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ASSESSMENT OF THE GEOTHERMAL RESOURCE WITHIN THE FOURMILE HILL PROJECT AREA, GLASS MOUNTAIN KGRA

DRAFT

CONFIDENTIAL

for

BONNEVILLE POWER ADMINISTRATION
PORTLAND, OREGON

by

GeothermEx, Inc.
Richmond, California
AUGUST 1999

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TRANSMITTAL

To: George Darr, BPA
Tom Box, Calpine

Date: 31 August 1999

From: Ann Robertson-Tait

Subject: Fourmile Hill

Gentlemen:

Enclosed is our draft report on the Fourmile Hill project. You will note that it is stamped "CONFIDENTIAL" as it contains proprietary material. We will work with Calpine to develop a version of the report suitable for releasing to the public.

Meanwhile, we look forward to your comments or questions. Best regards.

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EXECUTIVE SUMMARY

Calpine Corporation (Calpine) has proposed the development of a 49.9 MW (gross) geothermal power project in the Fourmile Hill area, located in the northwestern sector of the Glass Mountain Known Geothermal Resource Area (KGRA). Bonneville Power Administration (BPA) has asked GeothermEx to make an independent assessment of the geothermal resource beneath the proposed project area, with emphasis on evaluating the likelihood that this project can be successfully developed. Proprietary data supplied by Calpine and published documents were used to evaluate the project area. The proprietary data consist of drilling records, temperature and pressure surveys and production test data from the temperature-observation holes and full-sized wells that have been in the area. Published documents include numerous articles on the geology and geophysics of the area, and the February 1999 Final Environmental Impact Statement and Environmental Impact Report, prepared by the U.S. Bureau of Land Management, the U.S. Forest Service, the Siskiyou County Air Pollution Control District and BPA.

The Glass Mountain KGRA encompasses part of the Medicine Lake Highland, a broad-based Quaternary volcano in northeastern California. The Highland lies on the eastern side of the Cascade Range, in an area where prolonged volcanism and crustal extension have created conditions favorable for active geothermal systems. Abundant normal faulting occurs along several prominent trends, with volcanic centers aligned along faults in some areas. An oval-shaped caldera (volcanic depression) and its bounding ring-fracture system have been mapped within the KGRA; this feature is closely associated with the location of the youngest volcanic eruptions, and may be related to the location of deep magmatic intrusions. Although not yet well understood, it is likely that permeability within the Glass Mountain geothermal system is controlled by a combination of these regional and local structural features.

Beginning in the late 1970s, government and private interest in geothermal resource development of the Glass Mountain KGRA led to studies aimed specifically at geothermal exploration. Several companies took major lease positions after 1981, and began drilling temperature-observation wells around the Highland. In the middle to late 1980s, four full-diameter deep wells were drilled in the east-central and southeastern part of the KGRA. One suffered mechanical damage, but the other three were commercial successes with estimated outputs ranging from 3 to 5 MW (gross) each. All encountered temperatures in the range of 500 to 550°F.

Fluid chemistry data from these wells indicates that the reservoir fluids are typical of most geothermal systems, with about 0.3 weight-% total dissolved solids and chloride (Cl) concentrations of 1,200 to 1,320 parts per million by weight. Temperatures calculated from chemical geothermometers span the range from 470 to 515°F, in excellent agreement with measured temperatures. In one of the tested wells, the flow was initially slightly acidic, but became neutral with time. Gases in steam are relatively low, and the relative concentrations of different gas species are typical of geothermal production worldwide.

Of all data available from the Glass Mountain area, temperature data from deep and shallow wells provide the most direct evidence concerning the source of heat for the geothermal system, the position of the geothermal reservoir and the patterns of fluid movement in the system. The subsurface temperature anomaly defined by these data has the shape of a broad oval that coincides with the caldera ring fracture, indicating a close association between the volcano and the source of heat for the geothermal system. Two zones of higher temperature are present within the overall anomaly: one in the southeastern part of the field, where the deep wells were drilled; and another in the northwestern part of the field, beneath the southern part of the Fourmile Hill project area. In both zones, temperatures greater than 450°F occur at relatively shallow depths, indicating upflow from deeper levels and the presence of elevated rock permeability. In the southeastern high-temperature zone, this permeability has been confirmed by three commercially productive wells, which suggests that in a substantial portion of the Fourmile Hill area, permeability will be sufficient to provide commercial production from deep wells. Deep drilling and testing will be required to confirm this.

Because of the lack of deep production wells, no proven recoverable reserves of geothermal energy have been identified in the Fourmile Hill area. However, it is possible to estimate the reserves that are potentially available, assuming that productive wells can be successfully drilled. A volumetric method of reserve estimation, developed by the U.S. Geological Survey and modified by GeothermEx to include a probabilistic approach to account for uncertainties in certain reservoir-related parameters, is used herein.

Triangular probability distributions, defined by minimum, maximum and most-likely estimates of a given parameter, were used to describe reservoir area, reservoir thickness and average temperature within the project area. Rectangular probability distributions, which are defined only by minimum and maximum estimated values, were used to describe porosity and recovery factor (the fraction of the heat-in-place that can be converted to electrical energy at the power plant). The values used for each parameter, assigned on the basis of our understanding of the conceptual hydrogeologic model of the Glass Mountain geothermal system, can be found in the main text of the report. Relatively conservative values were used for the uncertain parameters, reflecting the fact that there has been no deep drilling in the project area.

The uncertain parameters were sampled randomly several thousand times using a process called Monte Carlo simulation, which is used extensively to estimate reserves in the petroleum and mining industries. Together with defined values of parameters used in the reserve estimation methodology that have little or no uncertainty (volumetric specific heat, average ambient temperature, utilization factor, plant capacity factor and plant life), each set of randomly sampled uncertain parameters was used to calculate the recoverable reserves. The resulting probability distributions are presented as a histogram and as a cumulative probability plot of MW capacity. Nearly all of the probability distribution of energy reserves in the Fourmile Hill project area lies in the range of 40 to 150 MW (assuming a 30 year plant lifetime). The most-likely level of reserves is estimated to be about 85 MW, whereas the mean value is about 96 MW. There is more than a 90% probability that the reserves exceed 50 MW, and a 50% probability that they exceed 92 MW.

These results, which are based on reasonably conservative assumptions of resource characteristics, indicate a very high probability that the reserves exceed 50 MW for a 30-year power plant life. It is therefore reasonable to conclude that the Fourmile Hill area can support a development of this size, provided that commercially productive wells can successfully be drilled within the project area.

Calpine's plan to develop the project includes drilling 9 to 11 initial production wells to depths of ±8,500 feet in the part of the project area with highest temperatures. The depths and locations of the wells are reasonable and consistent with the existing conceptual model of the resource.

Each production well is anticipate to have an initial capacity of 4.5 to 5.5 MW (gross). The three deep wells drilled and tested in the southeastern part of the KGRA had capacities ranging from 3 to 5 MW; however, all were completed with casings of smaller diameter than is planned for the Fourmile Hill wells. It is usually the case that, for wells encountering similar resource conditions, increasing the wellbore diameter will increase well productivity. An estimation of the magnitude that could be expected from such an increase in wellbore diameter, which can only be accomplished by detailed wellbore modeling, is beyond the scope of this study. However, Calpine's assumption of per-well productivity for Fourmile Hill is conservative compared to the worldwide average of about 6 MW (gross). Furthermore, the productivity of wells in volcanic systems like Glass Mountain often exceeds this average value. Therefore, it is our opinion that Calpine's estimate of the number of initial wells required to supply the Fourmile Hill project is reasonable.

It is planned that waste fluids will be injected at the periphery of the production area in three wells (initially) with an average injectivity of 800,000 pounds per hour, which is reasonable. The locations of the proposed injection pads provide enough flexibility to modify the injection plan as the reservoir becomes better defined during the development drilling campaign. Injection is unlikely to limit the development of the Fourmile Hill project.

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1. INTRODUCTION

Bonneville Power Administration (BPA) has contracted GeothermEx, Inc. to make an independent assessment of the resource for the proposed Fourmile Hill geothermal power project at Glass Mountain, California (figure 1.1). This 49.9 MW (gross) project is being developed by Calpine Corporation, and will be supplied by steam from geothermal wells. A double-flash power plant is planned, and the wastewater (separate brine plus steam condensate) will be injected to the subsurface.

This assessment has been based on the following Scope of Work:

Task 1: Obtain (from Calpine) maps, cross sections, drilling information (well completion, lithology, temperature and pressure data), flow or injection test data, chemical data and a development plan for the Fourmile Hill project.

Task 2: Use the above data to develop a conceptual hydrogeologic model of the Glass Mountain geothermal resource, with emphasis on evaluating conditions beneath the Fourmile Hill area.

Task 3: Using a probabilistic approach, estimate the recoverable geothermal energy reserves within the area dedicated to the Fourmile Hill project.

Task 4: Review Calpine's development plan and opine on the likelihood of successfully developing a 49.9 MW (gross) geothermal power project in the Fourmile Hill area.

Task 5: Prepare a report for BPA summarizing GeothermEx's opinion.

A lease and well location map covering most of the Glass Mountain Known Geothermal Resource Area (KGRA) is shown in figure 1.2. There are two major leaseholders in the area: Calpine and CalEnergy Company, Inc. ("CECI"). The areas with the cross-hatched pattern in figure 1.2 are leased by Calpine, while CECI has leases on the stippled areas. CECI is developing the Telephone Flat project in the proposed Participating Area southeast of Medicine Lake. The leases in the areas shown with the diagonal line pattern are held jointly by Calpine and CECI.

Most of the wells in the area have been drilled for the purpose of obtaining temperature data; in most cases, no flow from or injection into these wells was permitted. Such temperature-observation wells (called "strat test" holes by some operators) are shown with triangular symbols in figure 1.2. Production tests were conducted in the four large-diameter wells, which are shown with round symbols on the well location map.

Calpine provided data from all but two of the wells shown in figure 1.2. The two wells not included with the data package were 56-3, located northwest of Medicine Lake, and 52-30, located south of CECI's proposed Participating Area. For the other wells, a variety of information was provided. Some wells had most of the requested information while others were missing completion data, lithologic data, or both. Available temperature and well completion data are presented in the Downhole Summary Plots in the Appendix.

The following chapter of this report describes the geologic setting of the Glass Mountain area. Chapter 3 presents a brief history of geothermal exploration and development, which began in the 1970s. In Chapter 4, the conceptual model of the geothermal resource beneath the Fourmile Hill project area is used as a basis for estimating the recoverable geothermal energy reserves. Calpine's development plan is reviewed in Chapter 5.

Done

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2. GEOLOGIC SETTING

The Glass Mountain KGRA is part of the Medicine Lake Highland, a young volcanic complex approximately 6,500 feet above mean sea level in northeastern California. The Highland is part of the Cascades volcanic arc, which includes such prominent volcanoes as Mt. Ranier, Mt. St. Helens, and Mt. Shasta. The area is used for timber harvesting and seasonal recreation; there are no permanent residents within the KGRA.

The Medicine Lake Highland is a broad-based Quaternary volcano formed over the last 700,000 years. The region is characterized by bimodal volcanism, with thin flows of basalt and basaltic andesite being predominant over more silicic eruptives in the earlier volcanic history. The summit of the volcano collapsed about 100,000 thousand years ago, forming an elliptical caldera (depression) 10 km long and 7 km wide in the central part of the Highland. The ring-fracture boundary of the caldera is shown in figure 2.1. Later eruptions buried much of the caldera and produced a series of young, silicic volcanic domes and flows (also shown on figure 2.1), some of which are less than 2,000 years old. Glass Mountain, for which the KGRA is named, erupted rhyolitic pumice and obsidian flows 900 years ago. Medicine Lake lies in the central part of what is left of the caldera.

Prolonged volcanism and crustal extension are associated with anomalously high regional heat flow and shallow magmatic heat sources, both of which are favorable for active geothermal systems. The Medicine Lake Highland is located at the intersection of two major lineaments: the east-northeast-trending Mt. Shasta - Medicine Lake lineament; and the north-south-trending Klamath Falls - Fall River Graben. Both of these regional features are associated with a concentration of volcanic vents. Normal faulting is common across the Highland, and includes older, northwest-trending deep basement faults and younger, north-northwest trending faults.

The younger faults are an expression of ongoing crustal extension mentioned above. The caldera boundary apparently controls the location of the youngest eruptive centers within the Highland, and may control the location of deep magmatic intrusions. Although not yet well understood, permeability within the Glass Mountain geothermal system is likely to be affected by some of these same structural features, both local and regional.

The occurrence of extremely young silicic eruptions and interpretation of geophysical data suggest that one or more relatively small magma chambers exist beneath the caldera at depths estimated to be less than 10 km. These cooling magma bodies are the likely source of heat for the geothermal system in the Glass Mountain KGRA. The geothermal system is manifested at the surface by an area of warm ground east of Medicine Lake and a weak fumarole immediately west of Glass Mountain. The lack of significant surface manifestations is not surprising because most of the precipitation in the Highland penetrates deep into the permeable volcanic cover, yielding a relatively deep water table and suppressing regional heat flow.

3. EXPLORATION AND DEVELOPMENT HISTORY

Interest in the Glass Mountain area for potential development of geothermal resources was attracted by:

- the presence of the large Medicine Lake volcanic complex, which features a sizable caldera and abundant young volcanic activity; and
- surface thermal manifestations, which include, principally, an area of warm ground located east of Medicine Lake, and a weak fumarole immediately west of Glass Mountain.

Basic geologic and geophysical studies of the area were carried out intermittently beginning in the 1930s, as part of regional scientific investigations and, in some cases, for petroleum exploration. Government and private interest in geothermal resource development led to studies aimed specifically at geothermal exploration beginning in the late 1970s. The U.S. Geological Survey designated 15,371 acres of the Glass Mountain area as a Known Geothermal Resource Area (KGRA) in 1970. The Glass Mountain KGRA has subsequently been expanded considerably, to include at present a total of 134,254 acres.

The Bureau of Land Management (BLM) initiated the process of leasing Federal lands within the Glass Mountain KGRA for geothermal exploration in 1981. Union Oil Company (now Unocal), Occidental Geothermal, Inc. and Phillips Petroleum Company obtained major lease positions during this period. Other companies that had exploration interests in the area during the 1980s included Geothermal Resources International, Anadarko Production Company, Hunt Energy Company and Vulcan Geothermal Group.

Surface exploratory investigations carried out in the 1980s by private and, in some cases, public entities included:

- regional and detailed geologic mapping;
- volcanological studies;
- petrologic studies;
- electrical resistivity and magnetotelluric surveys;
- aeromagnetic surveys;
- seismic surveys (including seismic refraction and teleseismic techniques);
- gravity surveys;
- soil geochemistry surveys, including analysis of soil mercury contents; and
- analyses of water chemistry, including stable isotope analysis.

During 1981-1984 the three major leaseholders drilled a total of 24 core holes within the KGRA, mostly to depths between 1,500 feet and 4,000 feet, for the purpose of measuring temperature gradients. In 1984 Phillips and Occidental drilled the field's first deep exploratory well, 17A-6, near the site of a core hole in the east-central part of the KGRA (figure 1.2). This well reached a total depth of 9,620 feet, but suffered mechanical problems after an initial attempt at production testing. It remained unproductive despite attempts at repair and workover.

Unocal subsequently drilled three deep wells in the southeastern sector of the field. These were:

- well 68-8, drilled to 8,417 feet in 1985;

- well 31-17, located less than one mile to the southwest of 68-8 and drilled to 8,787 feet in 1988; and

- well 87-13, located about 1.5 miles southwest of 31-17, drilled to an initial depth of 3,010 feet in 1989 and deepened in 1991 by coring to a total depth of 5,934 feet.

All three of these wells were commercially productive, with estimated outputs of 3 to 5 MW each, and all encountered maximum temperatures in the range of 500 to 550°F.

The BLM approved a Unit Agreement for the Glass Mountain KGRA in 1982. The Unit Area included the majority of the KGRA, and Unocal was designated as the Unit Operator. The Unit Agreement provides for the coordinated exploration, development and exploitation of the geothermal resource by the participating leaseholders.

Subsequent to the approval of the Unit Agreement there have been several major changes in lease ownership. Freeport-McMoRan Resource Partners (FMRP) acquired an interest in the field as part of a broader acquisition of part of Phillips's geothermal assets, and by 1988 Unocal and FMRP were the primary leaseholders in the Unit Area. In 1993 California Energy General Corporation (later CalEnergy Company, Inc. or CECI, now an affiliate of MidAmerican Energy Holdings Company) purchased Unocal's leases and became the Unit Operator. Calpine Corporation was designated by FMRP as its agent for geothermal exploration at the Unit Area in 1994, and in 1996 Calpine acquired FMRP's leases. The history of lease acquisitions and transactions has led to the present, somewhat complex pattern of lease ownership shown in figure 1.2.

