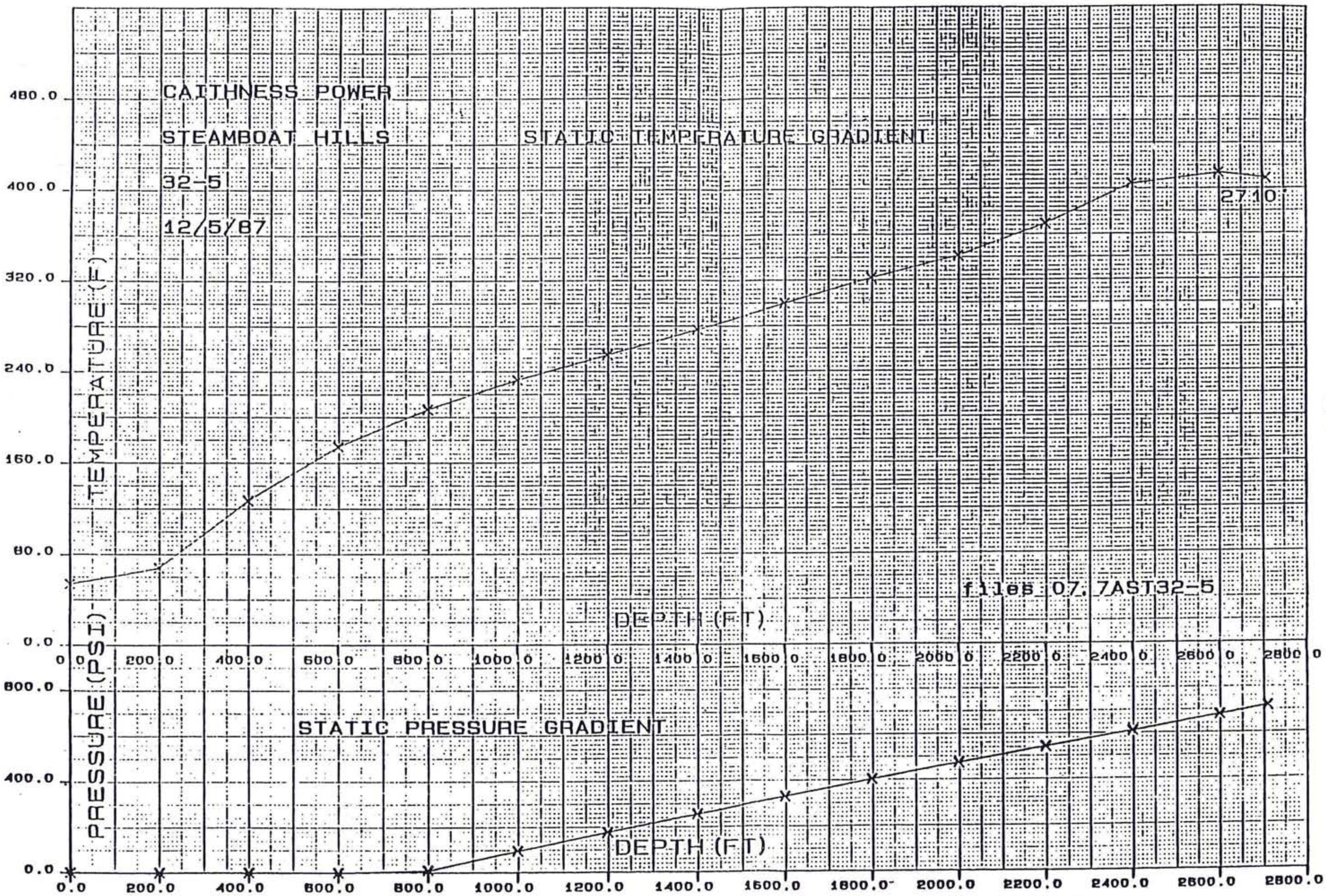
Ground elevation 5471'

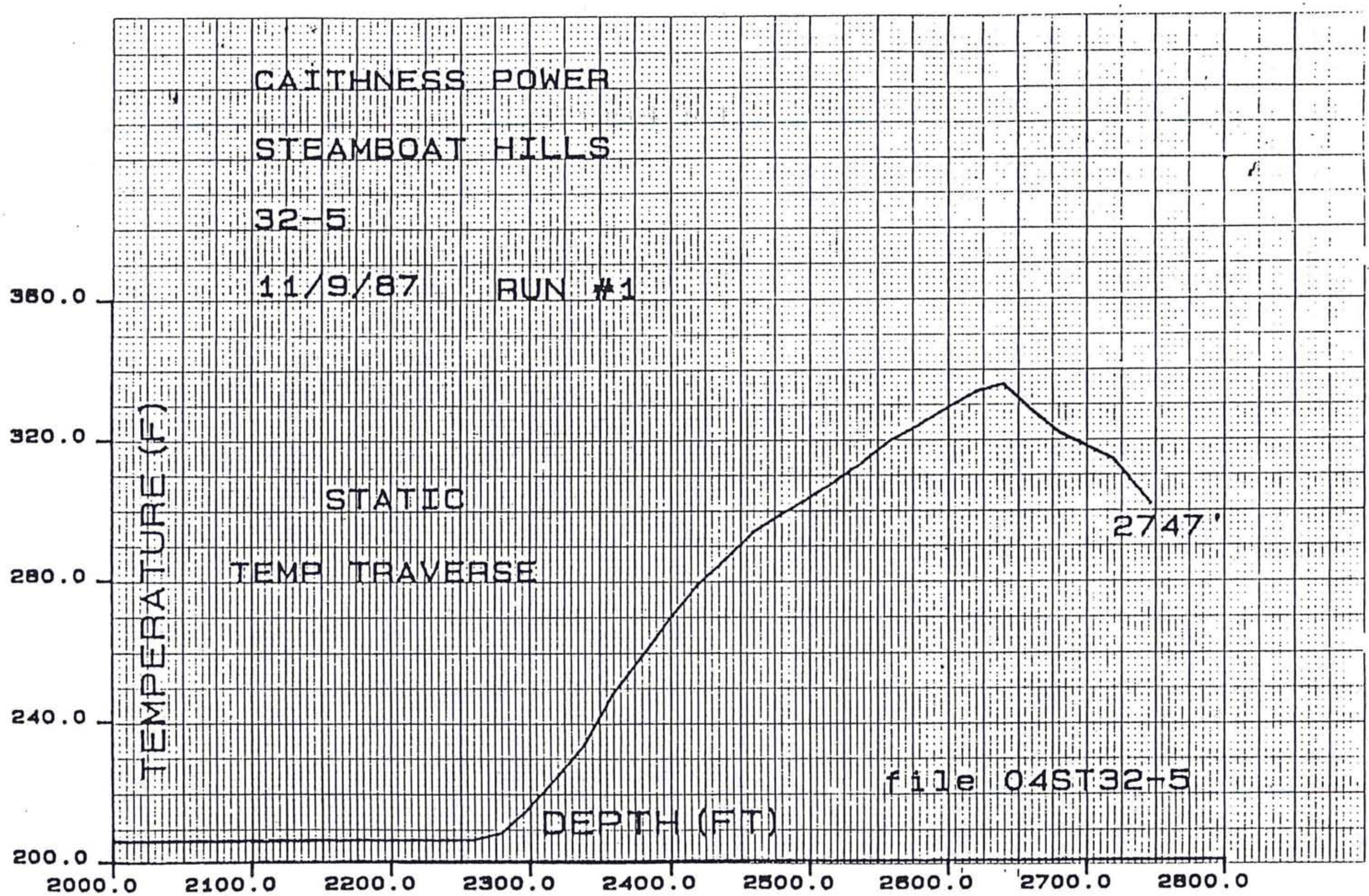
Well spudded 10/19/87, T.D. 11/9/87

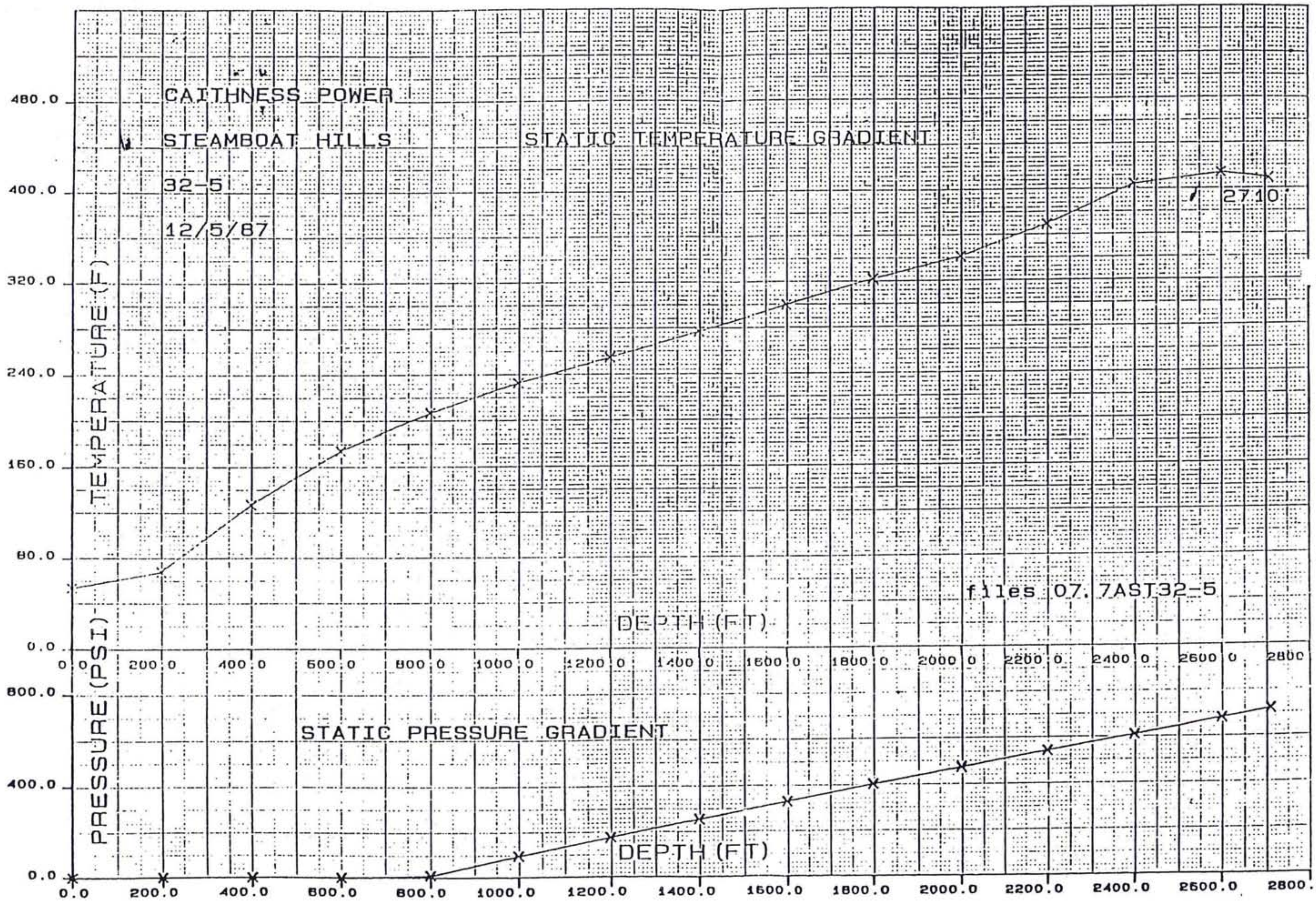
Veco Drilling Rig #10



TSi ThermaSource Inc. P.O. Box 1236 • Santa Rosa, California 95402 • (707) 523-2960	DRAWN FOR: BY:
SS 32 - 5 WELL SCHEMATIC	DATE: SCALE: DRAWING No.


CAITHNESS POWER
STEAMBOAT HILLS
32-5
12/5/87
STATIC TEMPERATURE GRADIENT
TEMPERATURE (F)
480.0
400.0
320.0
240.0
160.0
80.0
0.0
2710
files 07.7AST32-5
DEPTH (FT)
0.0 200.0 400.0 600.0 800.0 1000.0 1200.0 1400.0 1600.0 1800.0 2000.0 2200.0 2400.0 2600.0 2800.0
STATIC PRESSURE GRADIENT
PRESSURE (PSI)
800.0
400.0
0.0
DEPTH (FT)
0.0 200.0 400.0 600.0 800.0 1000.0 1200.0 1400.0 1600.0 1800.0 2000.0 2200.0 2400.0 2600.0 2800.0


CAITHNESS POWER
STEAMBOAT HILLS
32-5
11/9/87 RUN #1
STATIC
TEMP TRAVERSE
2747'
file 04ST32-5
TEMPERATURE (F)
DEPTH (FT)
380.0
320.0
280.0
240.0
200.0
2000.0
2100.0
2200.0
2300.0
2400.0
2500.0
2600.0
2700.0
2800.0

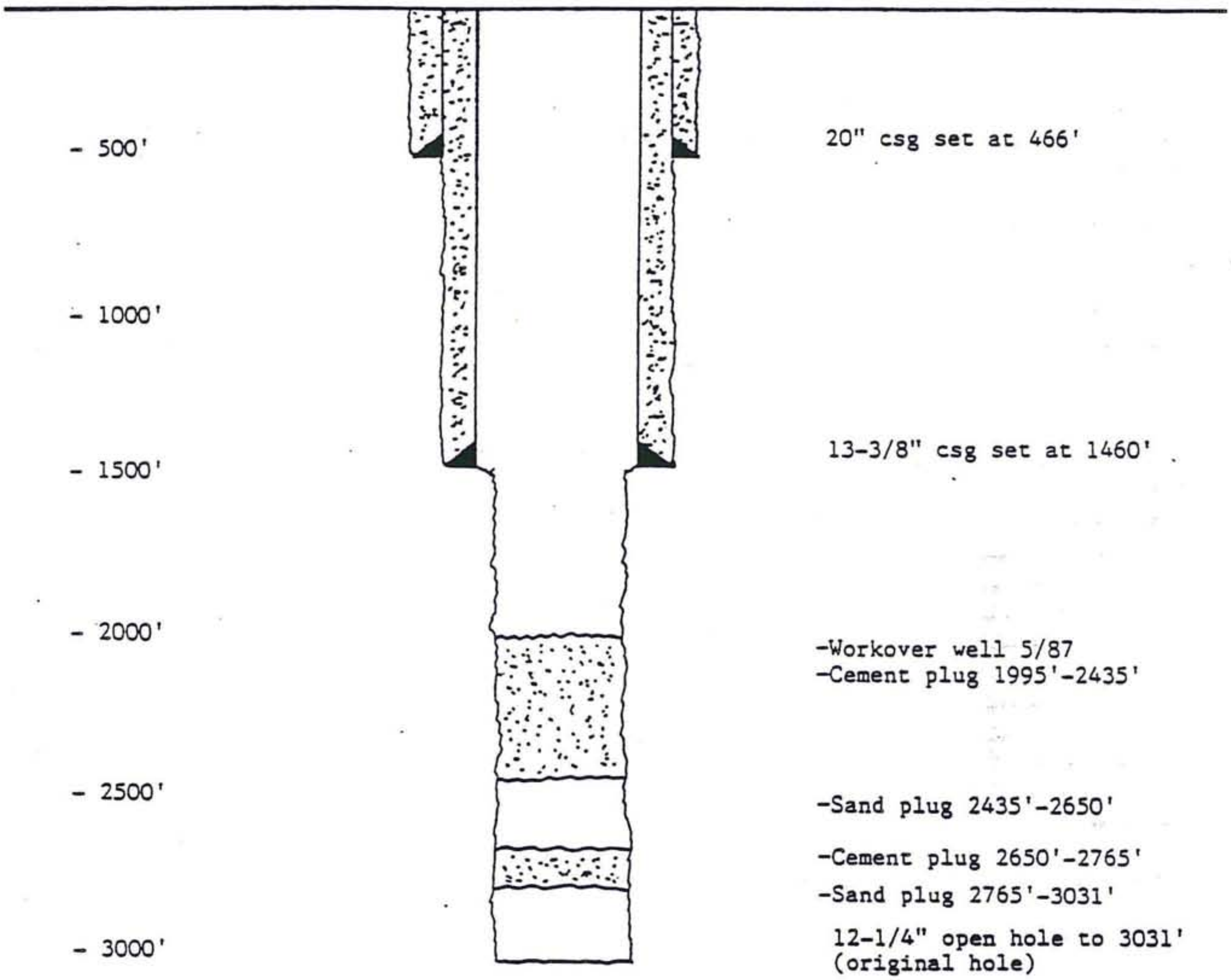

CAITHNESS POWER
STEAMBOAT HILLS
32-5
12/5/87
STATIC TEMPERATURE GRADIENT
2710
TEMPERATURE (F)
480.0
400.0
320.0
240.0
160.0
80.0
0.0
files 07. 7AST32-5
DEPTH (FT)
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0
2600.0
2800
PRESSURE (PSI)
800.0
400.0
0.0
STATIC PRESSURE GRADIENT
DEPTH (FT)
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0
2600.0
2800.0

All depths based on kelly bushing elevation = ground level + 27'

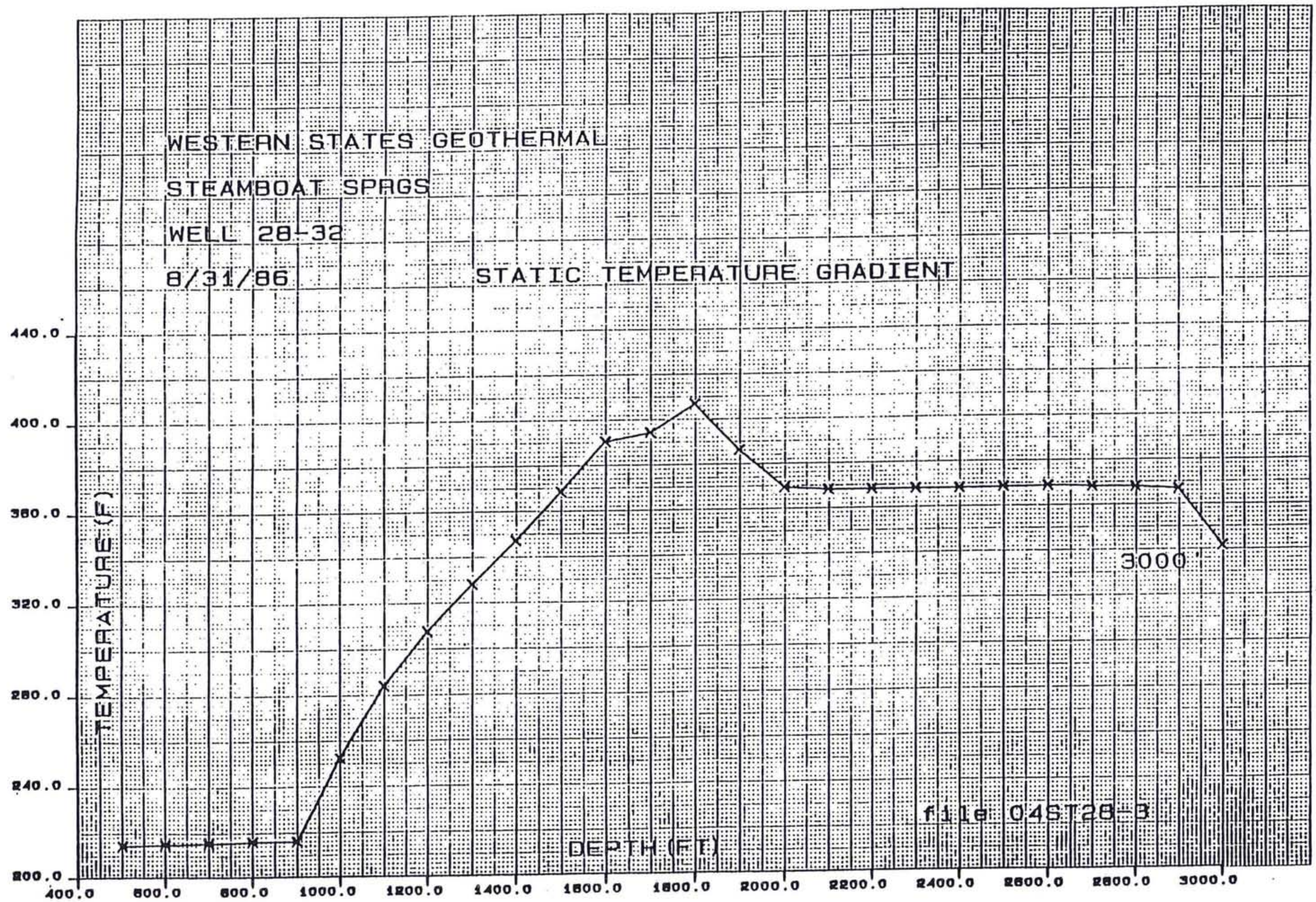
Ground elevation 5594'

Well spudded 3/31/86, T.D. 4/30/86

Montgomery Drlg Rig #19



TSi ThermaSource Inc. P.O. Box 1236 · Santa Rosa, California 95402 · (707) 523-2960	DRAWN
	FOR:
	BY:
SS 28 - 32 WELL SCHEMATIC	DATE:
	SCALE:
	DRAWING No.


WESTERN STATES GEOTHERMAL
STEAMBOAT SPRGS
WELL 28-32
8/31/86
STATIC TEMPERATURE GRADIENT
TEMPERATURE (F)
DEPTH (FT)
3000
file 04ST28-3
200.0
240.0
280.0
320.0
360.0
400.0
440.0
400.0
600.0
800.0
1000.0
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1600.0
1800.0
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2200.0
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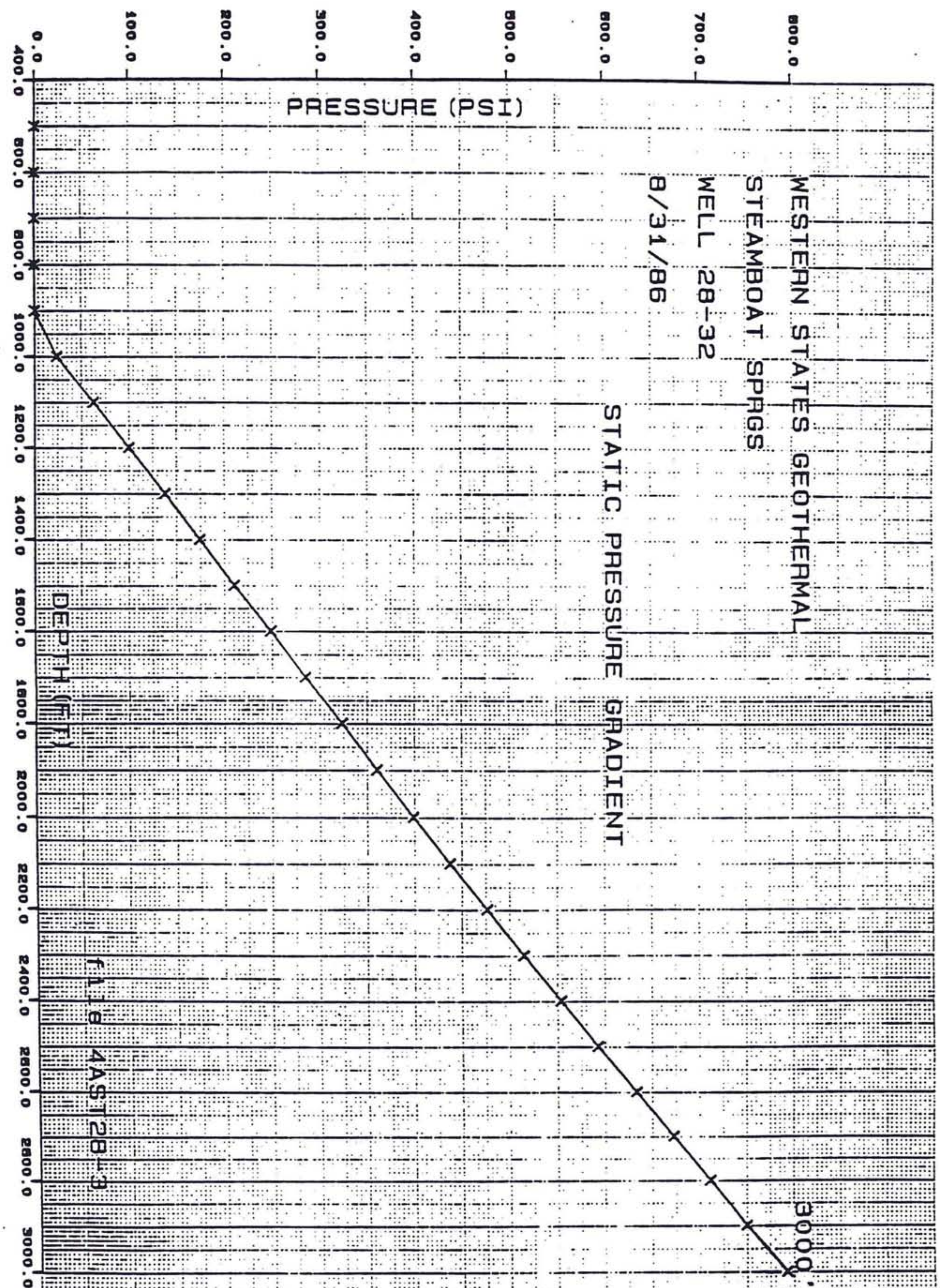
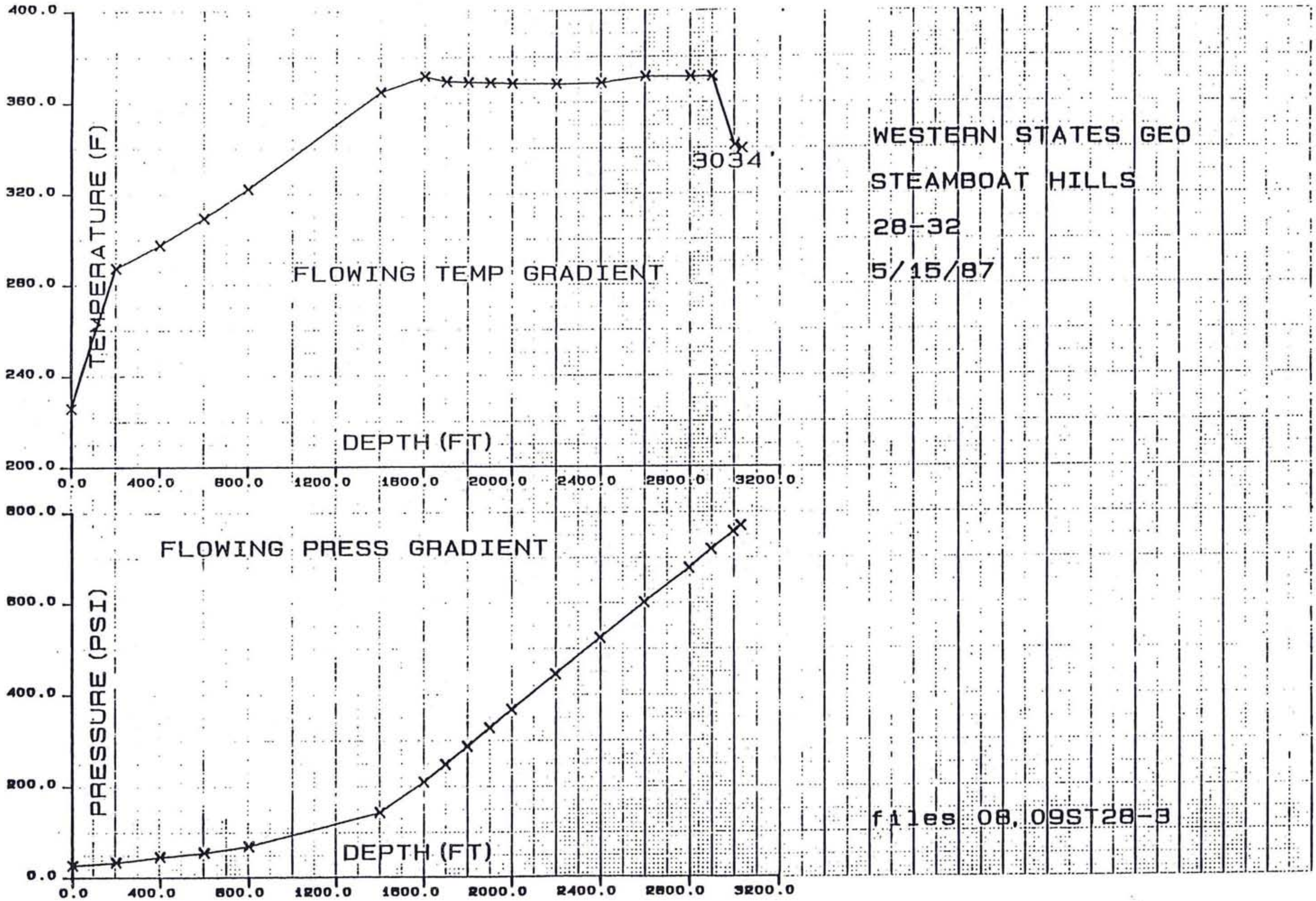
2600.0
2800.0
3000.0


PRESSURE (PSI)
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
WESTERN STATES GEOTHERMAL
STEAMBOAT SPRGS
WELL 28-32
8/31/86
STATIC PRESSURE GRADIENT
DEPTH (FT)
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0
2600.0
2800.0
3000.0
file 4AST28-3
3000'

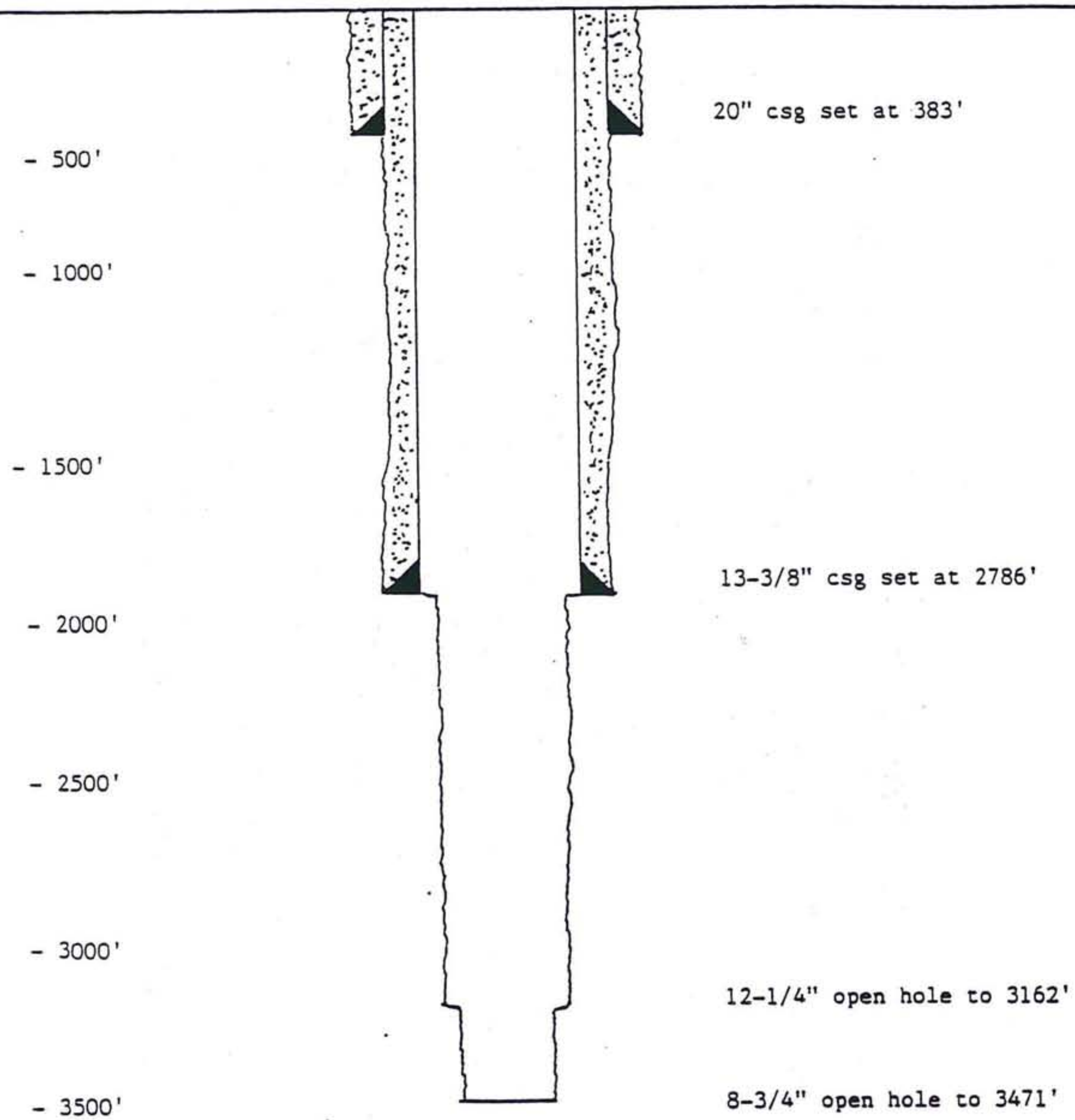

WESTERN STATES GEO
STEAMBOAT HILLS
28-32
5/15/87
FLOWING TEMP GRADIENT
TEMPERATURE (F)
DEPTH (FT)
3034'
FLOWING PRESS GRADIENT
PRESSURE (PSI)
DEPTH (FT)
files 08,09ST28-3
400.0
360.0
320.0
280.0
240.0
200.0
800.0
600.0
400.0
200.0
0.0
0.0
400.0
800.0
1200.0
1600.0
2000.0
2400.0
2800.0
3200.0

All depths based on kelly bushing elevation = ground level + 22'

Ground elevation 5057'

Spud date 4/1/81

T.D. date 5/7/81 H & W Drlg Co.