CECI has proposed and is in the process of permitting the 48 MW Telephone Flat project, to be developed within a Participating Area consisting of approximately 8 square miles of leasehold, owned 100% by CECI, within the Unit Area. A Final Environmental Impact Statement/Environmental Impact Report (EIS/EIR) was issued for this project in February 1999.

Calpine's proposed Fourmile Hill project is to be developed within 7 square miles of 100% Calpine-owned leasehold in the northwestern part of the Unit Area. However, it is reported that the leases for the Fourmile Hill project are not committed to the Unit, as per the 1982 Unit Agreement. Furthermore, Calpine reports that the Unit boundary has now collapsed to the CECI Participating Area shown in figure 1.2. In any case, the Fourmile Hill area is apparently not subject to the Unit Agreement, which means that Calpine's activities within the Fourmile Hill area do not require any coordination with CECI.

Three of the older core holes (14-23, 35-28 and 68-16) are located within the Fourmile Hill project area. In 1994 Calpine drilled a deeper (3,600 foot) core hole, 88-28, in the project area. No drilling activity has since taken place in any of the leases of the KGRA.

4. CONCEPTUAL MODEL AND ENERGY RESERVES

4.1 Conceptual Model

The information available from surface studies and from the various exploratory holes and deep wells drilled in the Glass Mountain area makes it possible to develop a conceptual model of the geothermal system. The critical elements of a conceptual model are descriptions of:

- the source of heat for the system;
- the origin and composition of fluids in the system;
- the nature, location and shape of the geothermal reservoir;
- the movement of fluid through the system; and
- geologic factors that control or influence the position of the reservoir and the movement of fluid.

Data from drillholes are especially important in defining subsurface conditions that reveal the nature of the geothermal system. In particular, definition of the subsurface distribution of temperature provides the most direct evidence concerning the source of heat, the position of the geothermal reservoir, and the patterns of fluid movement in the system. Also important are the definition and interpretation of thermal fluid composition from chemical analysis of fluids produced from wells, and indications of subsurface permeability from deduced permeable zones in deep wells.

Stabilized temperature profiles were examined and interpreted for all drillholes from which such data were provided, in order to interpret the subsurface distribution of temperature. Maps of temperature contours within the field were constructed at various levels, using the interpreted stable formation temperature in the different wells, and maps of selected isothermal surfaces (surfaces of equal temperature) were also prepared. Although several deep wells (deeper than 5,000 feet) have been drilled in the field, drilling in most areas has been limited to depths of 4,000 feet or less. This is true of the Fourmile Hill project area, where the deepest drillhole (88-28) is about 3,600 feet. As a result, temperatures can be reliably interpolated (without excessive extrapolation) to an elevation of about +2,000 feet (msl) over most of the field.

Figures 4.1 and 4.2 show the deduced distribution of temperature at elevations of 4,000 feet and 2,000 feet, respectively. Figure 4.3 shows contours of elevation on the 400°C isothermal surface. As these figures indicate, the temperature anomaly associated with the geothermal system has the shape of a broad oval that coincides approximately with the location and shape of the caldera of the Medicine Lake volcano. This suggests a close association between the volcano and the source of heat for the thermal fluids.

Although the heat source cannot be identified with certainty, it probably consists of one or more bodies of magma or cooling intrusive rocks associated with the young volcanism of the area. As geologic and geophysical evidence (discussed in Chapter 2) indicates the absence of a single, widespread silicic magma chamber beneath the volcano, it is most likely that one or several smaller bodies, located beneath or close to the caldera, supply the heat for the geothermal system.

As is the case in most geothermal systems, the water entering the Glass Mountain system is meteoric in origin. The water is heated and its composition modified as it circulates to substantial depths (probably exceeding 10,000 feet) in the vicinity of the heat source. Modification of the composition of the thermal fluid takes place from chemical interactions with the rocks through which it circulates, and, possibly, from mixing with a small amount of water and gases released by cooling magma.

Fluid chemistry data are available from wells drilled and tested in 1989 by Unocal. These wells are located in what is now the CECI Participating Area (figure 1.2). The data indicate that the reservoir contains a sodium-chloride (Na-Cl) water with about 0.3 wt.% total dissolved solids (TDS) and 1,200 to 1,350 ppm-wt Cl. The chemical equilibration temperatures of the deep thermal water (quartz solubility temperature and Na-K-Ca equilibration temperature) span the range from 470° to 515°F, in excellent agreement with 480° - 515°F logged downhole in the same wells. Stable isotopes of hydrogen (H) and oxygen (O) in the reservoir water show some shift of ^{18}O with respect to meteoric water (about +3 $^{0}/_{00}$ relative to standard mean ocean water, or SMOW). This shift is typical of high-temperature water-rock interaction.

The reservoir water where tested is essentially pH-neutral, although the initial flow from well 68-8 was weakly acidic (pH about 4.5), with elevated calcium and magnesium, which are characteristic of acidic fluids. Acidity declined progressively, and after a month of flow the water was pH-neutral (pH 7.1), but retained a slightly elevated calcium content as a residual effect of slight acidity. The composition of the acidic water indicates that it was a mixture of the typical Na-Cl thermal water with a cooler acidic sulfate water that probably came from a restricted and relatively shallow source. Such acid waters often form locally, above deeper thermal reservoirs, where steam carrying hydrogen sulfide mixes into deeply infiltrating meteoric water carrying dissolved oxygen. They rarely restrict the overall exploitation of a geothermal reservoir, but in some cases, localized shallow acidity can cause well damage. The acidity at well 68-8 was too low and transient to indicate that such a problem exists in the Glass Mountain field.

Gas-in-steam data are available from several samples each collected at wells 31-17 and 68-8. The total gas and hydrogen sulfide (H_2S) concentrations measured during flow testing in 1989 were stable and relatively low: 750 ppm-wt total gas at well 31-17; 1,400 ppm-wt total gas at well 68-8, and about 50 ppm-wt H_2S at each well. The gas composition is 80 - 85 vol.% CO_2 with 4 to 8 vol.% each of H_2S and N_2, and traces of other species (CH_4, Ar, H_2, NH_3). The gas composition is within the range of typical geothermal production worldwide.

Figures 4.1 through 4.3 indicate the presence of two zones of higher temperature within the overall temperature anomaly. The larger of the two is located in the southeastern part of the field, where the deep wells that have been drilled to date are located. A smaller high-temperature zone is located in the southern part of the Fourmile Hill project area, in the northwestern sector of the geothermal field. In both zones, temperatures exceeding 450°C occur at relatively shallow depths; this indicates upflow of hot fluids from deeper levels within these zones. The data from drillholes are insufficient to determine whether the two high-temperature zones are distinct upflows of thermal fluid from separate sources, or branches of a single, larger upflow centered closer to the middle of the broader temperature anomaly. In either case, the persistence of both zones of high temperature over a considerable vertical interval (figures 4.1, 4.2) suggests that they both are expressions of upflow from deeper levels, and therefore indicative of the presence of geothermal reservoir conditions in their respective sectors of the field.

Localized upflow of thermal fluid also indicates elevated rock permeability where the upflow occurs. In the southeastern sector, this permeability has been confirmed by the three commercially productive wells that have been drilled there. This suggests a strong likelihood that permeability in at least a part of the Fourmile Hill project area will also be sufficient to provide commercial levels of production in deep wells. However, until such wells are drilled and successfully tested within the project area, the feasibility of commercial production will remain unconfirmed. Assuming that the Fourmile Hill area is similar to the southeastern sector, and based on the temperature profile observed in drillhole 88-28, significant production zones may be encountered at depths as shallow as about 4,000 feet (about +3,000 feet elevation), but may also occur up to several thousand feet deeper.

The total extent of the geothermal reservoir is not yet known. However, the shape and magnitude of the overall thermal anomaly suggest that a high-temperature reservoir (in which temperatures exceed 450°C) may be present over a broad, arcuate zone extending northwestward across Medicine Lake and including the two zones of higher temperatures described above. The zone encompasses a substantial area (roughly 8 miles by 6 miles), which is relatively large compared with many geothermal fields throughout the world. This indicates a considerable geothermal energy potential for the Glass Mountain area, even if commercially productive wells cannot be successfully drilled in some portions of the high-temperature zone.

The shape of the thermal anomaly suggests that the location and shape of the geothermal reservoir are controlled by the structure of the caldera of the Medicine Lake volcano. Arcuate fractures at the caldera margin may be responsible for localized fluid upflow; alternatively, lithologic changes across the caldera boundary may restrict outward fluid movement. Faulting that is not related to the caldera may also contribute to localizing upflow of geothermal fluids. The relationship between specific faults or other structures cannot be determined from available data. However, it should be noted that both of the zones of higher temperature noted within the broader thermal anomaly are located where the density of faults identified by surface mapping is significantly greater than in most other parts of the KGRA, possibly indicating a relationship between faulting and upflow.

The important aspects of the conceptual model of the Glass Mountain geothermal field can be summarized as follows:

- The fluid of the geothermal system originates as meteoric water, which circulates deep below the Medicine Lake volcano and is heated by one or more relatively small magma chambers or intrusive bodies.

- The heated fluid flows upward into what is probably a broad geothermal reservoir that occupies a significant area within the volcano's caldera. The rocks making up the reservoir (based on indications from surface geology and from deep wells) probably consist of basaltic to rhyodacitic volcanics (including lavas and pyroclastic rocks) and their subvolcanic or intrusive equivalents. There is not yet enough information to determine whether the zones of greatest permeability are restricted to certain stratigraphic horizons or lithologic units.

- The shape of the reservoir is controlled by the overall structure of the caldera, and probably to some extent by tectonic faulting not related to the caldera.

- Localized zones of more intense upflow occur in the southeastern and northwestern sectors of the geothermal field. The northwestern upflow is located in and near the southern part of the Fourmile Hill project area.

- The Fourmile Hill area is close to the inferred margin of the geothermal reservoir. Therefore, not all of the project area may be suitable for drilling commercially productive wells. However, the distribution of subsurface temperatures implies that a substantial portion of the area is likely to overlie the productive reservoir.

4.2 Estimate of Recoverable Energy Reserves

At present no proven recoverable reserves of geothermal energy have been identified in the Fourmile Hill project area; this will require the drilling of commercially productive deep wells to confirm that energy can be extracted economically. However, it is possible to estimate the reserves are potentially available, assuming such wells can be successfully drilled.

To evaluate reserves we employ a volumetric reserve estimation methodology introduced in 1970 by the U.S. Geological Survey; this has become the standard methodology of volumetric estimation of geothermal reserves. We have applied also a probabilistic approach to account for uncertainties in some of the parameters used in the estimation process. Such uncertainties are inherent in any geothermal project, and are particularly significant before information from deep wells is available. The details of the probabilistic volumetric estimation method are described below.

4.2.1 Principles of Volumetric Reserve Estimation

The amount of thermal energy stored within a unit volume of rock (containing geothermal fluid) is given by the formula:

Thermal Energy Stored in Unit Volume = Volumetric Specific Heat
x (Temperature of the Rock - Base Temperature)

Volumetric specific heat gives the amount of heat energy that can be recovered per unit volume per degree of cooling of the volume, the maximum allowable amount of cooling being from the initial temperature within the volume to a chosen base (or minimum) temperature.
The thermal energy stored within a geothermal reservoir is then given by:

Thermal Energy Stored in Reservoir
= Reservoir volume x thermal energy stored per unit volume
= Reservoir volume x volumetric specific heat x (Temperature - Base Temperature)

However, less than half of the stored thermal energy is recoverable by production of steam and water at the wellhead. Of this amount of recoverable thermal energy, less than 20% can be converted to electrical energy. The fraction of the stored thermal energy in the reservoir that is recoverable as electrical energy at the wellhead is called the Recovery Factor. Therefore, the amount of electrical energy recoverable from the reservoir is given by:

Electrical Energy = Reservoir Volume x Volumetric Specific Heat
x (Temperature - Base Temperature) x Recovery Factor

The amount of electrical energy recoverable from the reservoir is usually expressed on a yearly basis as megawatt-years (MW-yr); one megawatt-year is the amount of electricity generated by a 1 MW capacity plant over a year and is equivalent to 8.76 million kilowatt-hours. Given the total amount of recoverable electrical energy calculated as above, the maximum sustainable power plant capacity will depend on the assumed project life. For example, for a project life of 30 years:

Maximum Plant Capacity (in MW)
= Megawatt-years of recoverable electrical energy ÷ 30 years.

However, a plant does not generate power 100% of the time. The capacity factor of a power plant defines the ratio of the actual amount of electricity generated in a year to the amount of electricity expected to be generated in a year if the plant could run at 100% capacity. Therefore, the maximum plant capacity is given by:

Maximum Plant Capacity (MW)
= Recoverable Electrical Energy (MW years) ÷ Project Life (years) ÷ Capacity Factor

In the following paragraphs, the above principles are reduced to detailed formulas to calculate the recoverable geothermal energy reserves.

In our method, the maximum sustainable capacity of a geothermal system (the reservoir and the plant considered together) is given by:

$$E = \frac{A \cdot h \cdot C_v \cdot (T-T_o) \cdot R}{F \cdot L} \qquad (1)$$

where

A = areal extent of the reservoir,
h = thickness of the reservoir,
C_v = volumetric specific heat of the reservoir,
T = average temperature of the reservoir,
T_o = base temperature (equivalent to the average annual ambient temperature),
R = overall recovery efficiency (the fraction of thermal energy in place in the reservoir at a temperature of T_o or greater that is converted to net electrical energy at the power plant),
F = power plant capacity factor (the fraction of time the plant produces power on an annual basis), and
L = power plant life.

The parameter R can be determined as follows:

$$R = \frac{W \cdot r \cdot e}{C_f \cdot (T-T_o)} \qquad (2)$$

where

r = recovery factor (the fraction of thermal energy in place that is recoverable at the surface as thermal energy),
C_f = specific heat of reservoir fluid,
W = maximum available work from the produced fluid, and
e = utilization factor, which accounts for mechanical and other losses that occur in a real power cycle.

The parameter C_v in (1) is given by:

$$C_v = \rho_r \cdot C_r \cdot (1-\phi) + \rho_f \cdot C_f \cdot \phi \qquad (3)$$

where

ρ_r = density of rock matrix,
C_r = specific heat of rock matrix,
ρ_f = density of reservoir fluid, and
ϕ = reservoir porosity.

The parameter W in (2) is derived from the First and Second Laws of Thermodynamics as follows:

$$dW = dq \cdot (1-T_o/T), \text{ and} \qquad (4)$$

$$dq = C_f \cdot dT \qquad (5)$$

where q represents thermal energy.

The following parameters required for reserves estimation can be assumed for the Fourmile Hill project area with little uncertainty:

Volumetric Specific Heat	=	34 BTU/ft^3/°F (based on representative specific heat of rock types at Glass Mountain)
Base Temperature	=	45°F (average ambient temperature in the project area)
Utilization Factor	=	0.45 (typical for modern geothermal plants)
Plant Capacity Factor	=	0.90 (typical for modern geothermal plants)
Plant Life	=	30 years (assumed amortization period for the project).

4.2.2 Probabilistic Approach to Reserve Estimation

The remaining parameters needed to estimate the reserves in any geothermal field are sufficiently uncertain that they are best described and used in terms of probabilities rather than fixed values. The most common method of such probabilistic analysis is the Monte Carlo simulation method, described below. Monte Carlo simulation is also commonly used for estimation of reserves in the petroleum and mining industries.

The Monte Carlo simulation method builds a probability distribution, or profile, of reserves by considering a statistically large set of random combinations of possible values for the uncertain parameters in the reserves calculation. The method requires:

- the estimation of a probability distribution for each of the uncertain parameters, and

- a technique for random sampling of these distributions; random sampling is a mathematical process that is described below.

The basic method of Monte Carlo simulation can be outlined as a series of steps as follows:

- The range and relative frequency (probability distribution) of the possible values of each uncertain parameter are estimated. The ranges of some parameters, such as area, thickness and temperature are deduced from the measured characteristics of the specific resource; other ranges are taken from the observed maximum and minimum values at all geothermal fields now in commercial production. Depending on the parameter, the values in the range may be assigned an equal probability of occurrence (uniform distribution) or a "most likely" value may be assigned within the range (triangular distribution).

- From the distribution of each variable, one random value is selected. This is usually done in a computer program by using a random number generator. This random sampling process is the exact mathematical equivalent of picking blindly a token from a hat that contains a large number of tokens, each marked with a number. The range of numbers on the tokens represents the range of possible values of the parameter being sampled. The relative frequencies of the numbers on the tokens represent the nature of the distribution of values of the parameter within the range (triangular or uniform). One sample is drawn for each uncertain parameter and a value of the reserves is calculated from the resulting combination of uncertain values. The reserves value thus calculated determines one point in the final distribution of the values of the reserves.

- A second random value for each parameter is then selected in the same fashion (all tokens are first returned to their respective hats) and the resulting value of the reserves is computed again. This forms the second point in the distribution of values of the reserves. This process is repeated a large number of times; typically, several thousand such simulations are made. Mathematical methods are employed to ensure that the number of simulations is sufficient to provide a reliable result.

- Cumulative frequencies of the calculated reserves values are examined to determine the probability of the existence of a specific level of reserves. Frequencies of calculated reserves values are also examined to assess the relative probability of reserves at different levels, and the most likely value (the interval most often calculated).

4.2.3 Results of Reserve Estimation

The methodology described above was used to develop an estimate of the probability distribution of recoverable energy reserves in the Fourmile Hill project area. The uncertain parameters needed for the estimate are summarized in table 4.1, and were determined as follows:

Reservoir area: A triangular distribution was assumed. Heat is assumed to be recoverable from reservoir rocks at drillable depths that exceed a cutoff temperature of 400°F. Therefore, the minimum reservoir area can conservatively be assumed to be the area within the 400°F contour at the elevation of 2,000 feet (figure 4.2). This area is approximately 2 square miles. Although there is a possibility that reservoir temperatures are present over the entire project area, to be conservative it was assumed that the maximum reservoir area is the area within the 300°F contour at 2,000 feet, which reasonably permits projection of temperatures greater than 400°F at drillable depths. This area is approximately 5 square miles. The most likely reservoir area was (also conservatively) assumed to be closer to the minimum than the maximum area; an area of 3 square miles was selected as most likely.

Reservoir thickness: The results of deep wells drilled in the southeastern sector of the field indicate that reservoir conditions may exist over a vertical interval of 4,000 feet or greater. To be conservative, it was assumed that the average reservoir thickness in the project area is between 2,000 feet and 4,000 feet, with a most likely value of 3,000 feet.

Rock porosity: A range of rock porosity from 2% to 8%, with equal probability, was assumed. This range is typical for geothermal fields. The volumetric estimate of reserves is not strongly sensitive to variations in rock porosity.

Average reservoir temperature: The temperature distribution shown in figures 4.1 to 4.3 allows average reservoir temperatures of at least 450°F to be projected. The maximum average reservoir temperature was conservatively assumed to be 500°F, and 475°F was selected as the most likely temperature.

Recovery factor: This factor is difficulty to estimate for an area where no deep drilling or production data are yet available. Therefore, a broad range of recovery factors that is typical of geothermal fields was selected. This range is from 10% to 20%, with equal probability.

Values within the specified ranges of the uncertain parameters were sampled randomly 1,000 times, and reserves were calculated for each sampled set of parameters. The results are summarized in table 4.1, and shown graphically as a histogram and cumulative probability plot in figure 4.4.

Nearly all of the probability distribution of energy reserves lies within the range of about 40 and 150 MW for an assumed project lifetime of 30 years. Some possibility of higher levels of reserves is indicated, but the probability of such outcomes is low. The most likely level of reserves is estimated to be about 85 MW, whereas the mean (weighted average) value of the probability distribution is about 96 MW. There is greater than a 90% probability that reserves exceed 50 MW, and a 50% probability that they exceed 92 MW.

The results of the reserves estimation, which are based on reasonably conservative assumptions of resource characteristics, indicate a very high probability that recoverable reserves of heat energy are in excess of 50 MW for a typical power plant lifetime. It is therefore reasonable to conclude that the Fourmile Hill area can support a development of this size, provided that commercially productive wells can successfully be drilled within the project area.

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5. REVIEW OF CALPINE'S DEVELOPMENT PLANS

Information on Calpine's development plans was taken from the Final EIS/EIR. The design for the 49.9 MW (gross) Fourmile Hill power plant indicates a total fluid production requirement of 2.9 million pound per hour, from which 800,000 pounds per hour of steam will be separated. Calpine plans to supply the power plant initially with 9 to 11 production wells drilled from five production pads located in Section 28 (figure 5.1). The production well pads are designated P-1 through P-5. Each production well will be drilled to about 8,500 feet, yielding a bottomhole elevation of about -2,000 feet (msl).

The injection requirement consists of 2.1 million pounds per hour of separated brine and 325,000 pounds per hour of power plant condensate. Calpine plans to drill one injection well from each of the three injection pads (I-1 through I-3) shown in figure 5.1. Injection well depths were not specified.

The production well locations are within the area of highest temperature; a comparison of figures 5.1 and 4.2 shows that all of the production well pads lie within the 500°F isotherm at +2,000 feet (msl). Although not specifically stated, it is likely that some or all of these wells will be drilled directionally; that is, instead of being drilled vertically, they will deviate from vertical with depth. The planned well design includes a 13-3/8-inch cemented production casing to about 4,500 feet depth (an elevation of about +2,000 feet msl), below which a 12-1/4-inch hole will be drilled. The lower section of the hole will have a 9-5/8-inch diameter slotted liner. This type of well completion is fairly standard for the geothermal industry.

Calpine anticipates that productivity per well will range from 4.5 to 5.5 MW (gross). As mentioned in Chapter 3, the three deep wells completed by Unocal in the late 1980s had estimated productivities ranging from 3 to 5 MW (gross). All of these wells were originally completed with 9-5/8-inch production casings and 7-inch slotted liners, and one was later re-completed with 3-1/2-inch and 4-1/2-inch slotted liners. It is usually the case that, for wells encountering similar resource conditions, increasing the wellbore diameter will increase the productivity of the wells. However, the magnitude of the increase cannot be determined without understanding the inflow performance of the wells and using that to match flowing well behavior using wellbore modeling techniques; such modeling is beyond the scope of this study. Calpine's assumption of per-well productivity for Fourmile Hill is conservative compared to the worldwide average of 6 MW (gross), and in volcanic systems like Medicine Lake, productivities often exceed this average value. Therefore, it is our opinion that Calpine's estimate of the number of wells required to supply the Fourmile Hill project is reasonable.

Geothermal resources decline with production. After start-up, Calpine anticipates drilling one well every two years, either to replace damaged wells or to compensate for lost production as a results of the anticipated resource decline. This future production well drilling plan is reasonable.

Meeting the injection requirement is not usually a limiting factor in geothermal development, and it is likely that the three initial injection wells planned by Calpine will be sufficient to dispose of the separated brine and power plant condensate. This would imply a per-well injection rate of 800,000 lbs/hour, which is reasonable. It is important that injection wells be sited appropriately to minimize injection breakthrough while maximizing pressure support. Calpine has stated that it will inject on the periphery of the production area, which is consistent with the proposed injection pad locations (figure 5.1). The locations of the pads provide enough flexibility to modify the injection plan as more is revealed about the reservoir during the period when production wells are drilled and tested.

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TABLES

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Fourmile Hill Geothermal Project

Table 4.1. Estimate of Recoverable Energy Reserves

Input Parameter Distributions

Parameter	Type	Minimum	Most Likely	Maximum
Vol. Heat Cap. (BTU/cu. ft/F):	Fixed		34.0	
Rejection temperature (F):	Fixed		45	
Utilization factor:	Fixed		45.0%	
Plant load factor:	Fixed		90.0%	
Power plant life (years):	Fixed		30	
Reservoir area (sq. mi):	Triangular	2.0	3.0	5.0
Reservoir thickness (feet):	Triangular	2,000	3,000	4,000
Rock porosity:	Rectangular	2.0%		8.0%
Average temperature (F):	Triangular	450	475	500
Recovery factor:	Rectangular	10.0%		20.0%

Summary of Results

	Mean	Standard Deviation	Minimum	Maximum
MW Capacity:	96.2	29.6	36.7	229.4
MW per square mile:	29.1	7.0	14.8	52.2
Recovery Efficiency:	1.86%	0.37%	1.23%	2.56%

	Tenth Percentile	First Quartile	Median	Third Quartile
MW Capacity:	61.6	74.9	92.5	113.5
MW per square mile:	20.4	23.8	28.6	33.8
Recovery Efficiency:	1.35%	1.53%	1.86%	2.16%

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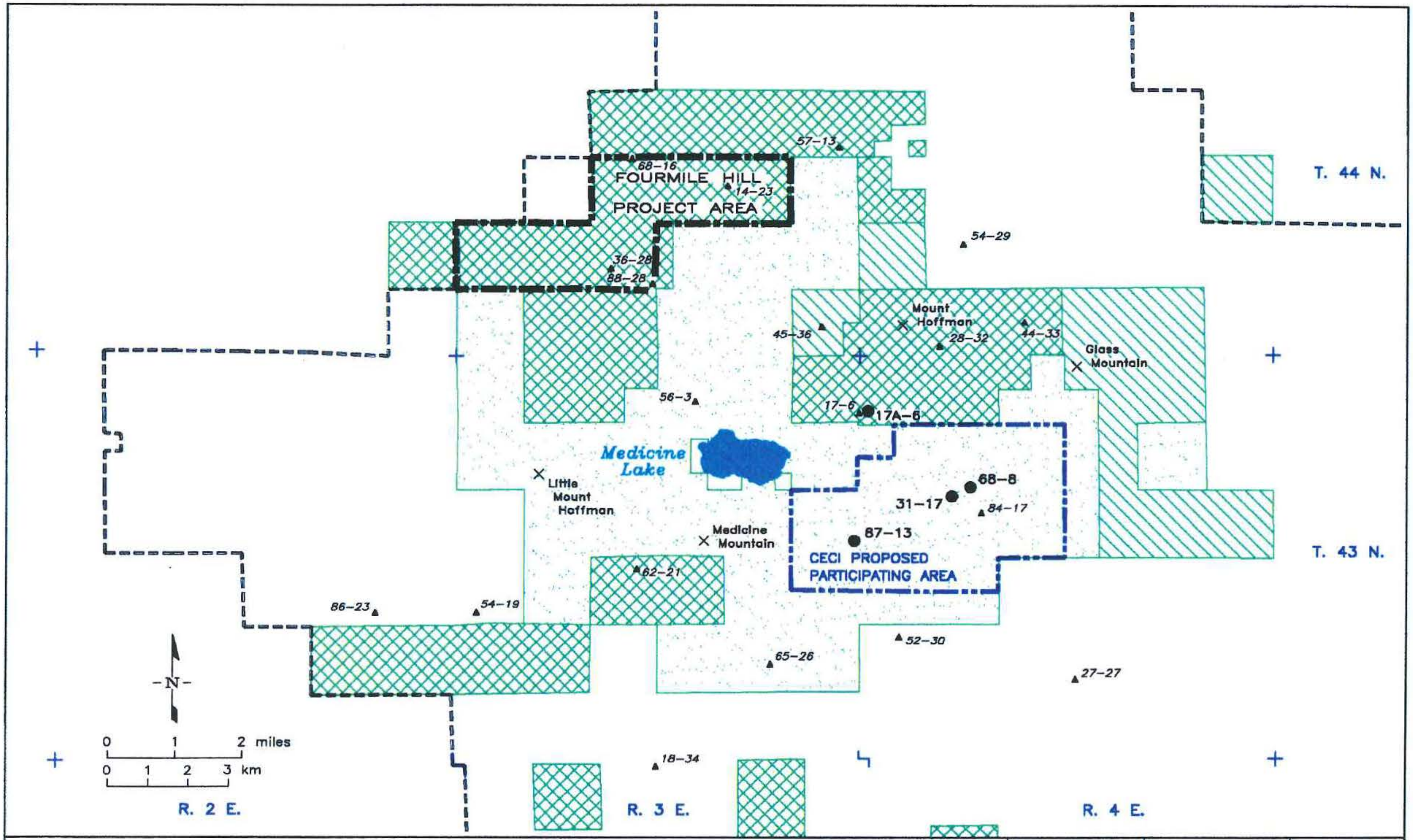
FIGURES

Figure 1.1: Location of the Glass Mountain KGRA

1999, GeothermEx, Inc. 4MILE_F1/31AUG99/P2410/EMY1=190/4MILE_F1.SSS



EXPLANATION

- ▲ 84-17 Strat test or temperature core hole
- ● 68-8 Large-diameter exploration well
- ▬▬ Fourmile Hill project area
- ‑·‑· CECI proposed PArticipating Area
- ‑ ‑ ‑ ‑ Glass Mountain KGRA

Lease Distribution:

- ▩ Calpine (100%)
- ▨ Calpine (50%) CECI (50%)
- ☐ CECI (100%)

FILE: 4MILE_F2.DWG	PLOTDATE: 27AUG99	EIMN1=11000
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Figure 1.2: Lease and well location map, Glass Mountain area, California