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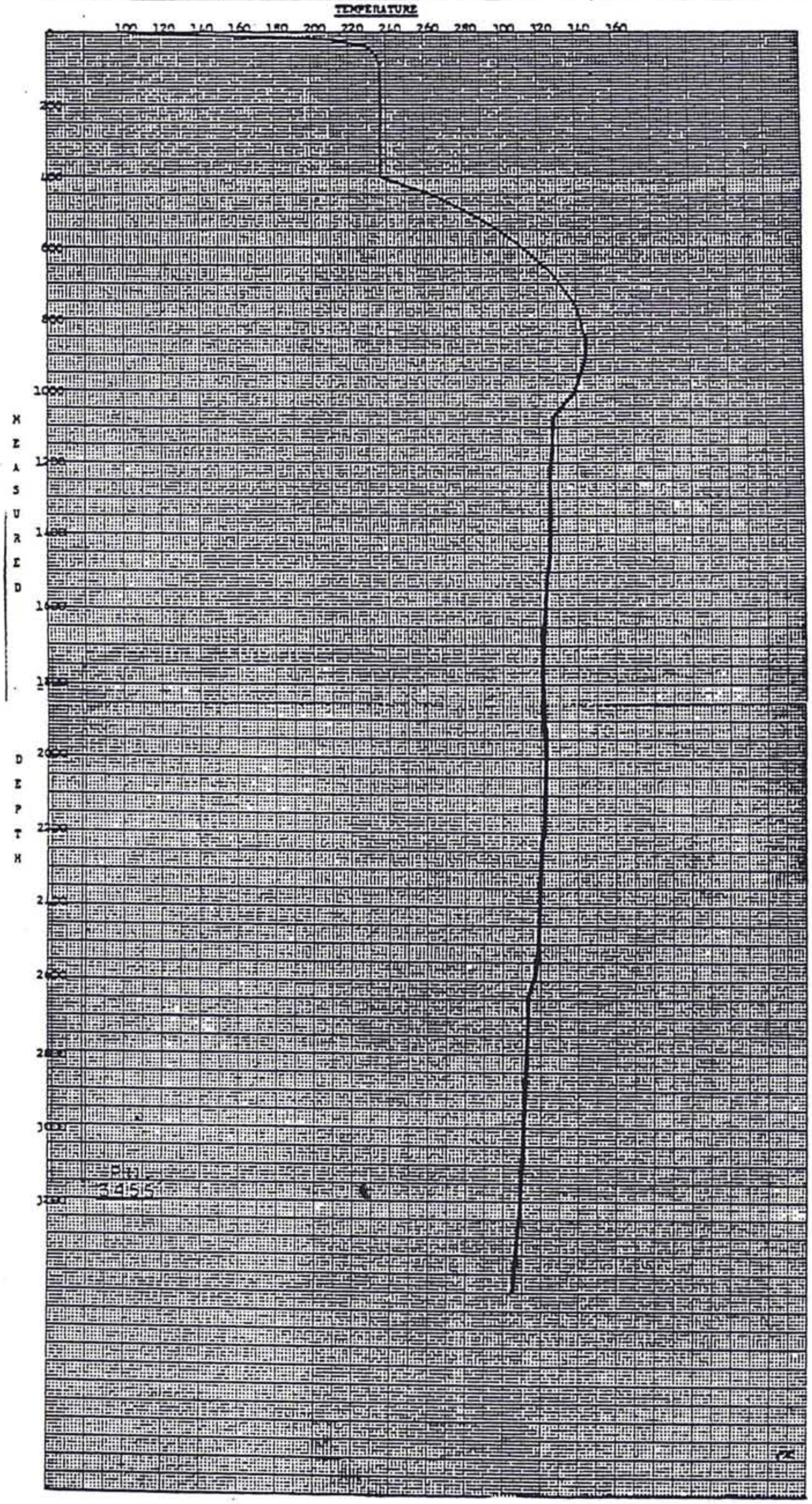
SS COX #1 WELL SCHEMATIC

DRAWN
FOR:
BY:
DATE:
SCALE:
DRAWING No.

SUB—SURFACE TEMPERATURE SURVEY

COMPANY Phillips FIELD Steamboat Springs WELL NAME Cox I-1

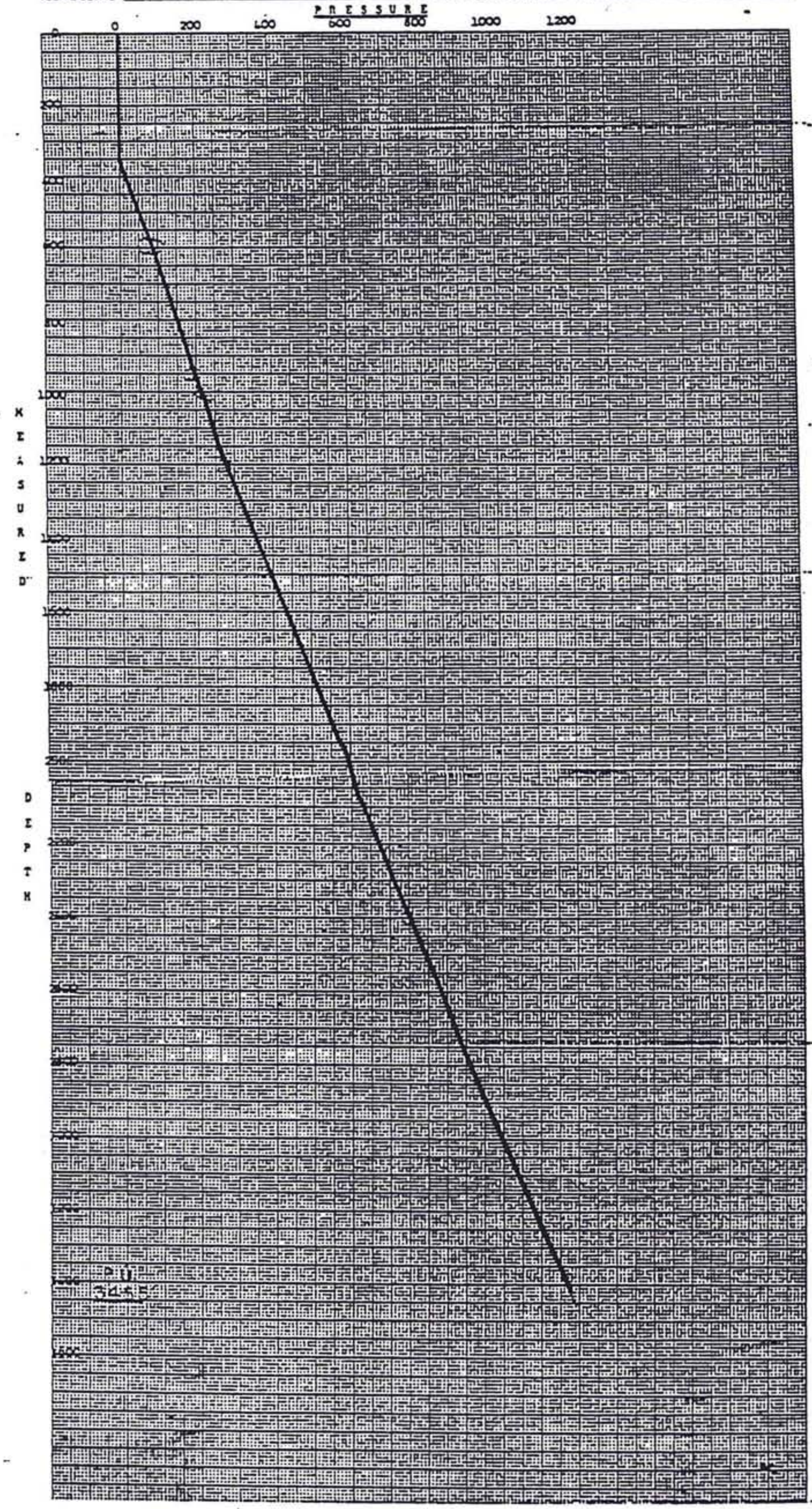
TOTAL DEPTH 3471'	WELL STATUS Static	BOMB HUNG @ none	DATE July 31, 1981
CASING 13 3/8" @ 1762'	CASING PRESSURE —	TIME ON BOTTOM 6:28	ELEMENT RANGE 40-485
LINER 12¼" @ 3162'	TUBING PRESSURE —	TIME OFF BOTTOM 6:38	ZERO POINT 22'
PERFORATIONS —	ZONE —	SHUT IN —	ELEVATION —
MPP —	MAX. °F. 345.00°	ON PRODUCTION —	PICKUP 3455'
TUBING DETAIL —		PURPOSE Traverse Temperature	

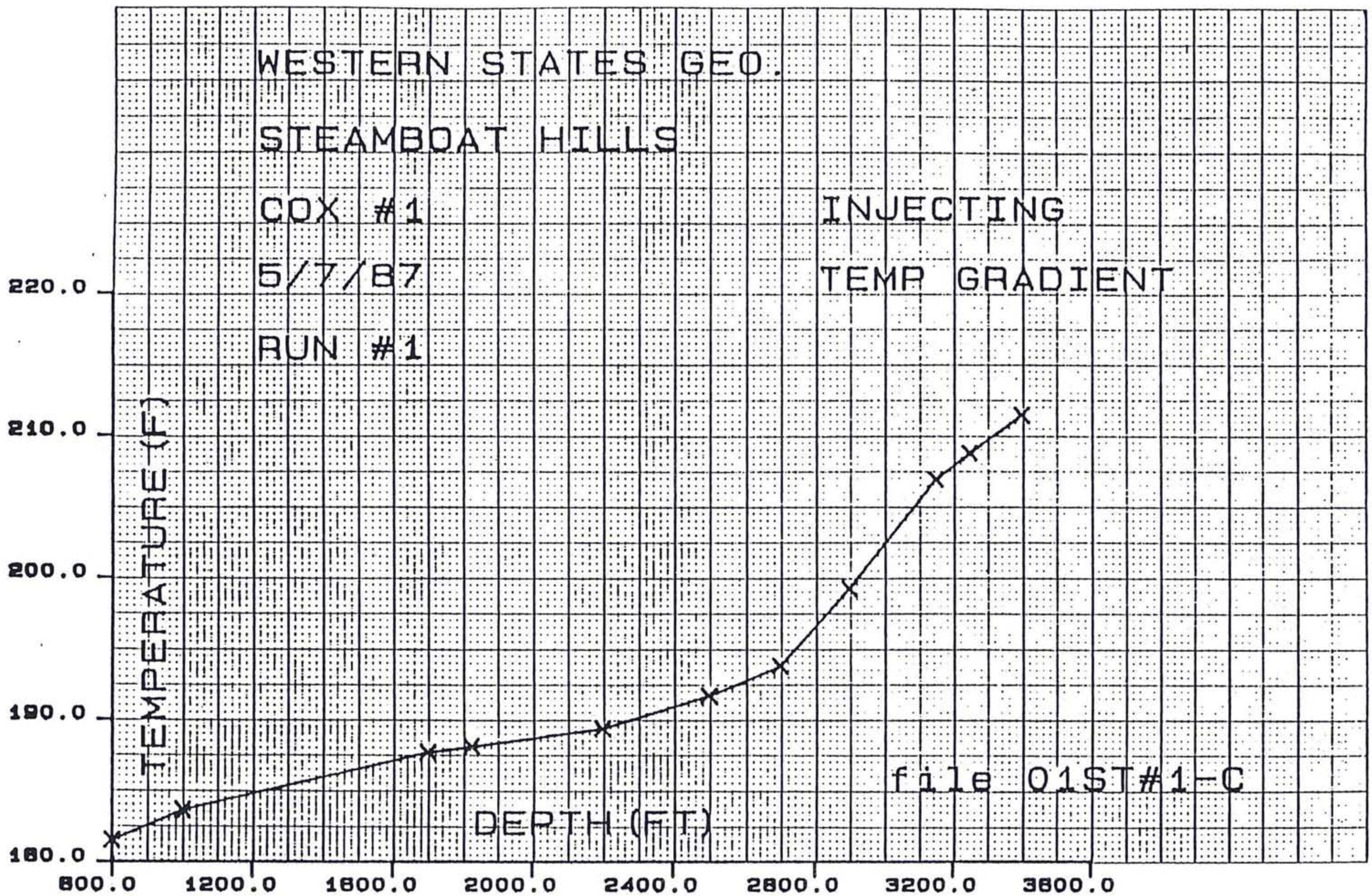


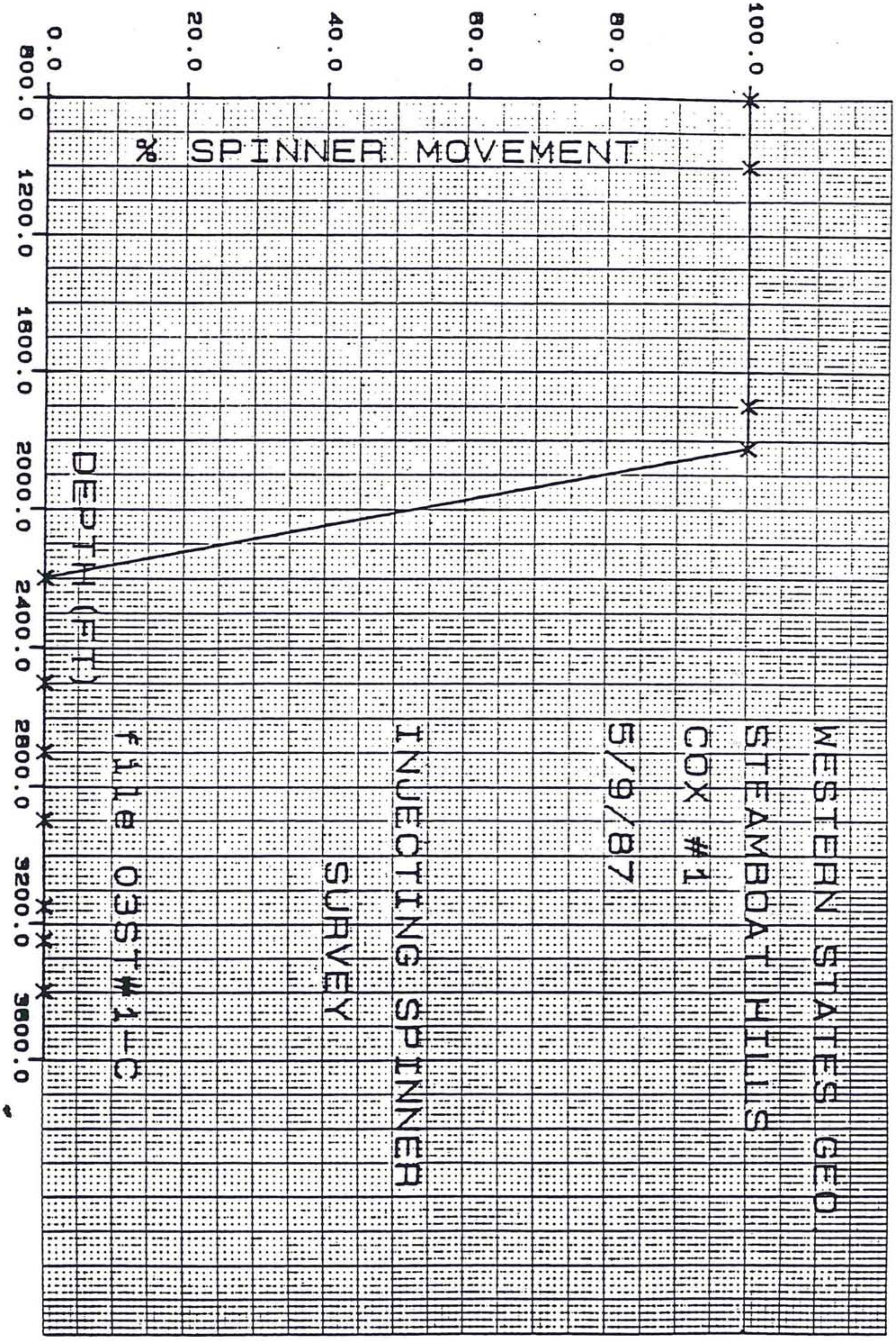
SUB—SURFACE PRESSURE SURVEY

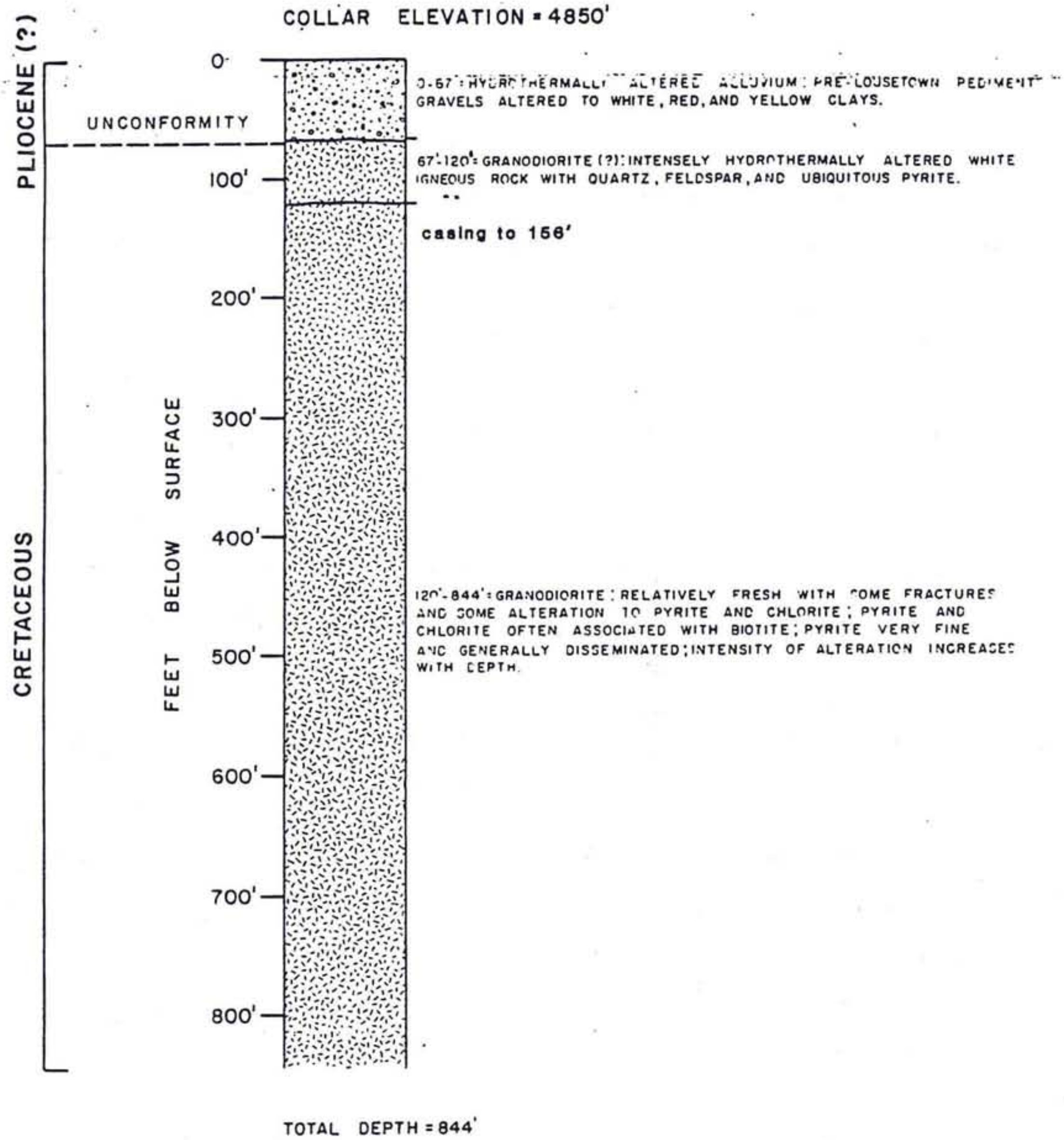
COMPANY Phillips FIELD Steamboat Springs WELL NAME COX I #1

TOTAL DEPTH 3471'	WELL STATUS Static	BOMB HUNG @ none	DATE Nov 6, 1981
CASING 1762'	CASING PRESSURE —	TIME ON BOTTOM 10:53	ELEMENT RANGE 2000 PSI
LINER —	TUBING PRESSURE —	TIME OFF BOTTOM 11:08	ZERO POINT 22.5'
PERFORATIONS —	ZONE —	SHUT IN —	ELEVATION —
MPP —	MAX °F 319.62°	ON PRODUCTION —	PICKUP 3455'
TUBING DETAIL —		PURPOSE Traverse Pressure @ 20' per minute	




WESTERN STATES GEO.
STEAMBOAT HILLS
COX #1
5/7/87
RUN #1
INJECTING
TEMP GRADIENT
TEMPERATURE (F)
DEPTH (FT)
file 01ST#1-C
220.0
210.0
200.0
190.0
180.0
800.0
1200.0
1600.0
2000.0
2400.0
2800.0
3200.0
3600.0


% SPINNER MOVEMENT
DEPTH (FT)
WESTERN STATES GEO
STEAMBOAT HILLS
COX #1
5/9/87
INJECTING SPINNER
SURVEY
0.0
20.0
40.0
60.0
80.0
100.0
800.0
1200.0
1600.0
2000.0
2400.0
2800.0
3200.0
3600.0



LITHOLOGIC LOG OF STEAMBOAT SPRINGS
STRATIGRAPHIC TEST NO. 2

LOCATION: 210' SOUTH OF THE NORTH LINE AND 2370' WEST OF THE EAST LINE OF SECTION 32, T.18 N., R.20 E., WASHOE COUNTY, NEVADA.

DATE STARTED: OCTOBER 7, 1977

DATE COMPLETED: OCTOBER 18, 1977

AGNEW AND SWEET

Production Specialists

WIRELINE SERVICE

PHONE (805) 327-2267
3914 GILMORE AVENUE
BAKERSFIELD, CALIFORNIA 93308

SUBSURFACE TEMPERATURE SURVEY

OWNER PHILLIPS PETROLEUM COMPANY FIELD STEAMBOAT SPRINGS WELL NAME Strat #2

WELL DATA

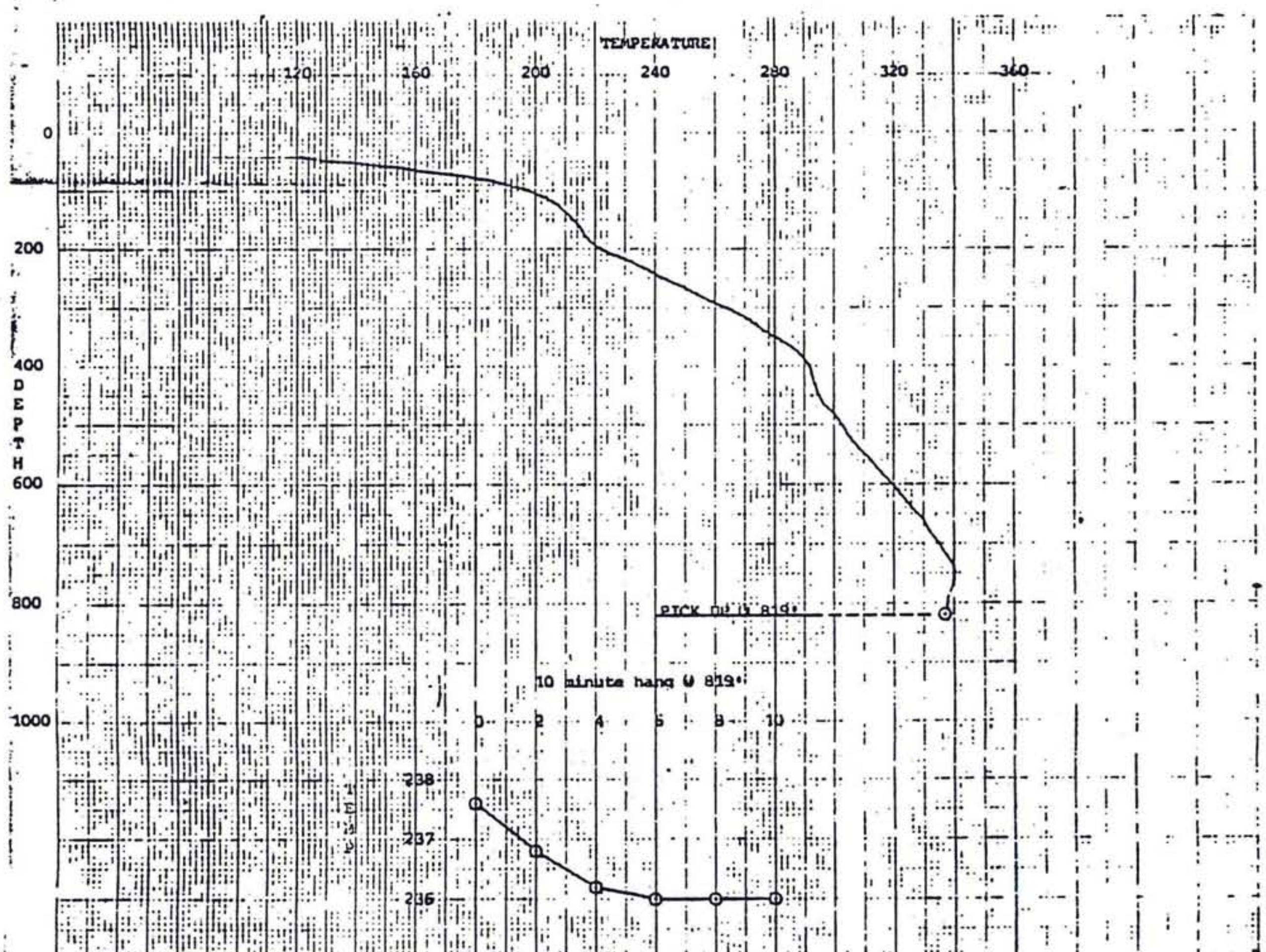
ZERO POINT Ground DEPTH
ELEVATION ZONE
CASING
LINER DESCRIPTION
TUBING DETAIL 2-7/8" 837' plugged

SURVEY CONDITIONS

DATE November 30, 1977
PURPOSE STATIC TEMPERATURE TRAVERSE SURVEY
REMARKS Open hole 20'/min/
3 HOUR 15 TURN ☒ TUBING ☐ ANNULUS
INSTRUMENT 85-645 °F. SERIAL NUMBER 10287
MAX. TEMPERATURE 340.3 °F. AT 740'
SHUT IN STABILIZATION PERIOD
PICK UP 819'
STATUS Static
TIME ON BOTTOM 11:33 am
TIME OFF BOTTOM 11:43 am

PRESSURE, P SIG	START	FINISH
CASING		
TUBING		

INSTRUMENT HUNG AT 819' BY Sundberg & Crider



PRUETT WIRELINE SERVICE

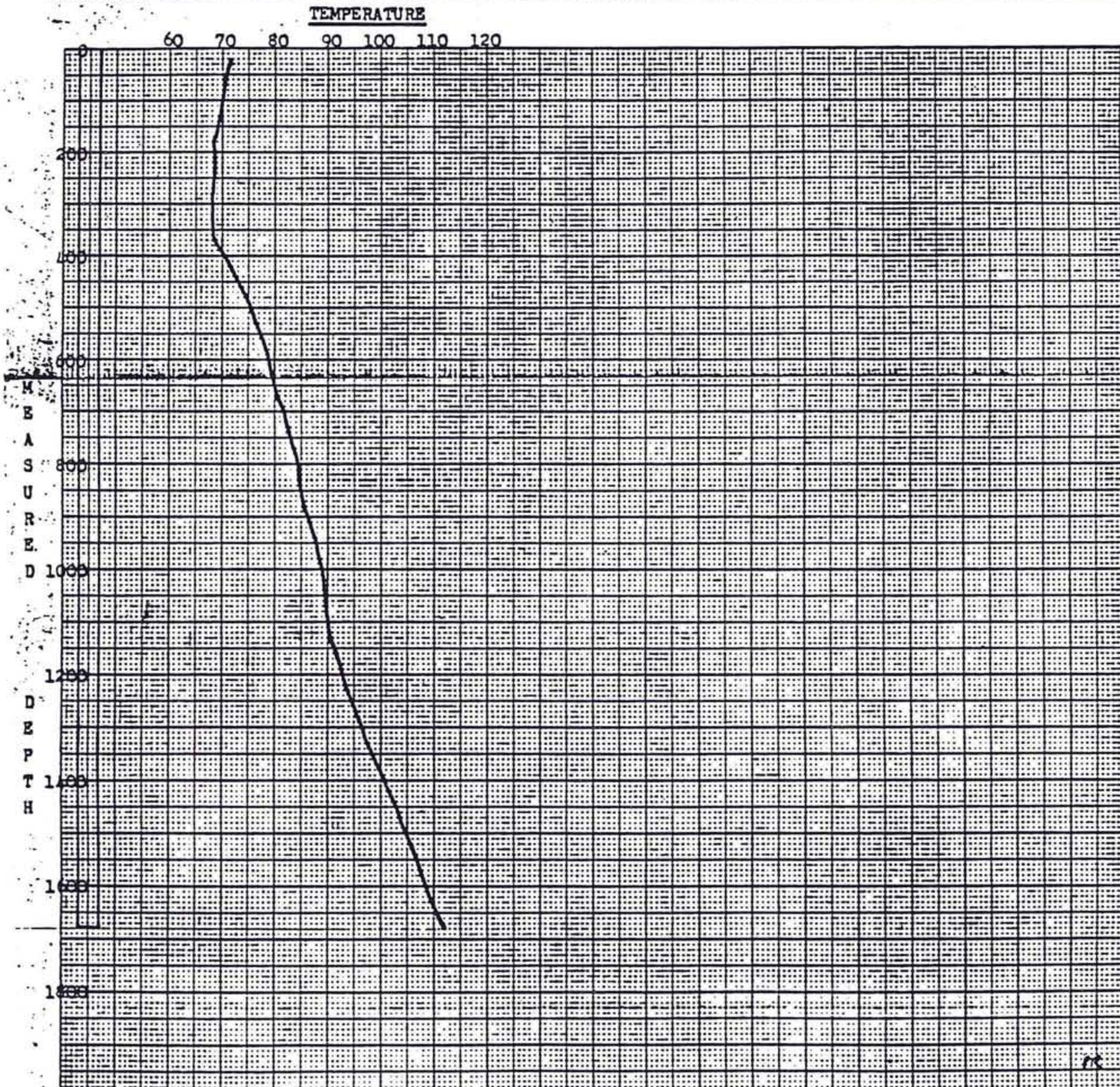
8915 ROSEDALE HWY., BAKERSFIELD, CA 93308
(805) 589-2768

Pruett Wireline

SUB—SURFACE TEMPERATURE SURVEY

COMPANY Phillips FIELD Steamboat Springs Sec 31 T 18 N R 20 E WELL NAME Strat 5

TOTAL DEPTH open Bottom	WELL STATUS Static	BOMB HUNG @ none	DATE May 29, 1980
CASING —	CASING PRESSURE —	TIME ON BOTTOM 5:44pm	ELEMENT RANGE 44-482°
LINER —	TUBING PRESSURE —	TIME OFF BOTTOM 5:54pm	ZERO POINT 0 at valve
PERFORATIONS —	ZONE —	SHUT IN —	ELEVATION —
MPP —	MAX. °F. 111.84°	ON PRODUCTION —	PICKUP none made
TUBING DETAIL 2 7/8" @ 1680'		PURPOSE Traverse Temperature Survey	



CONFIDENTIAL AND PROPRIETARY
DATA MAY NOT BE RELEASED WITHOUT PRIOR WRITTEN APPROVAL OF PHILLIPS PETROLEUM CO.