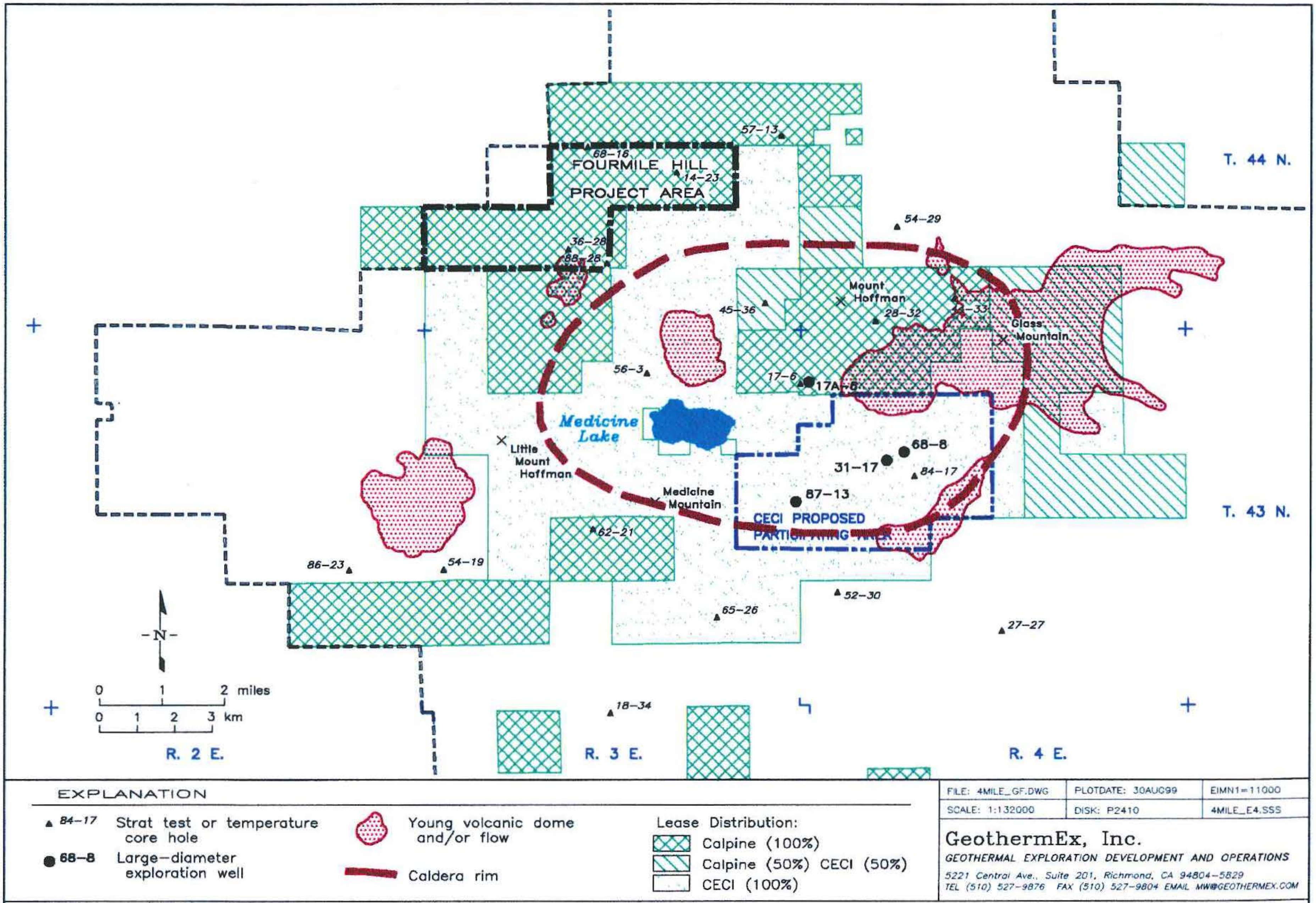


Figure 2.1: Selected geologic features of the Glass Mountain KGRA

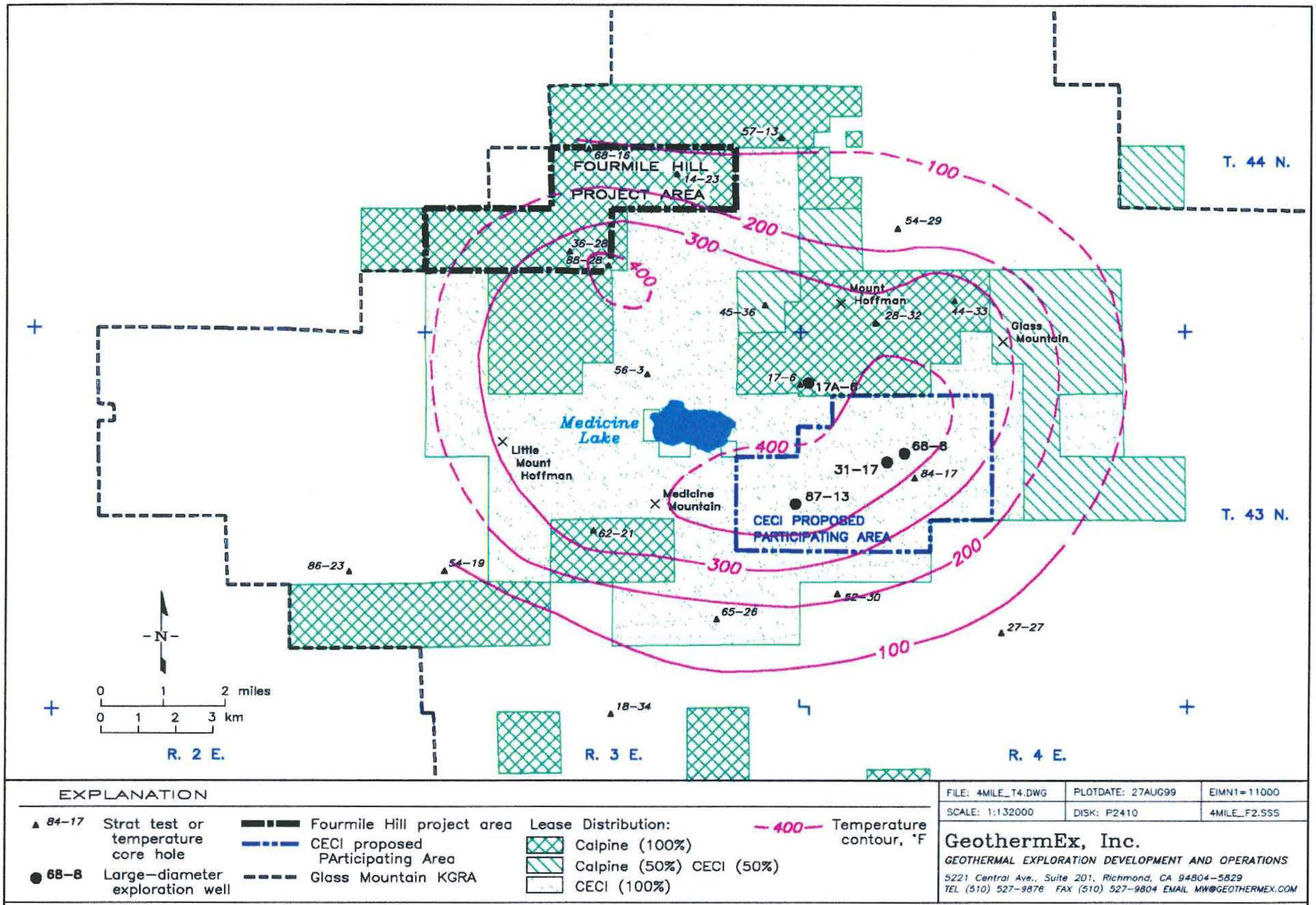


Figure 4.1: Subsurface temperature distribution at +4,000 feet (msl), Glass Mountain area

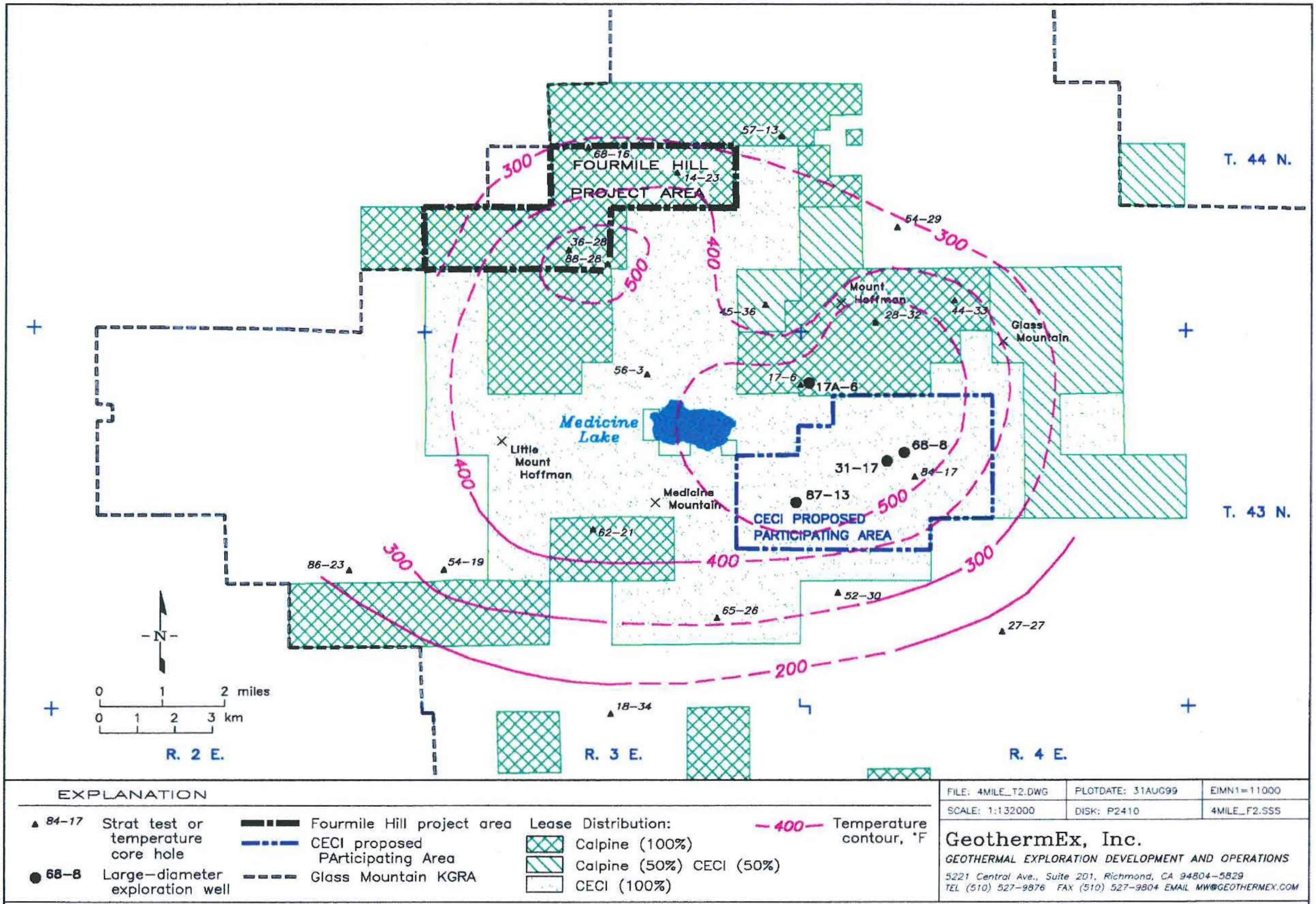


Figure 4.2: Subsurface temperature distribution at +2,000 feet (msl), Glass Mountain area

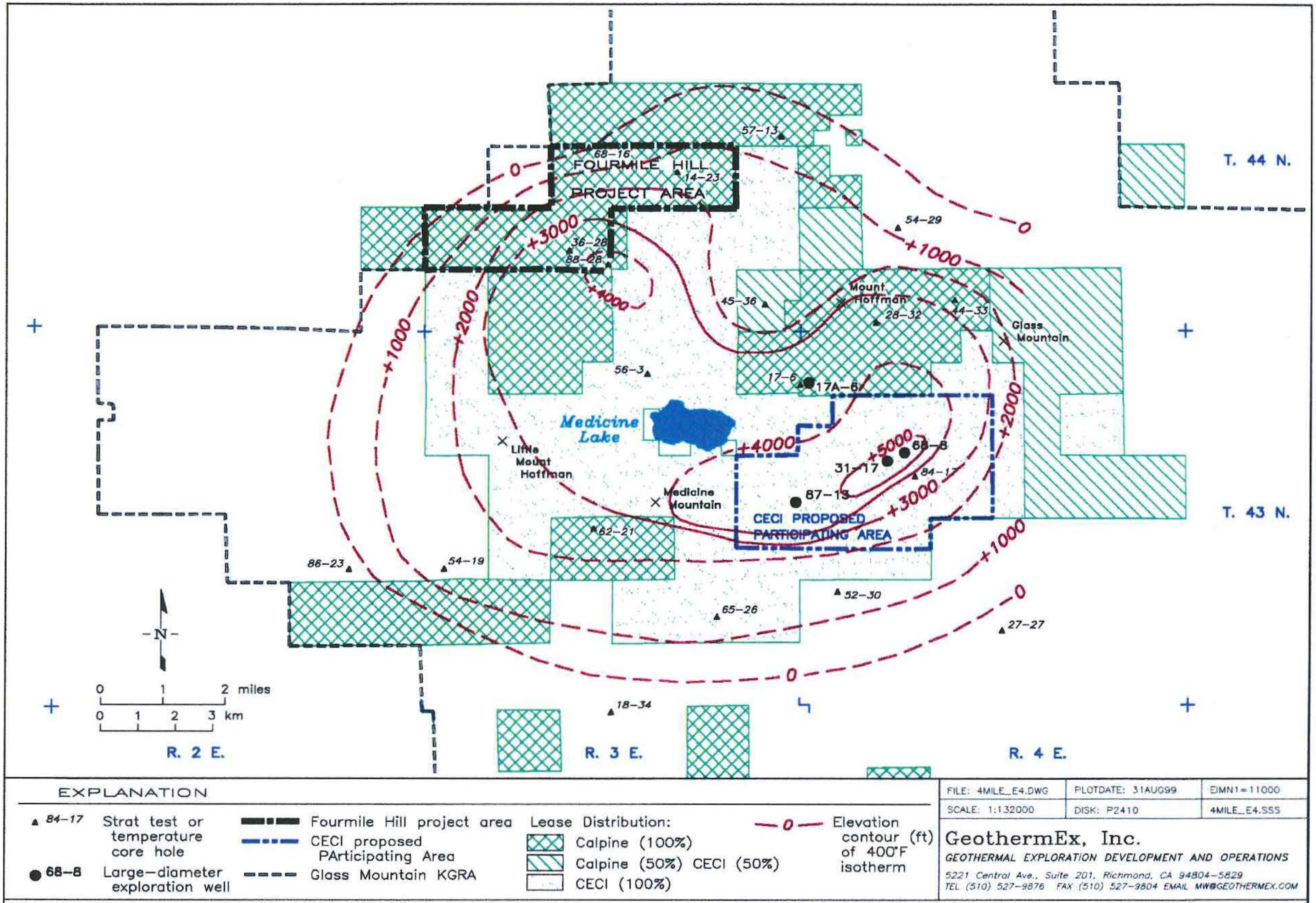
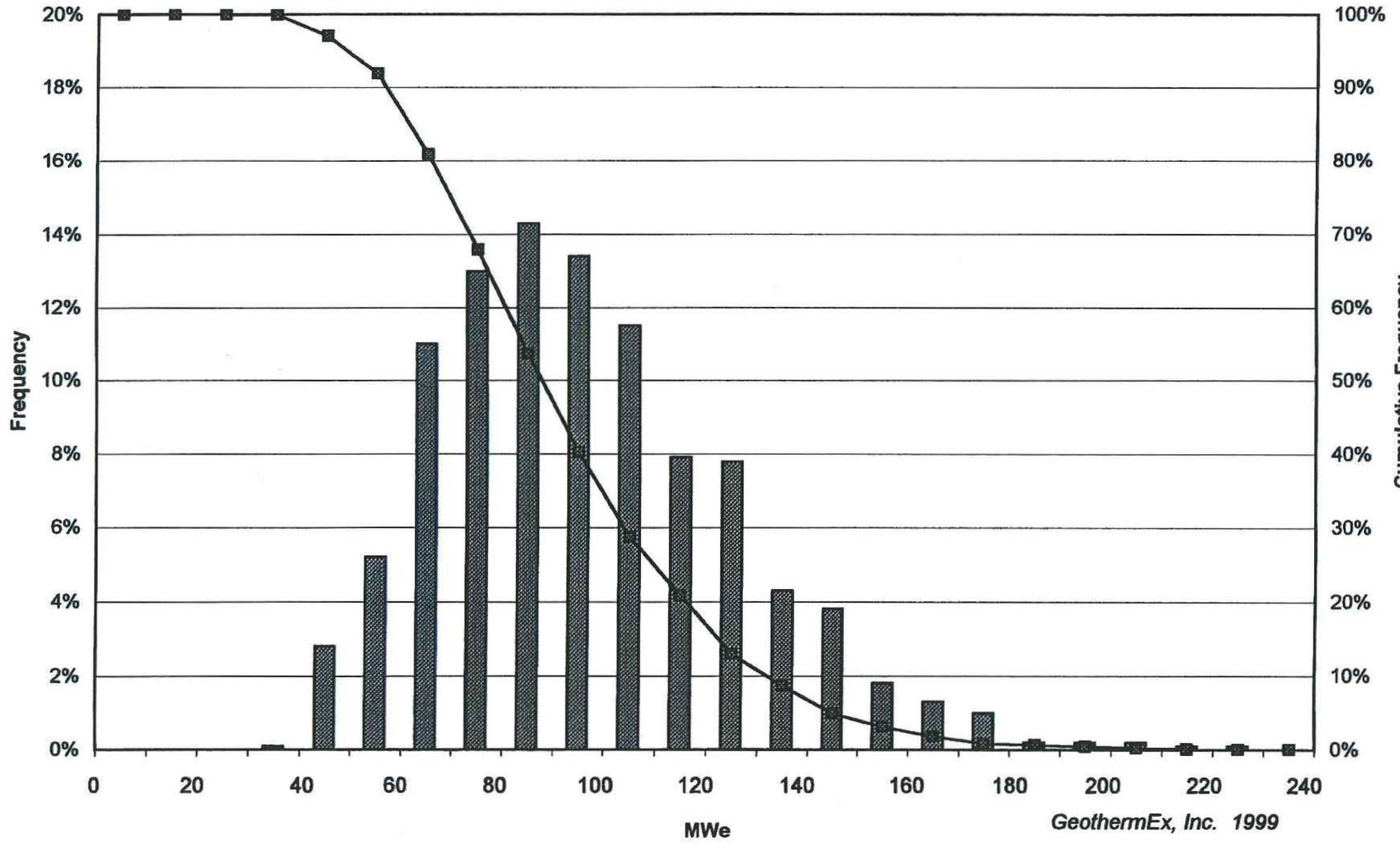


Figure 4.3: Elevation of the 400°F isotherm, Glass Mountain area

Figure 4.4: Estimate of Recoverable Energy Reserves, Fourmile Hill Project Area



GeothermEx, Inc. 1999

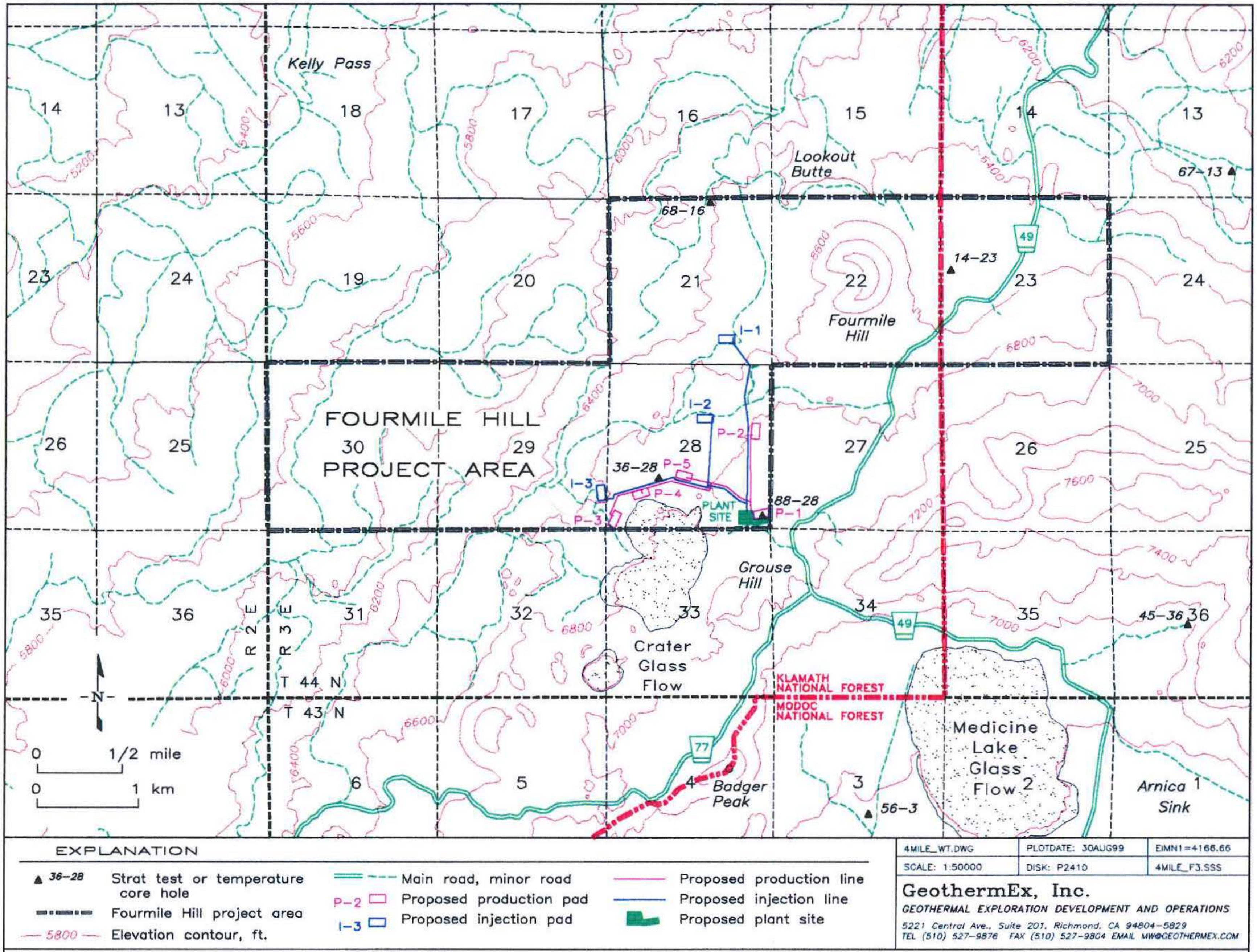


Figure 5.1: Proposed power plant and well pad locations for the Fourmile Hill project

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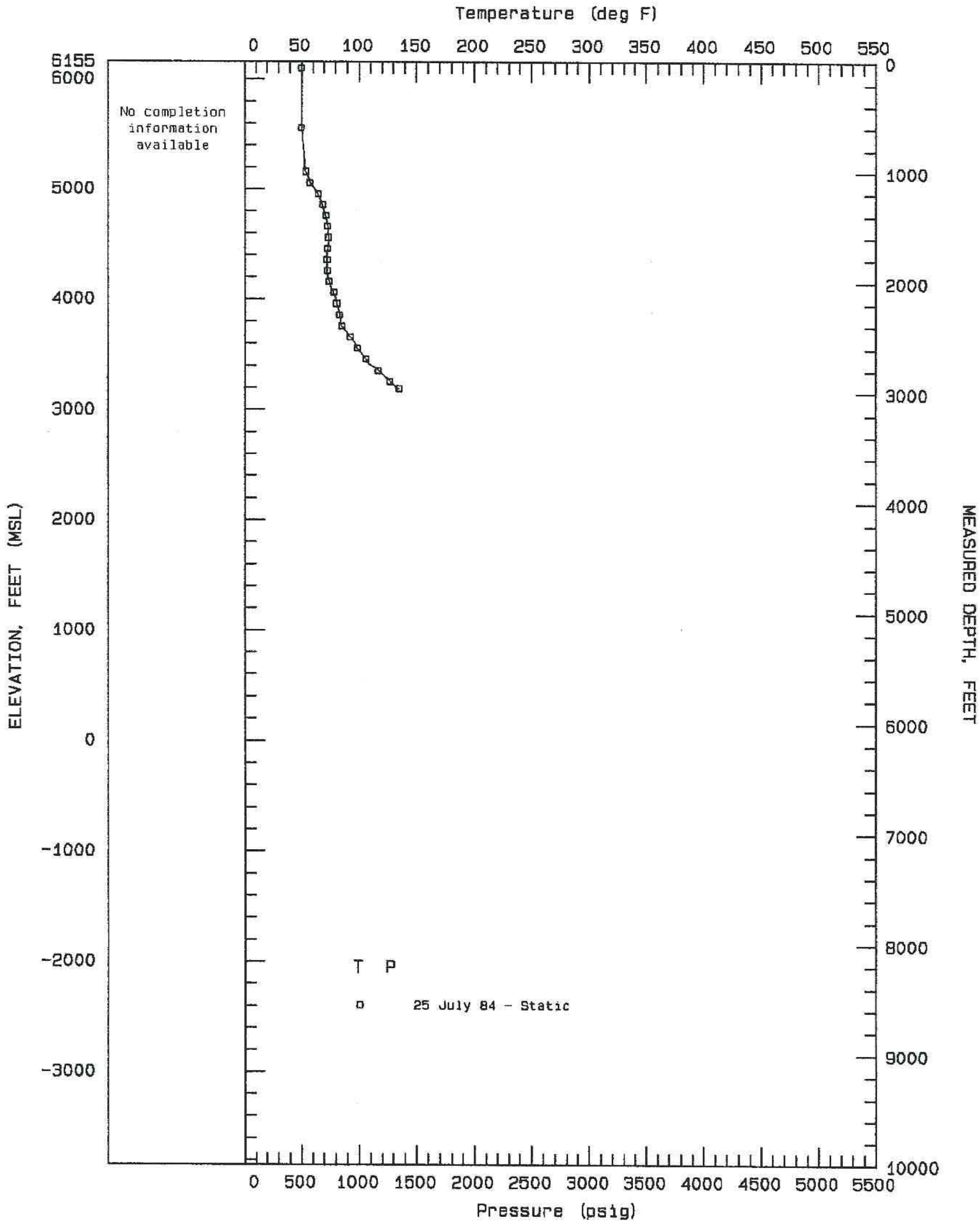
APPENDIX:

Downhole Summary Plots, Glass Mountain Wells

DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 57-13



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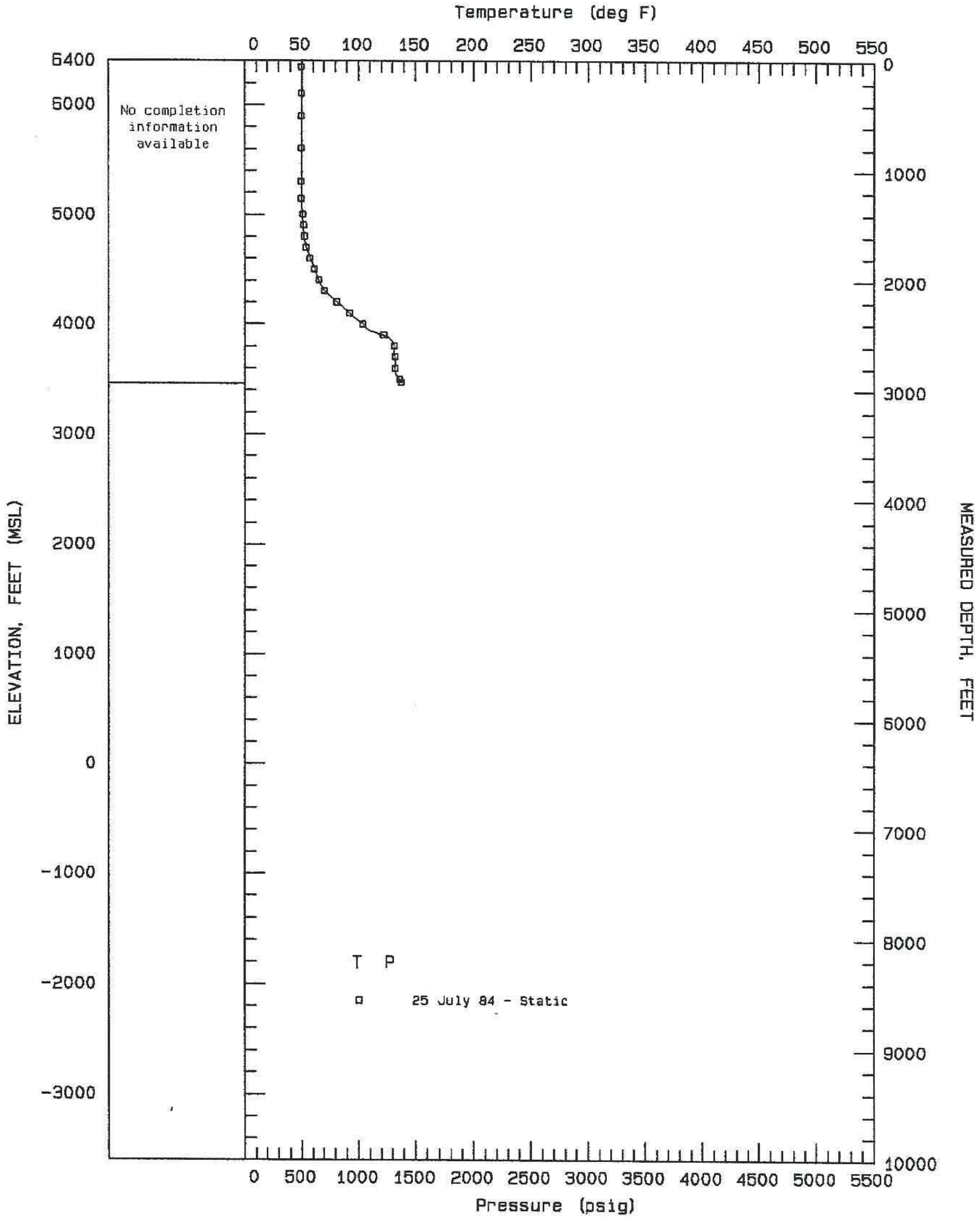
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 68-16



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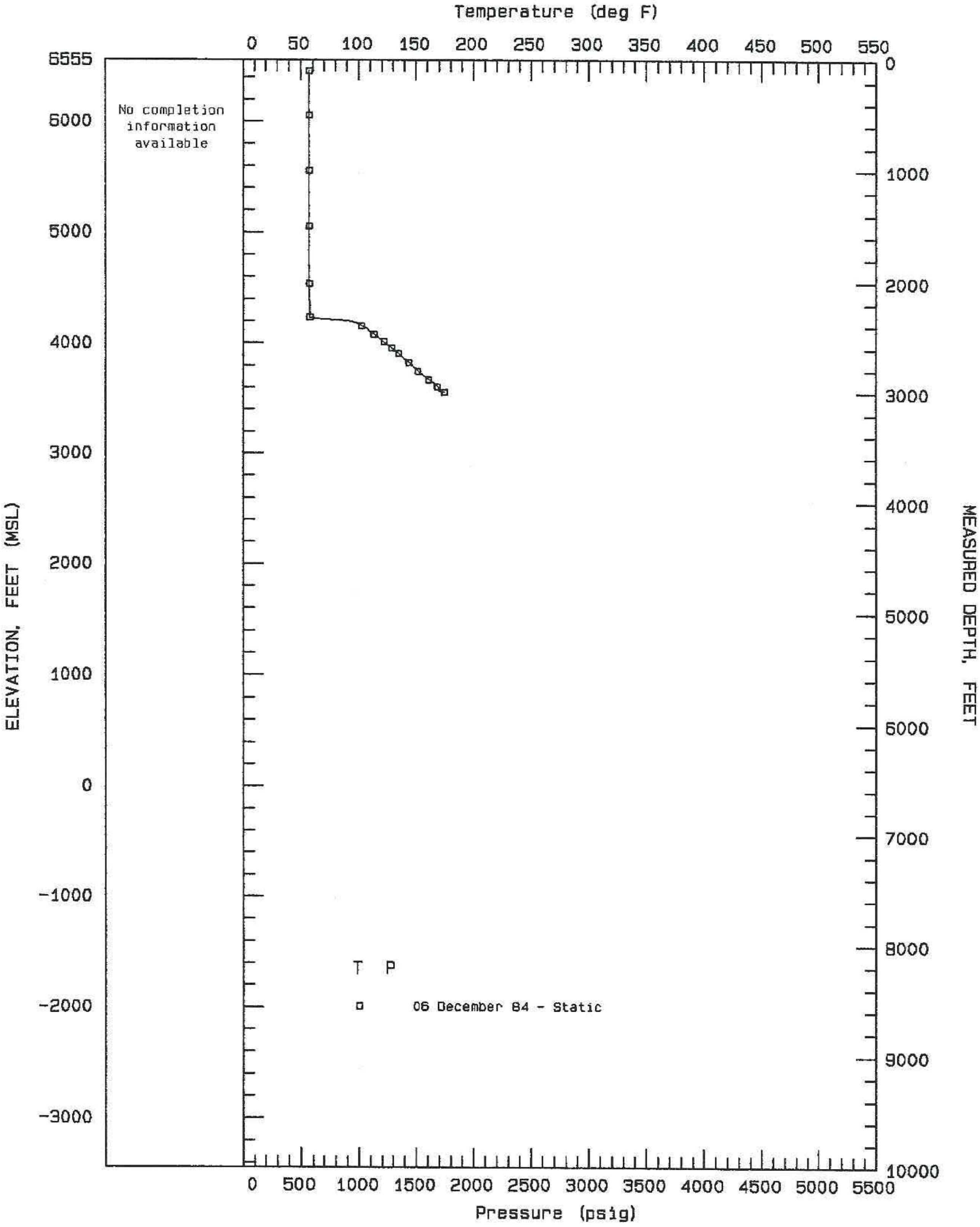
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 14-23



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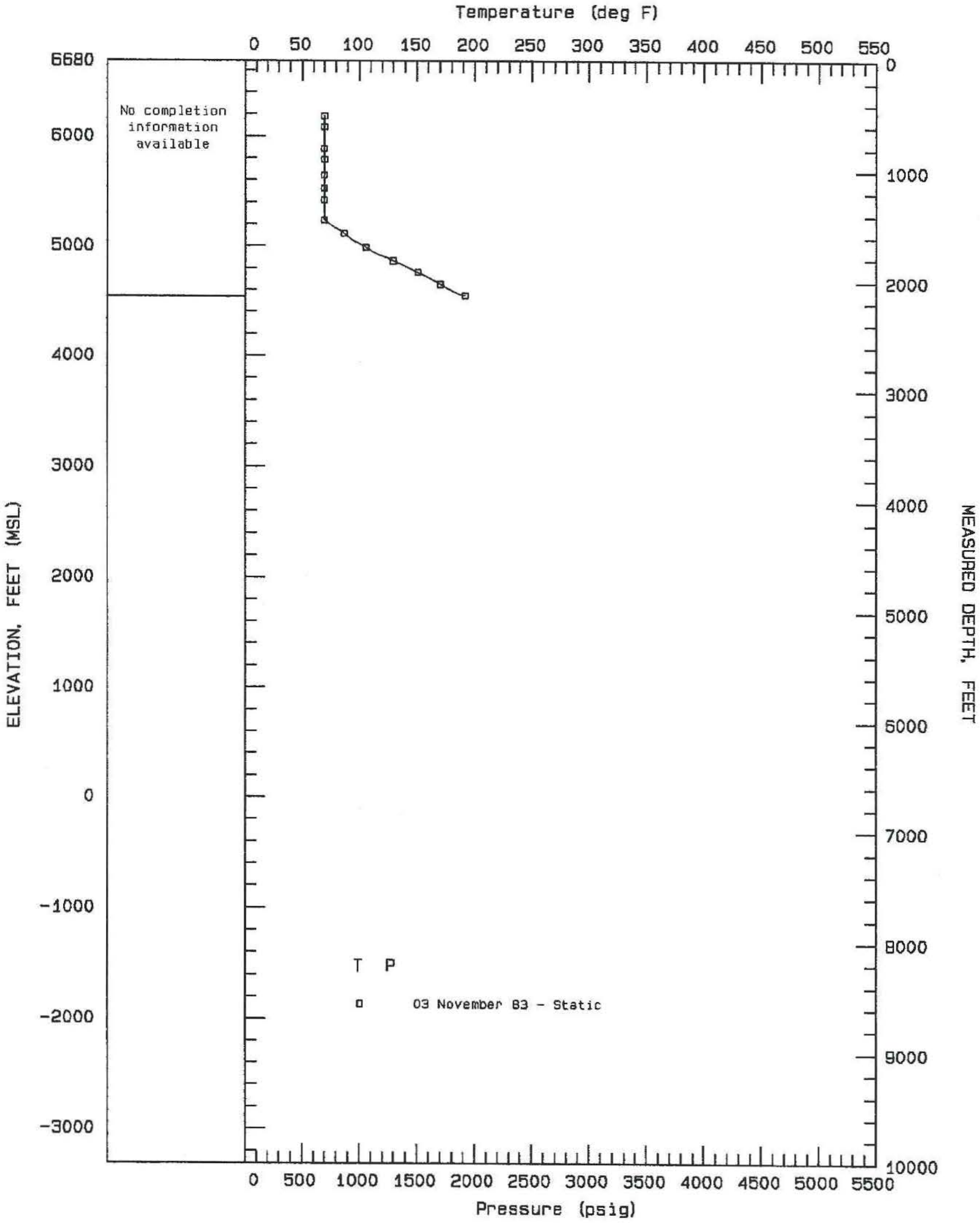
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 36-28