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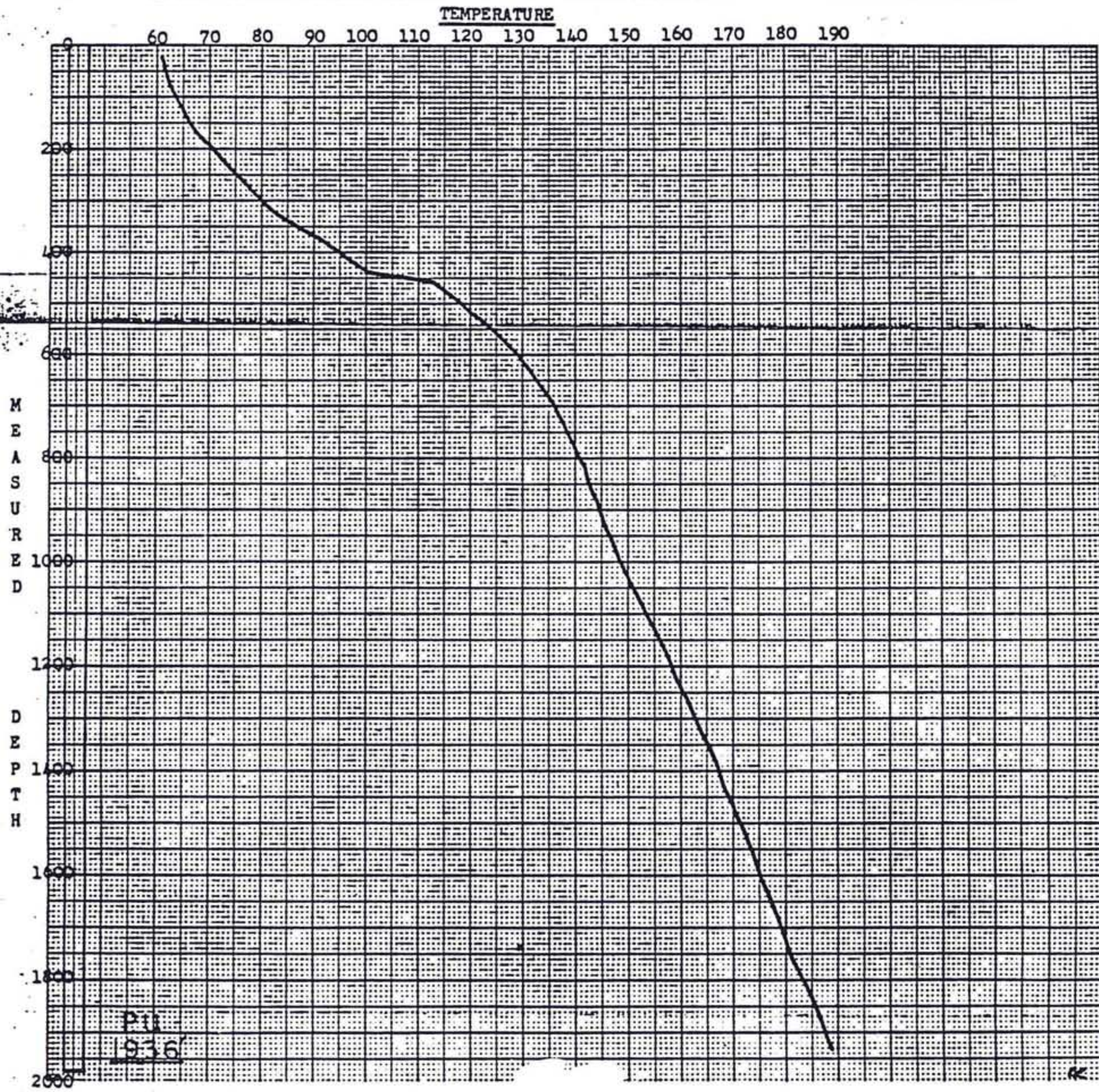
(805) 589-2768

Pruett Wireline

SUB—SURFACE TEMPERATURE SURVEY

COMPANY Phillips FIELD Steamboat Springs SENE 5 T 17 N RZOE WELL NAME Strat 6

TOTAL DEPTH 1976'	WELL STATUS Static	BOMB HUNG @ none	DATE May 28, 1980
CASING —	CASING PRESSURE —	TIME ON BOTTOM 5:52pm	ELEMENT RANGE 44-482°
LINER —	TUBING PRESSURE —	TIME OFF BOTTOM 6:00pm	ZERO POINT 0 at valve
PERFORATIONS —	ZONE —	SHUT IN —	ELEVATION —
MPP —	MAX. °F. 189.01°	ON PRODUCTION —	PICKUP 1936'
TUBING DETAIL 2 7/8" @ 1976'		PURPOSE Traverse Temperature Survey	



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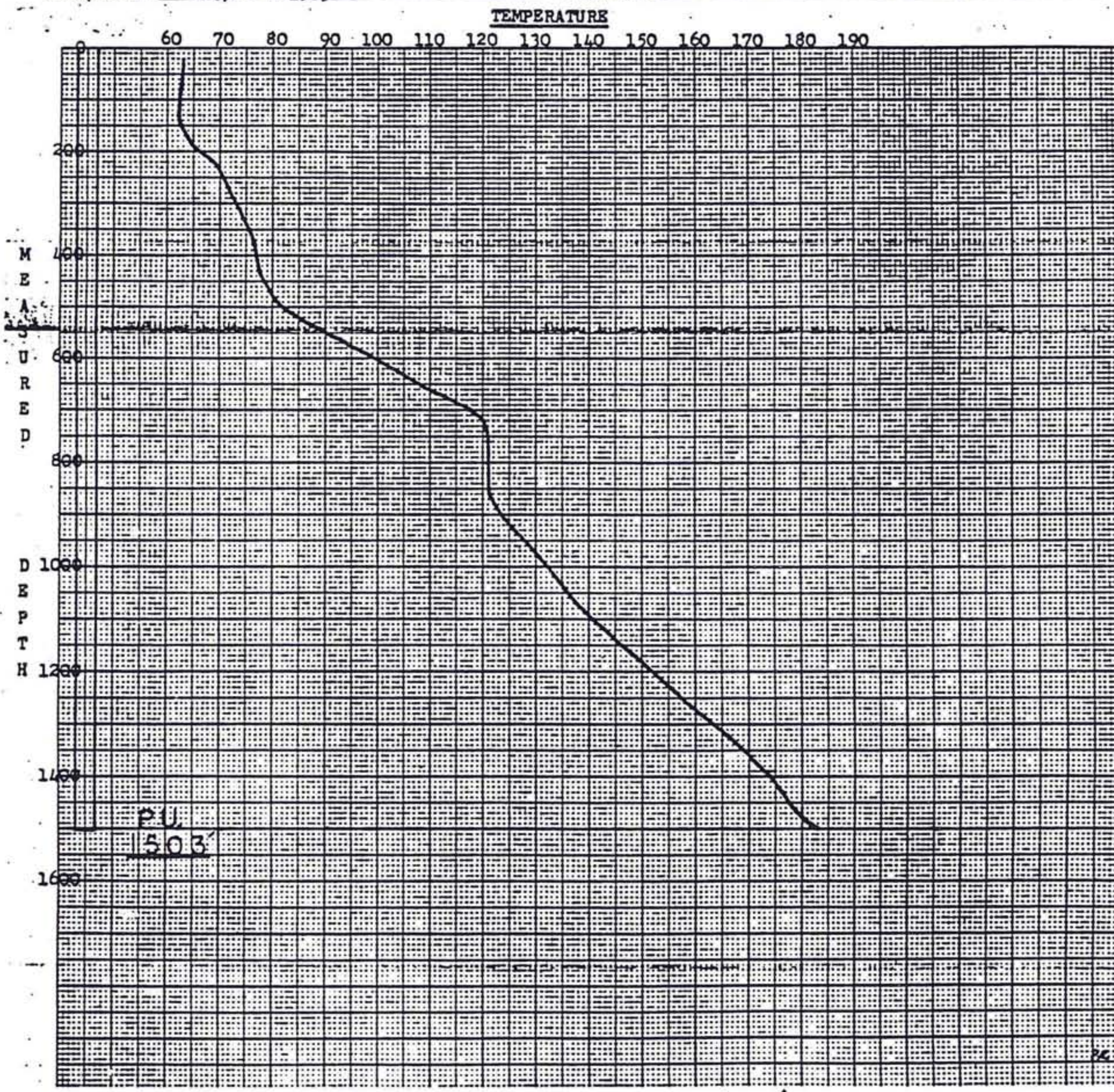
PRUETT WIRELINE SERVICE

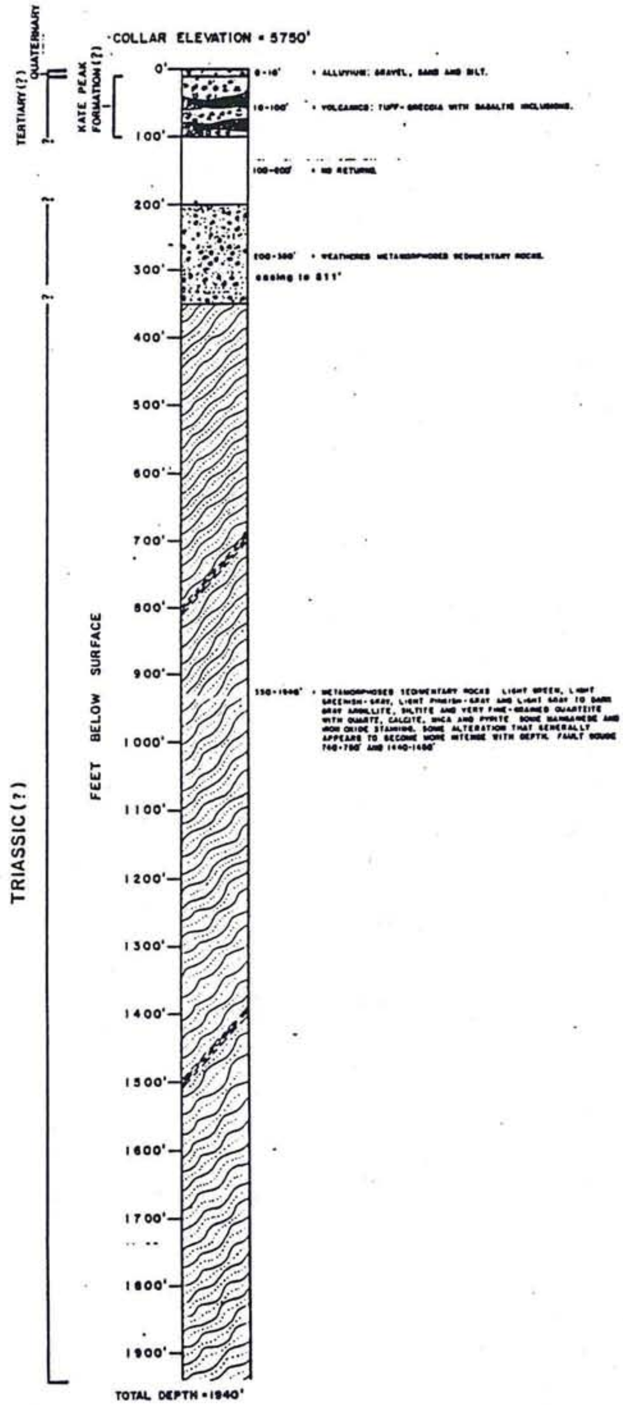
8915 ROSEDALE HWY., BAKERSFIELD, CA 93308
(805) 589-2788

SUB—SURFACE TEMPERATURE SURVEY

COMPANY Phillips FIELD Steamboat Valley NENW 7 T 17 NR 20 E WELL NAME Strat 7

TOTAL DEPTH —	WELL STATUS Static	BOMB HUNG @ none	DATE May 29, 1980
CASING —	CASING PRESSURE —	TIME ON BOTTOM 8:55pm	ELEMENT RANGE 44-482°
LINER —	TUBING PRESSURE —	TIME OFF BOTTOM 9:00pm	ZERO POINT 0 at valve
PERFORATIONS —	ZONE —	SHUT IN —	ELEVATION —
MPP —	MAX. °F 183.15°	ON PRODUCTION —	PICKUP 1503'
TUBING DETAIL 2 7/8" @ 1503'		PURPOSE Traverse Temperature Survey	





LITHOLOGIC LOG OF STEAMBOAT SPRINGS STRATIGRAPHIC TEST NO. 8

CONFIDENTIAL AND PROPRIETARY

LOCATION: 2010' SOUTH OF THE NORTH LINE AND 2170' WEST OF THE EAST LINE OF SECTION 6, T17N R20E, WASHOE COUNTY, NEVADA

DATE STARTED: JANUARY 24, 1990

DATE COMPLETED: MARCH 7, 1990

CONFIDENTIAL AND PROPRIETARY
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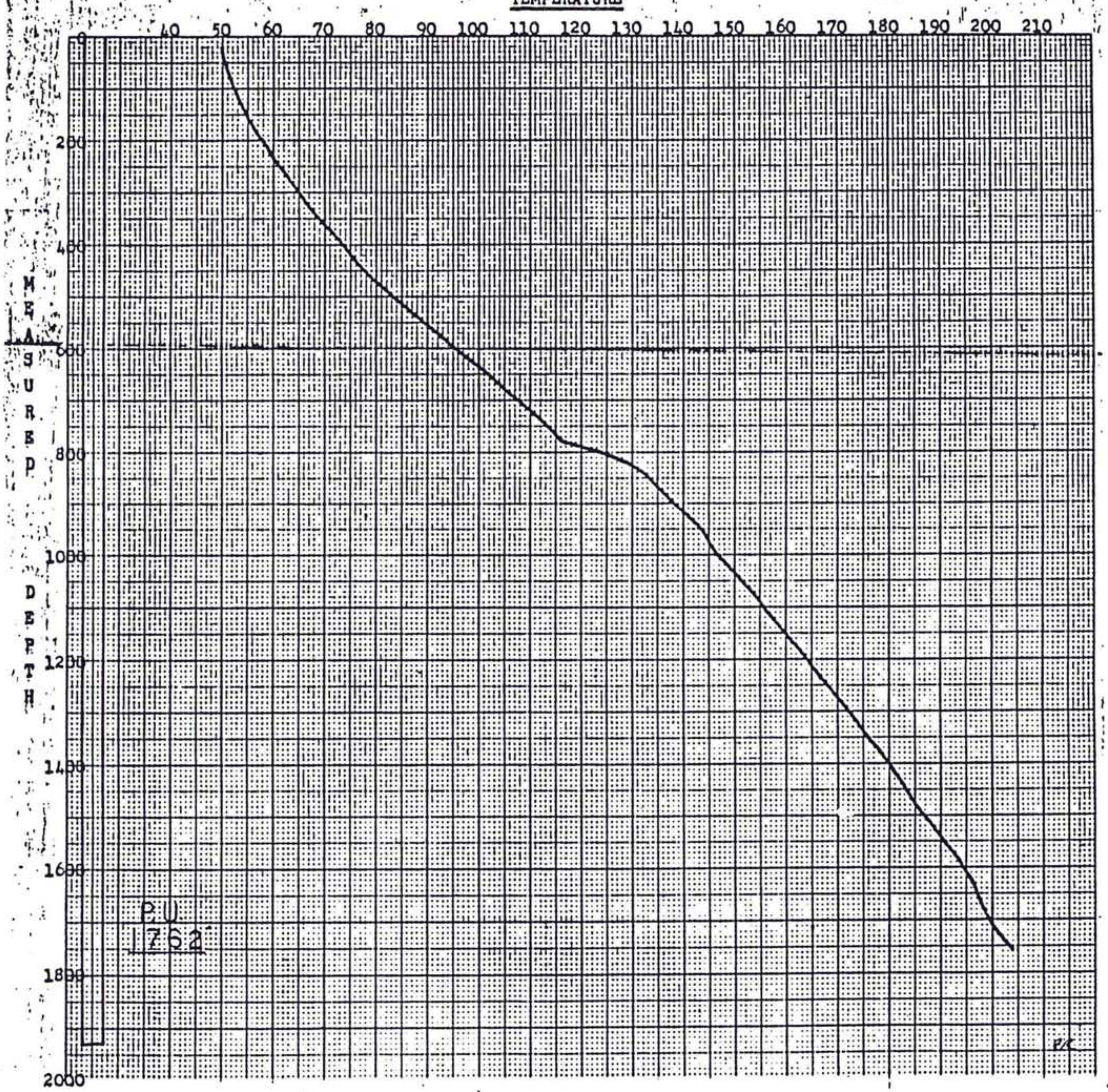
(805) 589-2768

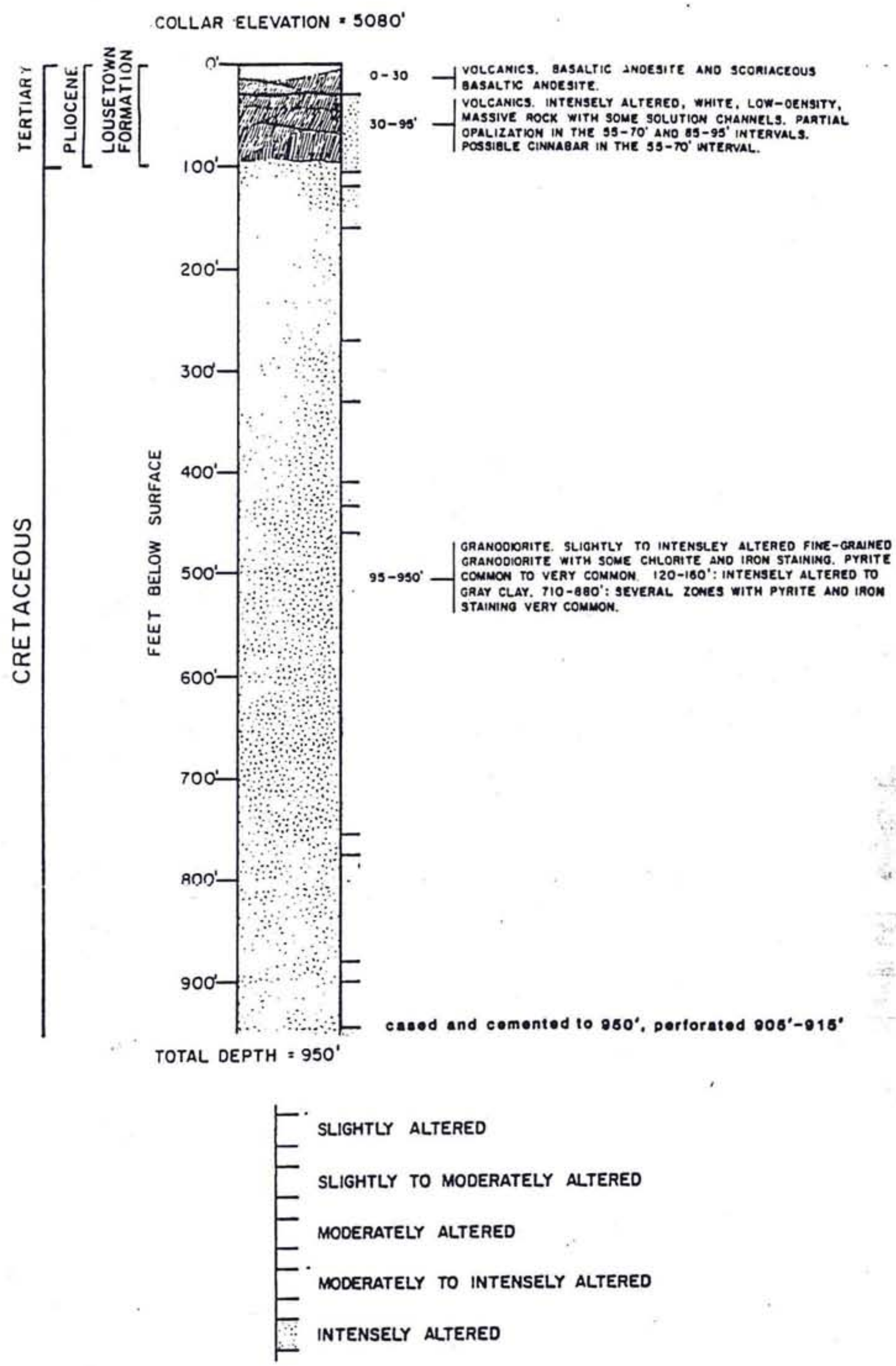
Pruett Wireline

SUB—SURFACE TEMPERATURE SURVEY

COMPANY Phillips FIELD Steamboat Springs SWNE 6 T 17 N R 20 E WELL NAME Strat 8

TOTAL DEPTH — WELL STATUS Static BOMB HUNG @ none DATE May 28, 1980
CASING — CASING PRESSURE — TIME ON BOTTOM 9:18am ELEMENT RANGE 44-482°
LINER — TUBING PRESSURE — TIME OFF BOTTOM 9:27am ZERO POINT 0 at 2" gate
PERFORATIONS — ZONE — SHUT IN — ELEVATION —
MPP — MAX. °F 203.86° ON PRODUCTION — PICKUP 1762'
TUBING DETAIL 2 7/8" @ 1930' PURPOSE Traverse Temperature Survey





LITHOLOGIC LOG OF STEAMBOAT SPRINGS STRATIGRAPHIC TEST NO. 9

LOCATION: 1875' WEST OF THE EAST LINE AND 2450' NORTH OF THE SOUTH LINE OF SECTION 32, T18N, R20E, WASHOE COUNTY, NEVADA

DATE STARTED: MAY 5, 1980

DATE COMPLETED: MAY 19, 1980

CONFIDENTIAL AND PROPRIETARY
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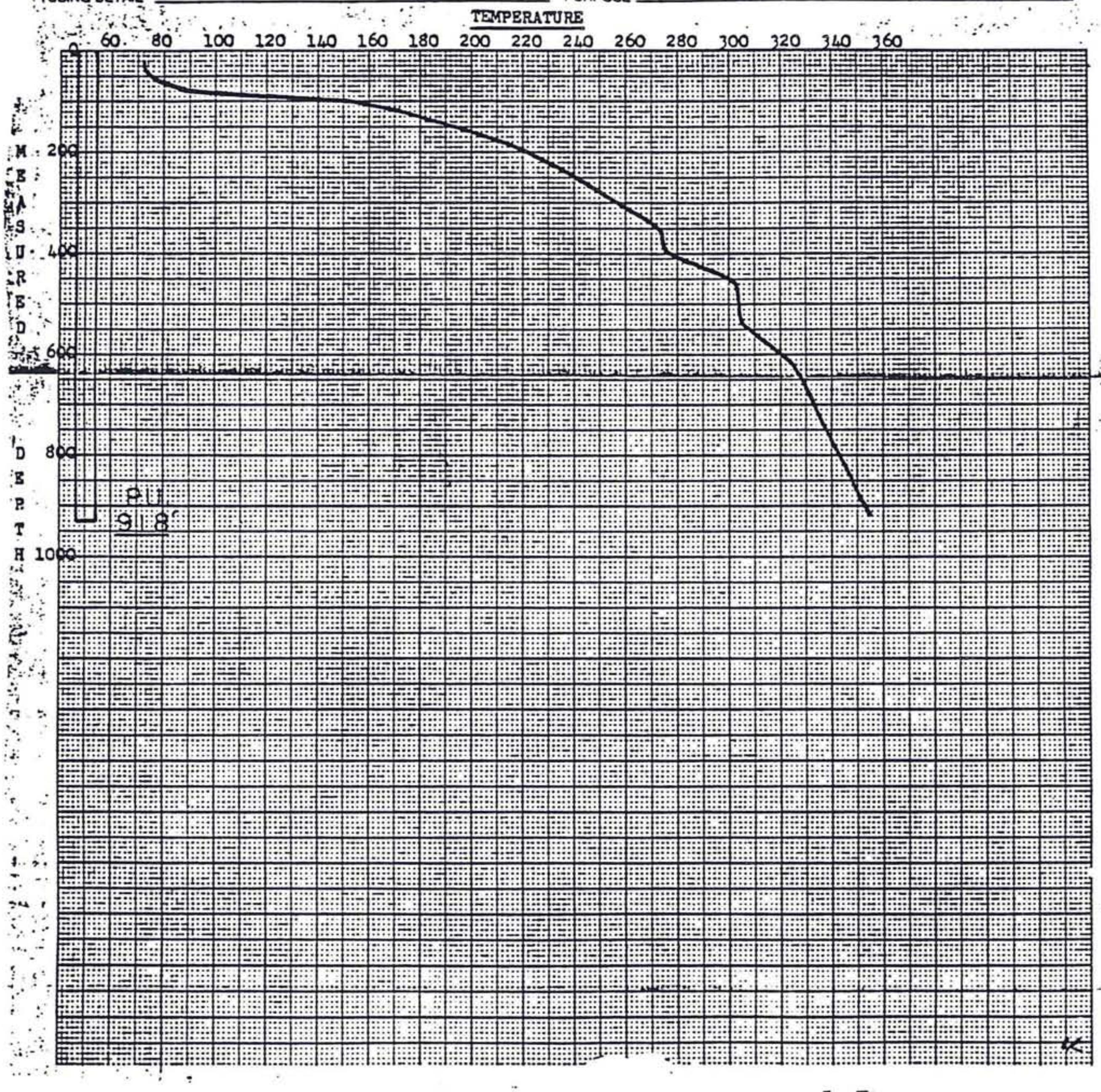
PRUETT WIRELINE SERVICE

8915 ROSEDALE HWY., BAKERSFIELD, CA 93308
(805) 589-2768

SUB—SURFACE TEMPERATURE SURVEY

COMPANY Phillips FIELD Steamboat Springs NWSE 32 T 18 NR 20 E WELL NAME Strat 9

TOTAL DEPTH	933'	WELL STATUS	Static	BOMB HUNG @	none	DATE	May 29, 1980
CASING	—	CASING PRESSURE	—	TIME ON BOTTOM	10:46am	ELEMENT RANGE	44-482°
LINER	" —	TUBING PRESSURE	—	TIME OFF BOTTOM	10:56am	ZERO POINT	0 at valve
PERFORATIONS	—	ZONE	—	SHUT IN	—	ELEVATION	—
MPP	—	MAX. °F.	354.71°	ON PRODUCTION	—	PICKUP	918'
TUBING DETAIL	2 7/8" @ 933'			PURPOSE	Traverse Temperature Survey		



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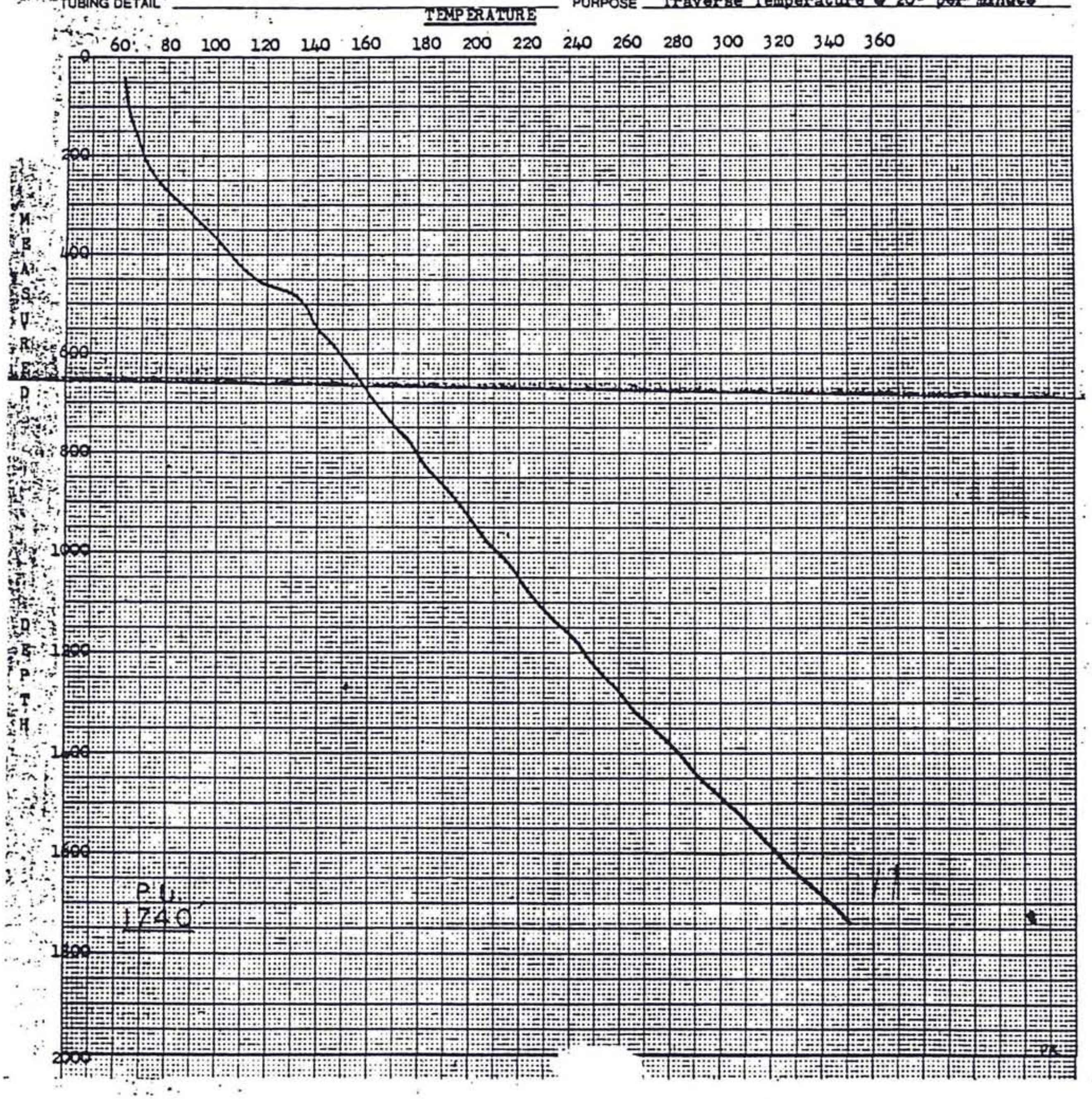
Pruett Wireline

SUB—SURFACE TEMPERATURE SURVEY

COMPANY: Phillips | FIELD: Steamboat | WELL NAME: Strat Test 13

TOTAL DEPTH: 1739'	WELL STATUS: Static	BOMB HUNG @: none	DATE: Dec 5, 1981
CASING:	CASING PRESSURE: —	TIME ON BOTTOM: 1:42	ELEMENT RANGE: 60-510°
LINER:	TUBING PRESSURE: —	TIME OFF BOTTOM: 1:52	ZERO POINT: 5'
PERFORATIONS:	ZONE: —	SHUT IN: —	ELEVATION: —
MPP:	MAX. °F: 350.93°	ON PRODUCTION: —	PICKUP: 1740'
TUBING DETAIL:		PURPOSE: Traverse Temperature @ 20' per minute	



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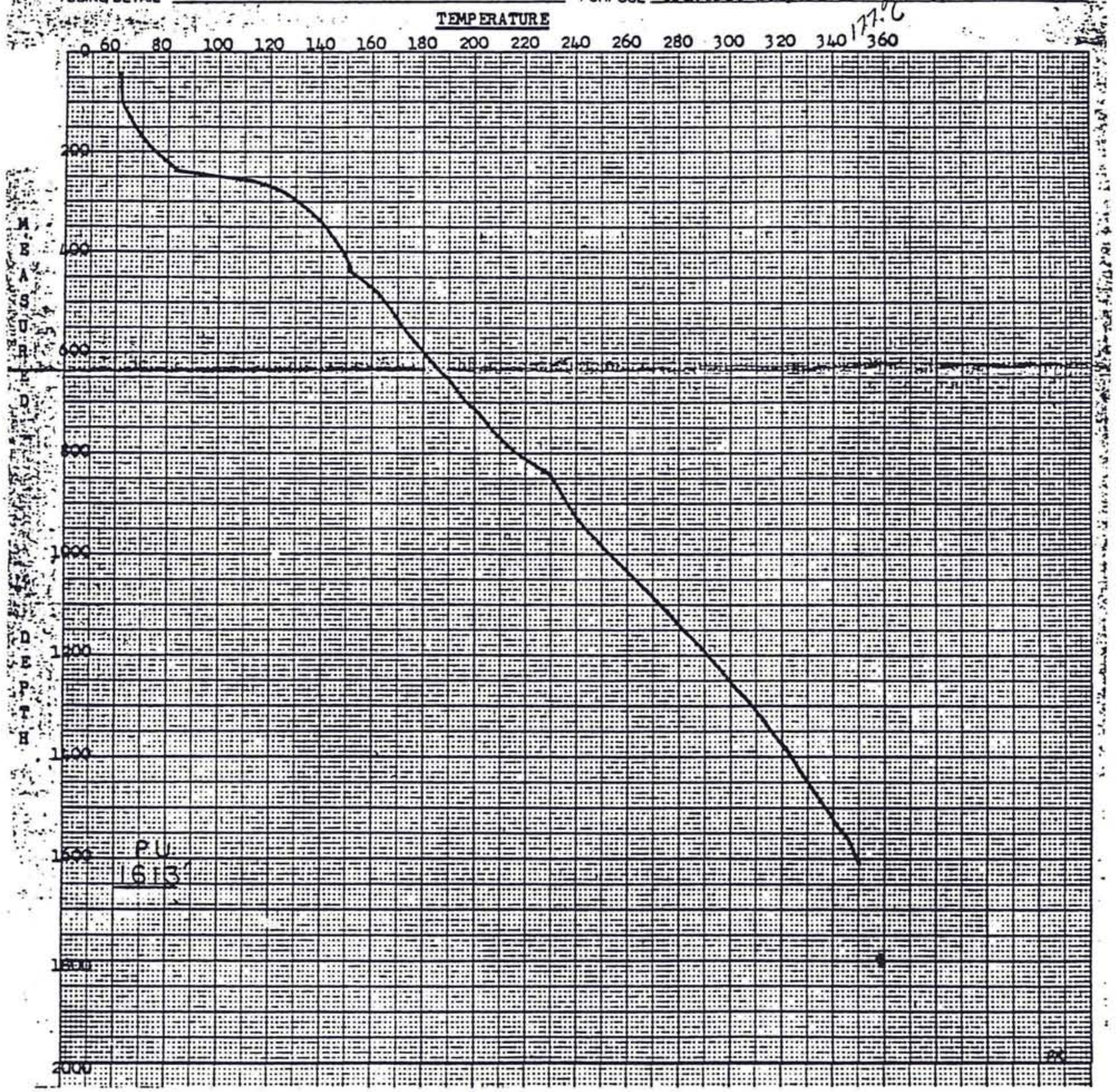
(805) 589-2768

Pruett Wireline

SUB—SURFACE TEMPERATURE SURVEY

COMPANY Phillips FIELD Steamboat WELL NAME Strat Test 14

TOTAL DEPTH	1609'	WELL STATUS	Static	BOMB HUNG @	none	DATE	Dec 5, 1981
CASING		CASING PRESSURE	—	TIME ON BOTTOM	10:41	ELEMENT RANGE	61–510°
LINER		TUBING PRESSURE	—	TIME OFF BOTTOM	10:51	ZERO POINT	5'
PERFORATIONS		ZONE	—	SHUT IN	—	ELEVATION	—
MPP		MAX. °F.	350.07°	ON PRODUCTION	—	PICKUP	1613'
TUBING DETAIL				PURPOSE	Traverse Temperature @ 20', per minute		



WHITE—DIVISION OF WATER RESOURCES
CANARY—CLIENT'S COPY
PINK—WELL DRILLER'S COPY

Strat 5

STATE OF NEVADA
DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 21795
Permit No.
Basin

1. OWNER Phillips Petroleum Company ADDRESS P. O. Box 10566
Reno, Nevada 89510

2. LOCATION SE ¼ NW ¼ Sec. 31 T. 18 N/S R. 20 E. Washoe County
PERMIT NO.

3. TYPE OF WORK
New Well ☐ Recondition ☐
Deepen ☐ Other ☒

4. PROPOSED USE
Domestic ☐ Irrigation ☐ Test ☒
Municipal ☐ Industrial ☐ Stock ☐

5. TYPE WELL
Cable ☐ Rotary ☒
Other ☐

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Gravel and sand		0	30	
Gravel, sand and silt		30	60	
Gravel		60	70	
Gravel, sand and silt		70	120	
Gravel		120	140	
Gravel, sand and silt		140	300	
Gravel and sand		300	340	
Gravel, sand and silt		340	370	
Granodiorite		370	1700	

Date started March 7, 1978
Date completed April 2, 1978

7. WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump

BAILER TEST

G.P.M. .... Draw down .... feet .... hours
G.P.M. .... Draw down .... feet .... hours
G.P.M. .... Draw down .... feet .... hours

8. WELL CONSTRUCTION

Diameter hole 8½ inches Total depth 1700 feet
Casing record 285' of 7"
Weight per foot .... Thickness ....