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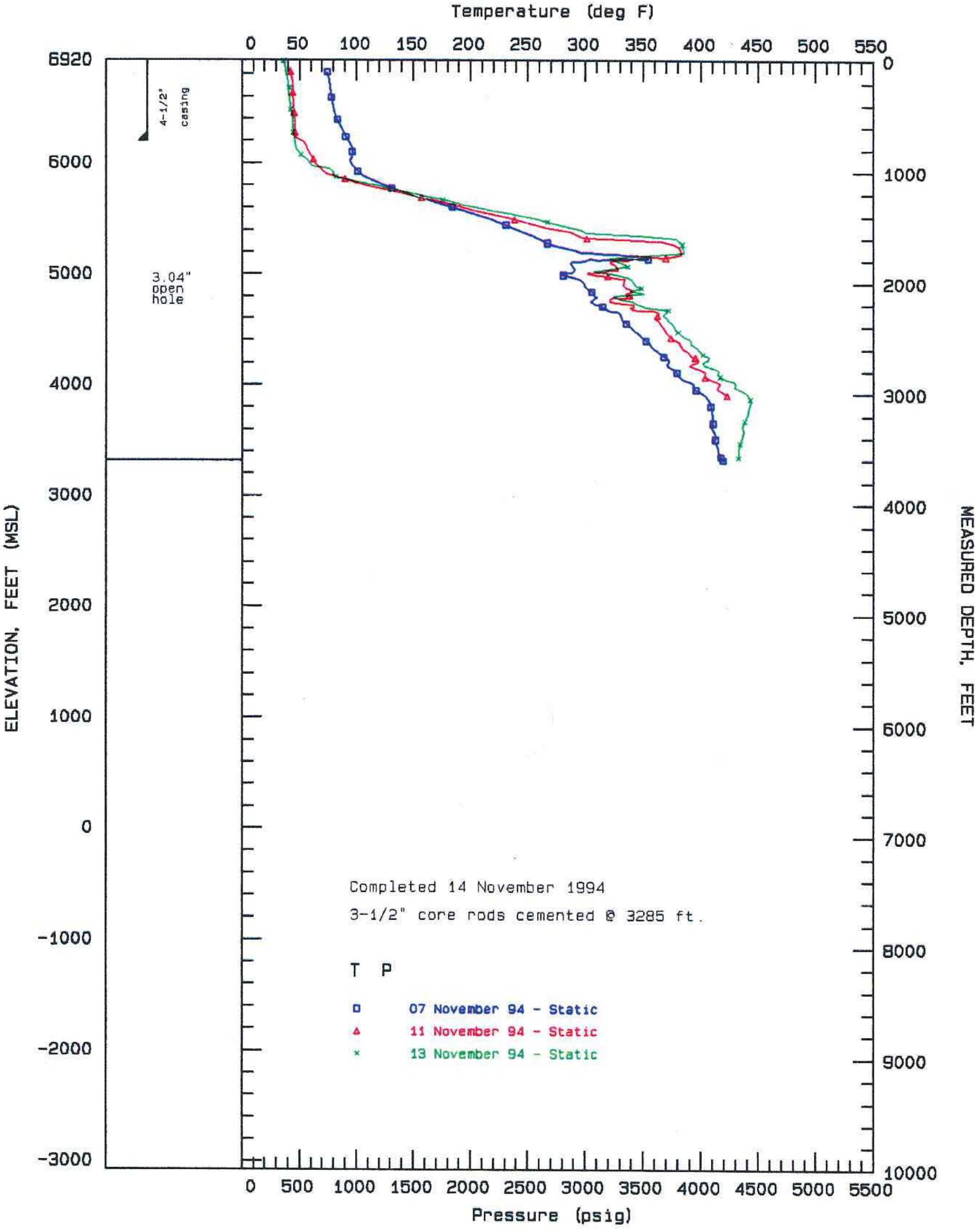
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 88-28



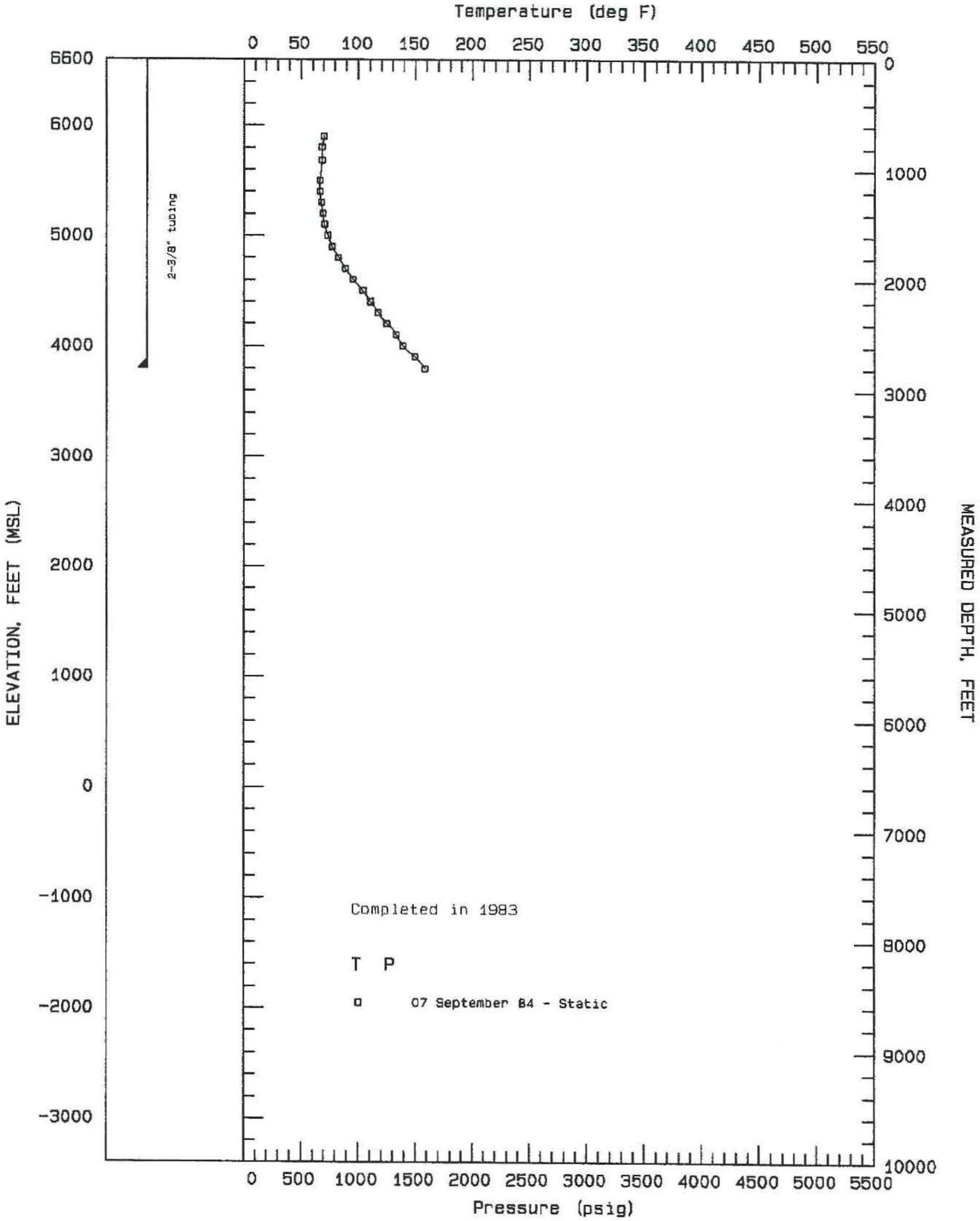
Completed 14 November 1994

3-1/2" core rods cemented @ 3285 ft.

GeothermEx, Inc.

08-27-1999 A: T941107.PLT

DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 54-29 (29-1)



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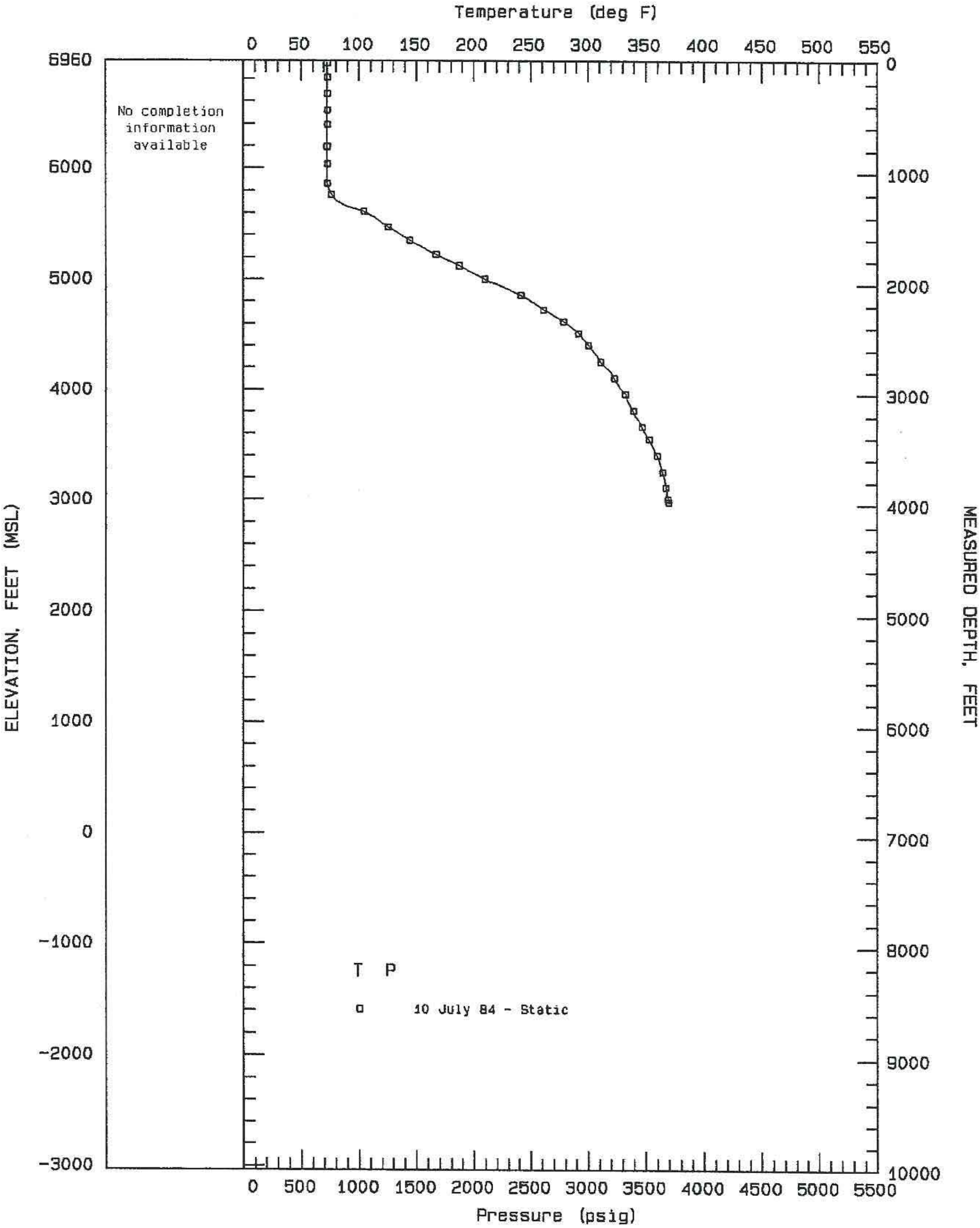
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 45-36



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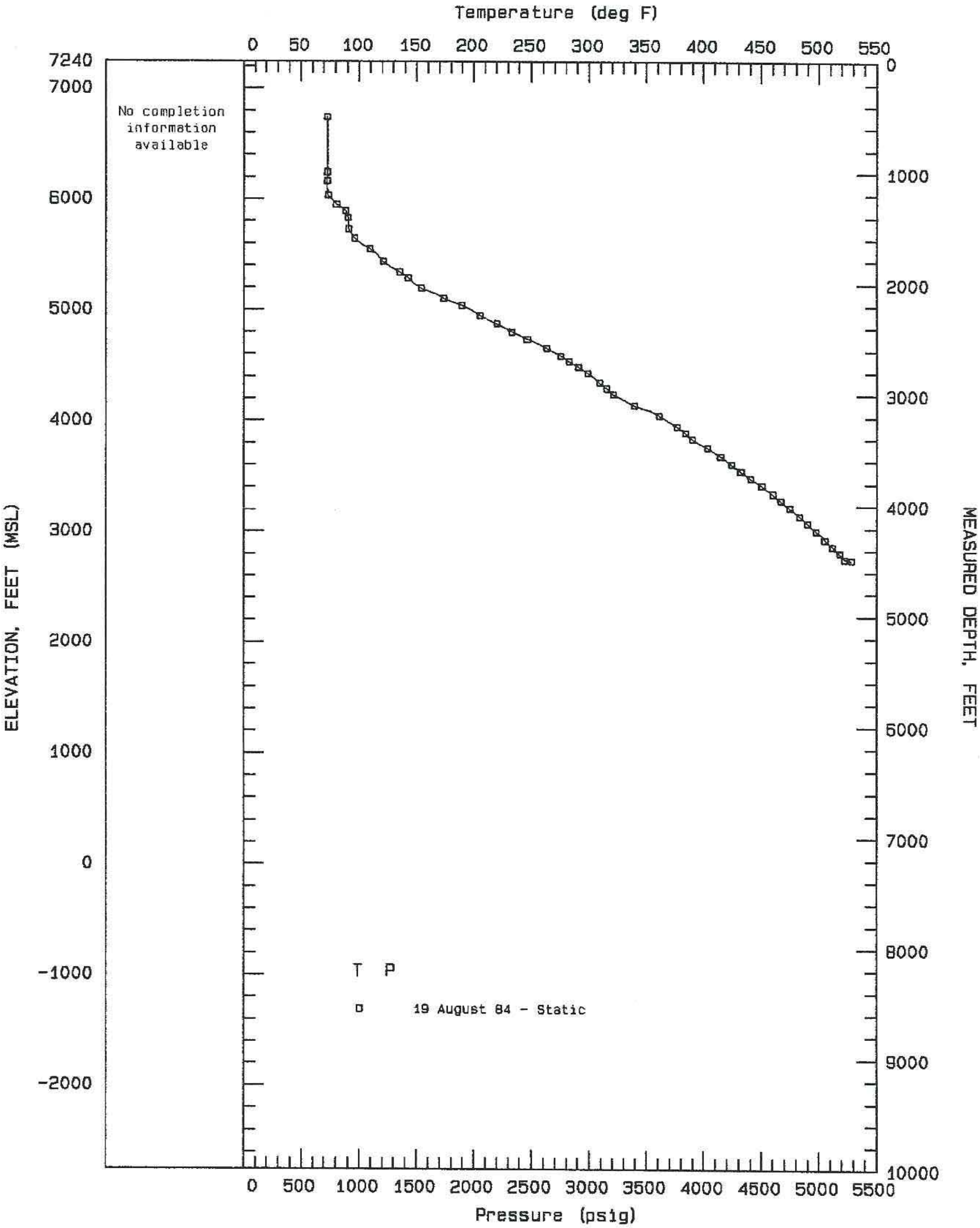
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 28-32