Diameter	From	To
7 inches	0 feet	285 feet
inches	feet	feet
inches	feet	feet
inches	feet	feet
inches	feet	feet
inches	feet	feet

Surface seal: Yes ☒ No ☐ Type Cement
Depth of seal 285 feet
Gravel packed: Yes ☐ No ☒
Gravel packed from .... feet to .... feet

Perforations:
Type perforation None
Size perforation
From .... feet to .... feet
From .... feet to .... feet
From .... feet to .... feet
From .... feet to .... feet
From .... feet to .... feet

9. WATER LEVEL

Static water level unknown Feet below land surface
Flow .... G.P.M.
Water temperature .... °F. Quality ....

10. DRILLERS CERTIFICATION

This well was drilled under my supervision and the report is true to the best of my knowledge.

Name Joe Bowden
Address P. O. Box 10566
Reno, Nevada 89510

Nevada contractor's license number 862

Nevada driller's license number 862

Signed Joe Bowden

Date April 14, 1978

CANARY—CLIENT'S COPY
PINK—WELL DRILLER'S COPY

Cox I-1

DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 22782
Permit No. 41126
Basin

1. OWNER Phillips Petroleum Company ADDRESS P. O. Box 6256 Reno, Nevada 89513

2. LOCATION SW ¼ NE ¼ Sec. 32 T. 18N ~~N/S~~ R. 20 E. Washoe County
PERMIT NO.

3. TYPE OF WORK: New Well [X] Recondition [ ] Deepen [ ] Other [ ]

4. PROPOSED USE: Domestic [ ] Irrigation [ ] Test [X] Municipal [ ] Industrial [X] Stock [ ]

5. TYPE WELL: Cable [ ] Rotary [X] Other [ ]

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Volcanics		0	48	
Siliceous sinter		48	83	
Decomposed granite		83	118	
Granite		118	508	
Quartzite		508	683	
Granite		683	3471	

6/86

Date started April 1, 1981
Date completed May 7, 1981

7. N/A WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump

BAILER TEST

G.P.M. Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

8. WELL CONSTRUCTION

Diameter hole 8 3/4 inches Total depth 3471 feet
Casing record
Weight per foot Thickness

Diameter	From	To
30 inches	0 feet	25 feet
20 inches	25 feet	361 feet
13 3/8 inches	361 feet	1765 feet

Surface seal: Yes [X] No [ ] Type cement
Depth of seal 1765 feet
Gravel packed: Yes [ ] No [X]
Gravel packed from feet to feet

Perforations:
Type perforation none
Size perforation
From feet to feet
From feet to feet
From feet to feet
From feet to feet
From feet to feet

9. WATER LEVEL

Static water level 400' Feet below land surface
Flow unknown G.P.M.
Water temperature hot °F. Quality medium

10. DRILLERS CERTIFICATION

This well was drilled under my supervision and the report is true to the best of my knowledge.

Name Sheldon Hopkins
Address P. O. Box 6256 Reno, Nevada 89513
Nevada contractor's license number
Nevada driller's license number 01059
Signed [signature]
Date May 7, 1981

WHITE—DIVISION OF WATER RESOURCES
CANARY—CLIENT'S COPY
PINK—WELL DRILLER'S COPY

Steamboat No. 1

STATE OF NEVADA
DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 21769
Permit No.
Basin.

1. OWNER Phillips Petroleum Company ADDRESS P. O. Box 6256 Reno, Nevada 89513

2. LOCATION NW ¼ NW ¼ Sec. 5 T. 17 N/S R. 20 E. Washoe County
PERMIT NO. 34917

3. TYPE OF WORK
New Well ☒ Recondition ☐
Deepen ☐ Other ☐

4. PROPOSED USE
Domestic ☐ Irrigation ☐ Test ☐
Municipal ☐ Industrial ☒ Stock ☐

5. TYPE WELL
Cable ☐ Rotary ☒
Other ☐

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Scoria		0	70	
No returns		70	160	
Basalt		160	165	
No returns		165	330	
Fine-grained metasediments		330	955	
Granodiorite		955	1790	
Fine-grained metasediments with granodiorite		1790	2930	
Granodiorite		2930	3035	
No returns		3035	3050	

Date started June 5, 1979
Date completed July 14, 1979

7. WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump
~~N.D.~~			

BAILER TEST

G.P.M. N.D. Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

8. WELL CONSTRUCTION

Diameter hole 12¼ inches Total depth 3050 feet
Casing record 0-1297'
Weight per foot Thickness

Diameter	From	To
30 inches	0 feet	20 feet
20 inches	0 feet	317 feet
13 3/8 inches	0 feet	1297 feet
inches	feet	feet
inches	feet	feet
inches	feet	feet

Surface seal: Yes ☒ No ☐ Type Cement
Depth of seal 1297' feet
Gravel packed: Yes ☐ No ☒
Gravel packed from feet to feet

Perforations:
Type perforation None
Size perforation
From feet to feet
From feet to feet
From feet to feet
From feet to feet
From feet to feet

9. WATER LEVEL

Static water level 675 Feet below land surface
Flow N.D. G.P.M.
Water temperature hot ° F. Quality poor

10. DRILLERS CERTIFICATION

This well was drilled under my supervision and the report is true to the best of my knowledge.

Name Al Cobb
Address P. O. Box 6256 Reno, Nevada 89513
Nevada contractor's license number
Nevada driller's license number 903
Signed William L. Dromier for Al Cobb
Date July 18, 1979

WHITE—DIVISION OF WATER RESOURCES
CANARY—CLIENT'S COPY
PINK—WELL DRILLER'S COPY

Strat 6

STATE OF NEVADA
DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 21768
Permit No.
Basin

1. OWNER Phillips Petroleum Company ADDRESS P.O. Box 6256
Reno, Nevada 89513

2. LOCATION SW ¼ NE ¼ Sec. 5 T. 17 N/S R. 20 E Washoe County
PERMIT NO.

3. TYPE OF WORK
New Well ☐ Recondition ☐
Deepen ☐ Other ☒

4. PROPOSED USE
Domestic ☐ Irrigation ☐ Test ☒
Municipal ☐ Industrial ☐ Stock ☐

5. TYPE WELL
Cable ☐ Rotary ☒
Other ☐

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Silt, sand and clay		0	5	5
Sinter		5	25	20
Gravel, sand and silt		25	60	35
Siltite and very fine-grained quartzite		60	1690	1630

Date started January 9, 1980
Date completed February 1, 1980

7. WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump

BAILER TEST
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

8. WELL CONSTRUCTION
Diameter hole 6¼ inches Total depth 1990 feet
Casing record 0-300 and 0-1967.94
Weight per foot 20 lb. and 6.5 lb. Thickness

Diameter	From	To
7 inches	0 feet	279.40 feet
2 7/8 inches	0 feet	1967.94 feet

Surface seal: Yes ☒ No ☐ Type cement
Depth of seal 279.40 feet
Gravel packed: Yes ☐ No ☒
Gravel packed from feet to feet

Perforations:
Type perforation slots
Size perforation ¼" in 2 7/8" tubing
From 1904.61 feet to 1965.94 feet
From feet to feet
From feet to feet
From feet to feet
From feet to feet

9. WATER LEVEL
Static water level N/D Feet below land surface
Flow G.P.M.
Water temperature warm °F. Quality

10. DRILLERS CERTIFICATION
This well was drilled under my supervision and the report is true to the best of my knowledge.

Name G. L. McComack
Address P.O. Box 6256
Reno, Nevada 89513
Nevada contractor's license number
Nevada driller's license number 01135
Signed G. L. McComack
Date Feb. 4, 1980

WHITE—DIVISION OF WATER RESOURCES
CANARY—CLIENT'S COPY
PINK—WELL DRILLER'S COPY

Strat 7

STATE OF NEVADA
DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 21772
Permit No.
Basin

1. OWNER Phillips Petroleum Company ADDRESS P.O. Box 6256, Reno, Nevada 89513

2. LOCATION NE ¼ NW ¼ Sec. 7 T. 17 N/S R. 20 E. Washoe County
PERMIT NO.

3. TYPE OF WORK: New Well ☐ Recondition ☐ Deepen ☐ Other ☒

4. PROPOSED USE: Domestic ☐ Irrigation ☐ Test ☒ Municipal ☐ Industrial ☐ Stock ☐

5. TYPE WELL: Cable ☐ Rotary ☒ Other ☐

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Sand and tan silt		0	35	
Gravel, sand and tan silt		35	55	
Tan clay		55	100	
Brownish gray clay		100	160	
Gray clay		160	190	
Sand and a little gravel and silt		190	215	
Pink to medium gray rhyolite		215	1360	
Sand and brown to brownish gray silt		1360	1460	
Sand and gray silt and clay		1460	1490	
sand and brownish-gray silt		1490	1550	
Dark gray siltite and very fine grained quartzite		1550	1630	
No returns		1630	1660	

Date started January 15, 1980
Date completed February 16, 1980

7. WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump

BAILER TEST

G.P.M. Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

8. WELL CONSTRUCTION

Diameter hole 6¼ inches Total depth 1660 feet
Casing record 7" and 2 7/8
Weight per foot 20 lb. and 6.5 Thickness

Diameter	From	To
7 inches	0 feet	300 feet
2 7/8 inches	0 feet	1500 feet

Surface seal: Yes ☒ No ☐ Type Cement
Depth of seal 300 feet
Gravel packed: Yes ☐ No ☒
Gravel packed from feet to feet

Perforations:
Type perforation slotted
Size perforation 12" x ¼ (16 ea)
From 1470 feet to 1500 feet
From feet to feet

9. WATER LEVEL

Static water level Feet below land surface
Flow G.P.M.
Water temperature °F. Quality

10. DRILLERS CERTIFICATION

This well was drilled under my supervision and the report is true to the best of my knowledge.

Name G. L. McComack
Address P. O. Box 6256, Reno, Nevada 89513
Nevada contractor's license number
Nevada driller's license number 01135
Signed G L McComack
Date

WHITE—DIVISION OF WATER RESOURCES
CANARY—CLIENT'S COPY
PINK—WELL DRILLER'S COPY

Strat 8

STATE OF NEVADA
DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 21771
Permit No.
Basin

1. OWNER Phillips Petroleum Company ADDRESS P. O. Box 6256 Reno, Nevada 89513

2. LOCATION SW ¼ NE ¼ Sec. 6 T. 17 N/S R. 20 E Washoe County
PERMIT NO.

3. TYPE OF WORK: New Well ☐ Recondition ☐ Deepen ☐ Other ☒

4. PROPOSED USE: Domestic ☐ Irrigation ☐ Test ☒ Municipal ☐ Industrial ☐ Stock ☐

5. TYPE WELL: Cable ☐ Rotary ☒ Other ☐

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Gravel, sand and silt		0	10	
Tuff breccia		10	100	
No returns		100	200	
Gravel, sand and silt		200	350	
Siltite and very fine-grained quartzite		350	1940	

Date started January 24, 19 80
Date completed March 7, 19 80

8. WELL CONSTRUCTION

Diameter hole 6¼ inches Total depth 1940 feet
Casing record 7" and 2 7/8"
Weight per foot 20 lb and 6.5 Thickness

Diameter	From	To
7" inches	0 feet	311 feet
2 7/8 inches	0 feet	1929 feet
inches	feet	feet
inches	feet	feet
inches	feet	feet
inches	feet	feet

Surface seal: Yes ☒ No ☐ Type cement
Depth of seal 311 feet
Gravel packed: Yes ☐ No ☒
Gravel packed from N/A feet to N/A feet

Perforations:
Type perforation slotted
Size perforation 12" x ¼; 8 per joint
From 1866.51 feet to 1929.57 feet
From 1771.60 feet to 1803.10 feet
From 1708.67 feet to 1708.67 feet
From feet to feet
From feet to feet

9. WATER LEVEL

Static water level Feet below land surface
Flow G.P.M.
Water temperature °F. Quality

7. WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump

BAILER TEST

G.P.M. Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

10. DRILLERS CERTIFICATION

This well was drilled under my supervision and the report is true to the best of my knowledge.

Name G. L. McComack
Address P.O. Box 6256 Reno, Nevada 89513
Nevada contractor's license number
Nevada driller's license number 01135
Signed G. L. McComack
Date

PINK—WELL DRILLER'S COPY

Strat 13

DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety.

OFFICE USE ONLY
Log No.
Permit No.
Basin

1. OWNER Phillips Petroleum Company ADDRESS P.O. Box 6256, Reno, Nevada 89513

2. LOCATION SW ¼ NW ¼ Sec. 5 T. 17 N/S R. 20 E Washoe County
PERMIT NO.

3. TYPE OF WORK
New Well ☐ Recondition ☐
Deepen ☐ Other ☒

4. PROPOSED USE
Domestic ☐ Irrigation ☐ Test ☒
Municipal ☐ Industrial ☐ Stock ☐

5. TYPE WELL
Cable ☐ Rotary ☒
Other ☐

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Basalt		0	57	
Metamorphosed Sedimentary and volcanic rock		57	1767	

Date started August 8, 19 81
Date completed September 17, 19 81

7. N/A WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump

BAILER TEST
G.P.M. N/A Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

8. WELL CONSTRUCTION
Diameter hole 6¼ inches Total depth 1767 feet
Casing record 204' 7" steel casing
Weight per foot 20-23# Thickness

Diameter	From	To
7 inches	0 feet	204 feet

Surface seal: Yes ☒ No ☐ Type cement
Depth of seal feet
Gravel packed: Yes ☐ No ☒
Gravel packed from feet to feet

Perforations:
Type perforation none
Size perforation
From feet to feet

9. WATER LEVEL
Static water level 550 Feet below land surface
Flow none G.P.M.
Water temperature hot °F. Quality saline

10. DRILLERS CERTIFICATION
This well was drilled under my supervision and the report is true to the best of my knowledge.

Name Les Woytek
Address 4662 Maynard Way Sparks, Nevada 89431
Nevada contractor's license number
Nevada driller's license number 01012
Signed Les Woytek
Date 9-17-81

CANARY—CLIENT COPY
PINK—WELL DRILLER'S COPY

Strat 14

DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 23432
Permit No.
Basin

1. OWNER Phillips Petroleum Company ADDRESS P.O. Box 6256
Reno, Nevada 89513

2. LOCATION NW ¼ SW ¼ Sec. 32 T. 19 N/S R. 20 E Washoe County
PERMIT NO.

3. TYPE OF WORK	4. PROPOSED USE	5. TYPE WELL
New Well ☐ Recondition ☐	Domestic ☐ Irrigation ☐ Test ☒	Cable ☐ Rotary ☒
Deepen ☐ Other ☒	Municipal ☐ Industrial ☐ Stock ☐	Other ☐

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Gravel, sand and silt		0	80	
Granodiorite		80	1632	

Date started September 18, 1981
Date completed October 25, 1981

8. WELL CONSTRUCTION

Diameter hole 6¼ inches Total depth 1632 feet
Casing record 280 feet 7" steel
Weight per foot 20# Thickness

Diameter	From	To
7 inches	0 feet	280 feet
inches	feet	feet
inches	feet	feet
inches	feet	feet
inches	feet	feet
inches	feet	feet

Surface seal: Yes ☒ No ☐ Type cement
Depth of seal 280 feet feet
Gravel packed: Yes ☐ No ☒
Gravel packed from feet to feet

Perforations:
Type perforation none
Size perforation
From feet to feet
From feet to feet
From feet to feet
From feet to feet
From feet to feet

9. WATER LEVEL

Static water level unknown Feet below land surface
Flow none G.P.M.
Water temperature hot °F. Quality saline

7. N/A WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump

BAILER TEST

G.P.M. none Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

10. DRILLERS CERTIFICATION

This well was drilled under my supervision and the report is true to the best of my knowledge.

Name Les Woytek
Address 4662 Maynard Way
Sparks, Nevada 89431

Nevada contractor's license number
Nevada driller's license number 01012
Signed Les Woytek
Date 11-16-81

APPENDIX D. WELL-COMPLETION DATA FOR WELLS IN THE SOUTH TRUCKEE MEADOWS

This appendix contains well-completion data from copies of driller's logs for wells in the South Truckee Meadows. The information was obtained from the files of the Nevada Division of Environmental Protection (Carson City office) and the Bureau of Land Management (Carson City and Reno offices).

WELL LOG AND REPORT TO THE STATE ENGINEER OF NEVADA

Bianco

PLEASE COMPLETE THIS FORM IN ITS ENTIRETY

Log No.	5916
Rec.	June 8 1961
Well No.	16464
Permit No.	19849

Do not fill in

Owner U.J. Bianco Driller J.N.Pitcher Co.

Address 1441 Giger Grade Reno, Nevada Address 9501 So. Virgina St. Lic. No.

Location of well: SW NE 1/4 SW NE 1/4 Sec. 28, T. 18 N/S, R. 20 E, in Washoe County

or

Water will be used for Irrigation Total depth of well 110 Ft.

Size of drilled hole 12" Weight of casing per linear foot

Thickness of casing 1/4" Temp. of water 70°

Diameter and length of casing 13" Out Side
(Casing 12" in diameter and under give inside diameter; casing 12" in diameter give outside diameter.)

If flowing well give flow in c.f.s. or g.p.m. and pressure NONE

If nonflowing well give depth of standing water from surface 40 Ft.

If flowing well describe control works NONE
(Type and size of valve, etc.)

Date of commencement of well 2 June 61 Date of completion of well 6June 61

Type of well rig Cable Tool

LOG OF FORMATIONS

From feet	To feet	Thickness feet	Type of material
0	6	6	Top Soil
6	10	4	Gravel Sandy Clay
10	12	2	Gravel
12	45	33	Sandy Clay & Small Gravel
45	47	2	Large Gravel
47	80	33	Course Sand & Small Gravel
80	85	5	Corse Sand Large Gravel
85	95	10	Small Gravel & Sandy Clay
95	97	2	Course Sand Small & Large Gravel
97	110	13	Clay &Small Gravel
110			Gravel

Water-bearing Formation, Casing Perforations, Etc.

Chief aquifer (water-bearing formation)

from 80 to 85 ft.

Other aquifers 85 - 95

95 - 110

First water at 45 feet.

Casing perforated

from 50 to 110 ft.

Size of perforations

1/4" Torch Perf.

LOG OF FORMATIONS—*Continued*

From feet	To feet	Thickness	Type of material

CASING RECORD

Diam. casing	From feet	To feet	Length	"Remarks"—Seals, Grouting, Etc.
12 1/4"	0	110	111	Butt welded casing w/ shoe attached

GENERAL INFORMATION—Pumping Test, Quality of Water, Etc.

WELL DRILLER'S STATEMENT

This well was drilled under my jurisdiction and the above information is true to my best information and belief.

Signed J. M. Pitcher Co.
Well Driller

By M. [illegible]

License No. 232

Dated 6/7, 19 61

(Not to be filled in by Driller)

1961 JUN 8 AM 8 54

STATE ENGINEER

WELL LOG AND REPORT TO THE STATE ENGINEER OF NEVADA

Boyd water level

Log No. 2959
Rec. May 18 1955
Well No. ✓
Permit No.
Do not fill in

Owner: Boyd, V. D. Driller: Mel Meyer Co.

Address: P. O. Box 24 Steamboat, Nevada Address: 190 Moana Lane Lic. No. 3

Location of well: ~~NE~~ NW ¼ ~~NE~~ NW ¼ Sec. ~~9~~ 4, T18 N/S, R.20 E, in Washoe County

or

Water will be used for: Domestic Total depth of well: 68

Size of drilled hole: 6 5/8" Weight of casing per linear foot: 14#

Thickness of casing: 3/16 Temp. of water: Cold

Diameter and length of casing: 6 1/8" - 69'
(Casing 12" in diameter and under give inside diameter; casing 12" in diameter give outside diameter.)

If flowing well give flow in c.f.s. or g.p.m. and pressure: Bailed at 30 G.P.M.

If nonflowing well give depth of standing water from surface: 35'

If flowing well describe control works:
(Type and size of valve, etc.)

Date of commencement of well: 4/26/55 Date of completion of well: 4/29/55

Type of well rig: Cable Tool

LOG OF FORMATIONS

From feet	To feet	Thickness feet	Type of material
0	25	25	Clay & Boulders , shattered rock.
25	35	60	Broken Rock
60	8	68	Basalt rock and water

Water-bearing Formation, Casing Perforations, Etc.

Chief aquifer (water-bearing formation) from 60 to 68 ft.

Other aquifers: None

First water at 35 feet.

Casing perforated from 48 to 68 ft.

Size of perforations: 1/16 x 6"

LOG OF FORMATIONS—*Continued*

From feet	To feet	Thickness	Type of material

CASING RECORD

Diam. casing	From feet	To feet	Length	"Remarks"—Seals, Grouting, Etc.

GENERAL INFORMATION—Pumping Test, Quality of Water, Etc.

WELL DRILLER'S STATEMENT

This well was drilled under my jurisdiction and the above information is true to my best information and belief.

Signed C. Carol Pilate
Well Driller

By For Mel Meyer Co.

License No. 3[illegible]

Dated 5/1/55, 19

(Not to be filled in by Driller)

STATE OF NEVADA
DIVISION OF WATER RESOURCES

Curti Domestic

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 13252.
Permit No.
Basin Truckee Meadows

1. OWNER Gene Curti ADDRESS 13355 Old Virginia City Rd.

2. LOCATION ¼ ¼ Sec. 21 T. 18 N N/S R. 20 E Washoe County
PERMIT NO.

3. TYPE OF WORK
New Well ☒ Recondition ☐
Deepen ☐ Other ☐

4. PROPOSED USE
Domestic ☒ Irrigation ☐ Test ☐
Municipal ☐ Industrial ☐ Stock ☐

5. TYPE WELL
Cable ☐ Rotary ☐
Other ☐ Air Rotary

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Dark Brown topsoil		0	3	3
Light brown sand w/some clay-soft	4-15	3	17	14
Gravels to 2" w/occasional cobble & coarse sand & some silt	53-77	17	77	60

Date started 6/23/73, 19
Date completed 6/23/73, 19

7. WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump
Air blown	140 @ 50'		
	175 @ 70'		

BAILER TEST

G.P.M. Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

8. 10" to 45' WELL CONSTRUCTION

Diameter hole 8" to 77' inches Total depth 77 feet
Casing record
Weight per foot 12.89 Thickness 188

Diameter	From	To
6 5/8 OD inches	0 feet	77 feet

Surface seal: Yes ☒ No ☐ Type cement grout
Depth of seal 45 feet
Gravel packed: Yes ☐ No ☒
Gravel packed from feet to feet

Perforations:
Type perforation torch cut
Size perforation 1/8" X 6"
From 52 feet to 77 feet
From feet to feet
From feet to feet
From feet to feet
From feet to feet

9. WATER LEVEL

Static water level 12 Feet below land surface
Flow G.P.M. Iron .6 ppm
Water temperature 56 °F. Quality Hardness 58 ppm

10. DRILLERS CERTIFICATION

This well was drilled under my supervision and the report is true to the best of my knowledge.

Name W. L. McDonald & Co.
Address 1955 18th Street Sparks, Nevada
Nevada contractor's license number 9767
Nevada driller's license number 685
Signed Michael D. Grace
Date 6/24/73

Log No. 4061
Rec. Apr. 22. 1958
Well No.
Permit No. 16935
Do not fill in

Herz Domestic

WELL LOG AND REPORT TO THE STATE ENGINEER OF NEVADA

Owner: Richard & Harold Herz. Driller: J. W. Cunningham
Address: 190 White Creek Lane Reno. Address: Old Virginia City Rd. Lic. No. 150
Location of well: SE 1/4 SE 1/4 Sec 20, T 18 N, R 20 E, in ________ County
or ________
Water will be used for: DOMESTIC Total depth of well: 112 feet.
Size of drilled hole: 12" Weight of casing per linear foot: 10 pounds
Thickness of casing: 1/4 Temp. of water: Cold.
Diameter and length of casing: 11 3/4
(Casing 12" in diameter and under give inside diameter; casing 12" in diameter give outside diameter.)
If flowing well give flow in c.f.s. or g.p.m. and pressure ________
If nonflowing well give depth of standing water from surface: 28 feet.
If flowing well describe control works ________ (Type and size of valve, etc.)
Date of commencement of well: Sept. 20, 1955 Date of completion of well: Sept. 29th, 195
Type of well rig: Keystone Cable Tool

LOG OF FORMATIONS

From feet	To feet	Thickness feet	Type of material
0	9	9	BOULDERS
9	30	21	SANDY CLAY
30	40	10	WATER SAND- FINE
46	68	22	FINE SAND & GRAVEL
68	93	25	COARSE GRAVEL
93	98	5	FINE SAND & GRAVEL
98	112	14	SANDY CLAY, YELLOW

Water-bearing Formation, Casing Perforations, Etc.

Chief aquifer (water-bearing formation)
from 30 to 112 ft.
Other aquifers ________

First water at 30 feet.

Casing perforated
from 40 to 112 ft.

Size of perforations
1/8" x 6"

LOG OF FORMATIONS—*Continued*

From feet	To feet	Thickness	Type of material

CASING RECORD

Diam. casing	From feet	To feet	Length	"Remarks"—Seals, Grouting, Etc.

GENERAL INFORMATION—Pumping Test, Quality of Water, Etc.

500 g. p m.

WELL DRILLER'S STATEMENT

This well was drilled under my jurisdiction and the above information is true to my best information and belief.

Signed J. W. Cunningham
Well Driller

By Richard Herz

License No. 180

Dated 4/22/, 1958

(Not to be filled in by Driller)

WHITE—DIVISION OF WATER RESOURCES
CANARY—CLIENT'S COPY
PINK—WELL DRILLER'S COPY

Jeppson water level

STATE OF NEVADA
DIVISION OF WATER RESOURCES

WELL DRILLERS REPORT

Please complete this form in its entirety

OFFICE USE ONLY
Log No. 17009
Permit No.
Basin

1. OWNER H. V. Jeppson, Pleasant Valley 89511 ADDRESS 20850 Ames Ln. Reno

2. LOCATION NW ¼ NW ¼ Sec. 5 T 17N N/S R 20 E M.D.B.&M. Washoe County
PERMIT NO.

3. TYPE OF WORK: New Well ☒ Deepen ☐ Recondition ☐ Other ☐

4. PROPOSED USE: Domestic ☒ Municipal ☐ Irrigation ☐ Industrial ☐ Test ☐ Stock ☐

5. TYPE WELL: Cable ☐ Rotary ☒ Other ☐

6. LITHOLOGIC LOG

Material	Water Strata	From	To	Thickness
Clay & Broken Rock		1	58	
Sand & Gravel		59	81	
Clay		82	121	

Date started Sept 12, 1977
Date completed Sept 13, 1977

8. WELL CONSTRUCTION

Diameter hole 6 inches Total depth 121 feet
Casing record [illegible]
Weight per foot Thickness [illegible]

Diameter	From	To
6 inches	1 feet	120 feet
inches	feet	feet
inches	feet	feet
inches	feet	feet
inches	feet	feet
inches	feet	feet

Surface seal: Yes ☒ No ☐ Type [illegible]
Depth of seal 50 feet
Gravel packed: Yes ☐ No ☒
Gravel packed from feet to feet

Perforations:
Type perforation [illegible]
Size perforation 1/16
From 60 feet to 80 feet
From 100 feet to 120 feet
From feet to feet
From feet to feet
From feet to feet

9. WATER LEVEL

Static water level Feet below land surface [illegible]
Flow G.P.M. 15
Water temperature [illegible] °F. Quality

7. WELL TEST DATA

Pump RPM	G.P.M.	Draw Down	After Hours Pump

BAILER TEST

G.P.M. Draw down feet hours
G.P.M. Draw down feet hours
G.P.M. Draw down feet hours

10. DRILLERS CERTIFICATION

This well was drilled under my supervision and the report is true to the best of my knowledge.

Name Kaurchack [illegible]
Address [illegible]
Nevada contractor's license number [illegible]
Nevada driller's license number [illegible]
Signed Steve Kaurchack
Date 10-7-77

Log No.	8023
Rec.	Aug 13 1964
Well No.	
Permit No.	

Do not fill in.

WELL LOG AND REPORT TO THE STATE ENGINEER OF NEVADA

Jeppson chemistry

PLEASE COMPLETE THIS FORM IN ITS ENTIRETY

Owner: H. G. Jeppson Driller: [illegible]

Address: 1105 [illegible] Springs Address: [illegible] 255 Carson City Lic. No. 301

Location of well: ¼ SW NW ¼ Sec 8, T. 17 N/S, R. 19 E, in Washoe County

or

Water will be used for Domestic Total depth of well 87 ft

Size of drilled hole 10" to 50 ft Weight of casing per linear foot 9.7 lbs

Thickness of casing 10 gage Temp. of water Cold

Diameter and length of casing 6" x 55 ft (4 ft [illegible])
(Casing 12" in diameter and under give inside diameter; casing 12" in diameter give outside diameter.)

If flowing well give flow in c.f.s. or g.p.m. and pressure

If nonflowing well give depth of standing water from surface 46

If flowing well describe control works
(Type and size of valve, etc.)

Date of commencement of well 7-31-64 Date of completion of well 8-1-64

Type of well rig Cable tool

LOG OF FORMATIONS

From feet	To feet	Thickness feet	Type of material
0	3	3	soil
3	56	53	yellow clay & rock
56	64	8	brown clay
64	67	3	gravel
67	72	5	clay
72	84	12	gravel
84	87	3	clay

Water-bearing Formation, Casing Perforations, etc.

Chief aquifer (water-bearing formation) from 72 to 84 ft.

Other aquifers 64-67

First water at 64 feet.

Casing perforated from 64 to 84 ft.

Size of perforations 3 x 3/32

LOG OF FORMATIONS—Continued

From feet	To feet	Thickness	Type of material

CASING RECORD

Diam. casing	From feet	To feet	Length	REMARKS—Seals, Grouting, etc.
6"	0	57	55	sealed to 50 ft with native clay.

GENERAL INFORMATION—Pumping Test, Quality of Water, etc.

Test by bailing - apx 32 G.P.M.

WELL DRILLER'S STATEMENT

This well was drilled under my jurisdiction and the above information is true to my best information and belief.

Signed W. E. Blain
Well Driller

By Florence Blain

License No. 301

Dated 8 - 11, 1964

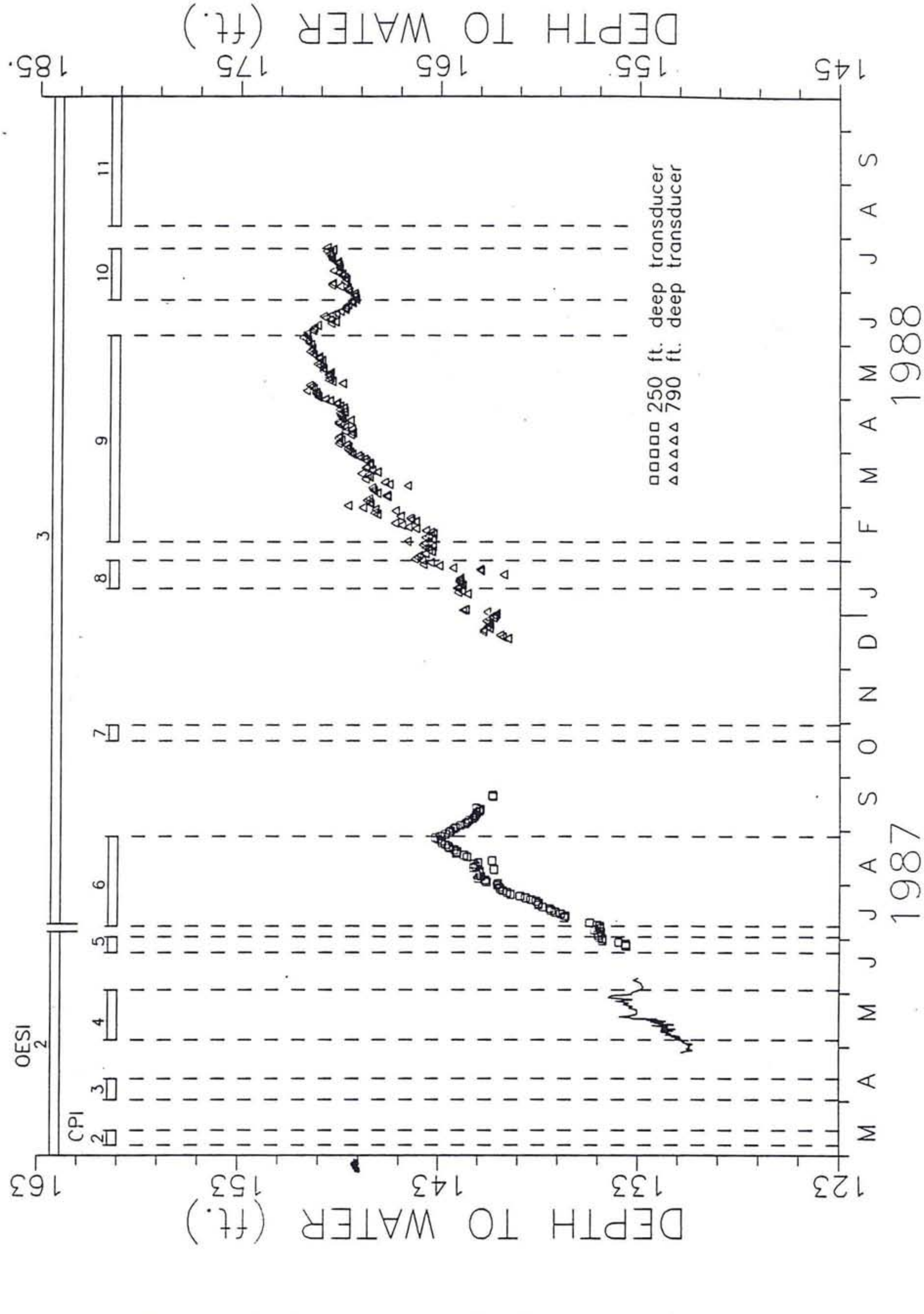
(Not to be filled in by Driller)

1964 AUG 13 AM 10 44

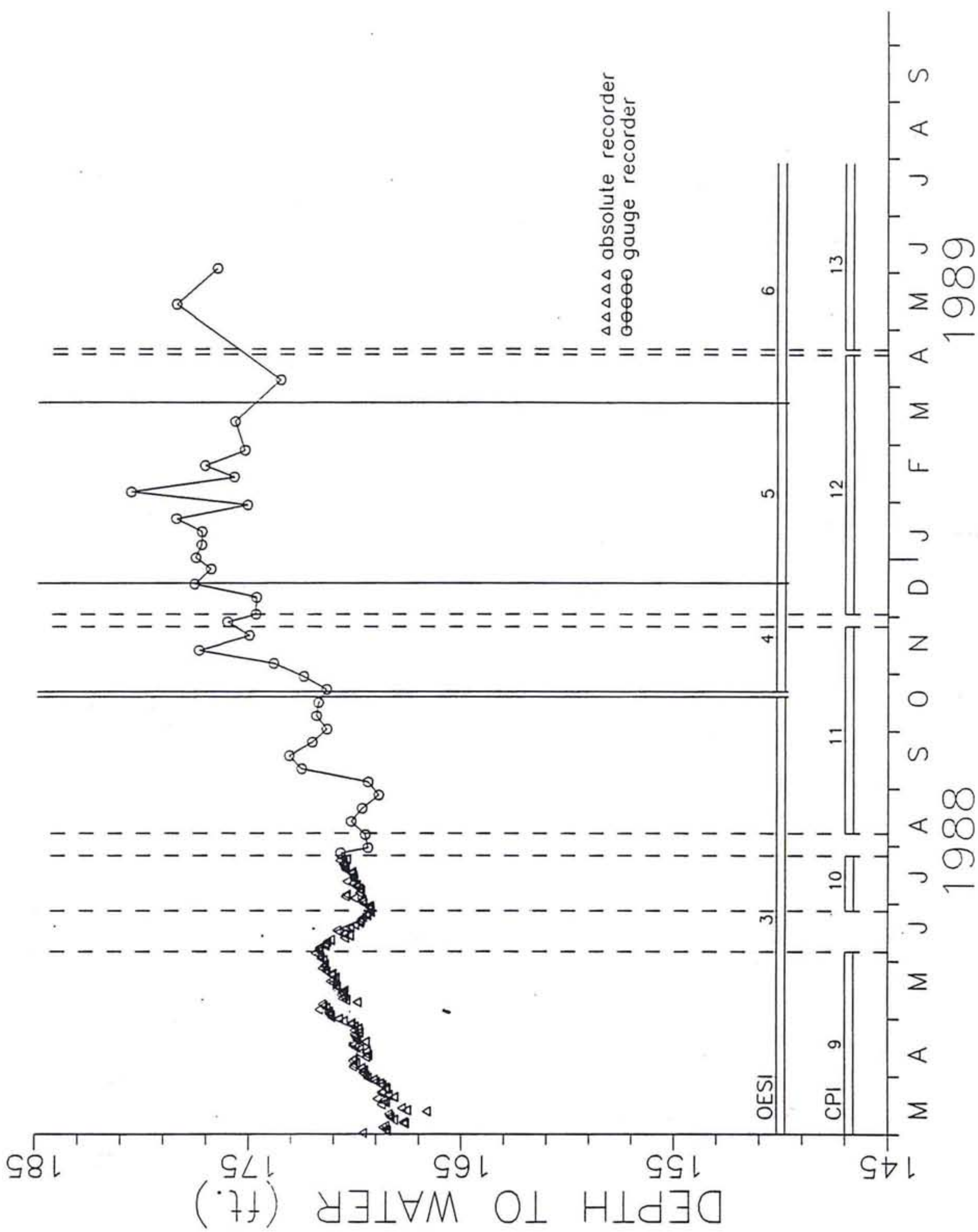
STATE ENGINEER
OFFICE

APPENDIX E. HYDROGRAPHS OF OBSERVATION WELLS IN THE STEAMBOAT HILLS AND ON THE LOW TERRACE

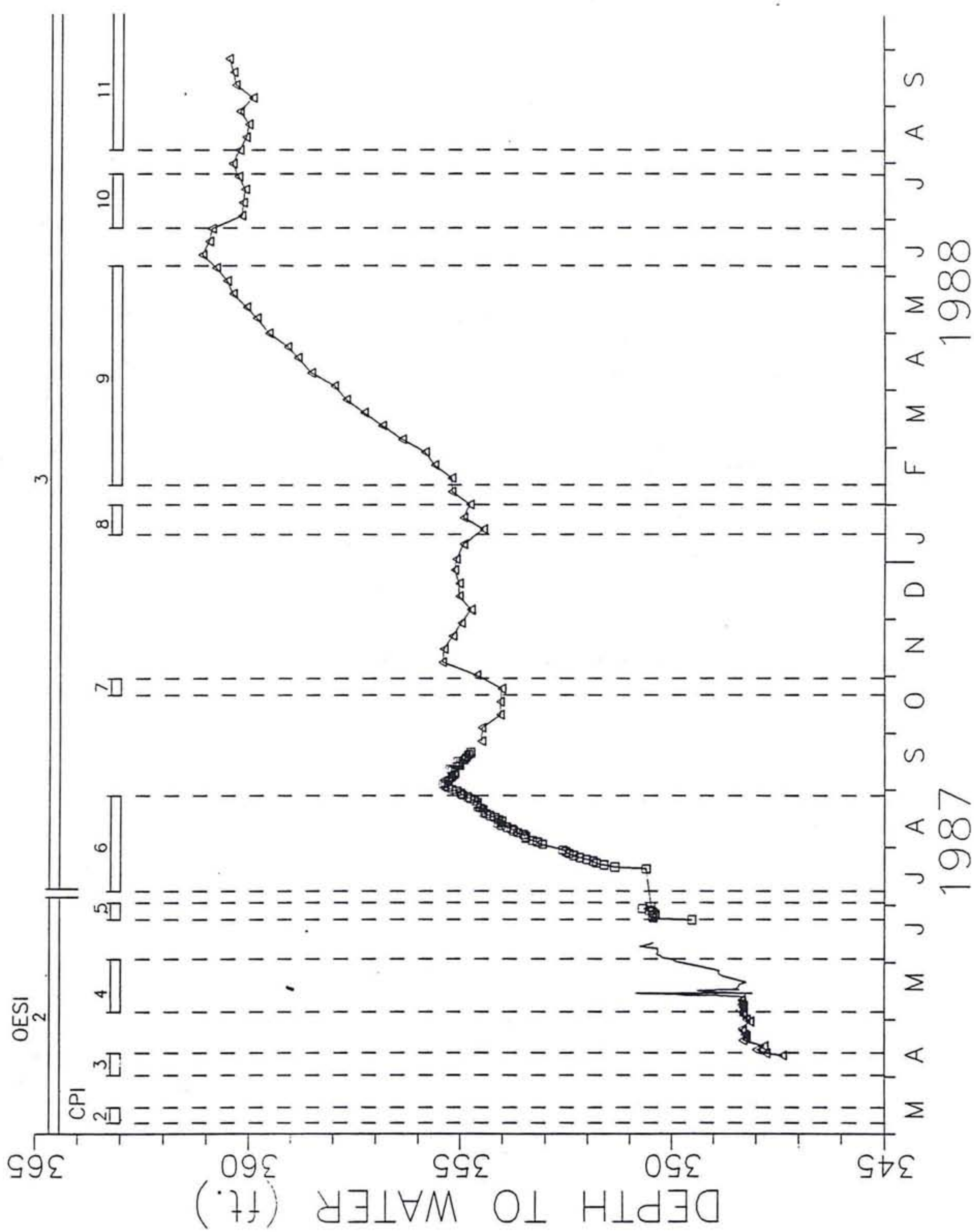
This appendix contains hydrographs of observation wells drilled in the Steamboat Hills and on the Low Terrace. These hydrographs are copies of those presented by Collar (1990) and are included here to provide more detailed records of water-level changes in these wells than are shown in the main part of the report. Well locations are shown on Plate 2 and figure 19.



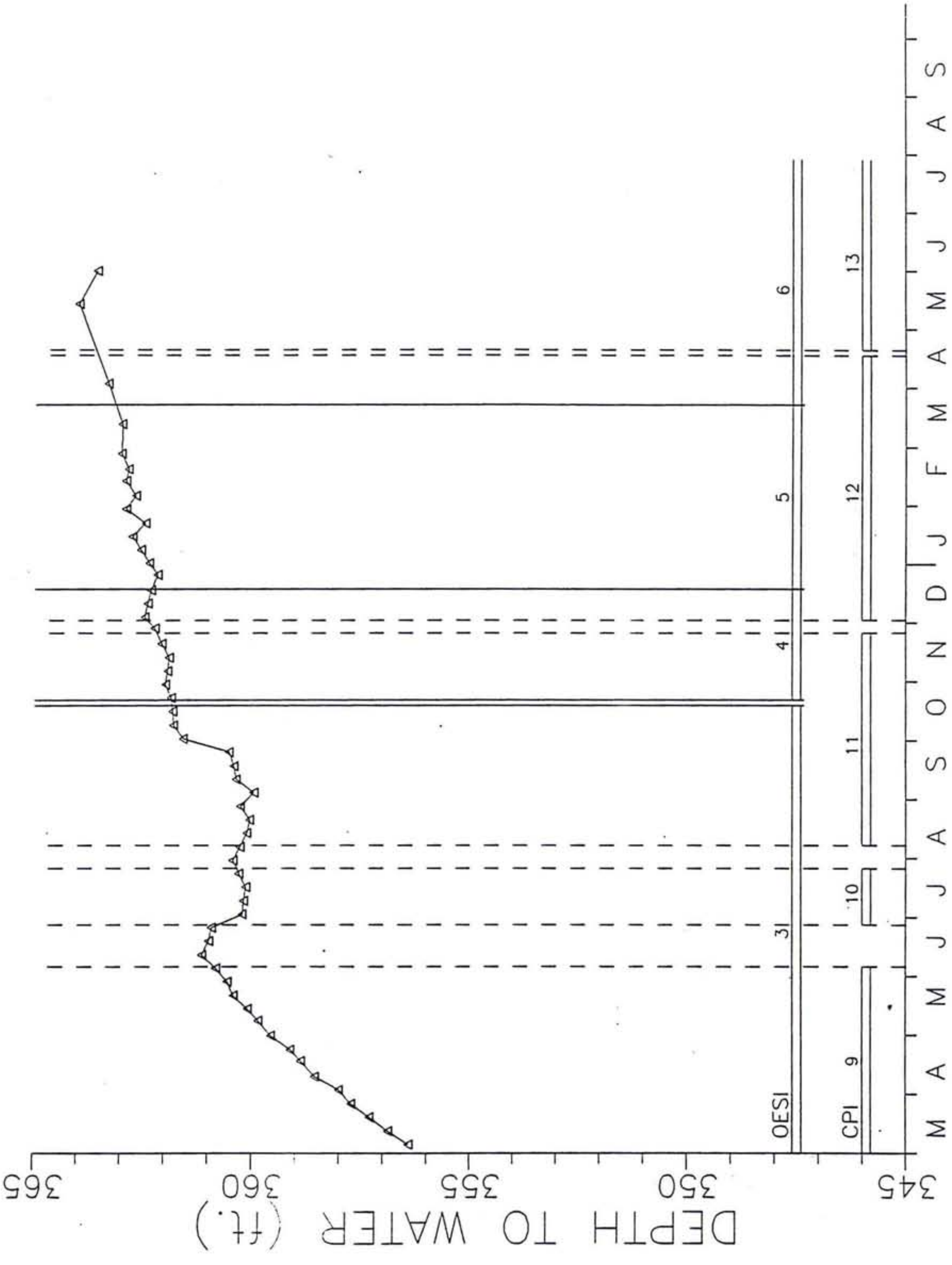
Hydrograph of strat well 2, April, 1987, to June, 1989.



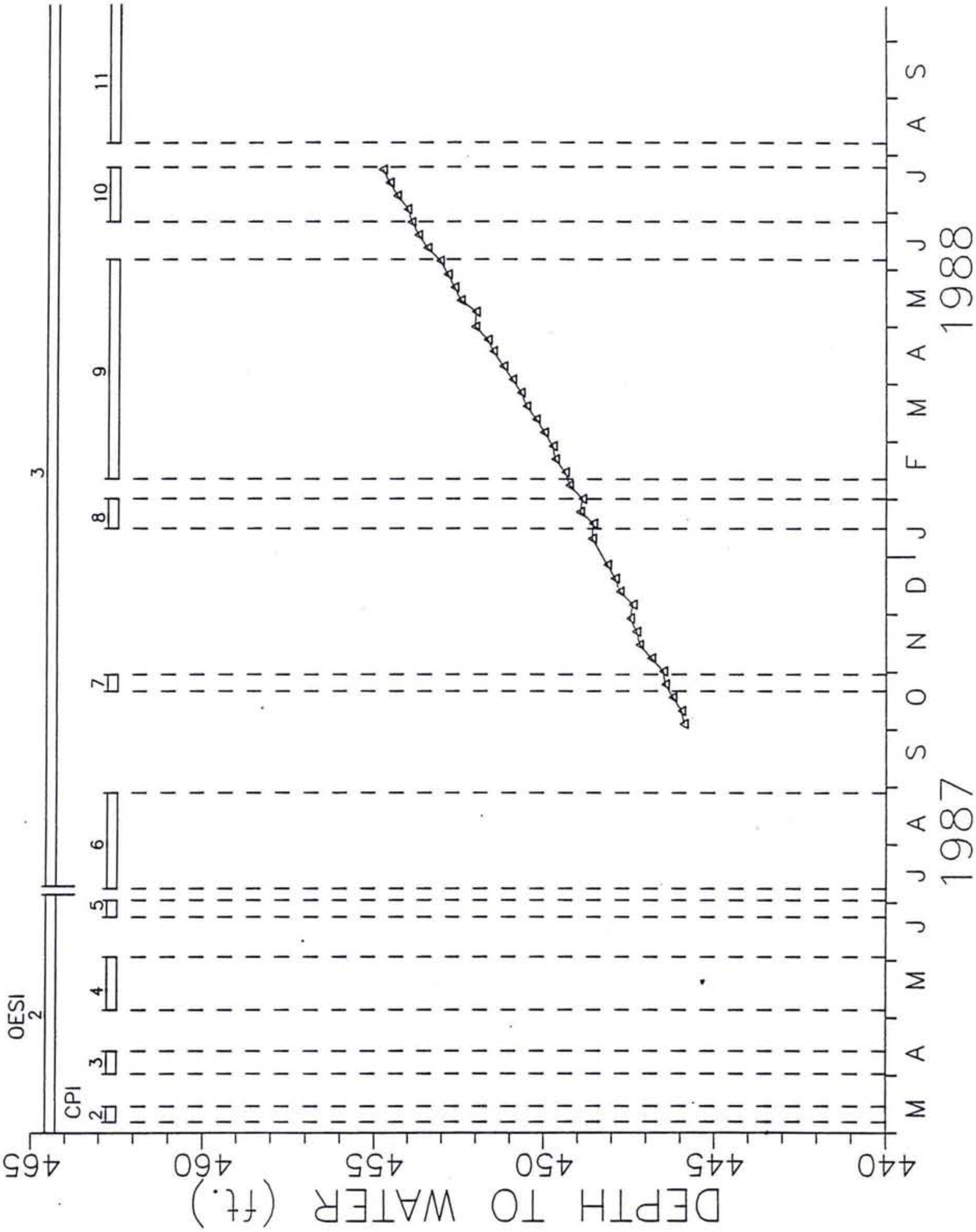
(cont'd) Hydrograph of strat well 2, April, 1987, to June, 1989.



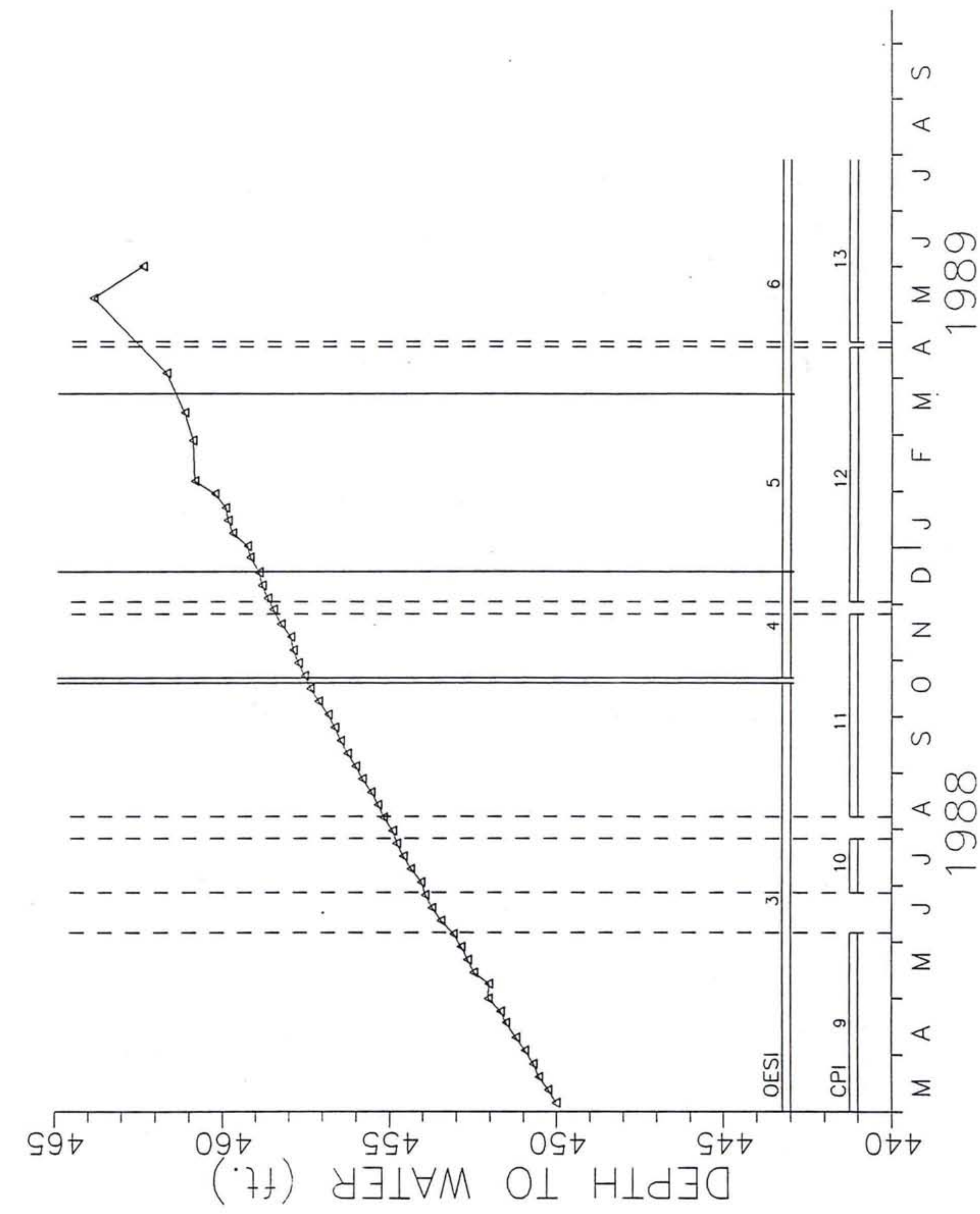
Hydrograph of strat well 5, April, 1987, to June, 1989.



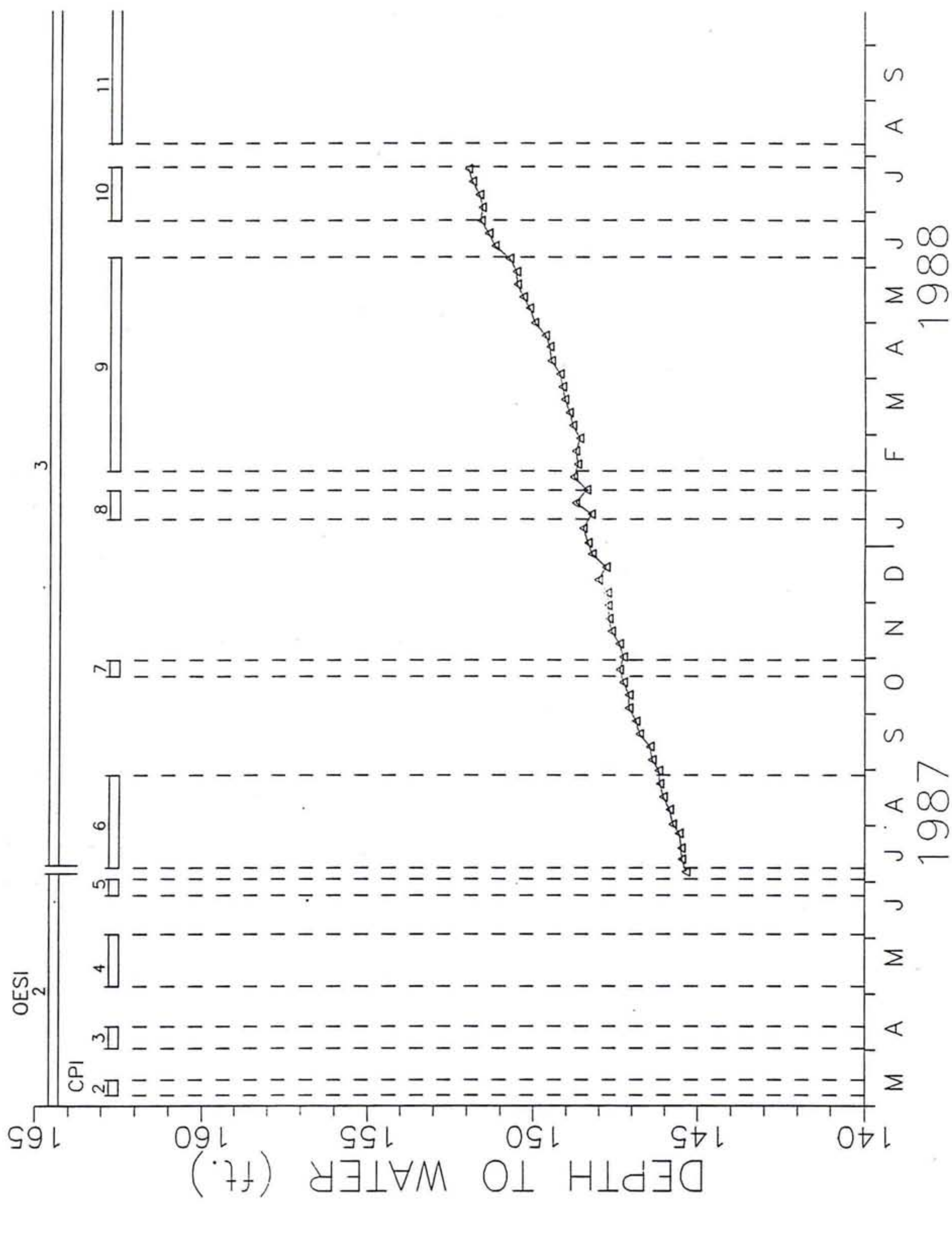
(cont'd) Hydrograph of strat well 5, April, 1987, to June, 1989.



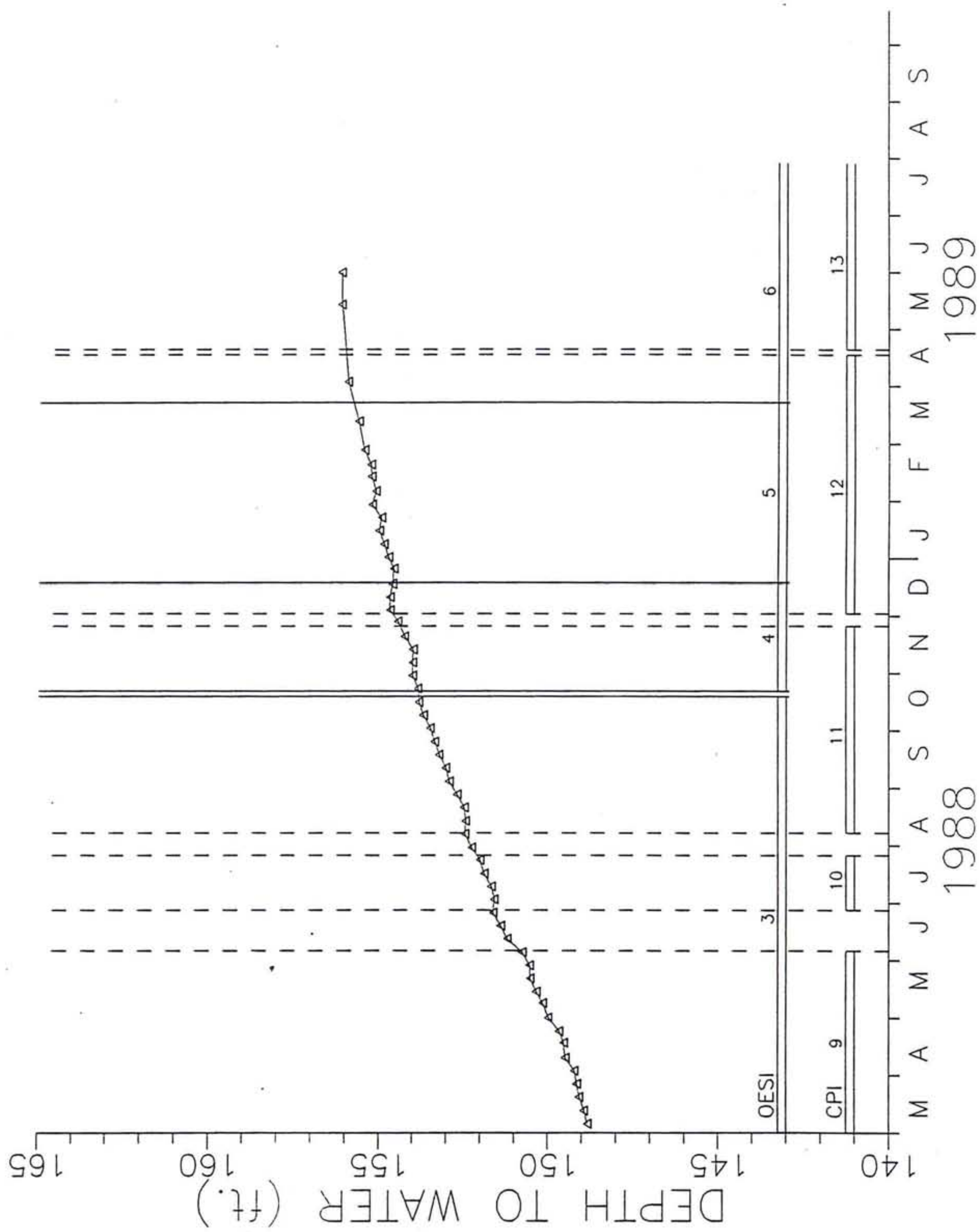
Hydrograph of strat well 6, October, 1987, to June, 1989.



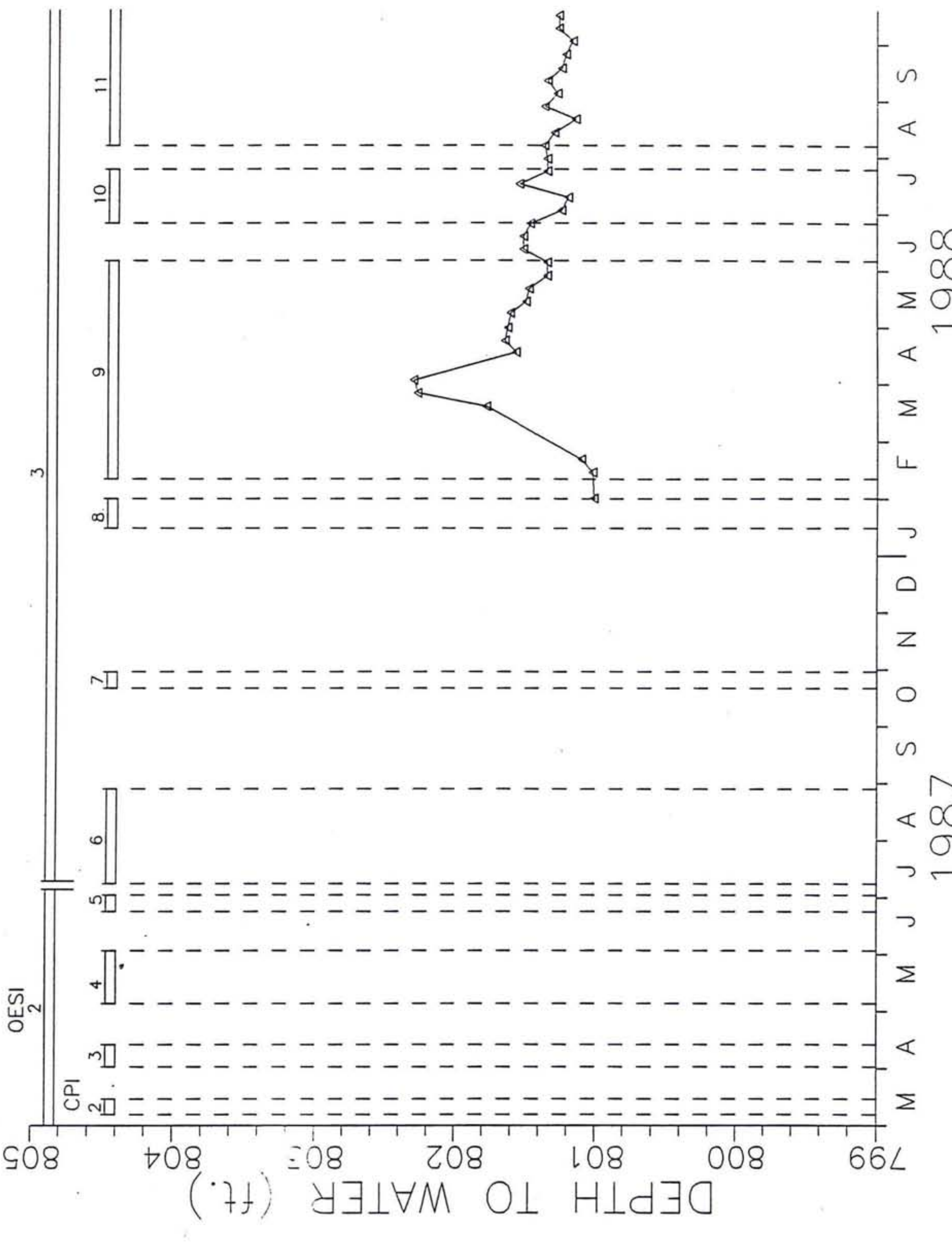
(cont'd) Hydrograph of strat well 6, October, 1987, to June, 1989.



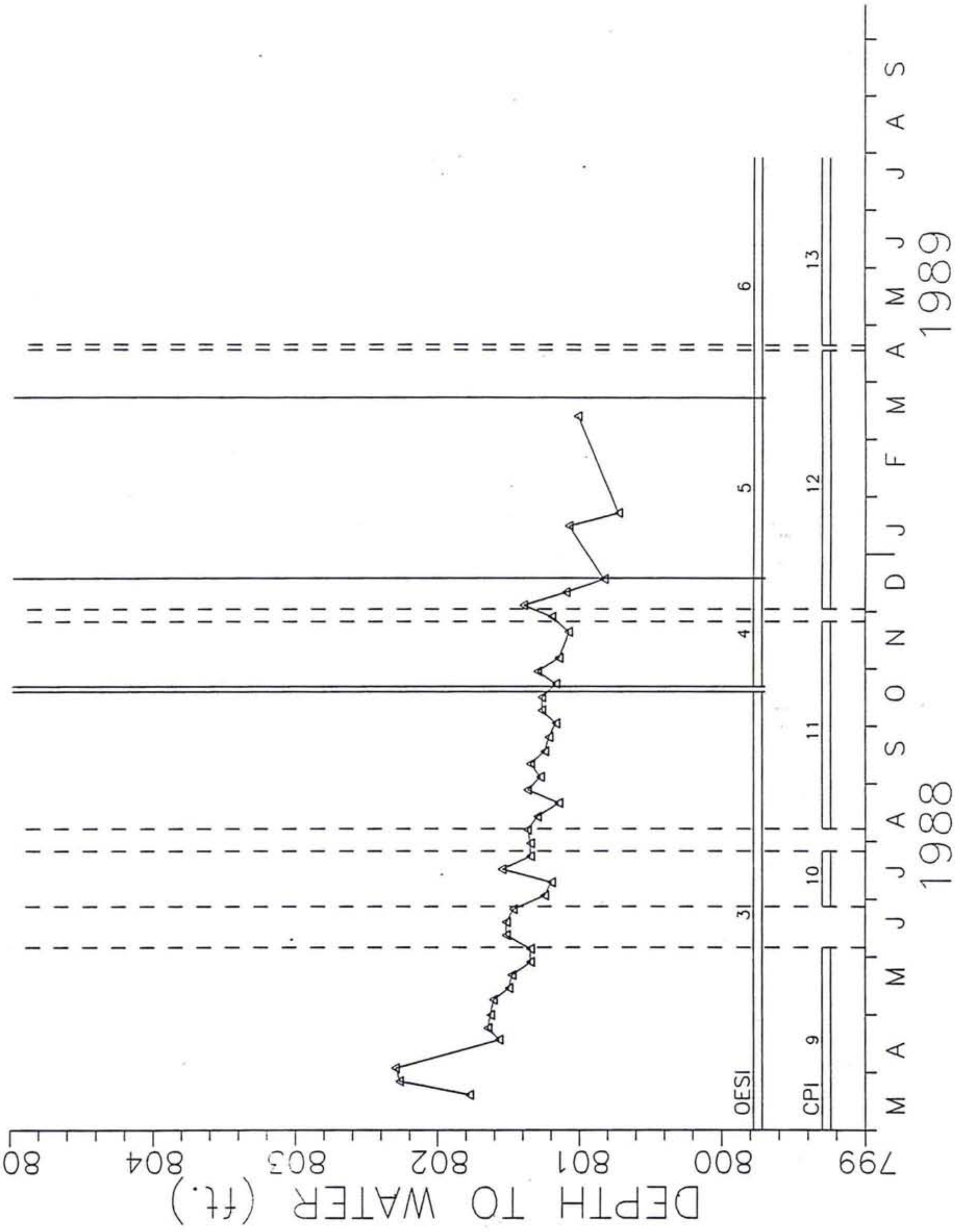
Hydrograph of strat well 7, July, 1987, to June, 1989.