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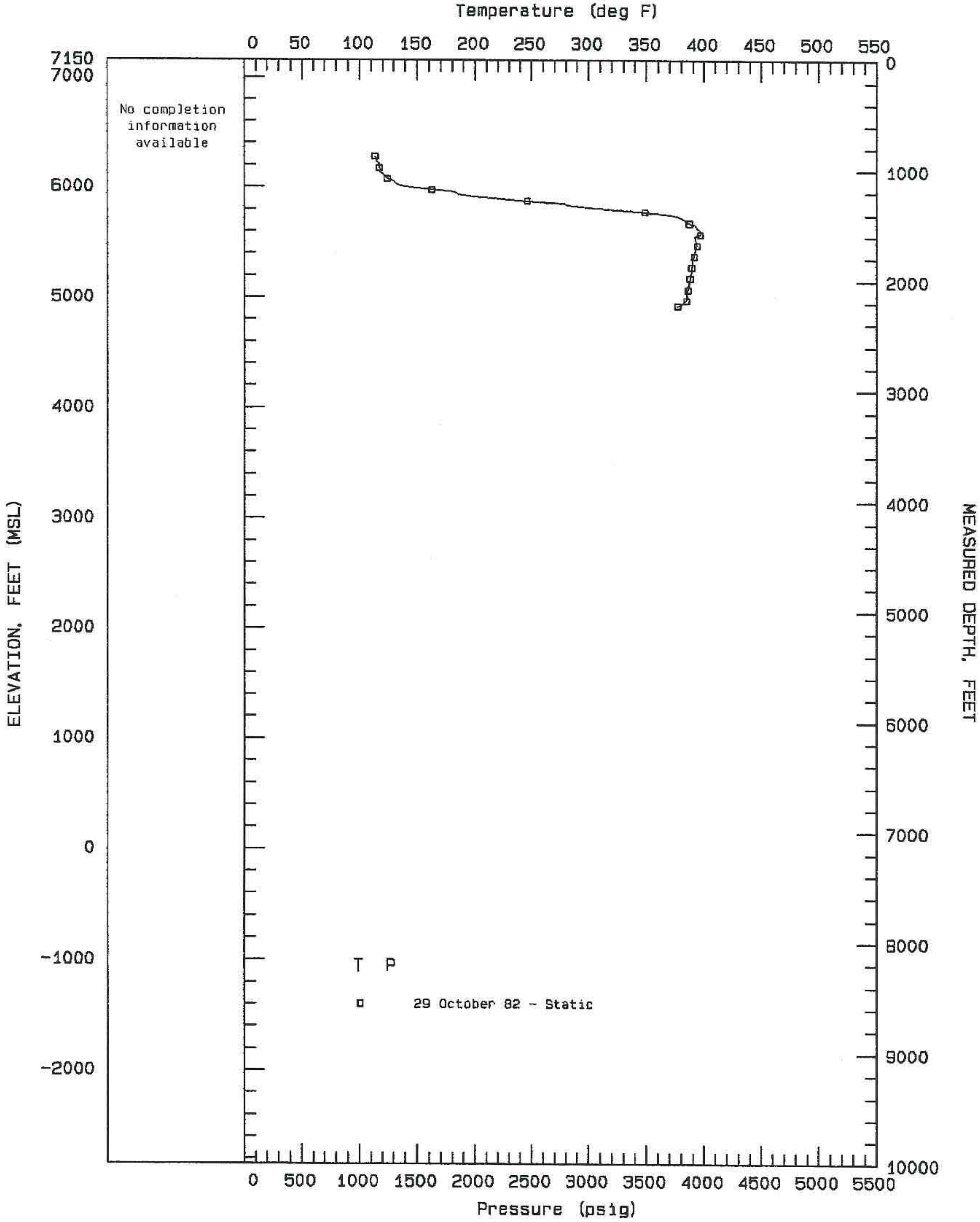
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 44-33



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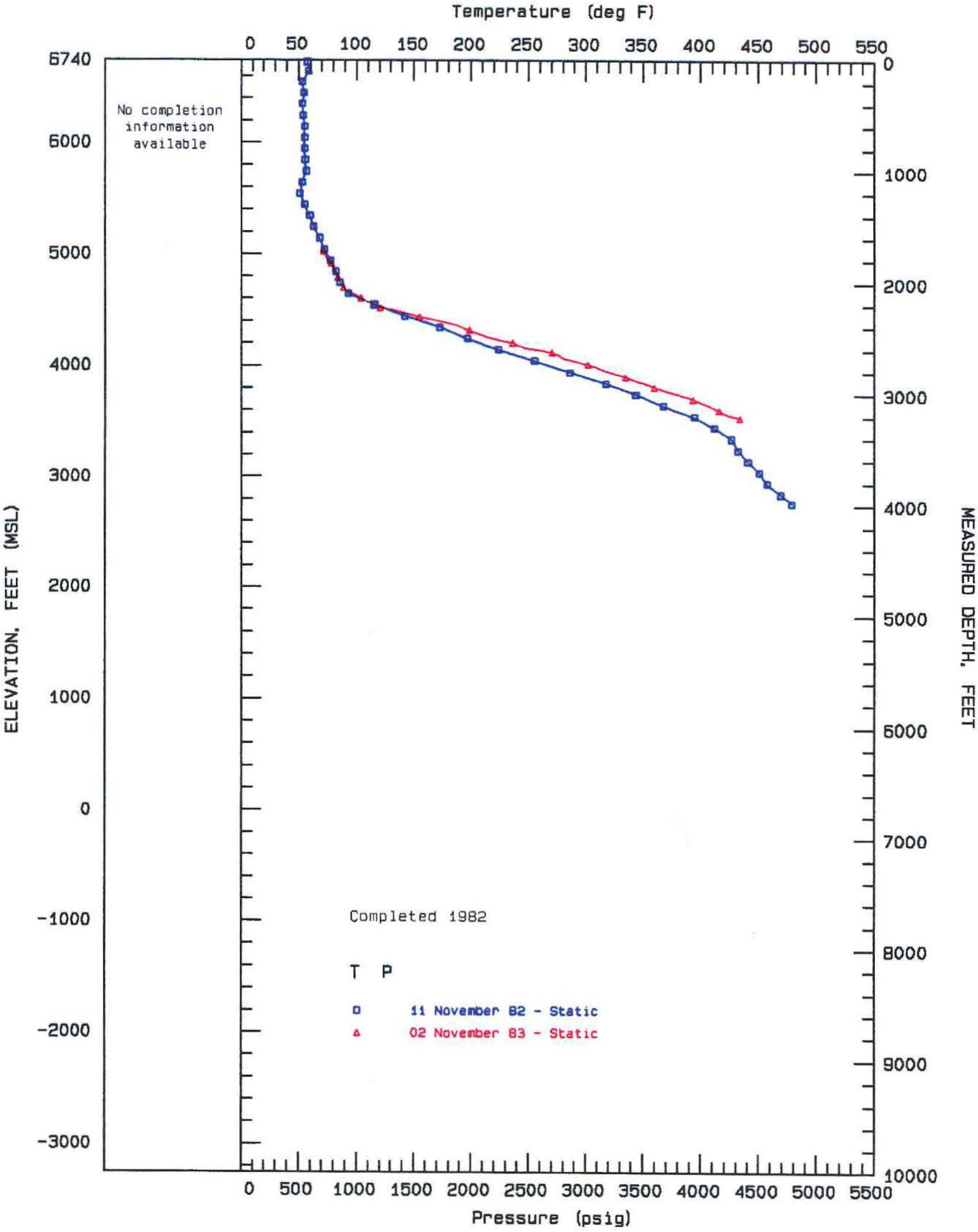
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 17-6



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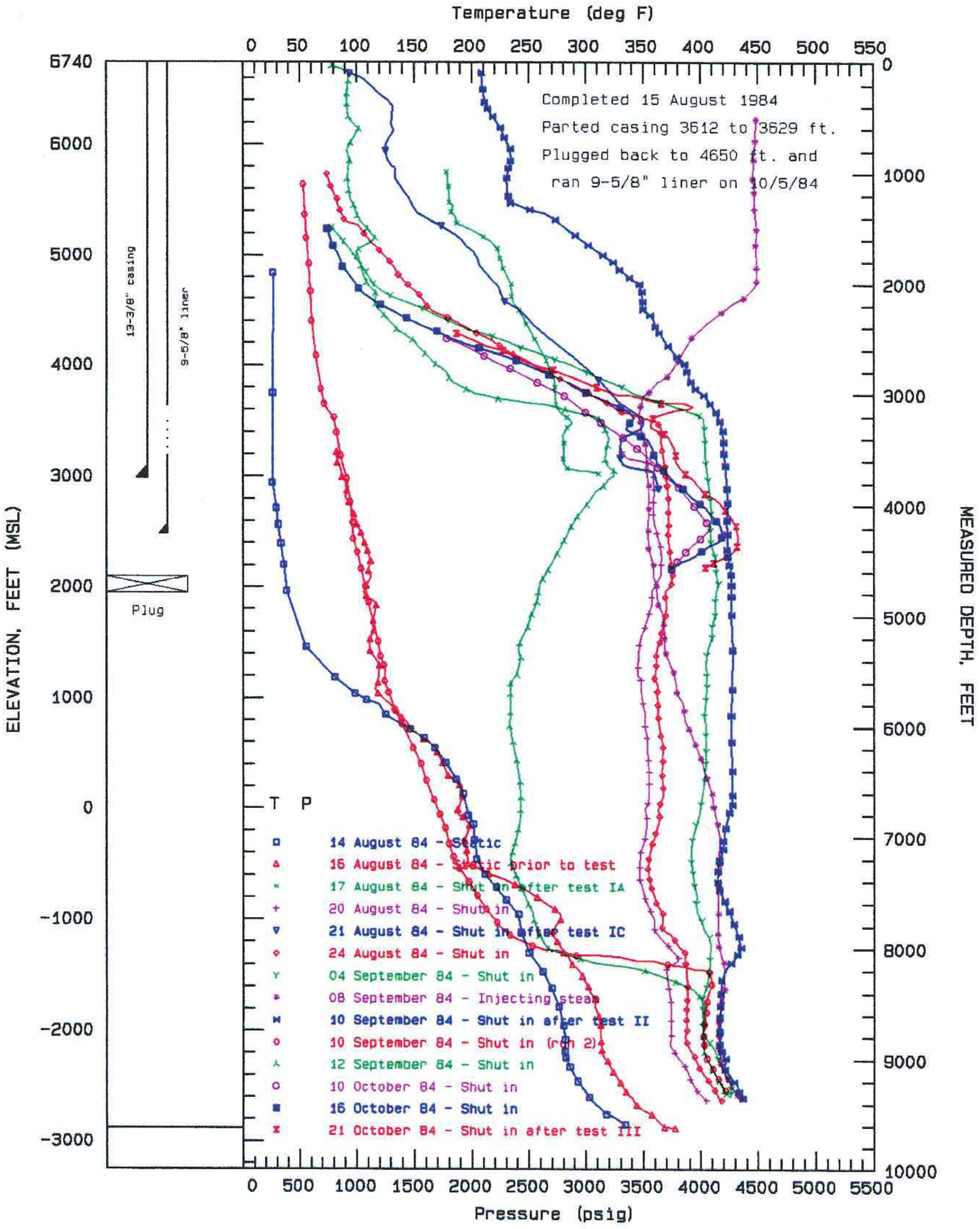
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 17A-6



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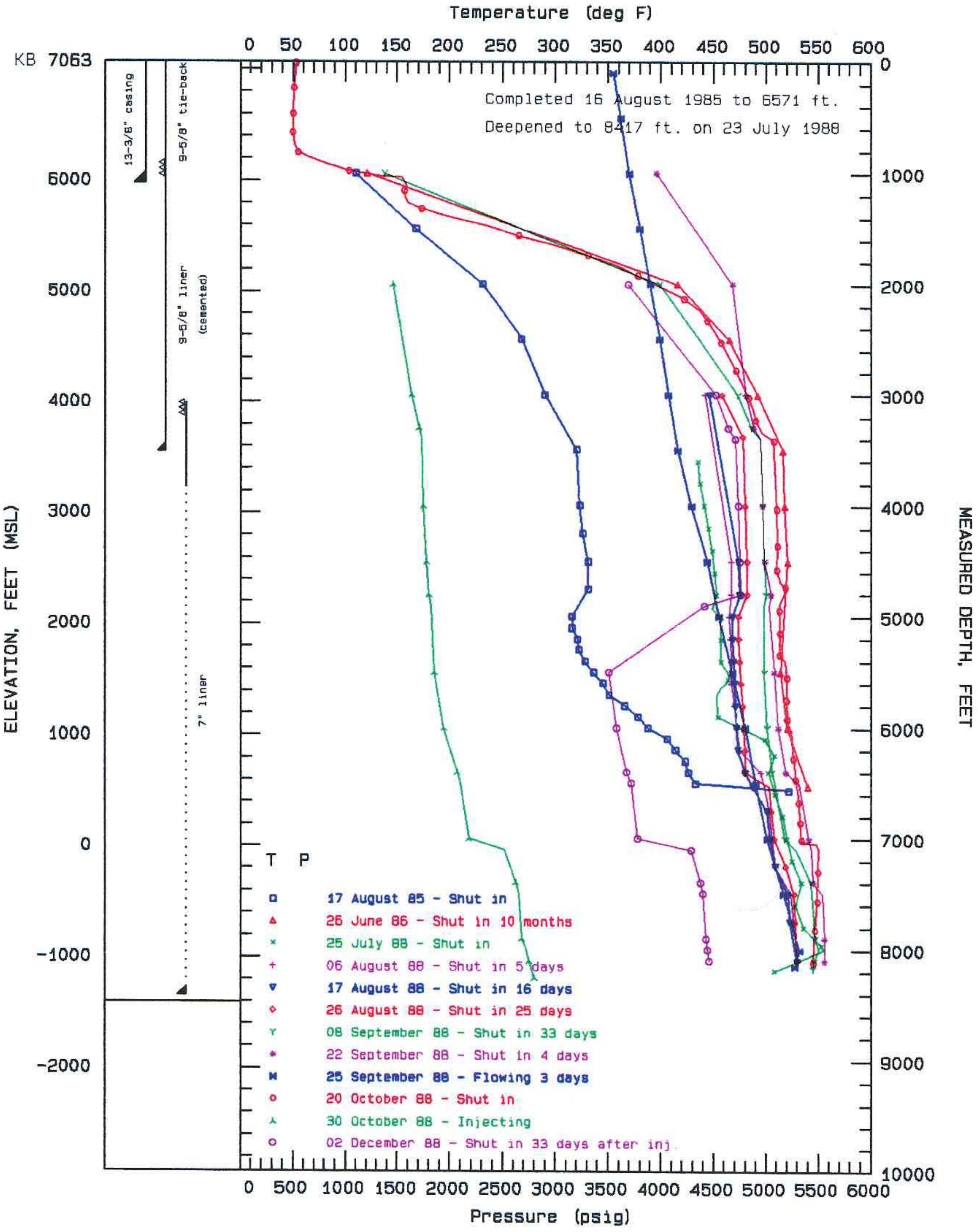
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 68-8



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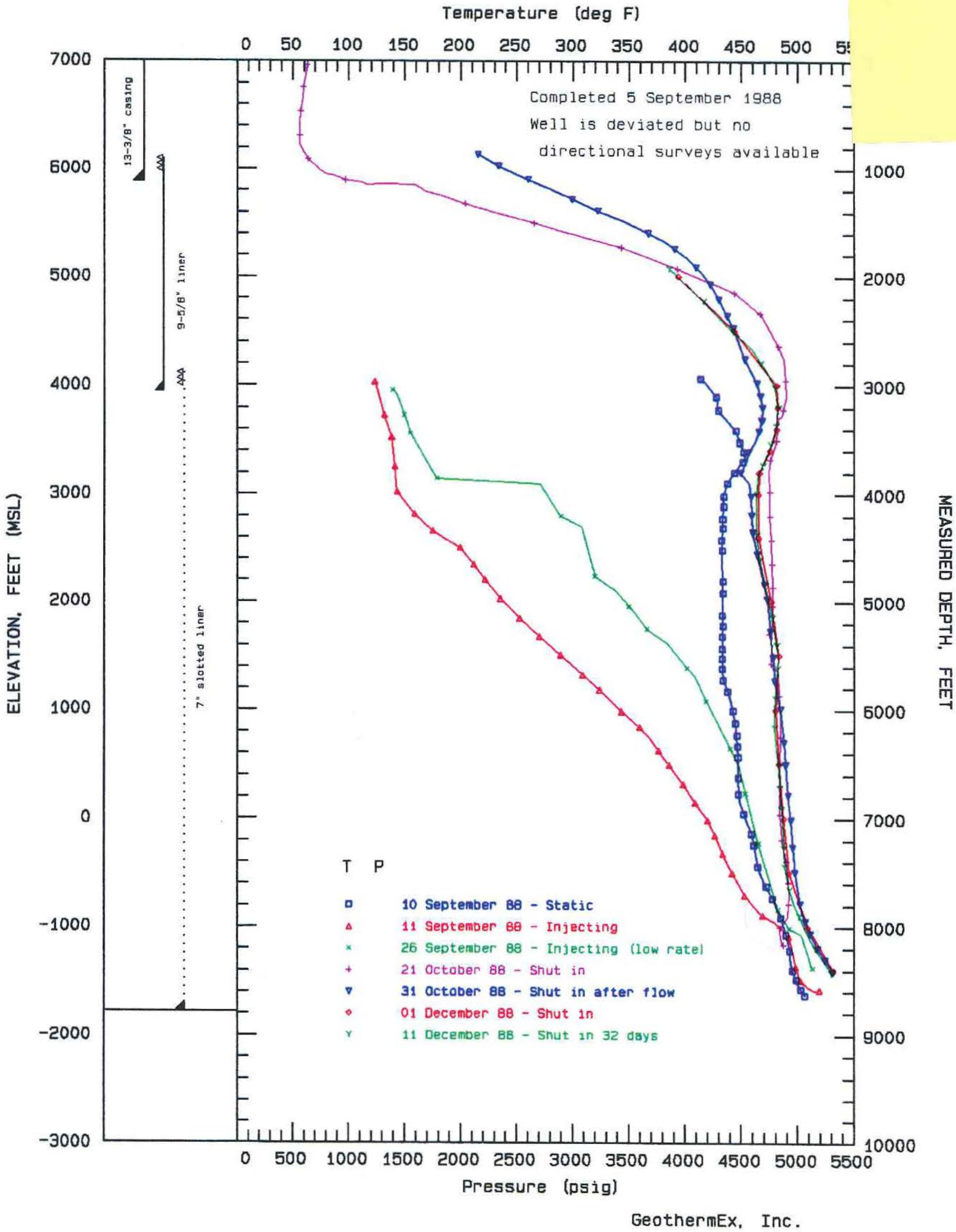
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 31-17