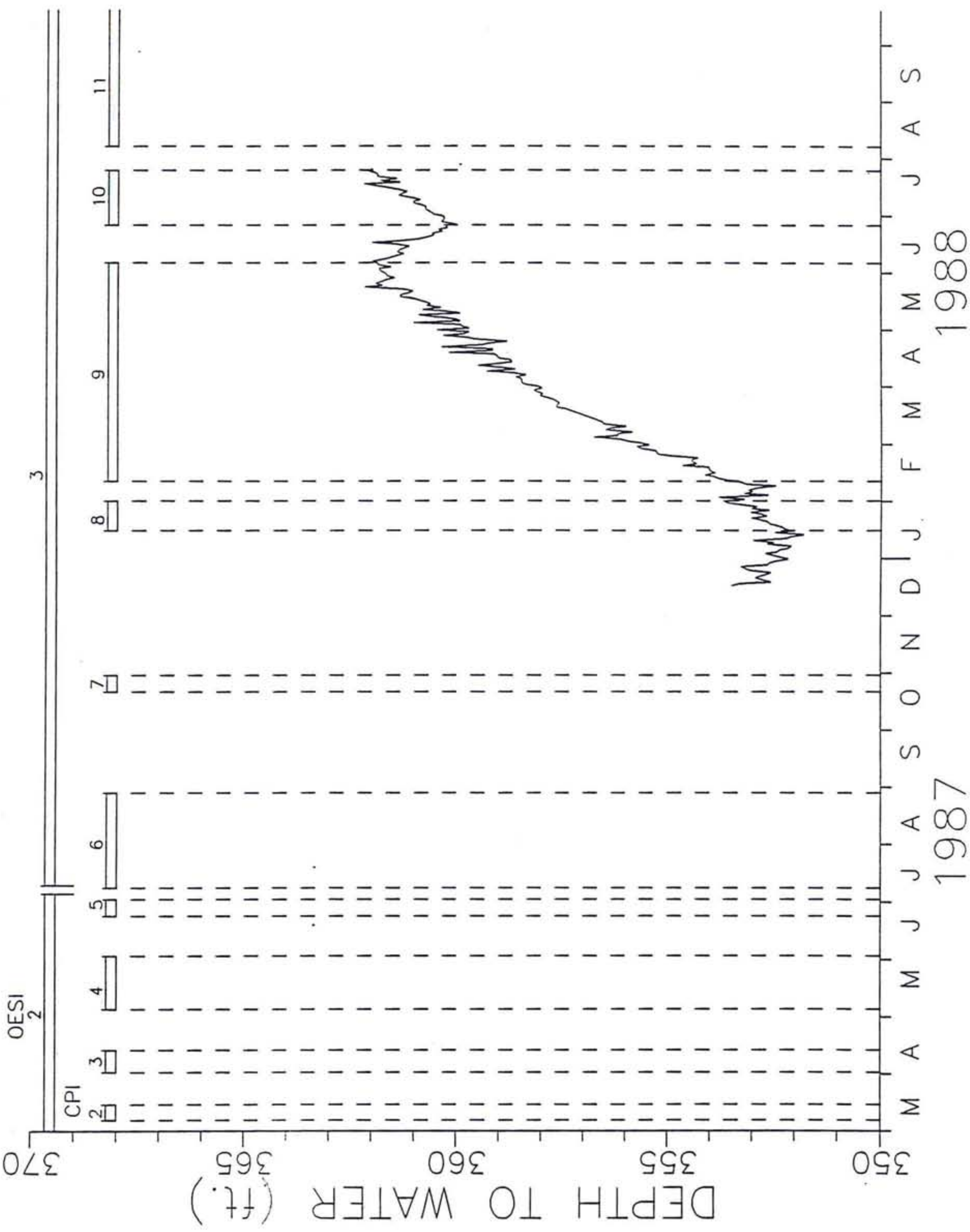
(cont'd) Hydrograph of strat well 7, July, 1987, to June, 1989.



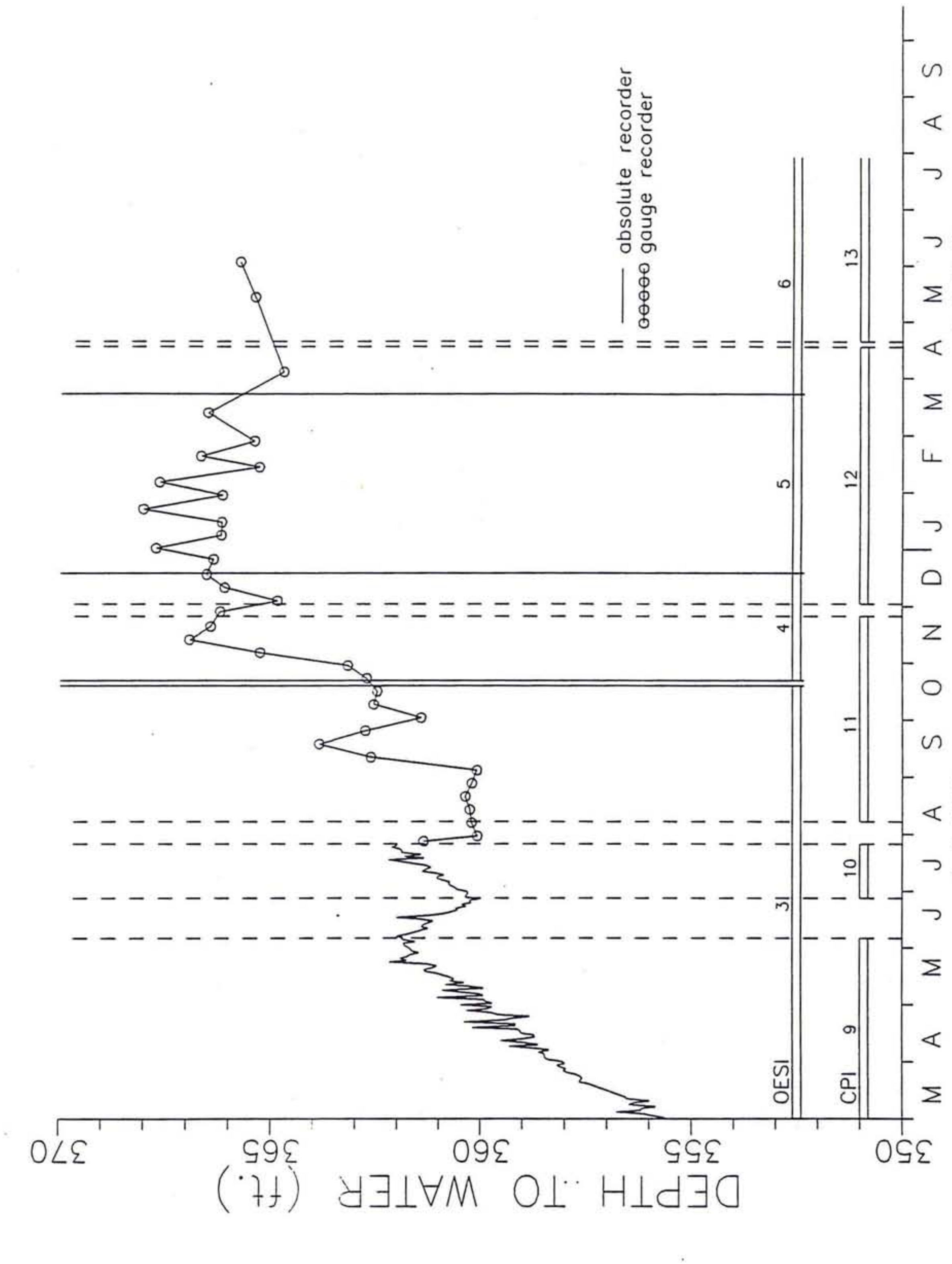
Hydrograph of strat well 8, February, 1988, to March, 1989 (F. Yeamans, unpub. data).



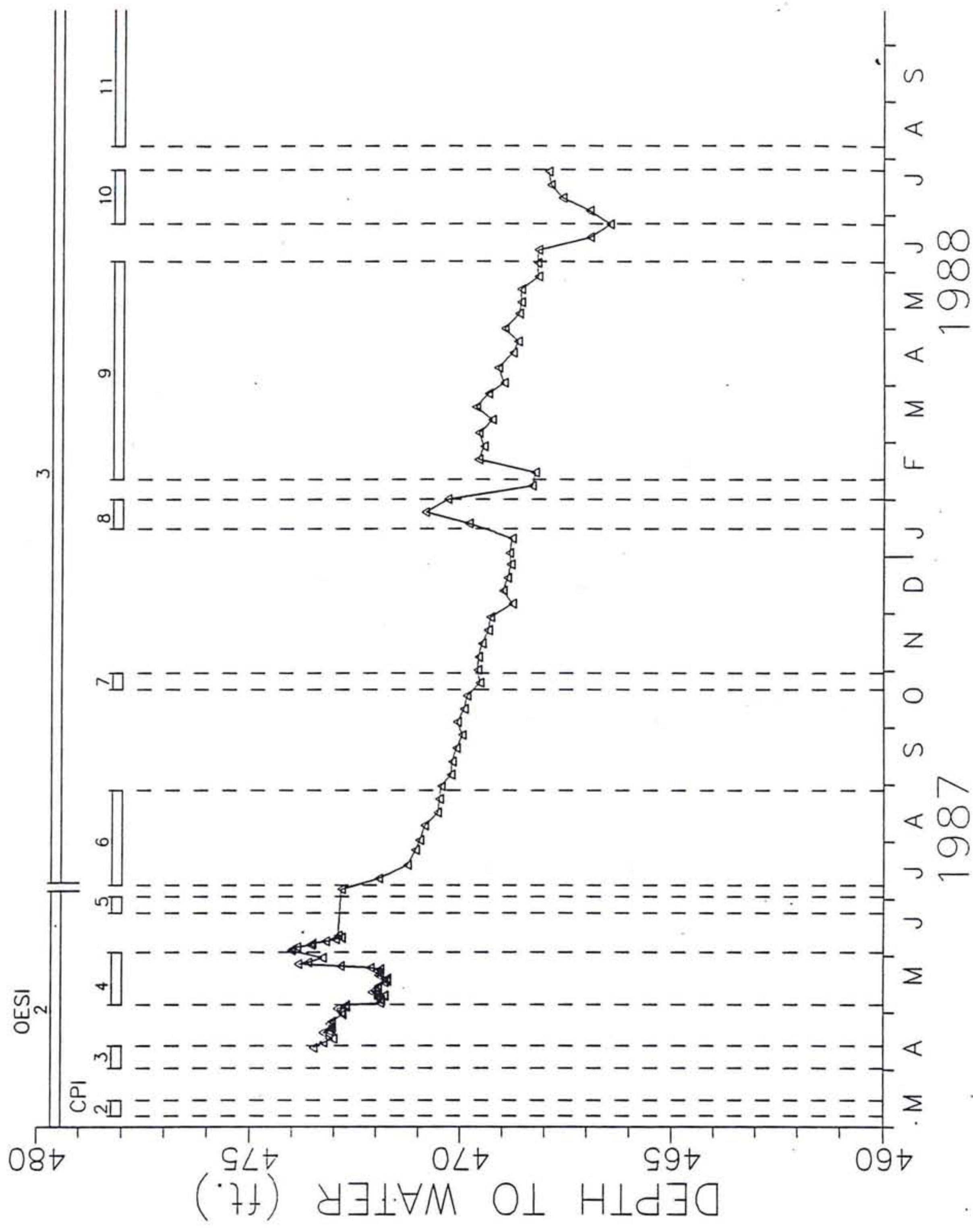
(cont'd) Hydrograph of strat well 8, February, 1988, to March, 1989 (F. Yeamans, unpub. data).



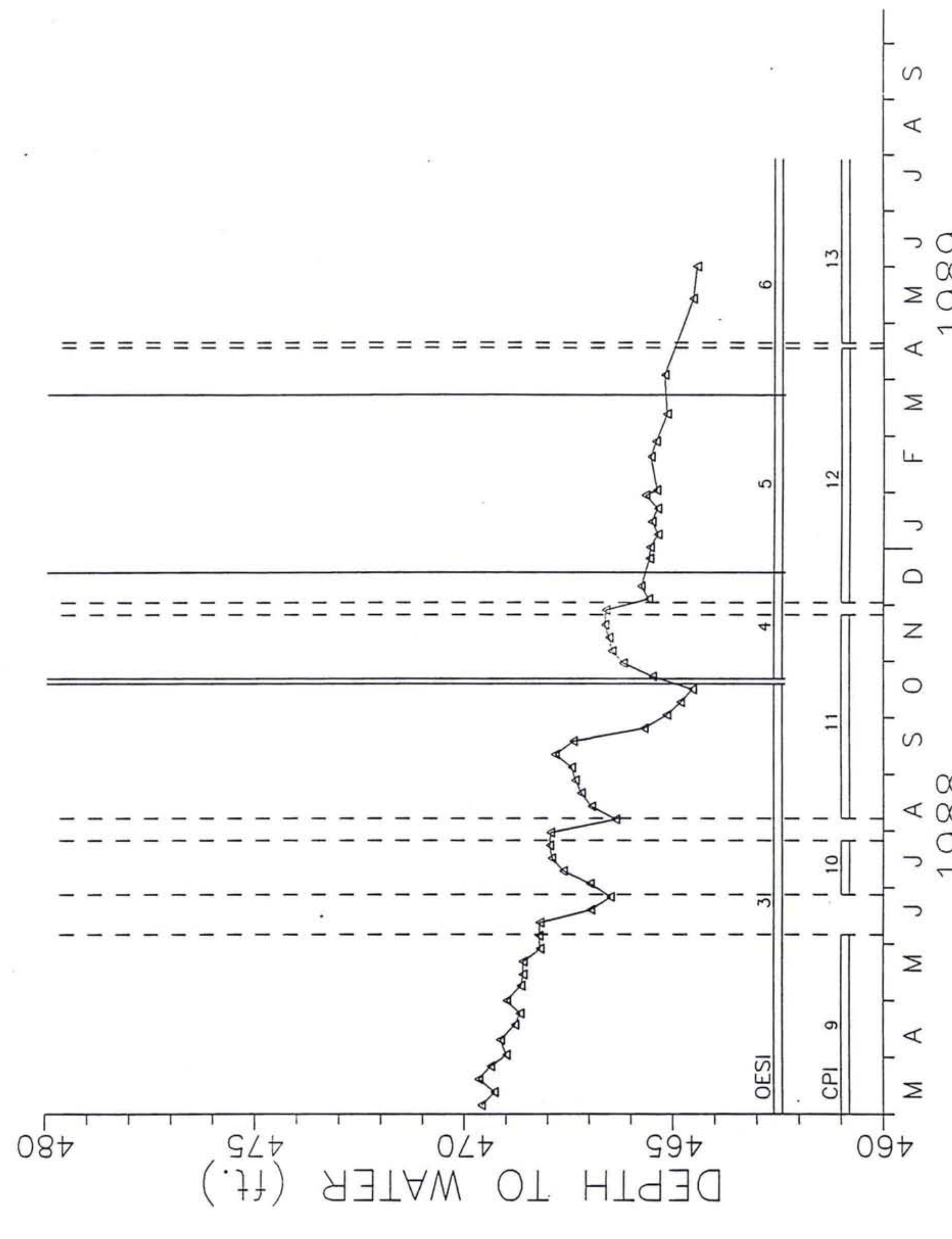
Hydrograph of strat well 9, December, 1987, to June, 1989.



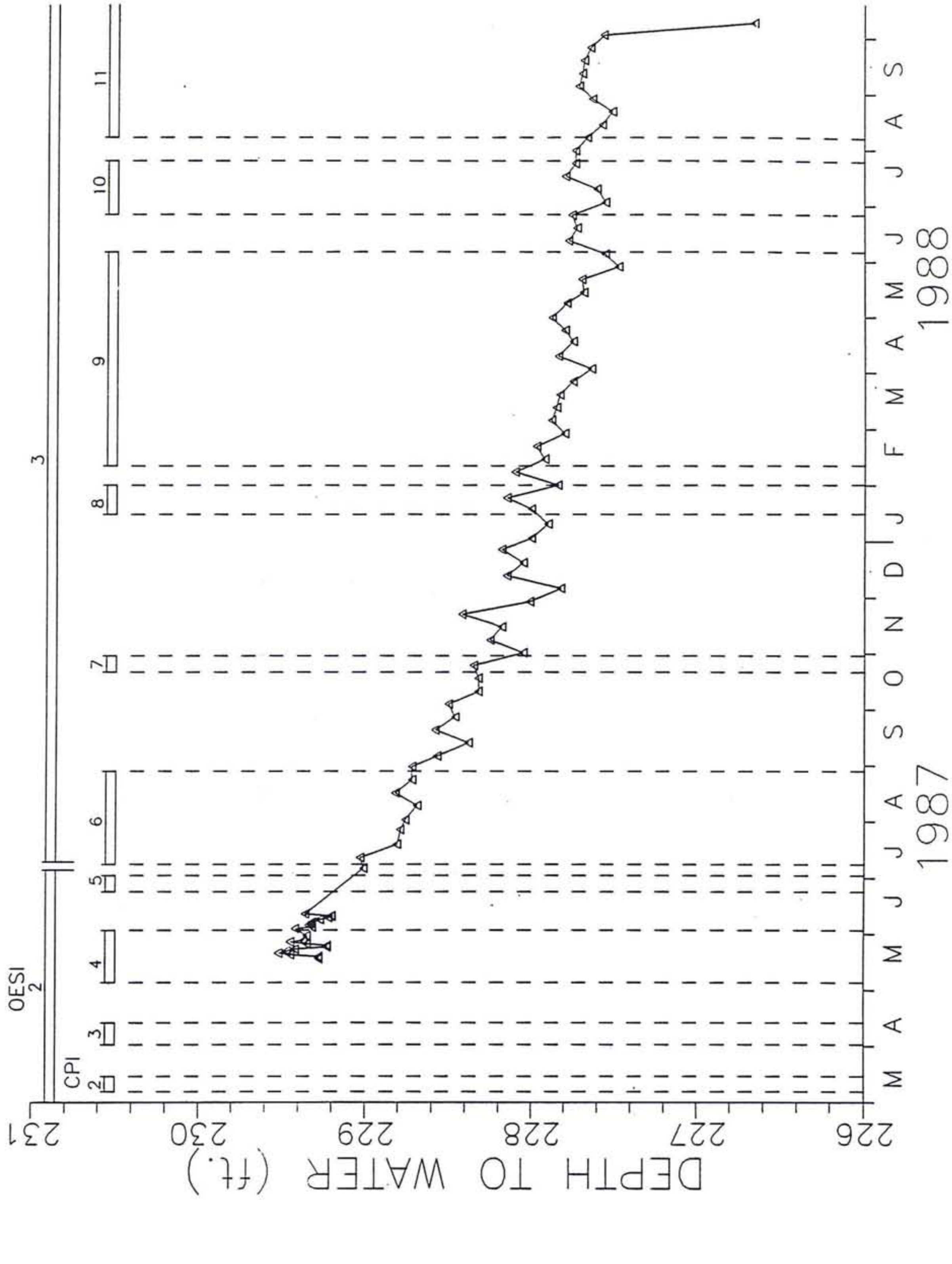
(cont'd). Hydrograph of strat well 9, December, 1987, to June, 1989.



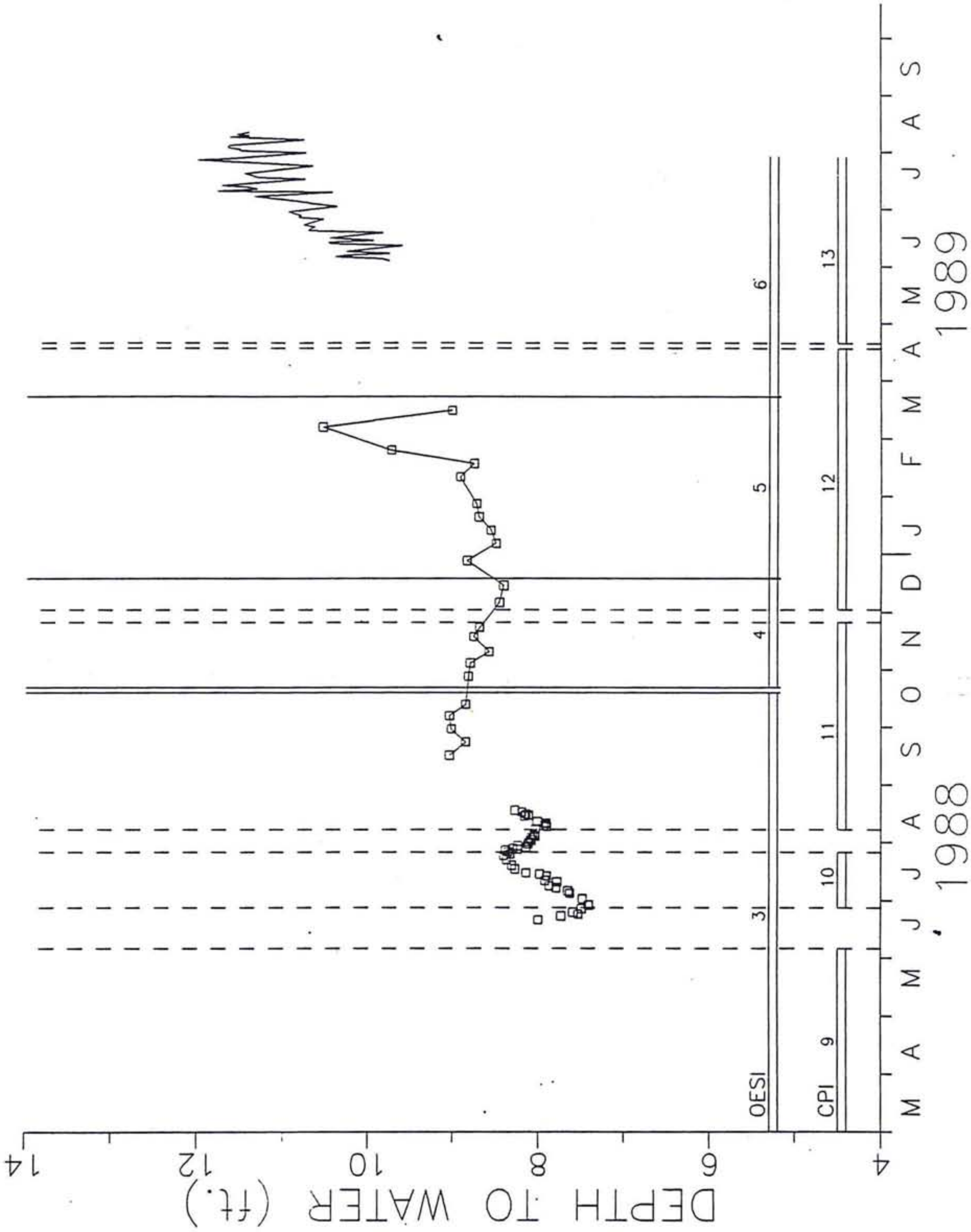
Hydrograph of strat well 13, April, 1987, to June, 1989.



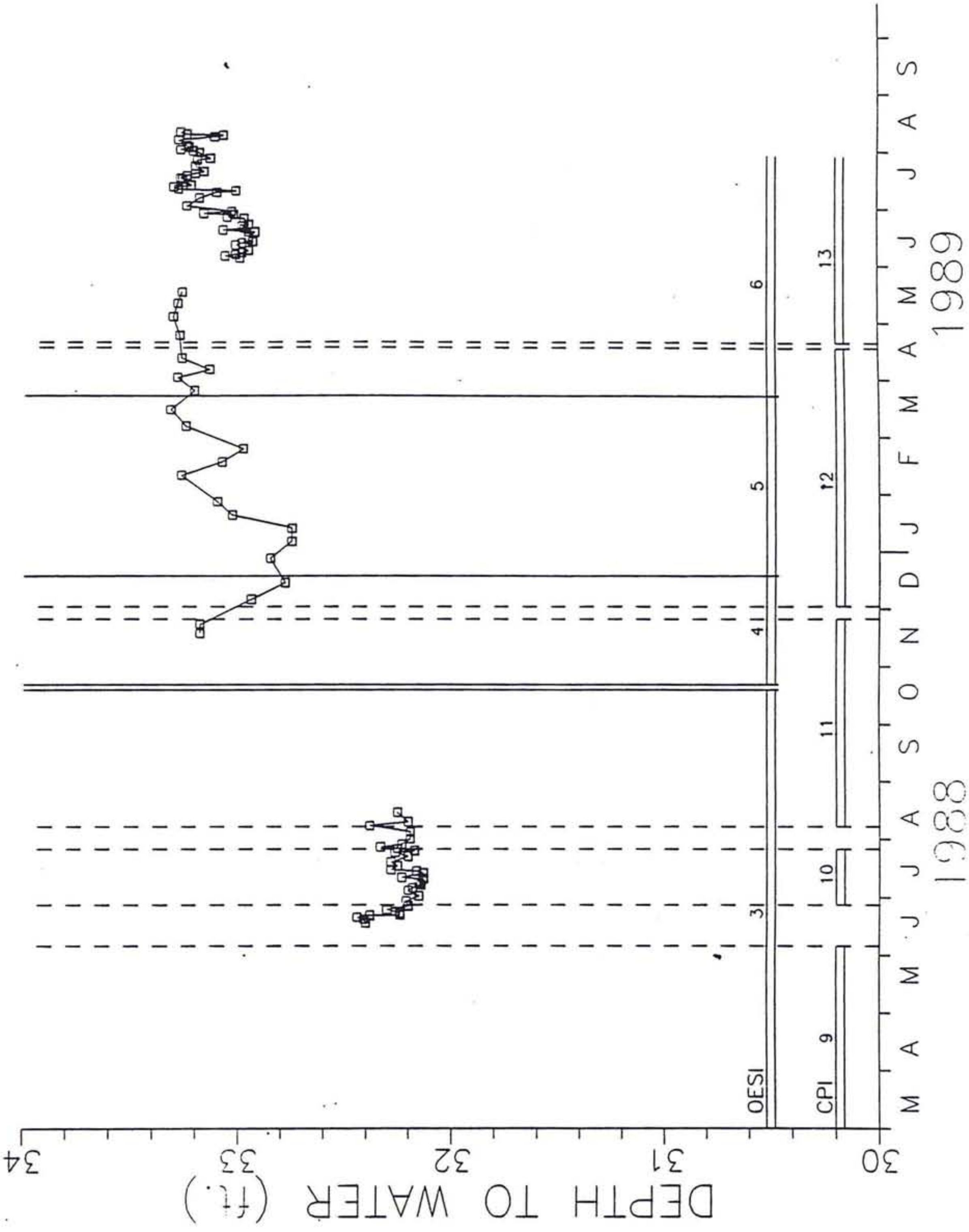
(cont'd) Hydrograph of strat well 13, April, 1987, to June, 1989.



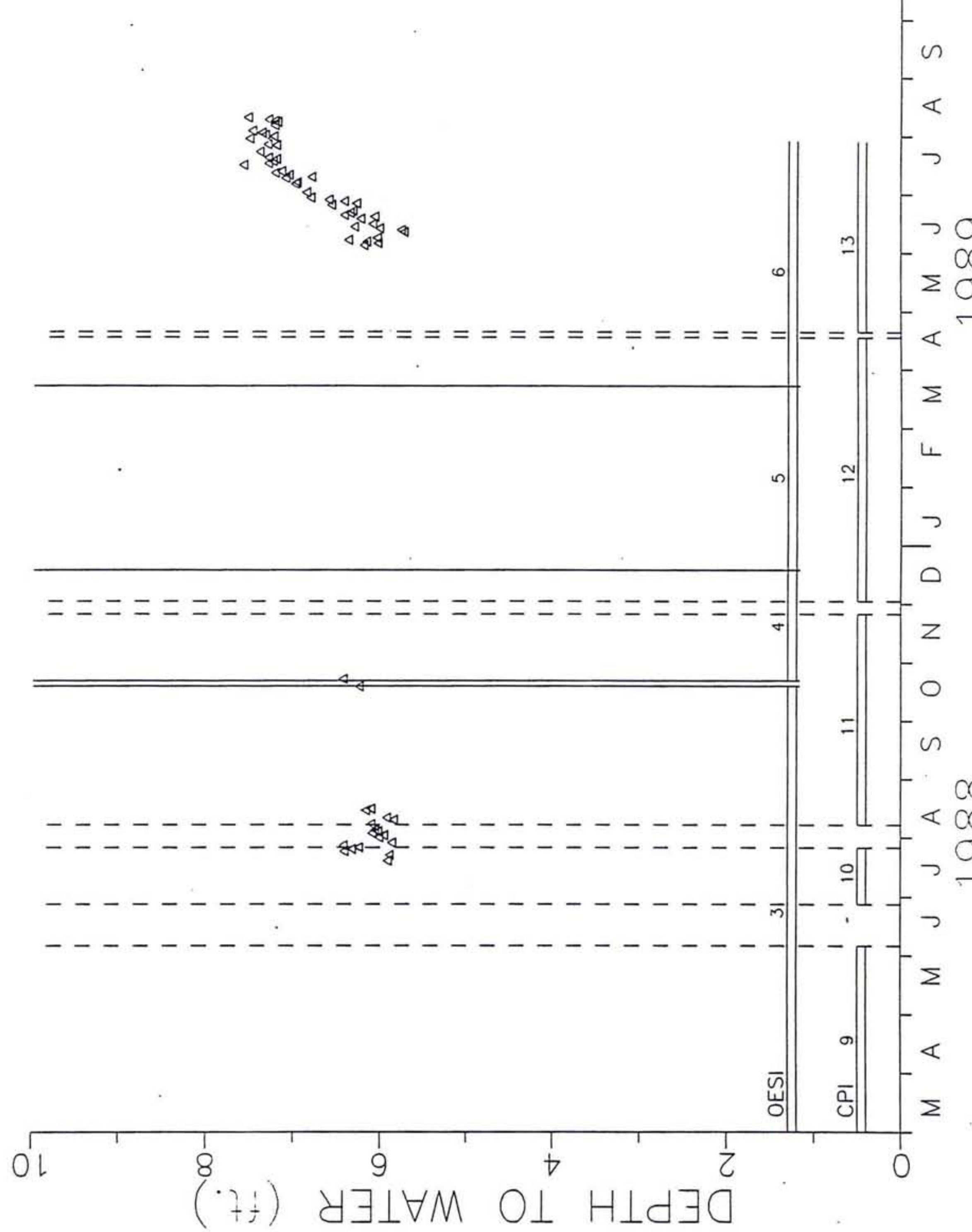
Hydrograph of strat well 14, May, 1987, to October, 1988.



Hydrograph of well GS-1, June, 1988, to August, 1989.



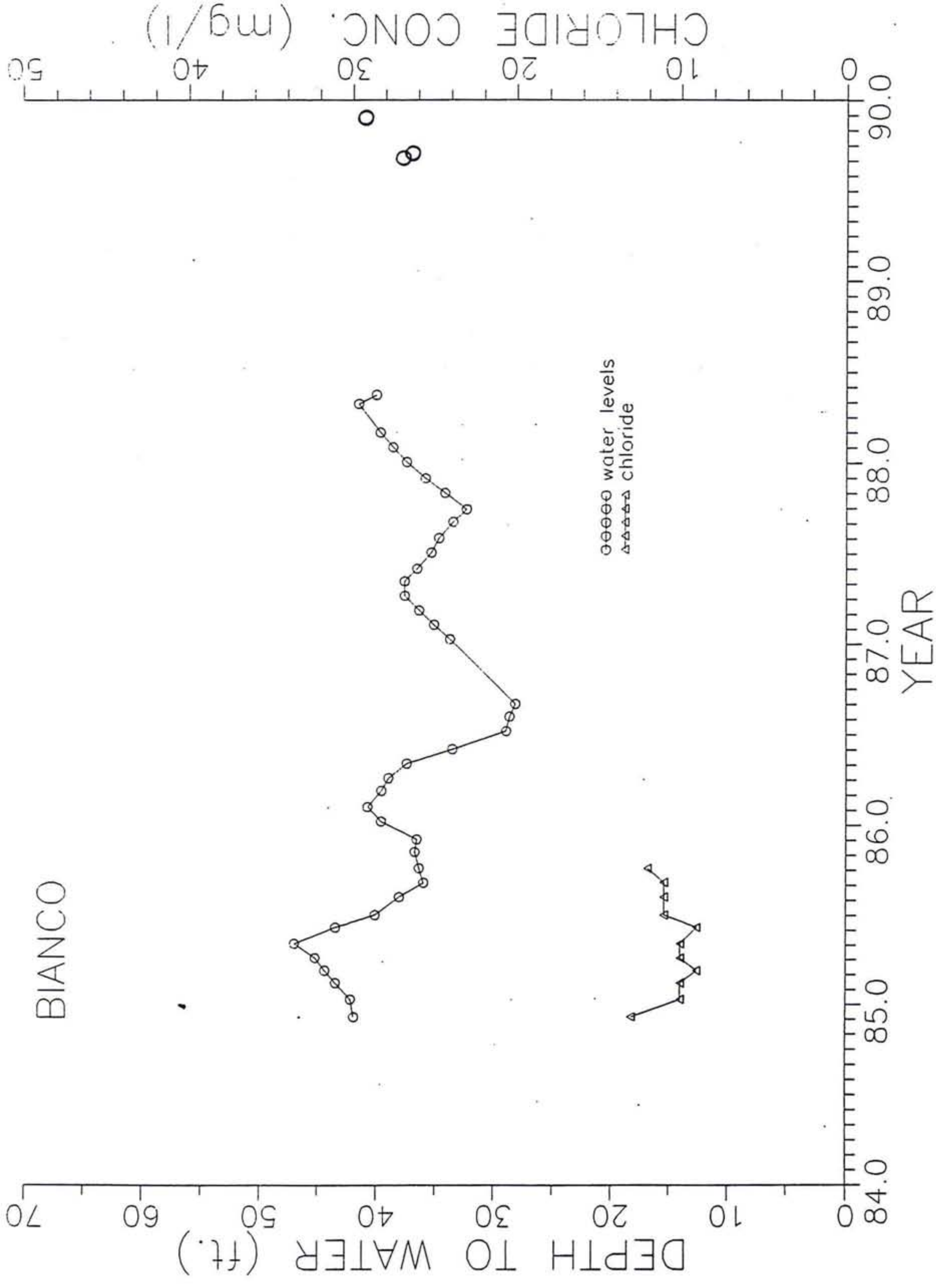
Hydrograph of well GS-8, June, 1988, to August, 1989.

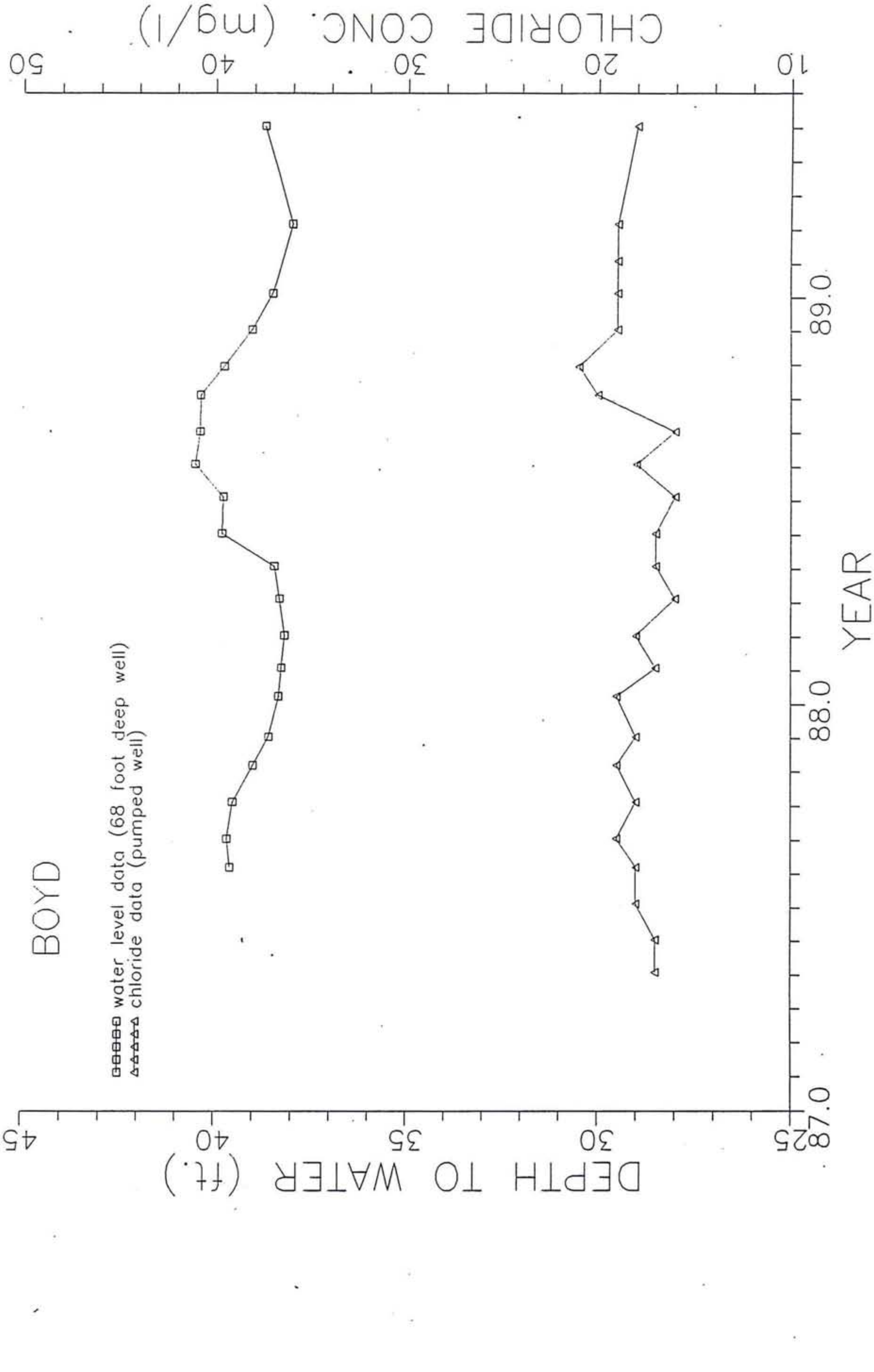


Hydrograph of Old Spa well, July, 1988, to August, 1989.

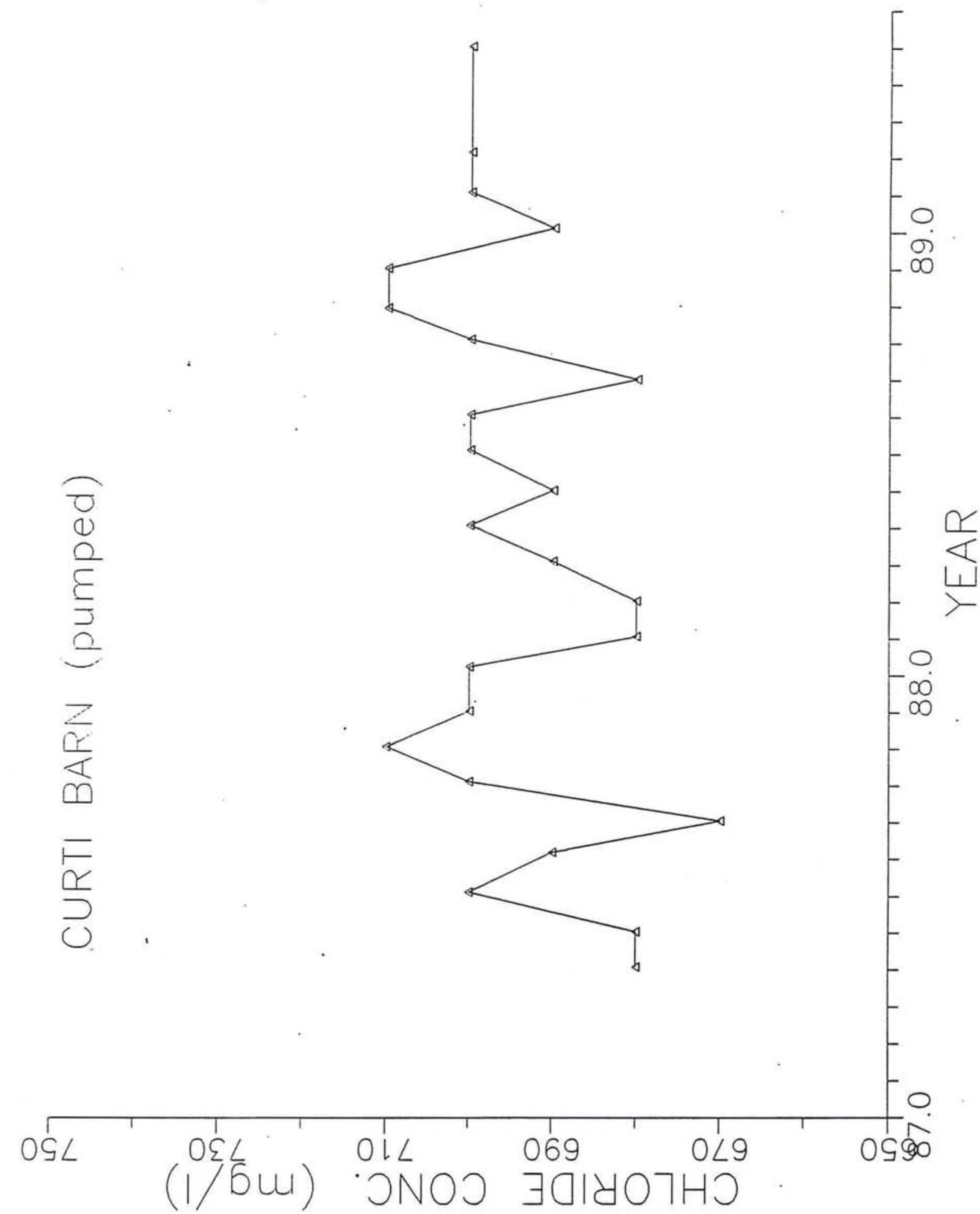
APPENDIX F. HYDROGRAPHS AND CHLORIDE DATA FOR MISCELLANEOUS WELLS

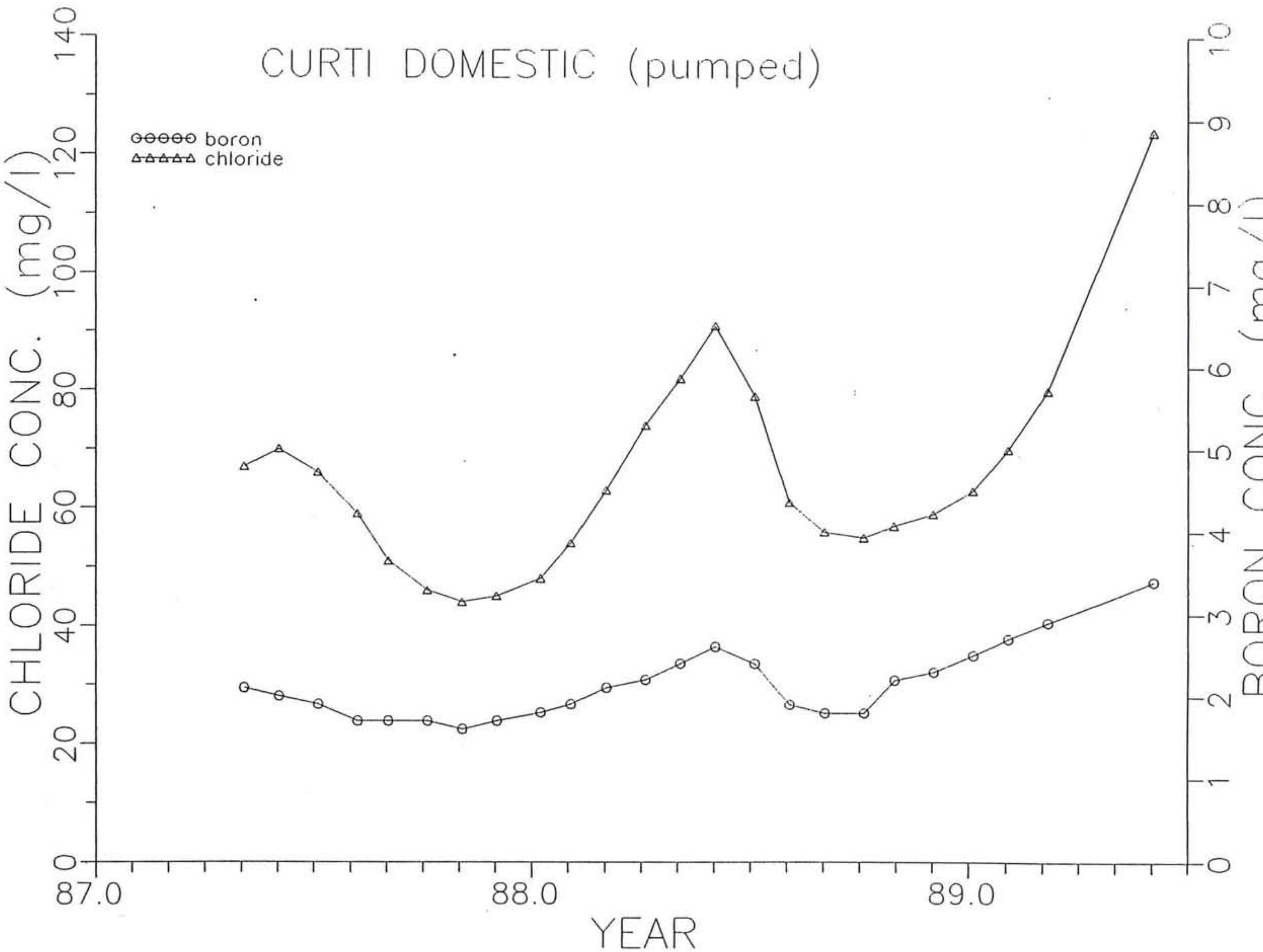
This appendix contains hydrographs and plots of chloride concentration for miscellaneous wells in the region surrounding the Steamboat Hills. These plots are copies of those presented by Collar (1990).

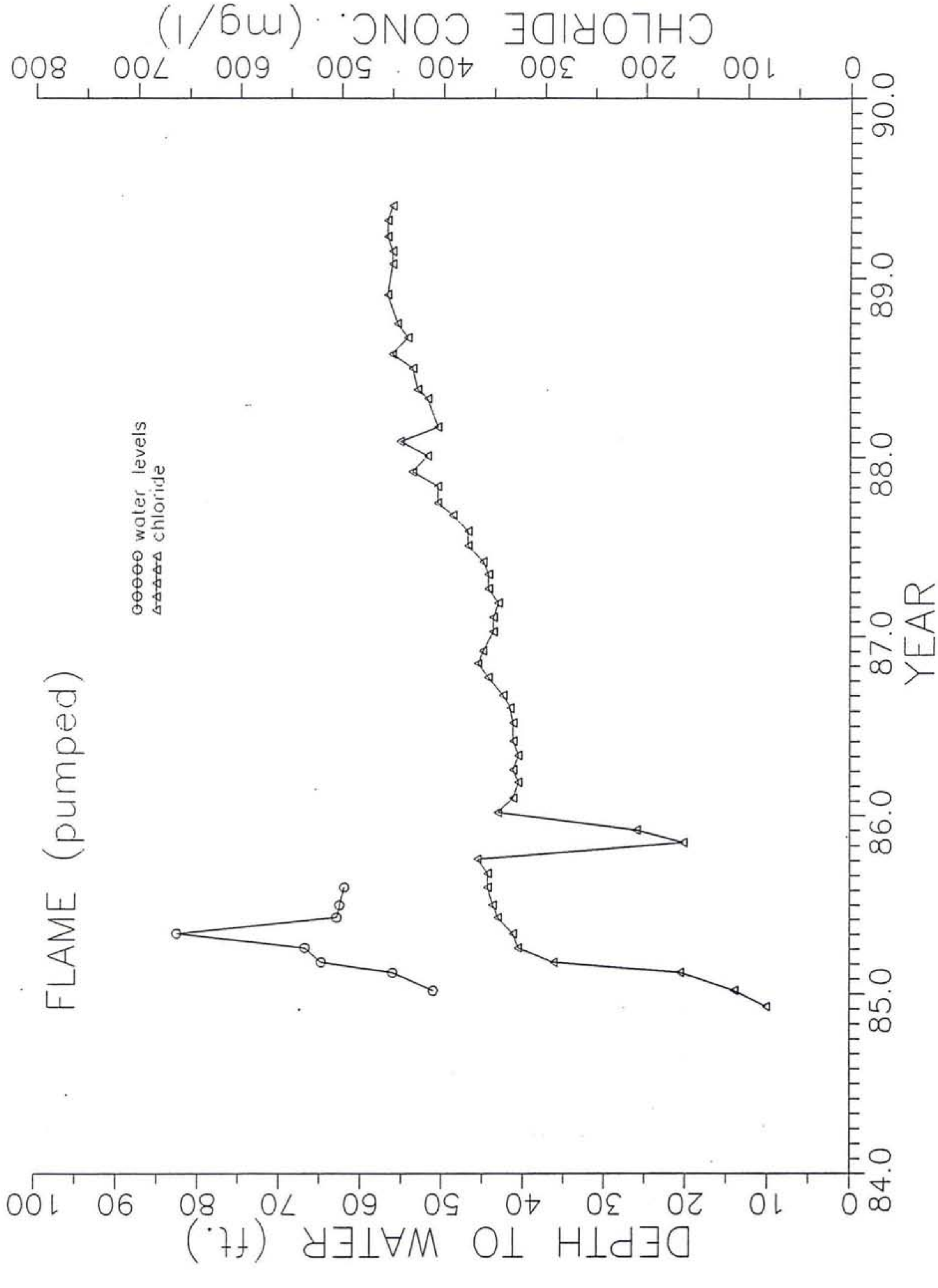

BIANCO
YEAR
DEPTH TO WATER (ft.)
CHLORIDE CONC. (mg/l)
water levels
chloride
84.0
85.0
86.0
87.0
88.0
89.0
90.0
0
10
20
30
40
50
60
70
0
10
20
30
40
50



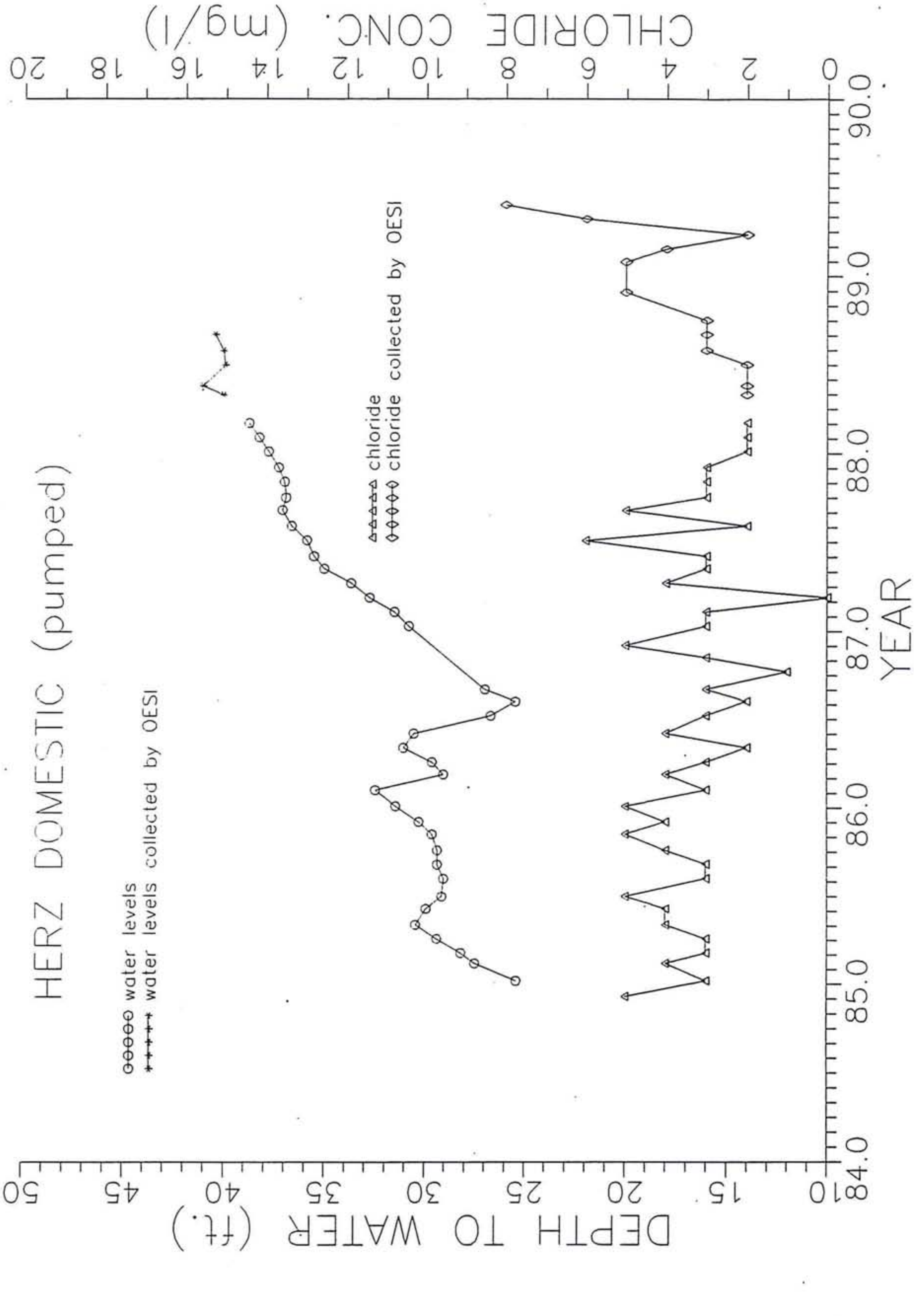
BOYD
water level data (68 foot deep well)
chloride data (pumped well)
CHLORIDE CONC. (mg/l)
DEPTH TO WATER (ft.)
YEAR
87.0
88.0
89.0
10
20
30
40
50
25
30
35
40
45

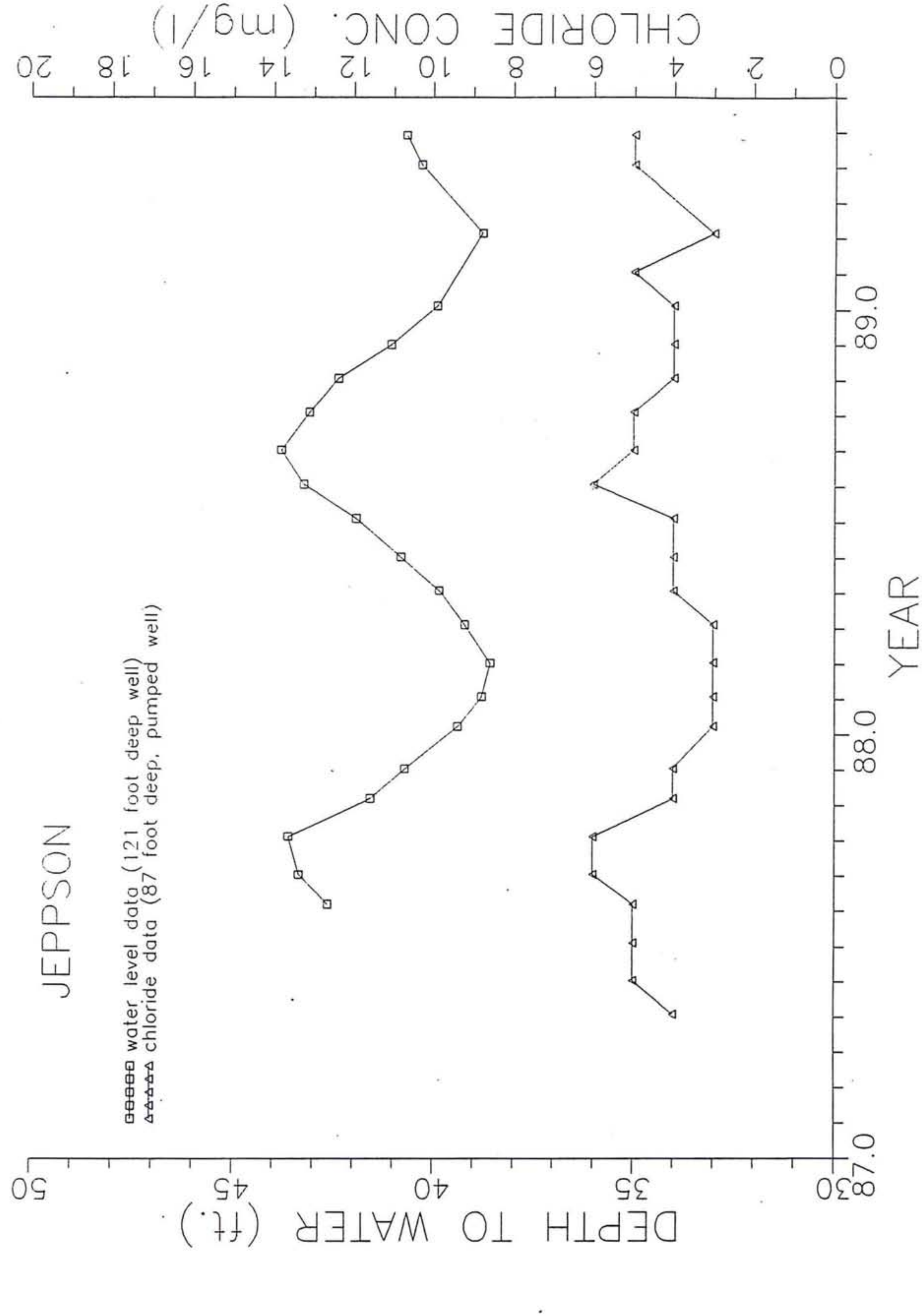

CURTI BARN (pumped)
CHLORIDE CONC. (mg/l)
750
730
710
690
670
650
YEAR
87.0
88.0
89.0

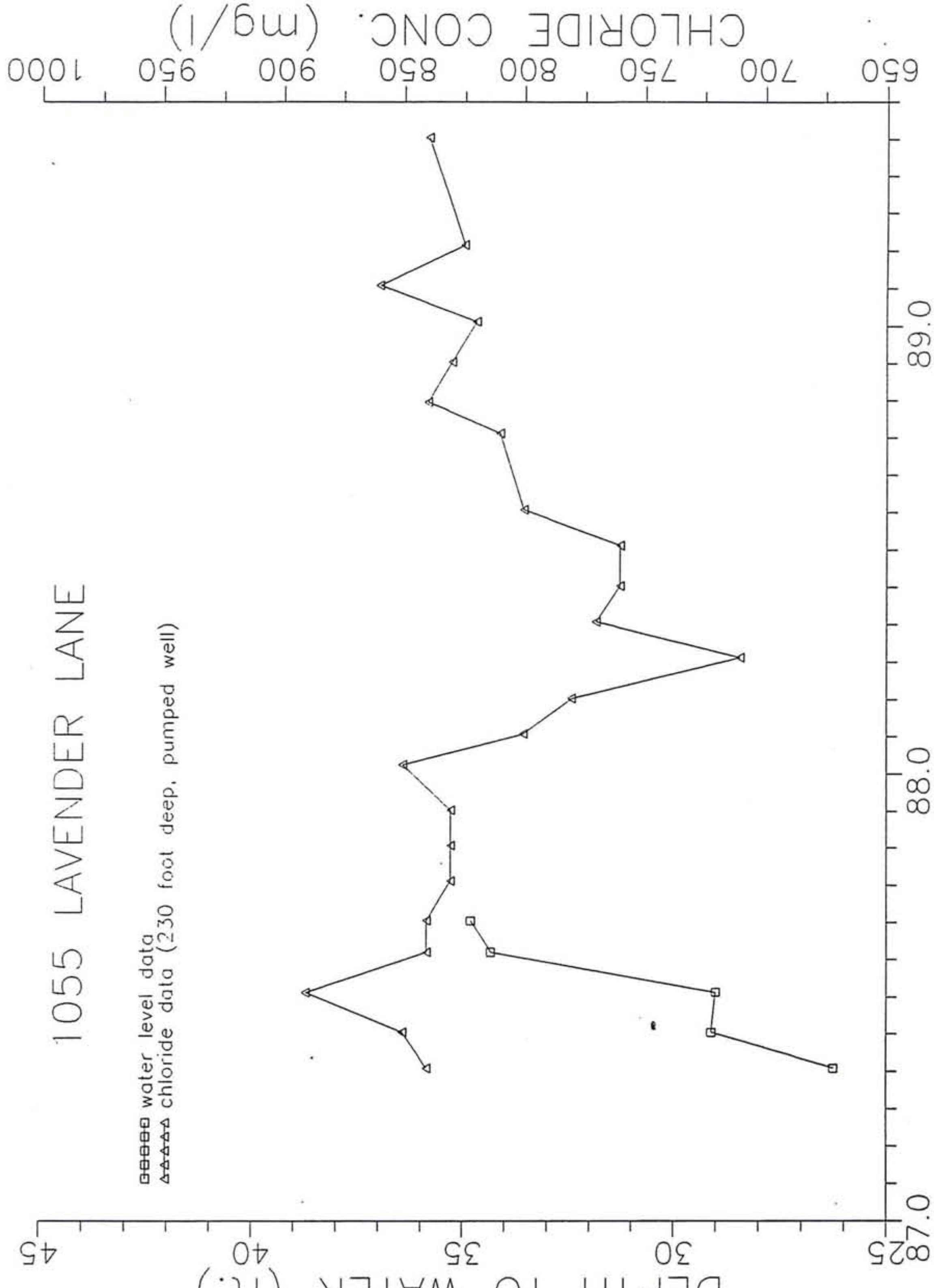

CURTI DOMESTIC (pumped)
boron
chloride
CHLORIDE CONC. (mg/l)
BORON CONC. (mg/l)
YEAR
0
20
40
60
80
100
120
140
0
1
2
3
4
5
6
7
8
9
10
87.0
88.0
89.0

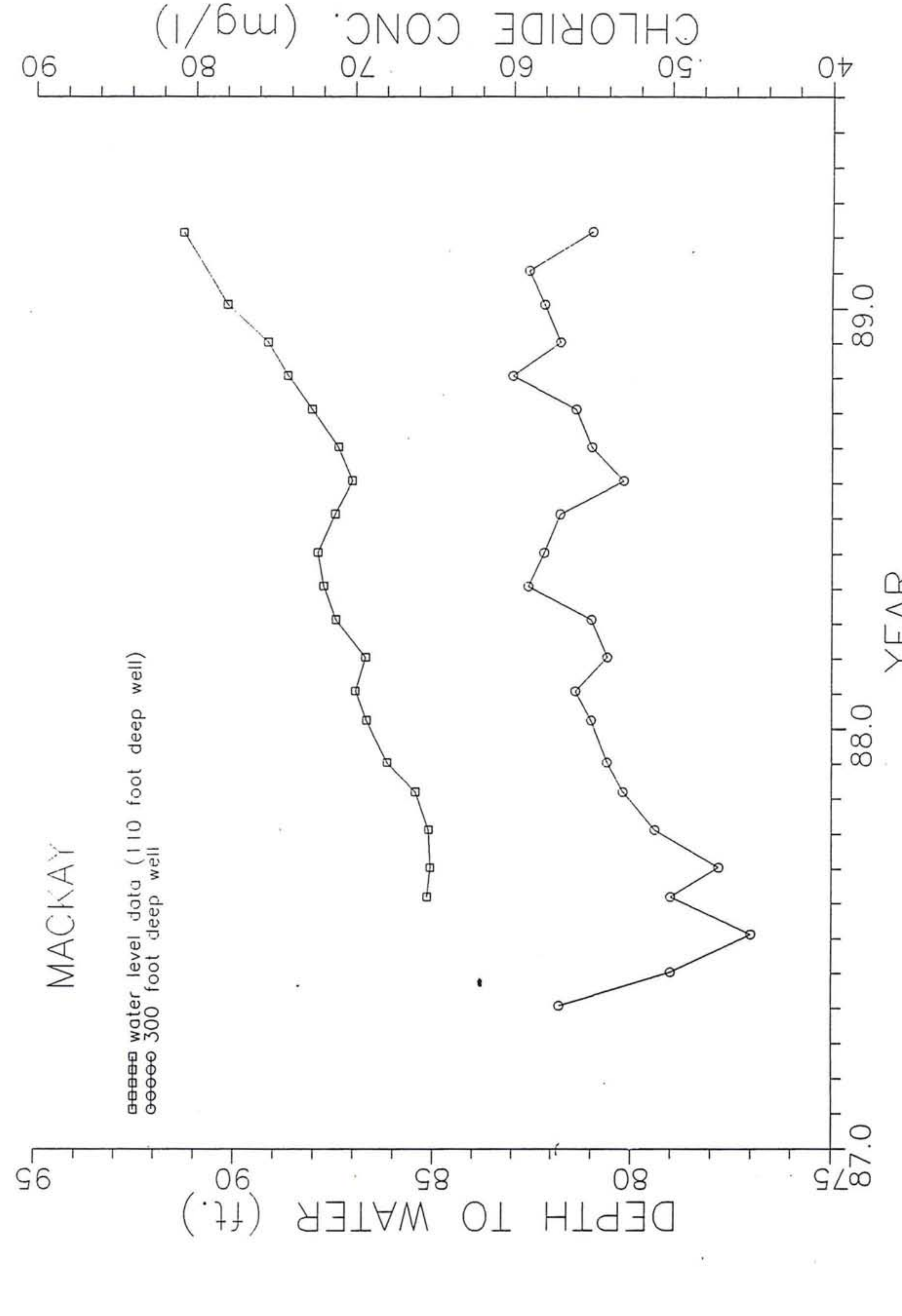


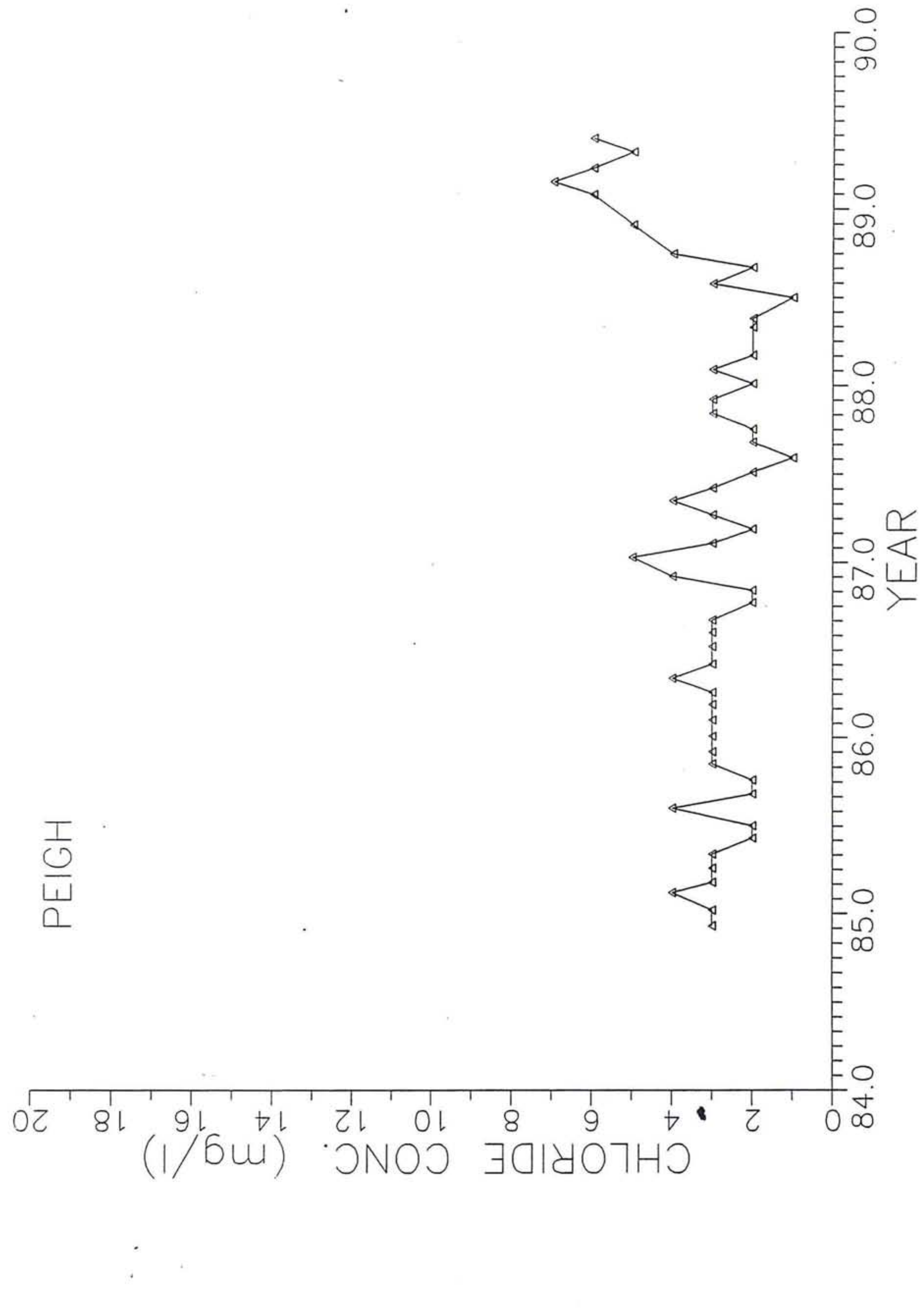
FLAME (pumped)
water levels
chloride
CHLORIDE CONC. (mg/l)
0
100
200
300
400
500
600
700
800
DEPTH TO WATER (ft.)
0
10
20
30
40
50
60
70
80
90
100
YEAR
84.0
85.0
86.0
87.0
88.0
89.0
90.0

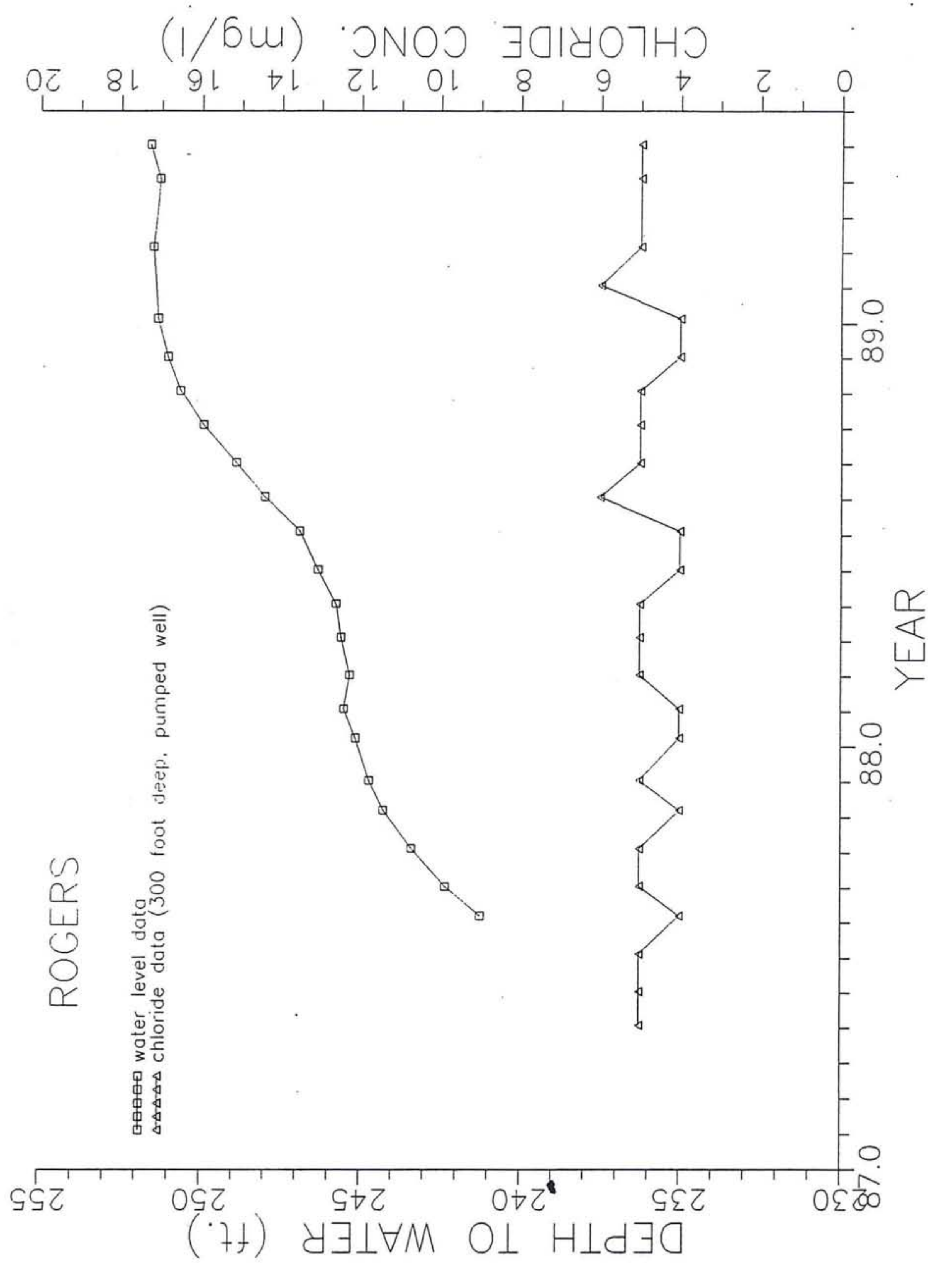

HERZ DOMESTIC (pumped)
water levels
water levels collected by OESI
chloride
chloride collected by OESI
DEPTH TO WATER (ft.)
CHLORIDE CONC. (mg/l)
YEAR
84.0
85.0
86.0
87.0
88.0
89.0
90.0
10
15
20
25
30
35
40
45
50
0
2
4
6
8
10
12
14
16
18
20


JEPPSON
water level data (121 foot deep well)
chloride data (87 foot deep, pumped well)
CHLORIDE CONC. (mg/l)
0
2
4
6
8
10
12
14
16
18
20
DEPTH TO WATER (ft.)
30
35
40
45
50
YEAR
87.0
88.0
89.0

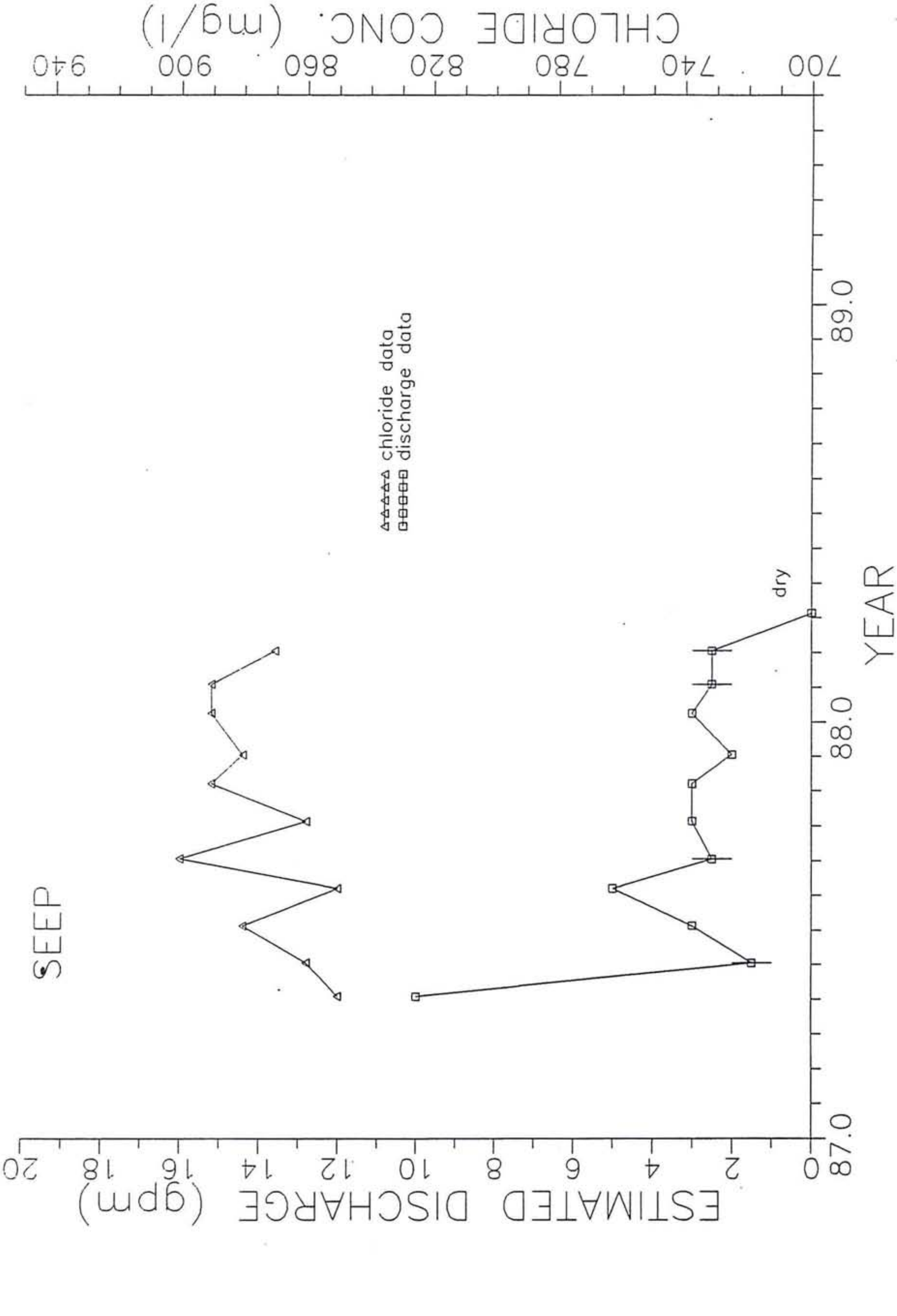

1055 LAVENDER LANE
water level data
chloride data (230 foot deep, pumped well)
CHLORIDE CONC. (mg/l)
650
700
750
800
850
900
950
1000
DEPTH TO WATER (ft.)
25
30
35
40
45
YEAR
87.0
88.0
89.0

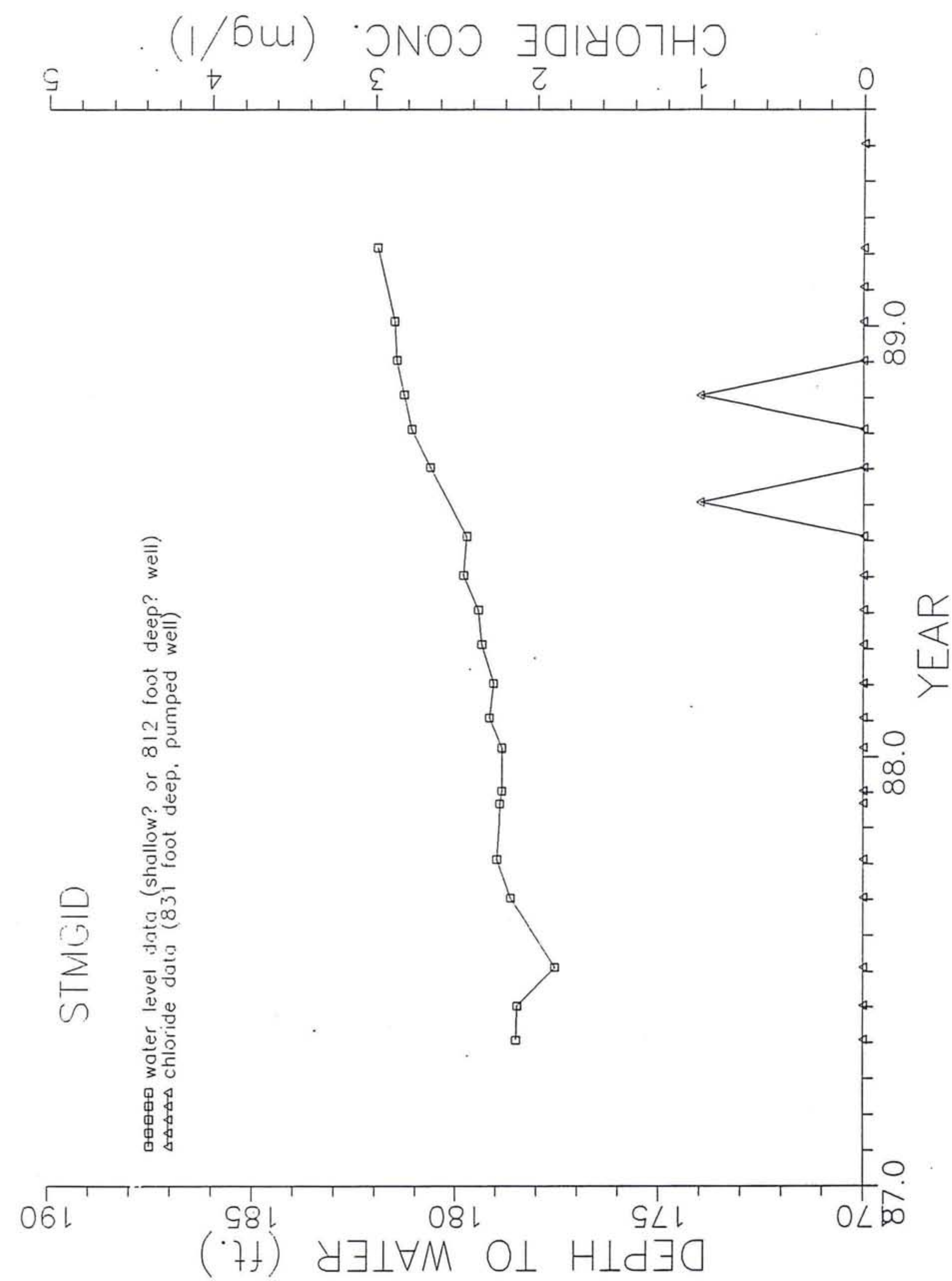

MACKAY
water level data (110 foot deep well)
300 foot deep well
CHLORIDE CONC. (mg/l)
40
50
60
70
80
90
DEPTH TO WATER (ft.)
75
80
85
90
95
YEAR
87.0
88.0
89.0


PEIGH
CHLORIDE CONC. (mg/l)
0
2
4
6
8
10
12
14
16
18
20
YEAR
84.0
85.0
86.0
87.0
88.0
89.0
90.0

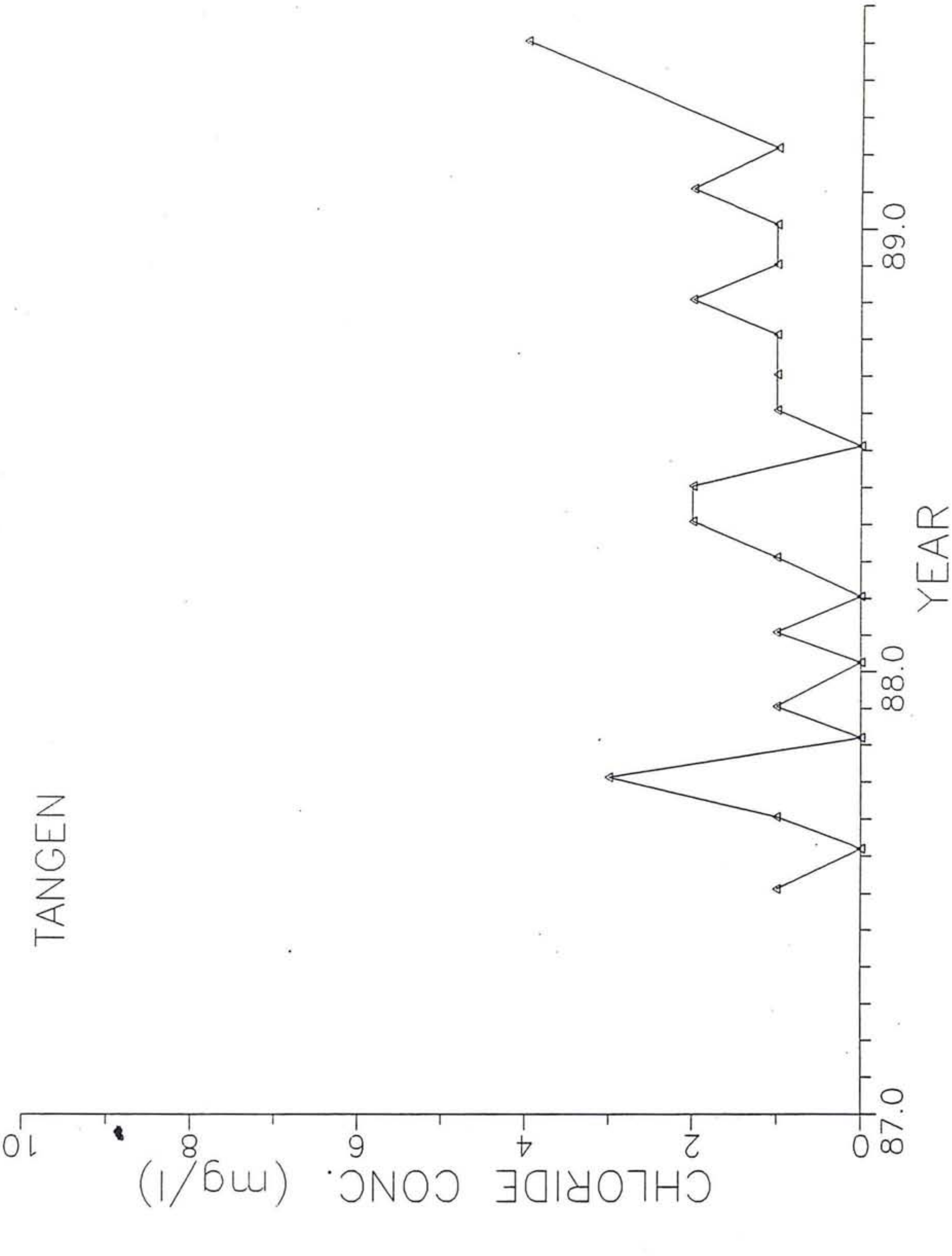


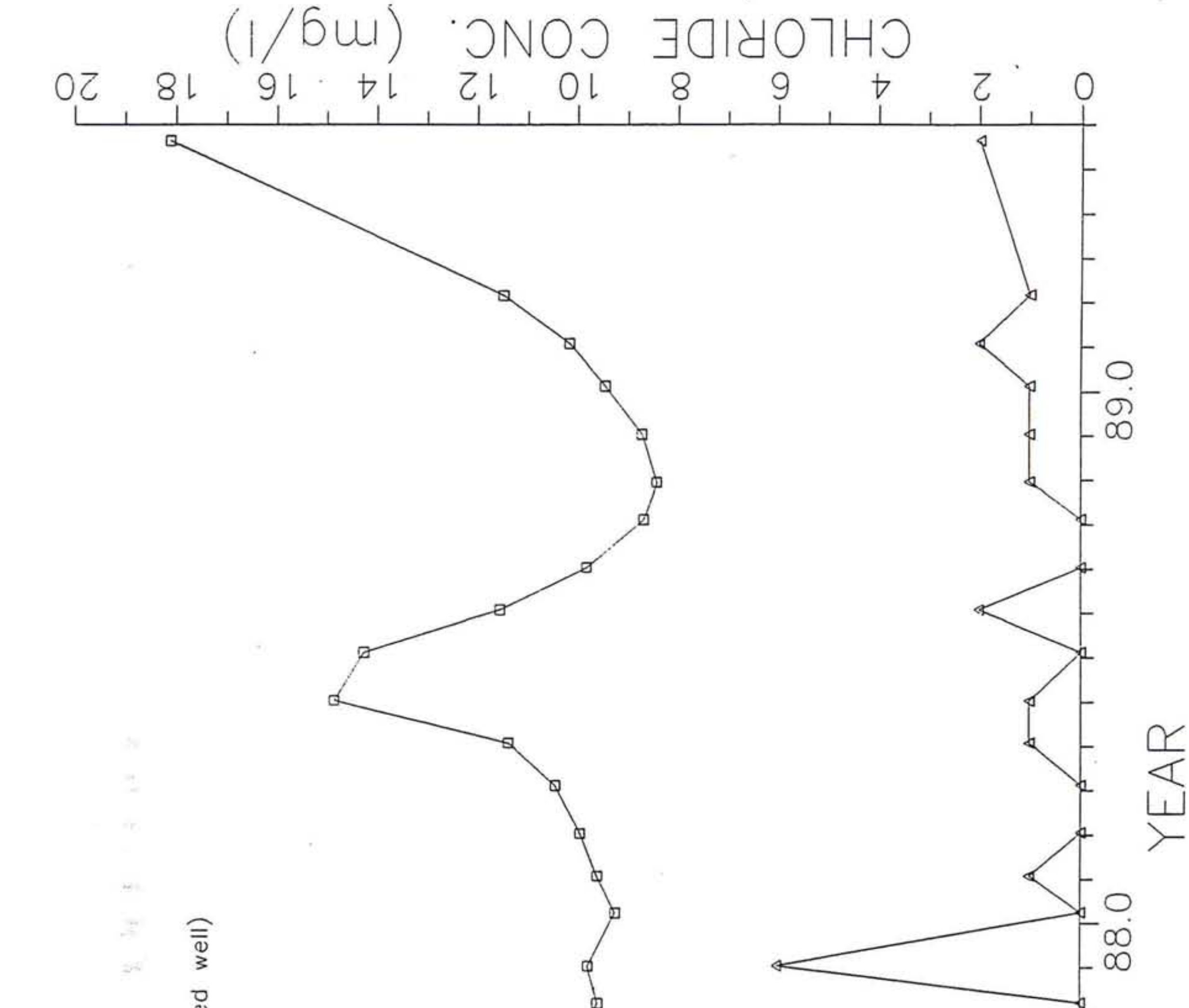
ROGERS
water level data
chloride data (300 foot deep, pumped well)
DEPTH TO WATER (ft.)
CHLORIDE CONC. (mg/l)
YEAR
87.0
88.0
89.0
230
235
240
245
250
255
0
2
4
6
8
10
12
14
16
18
20


SEEP
CHLORIDE CONC. (mg/l)
700
740
780
820
860
900
940
ESTIMATED DISCHARGE (gpm)
0
2
4
6
8
10
12
14
16
18
20
YEAR
87.0
88.0
89.0
chloride data
discharge data
dry



STMGID
water level data (shallow? or 812 foot deep? well)
chloride data (831 foot deep, pumped well)
YEAR
87.0
88.0
89.0
DEPTH TO WATER (ft.)
170
175
180
185
190
CHLORIDE CONC. (mg/l)
0
1
2
3
4
5


TANGEN
CHLORIDE CONC. (mg/l)
0
2
4
6
8
10
87.0
88.0
89.0
YEAR



WOODS
water level data (pumped well)
chloride data
CHLORIDE CONC. (mg/l)
DEPTH TO WATER (ft.)
YEAR
87.0
88.0
89.0

APPENDIX G. STREAM DISCHARGE AND CHLORIDE FLUX

Stream discharge was measured at various sites (stations) along Galena Creek, Steamboat Creek, Steamboat, Crane and Chandler irrigation ditches (Plate 3 and figure 13). In addition, stream discharge was measured on various tributaries and distributaries to the creeks and ditches. Chloride concentration was determined at key stream gaging stations, in part to enable the rate of thermal ground-water inflow to Steamboat Creek between Rhodes Road and Huffaker Hills to be estimated (Plate 3). Chloride concentration was measured in the collected water samples either by San Diego State University (SDSU) or the University of Utah Research Institute (UURI) using the mercuric nitrate and argentometric methods, respectively (American Public Health Association and others, 1985). Boron concentration was also measured in selected water samples by UURI using Inductively Coupled Plasma techniques.

Stream discharge was determined using a pygmy-type current meter according to "six-tenths depth" method and criteria described by Corbett and others (1943) and Buchanan and Somers (1969). Some tributaries consisted of surface water flow in pipes. The discharge in these tributaries was determined by capturing a volume of water over a measured time period.

The total thermal ground-water inflow rate to Steamboat Creek in the South Truckee Meadows was estimated by calculating the inflow rates to successive downstream reaches and summing the individual inflow rates. The calculations were performed assuming chloride, a conservative anion, to be a tracer indicative of the thermal ground water from Steamboat Springs. On the basis of data collected by White (1968), it was assumed that the thermal component of groundwater inflow to Steamboat Creek has a chloride concentration of 820 mg/l. From the chemistry of thermal water in wells, White considered this concentration to be representative of thermal ground water beneath the main terrace prior to dilution or boiling. The non-thermal chloride concentration was assumed to be 6 mg/l on the basis of chloride concentrations in non-thermal wells and springs in Steamboat Valley, along the periphery of the South Truckee Meadows and near Steamboat Springs (White, 1968).

In theory, the thermal flux calculations assume that each of the reaches gaged is a gaining reach; that is, the discharge of the downstream station, after accounting for losses and gains due to distributaries and tributaries, respectively, is greater than that of the upstream station because of ground-water inflow to the creek. However, on the basis of stream discharge rates, some stretches of Steamboat Creek were determined to be losing reaches during initial gaging. Because the downstream station chloride was higher than the upstream station, thermal ground-water inflow to the reach was indicated, however. Considering the above two scenarios, gaining and losing reaches, and making reasonable assumptions, thermal ground-water inflow to a particular reach of Steamboat Creek was calculated using the methods described below.

(1) Gaining Reach

In a hypothetical case with one upstream and downstream station, and one distributary, the following method was used to calculate the thermal ground-water inflow rate to the hypothetical reach:

$$Q_D = Q_U + Q_I - Q_d \qquad (1)$$

$$Q_D C_D = Q_U C_U + Q_I C_I - Q_d C_d \tag{2}$$

where the subscripts D, U, I and d represent downstream, upstream, inflow and distributary, respectively. Q is the stream discharge rate and C is the chloride concentration. Solving for Q_I in (1) and substituting into (2) allows one to calculate the chloride concentration of the influent ground water:

$$C_I = (Q_D C_D - Q_U C_U + Q_d C_d)/(Q_D - Q_U + Q_d) \tag{3}$$

Assuming the previously noted thermal (T) and non-thermal (NT) chloride end members and that,

$$Q_I = Q_T + Q_{NT} \tag{4}$$

$$Q_I C_I = Q_T C_T + Q_{NT} C_{NT} \tag{5}$$

we can calculate Q_T, the thermal ground water inflow rate to the reach by solving for Q_{NT} in (4) and substituting into (5) whereby,

$$Q_T = (Q_I C_I - Q_I C_{NT})/(C_T - C_{NT}) \tag{6}$$

(2) <u>Losing Reach: Upstream Gain</u>
In a hypothetical case with one upstream and one downstream station, the following method was used to calculate the thermal ground-water inflow rate to the reach:

$$Q_D = Q_U + Q_T - Q_O \tag{7}$$

$$Q_D C_D = Q_U C_U + Q_T C_T - Q_O C_O \tag{8}$$

where the subscript O represents the outflow or loss. Thermal (influent) ground water is gained upstream of the loss determined from the discharge measurements such that,

$$C_O = C_D \tag{9}$$

Solving for Q_O in (7) and substituting this result and (9) into (8) allows one to calculate the thermal ground-water inflow rate to the hypothetical reach, assuming the previously noted thermal chloride end member,

$$Q_T = (Q_U C_D - Q_U C_U)/(C_T - C_D) \tag{10}$$

This results in an upper limit estimate of the thermal ground-water inflow rate to the hypothetical reach.

(3) <u>Losing Reach: Downstream Gain</u>
In a hypothetical case with one upstream and one downstream station, method (2) above can be used to calculate the thermal ground-water inflow rate to the hypothetical reach. However, if it is assumed that the thermal (influent) groundwater is gained downstream of the loss determined from the discharge measurements, then

$$C_O = C_U \qquad (11)$$

and (10) becomes

$$Q_T = (Q_D C_D - Q_D C_U)/(C_T - C_U) \qquad (12)$$

This results in a lower limit estimate of the thermal ground-water inflow rate to the hypothetical reach.

Listed in table G-1 are stream gaging data collected, some of which were used to estimate the thermal ground-water inflow rate to Steamboat Creek in the South Truckee Meadows. An attempt was made to gage reaches similar to those gaged by Shump (1985) and consequently the station numbers are the same in many cases as those used by Shump (1985). However, in order to meet the stream cross section criteria of Corbett and others (1943), the station locations may have differed slightly from those of Shump (1985).

Table G-1. Stream discharge and chemistry in Steamboat Creek and various tributaries and distributaries

[ft^3/s, cubic feet per second; mg/L, milligrams per liter; --, Steamboat Creek; D, distributary; T, tributary]

Station	Type	Date	Discharge (ft^3/s)	Chloride (mg/L)	Boron (mg/L)
SD10	--	6/26/88	29.14	--	--
SD20	--	6/26/88	29.21	--	--
SD30	--	6/26/88	27.98	--	--
SD40	--	6/26/88	28.57	3.7	--
GC10	--	6/28/88	3.16	2.8	--
GC20	--	6/28/88	3.51	--	--
GC20A	D	6/28/88	0.18	--	--
GC30	--	6/28/88	0.68	--	--
GC30A	D	6/28/88	2.10	--	--
GC40	--	6/28/88	0.46	--	--
GC40A	T	6/28/88	0.01	--	--
GC50	--	6/28/88	0.84	5.0	<0.05
S5	--	6/28/88	0.76	12.8	--
S5A	T	6/28/88	<0.01	--	--
S5B	T	6/28/88	0.16	--	--
S5C	T	6/28/88	<0.01	--	--
S6	--	6/28/88	1.07	11.6	--
S6A	T	6/28/88	0.06	--	--
S6B	T	6/28/88	0.01	--	--
S7	--	6/29/88	2.52	7.3	--
S7A	--	6/29/88	3.58	--	--
S8	--	6/29/88	0.79	7.8	--
S8A	D	6/29/88	1.29	--	--
S8B	D	6/29/88	0.04	--	--
S8C	D	6/29/88	0.51	--	--
S8D	T	6/29/88	0.01	--	--
S8E	T	6/29/88	0.02	--	--
S9	--	6/29/88	0.21	11.0	--
S9	--	6/30/88	0.16	--	--
S20	--	6/30/88	26.77	3.7	<0.05
S20A	D	6/30/88	11.37	5.1	<0.05
S40	--	6/30/88	14.81	13.5	0.90
S50	D	6/30/88	14.02	15.31	1.05
S60	--	6/30/88	0.77	78.0	5.22
S60A	T	6/30/88	0.45	19.3	--
S70	--	6/30/88	0.72	139.1	8.04
S71	--	6/30/88	0.88	155.0	8.93
S71A	T	6/30/88	0.10	4.1	--

Table G-1. Stream discharge and chemistry in Steamboat Creek and various tributaries and distributaries--continued

Station	Type	Date	Discharge (ft^3/s)	Chloride (mg/L)	Boron (mg/L)
S71	--	7/1/88	0.93	--	--
S71B	D	7/1/88	1.25	--	--
S71C	T	7/1/88	0.05	7.3	--
S71D	T	7/1/88	0.21	--	--
S73	--	7/1/88	1.59	329.0	18.4
S73A	T	7/1/88	0.10	49.5	3.24
S73B	T	7/1/88	0.54	--	--
S74	--	7/1/88	2.17	233.5	13.4
S74A	D	7/1/88	0.05	--	--
S74B	D	7/1/88	0.65	241.3	13.5
S74C	D	7/1/88	<0.01	--	--
S75	--	7/1/88	0.99	239.4	13.6
S75A	--	7/1/88	1.29	--	--
S75B	T	7/1/88	0.07	--	--
S76	--	7/1/88	1.29	220.6	--
S76	--	7/2/88	1.45	--	--
S76A	T	7/2/88	0.21	117.4	6.45
S77A	T	7/2/88	7.67	82.1	5.68
S80	--	7/2/88	8.98	113.9	7.25
S90	T	7/2/88	0.10	--	--
S10	--	8/9/88	0.11	17.2	0.12
SD20	T	8/9/88	14.38	3.7	<0.05
S20	--	8/9/88	14.60	4.2	<0.03
S20A	D	8/9/88	7.83	5.1	0.14
CHD10	--	8/9/88	7.44	5.1	0.16
CHD20	--	8/9/88	7.88	4.7	0.14
S50	D	8/9/88	8.20	30.2	1.60
S60A	T	8/9/88	0.09	31.2	1.69
CRD10	--	8/9/88	8.48	29.3	1.44
CRD20	--	8/9/88	7.78	27.9	1.31
S70	--	8/9/88	0.14	417.7	24.4
S10	--	3/4/89	2.50	23.8	0.1
S50	D	3/4/89	3.34	106.5	4.57
S60A	T	3/4/89	3.32	107.5	4.65
S70	--	3/4/89	3.68	130.4	6.38
S71A	T	3/4/89	0.06	4.2	0.09
S71C	T	3/4/89	0.02	5.6	0.48
S71D	T	3/4/89	0.23	43.5	2.82
S73	--	3/4/89	5.32	202.3	10.6

Table G-1. Stream discharge and chemistry in Steamboat Creek and various tributaries and distributaries--continued

Station	Type	Date	Discharge (ft^3/s)	Chloride (mg/L)	Boron (mg/L)
S73B	T	3/4/89	0.23	32.2	1.2
S73C	D	3/4/89	0.39	191.6	10.2
S74	--	3/4/89	5.77	192.5	10.1
S74C	D	3/4/89	1.25	191.6	10.2
S75A	--	3/4/89	4.13	191.6	10.2
S75B	T	3/4/89	0.01	82.2	4.47
S75C	T	3/4/89	0.36	215.0	10.6
S76A	T	3/4/89	0.20	55.6	2.13
S77	--	3/4/89	5.02	196.7	10.0