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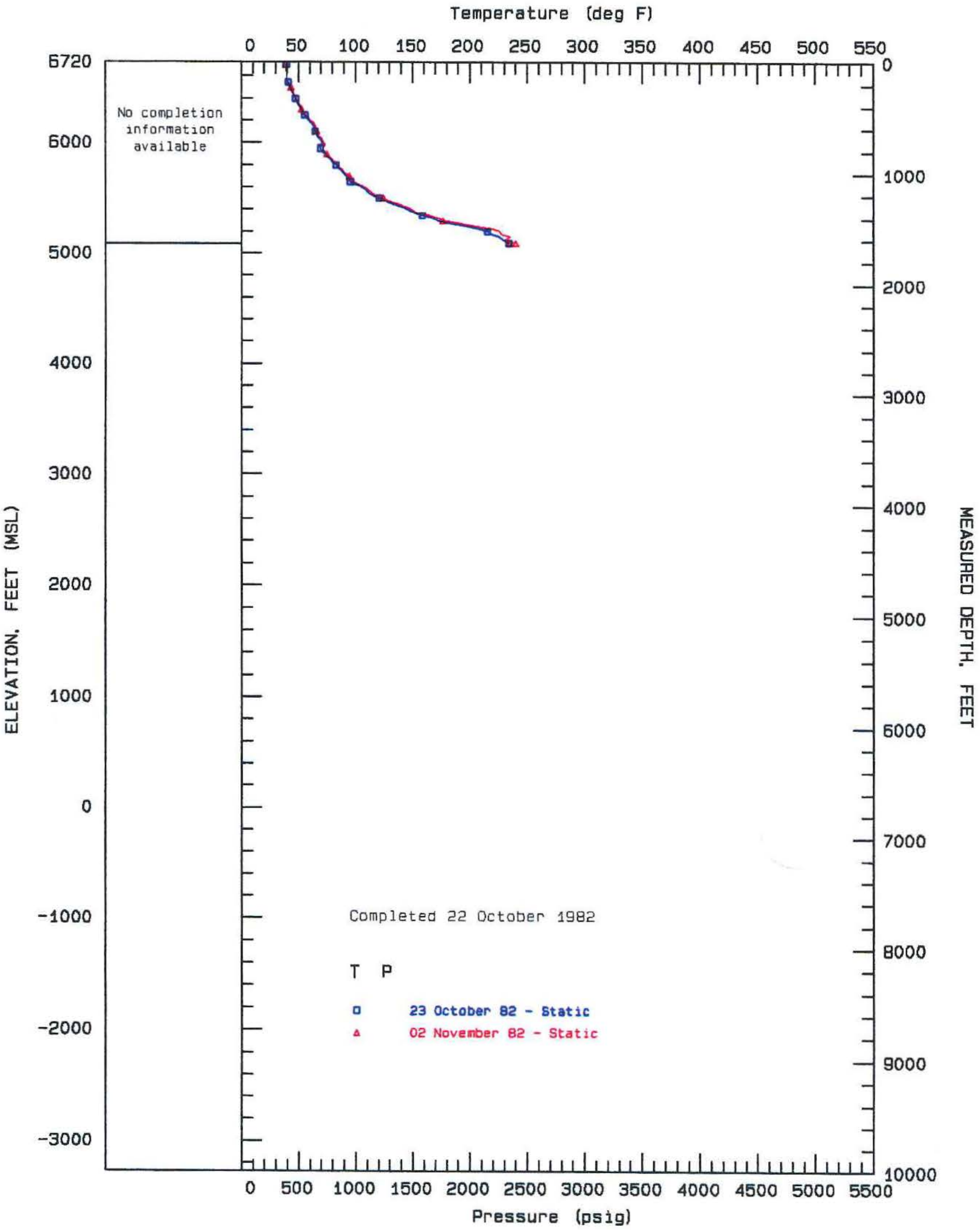
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 84-17



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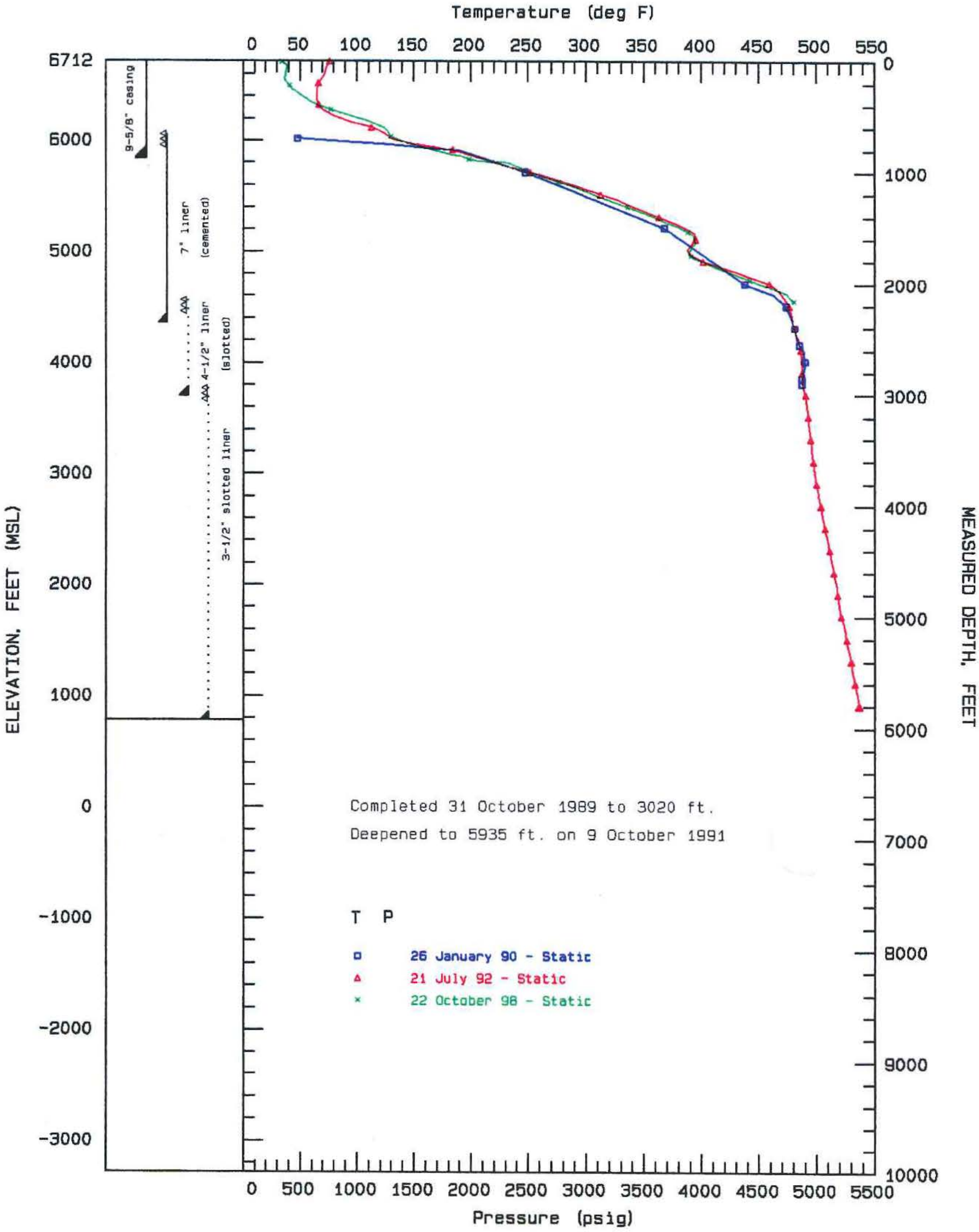
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 87-13



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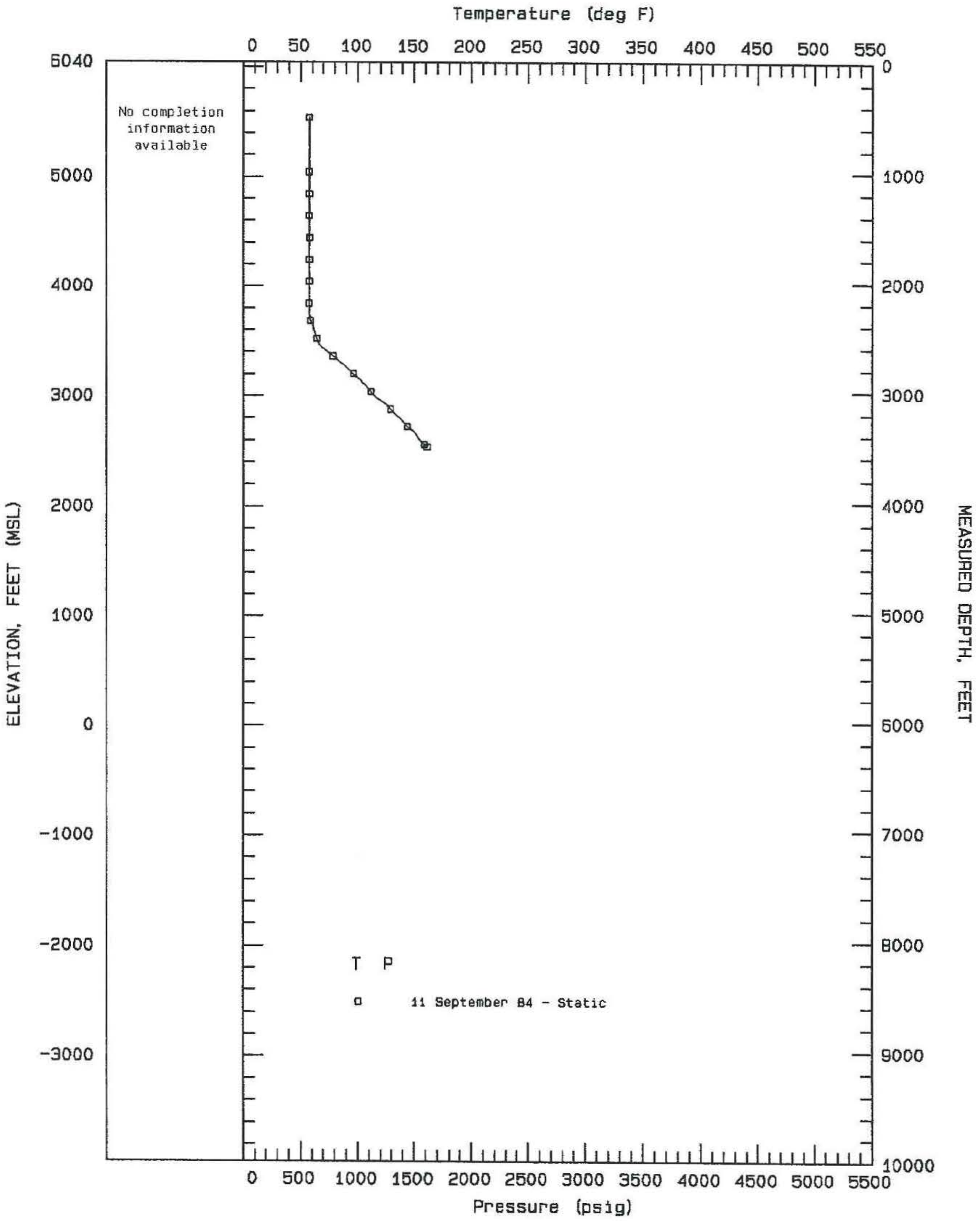
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 86-23



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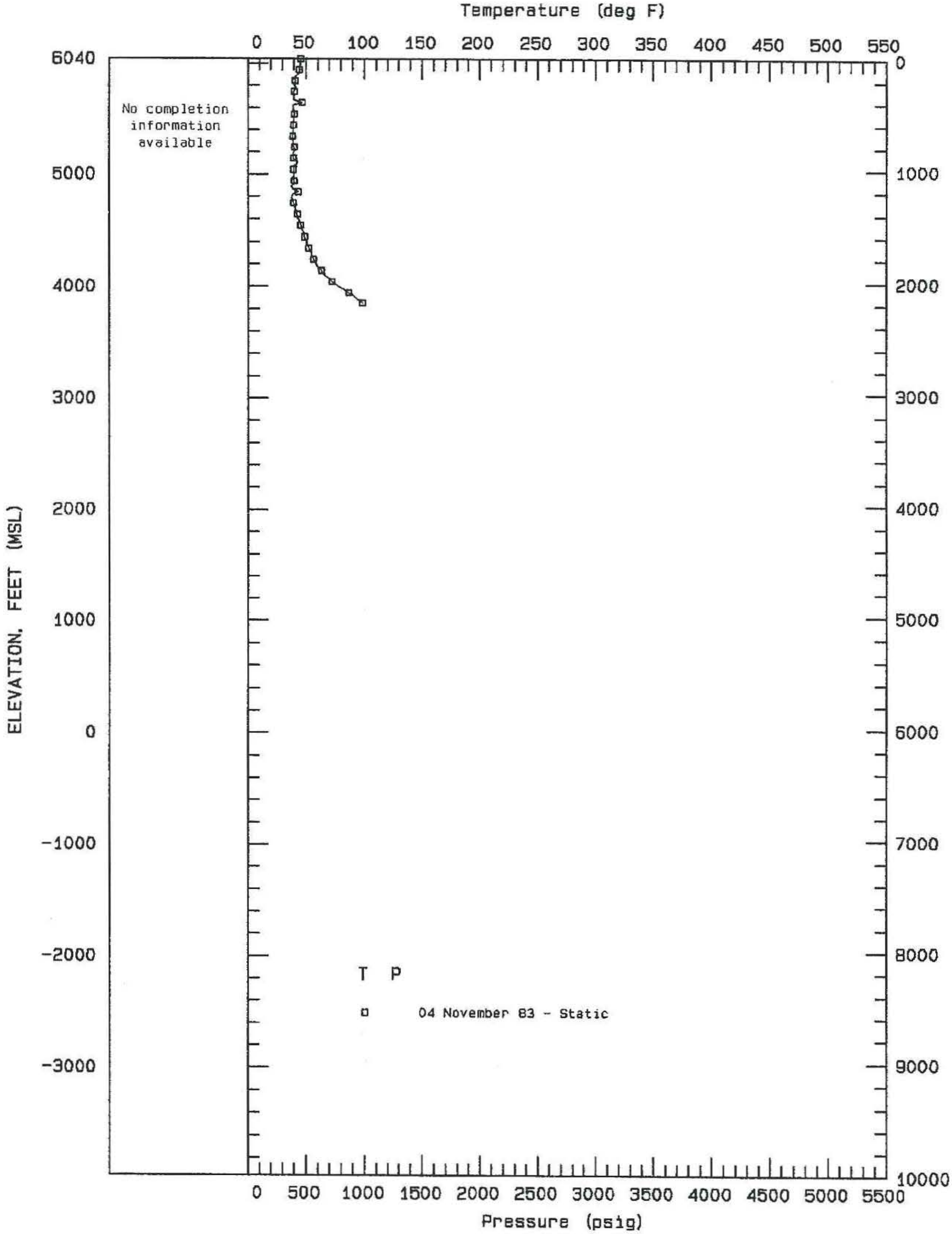
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 54-19



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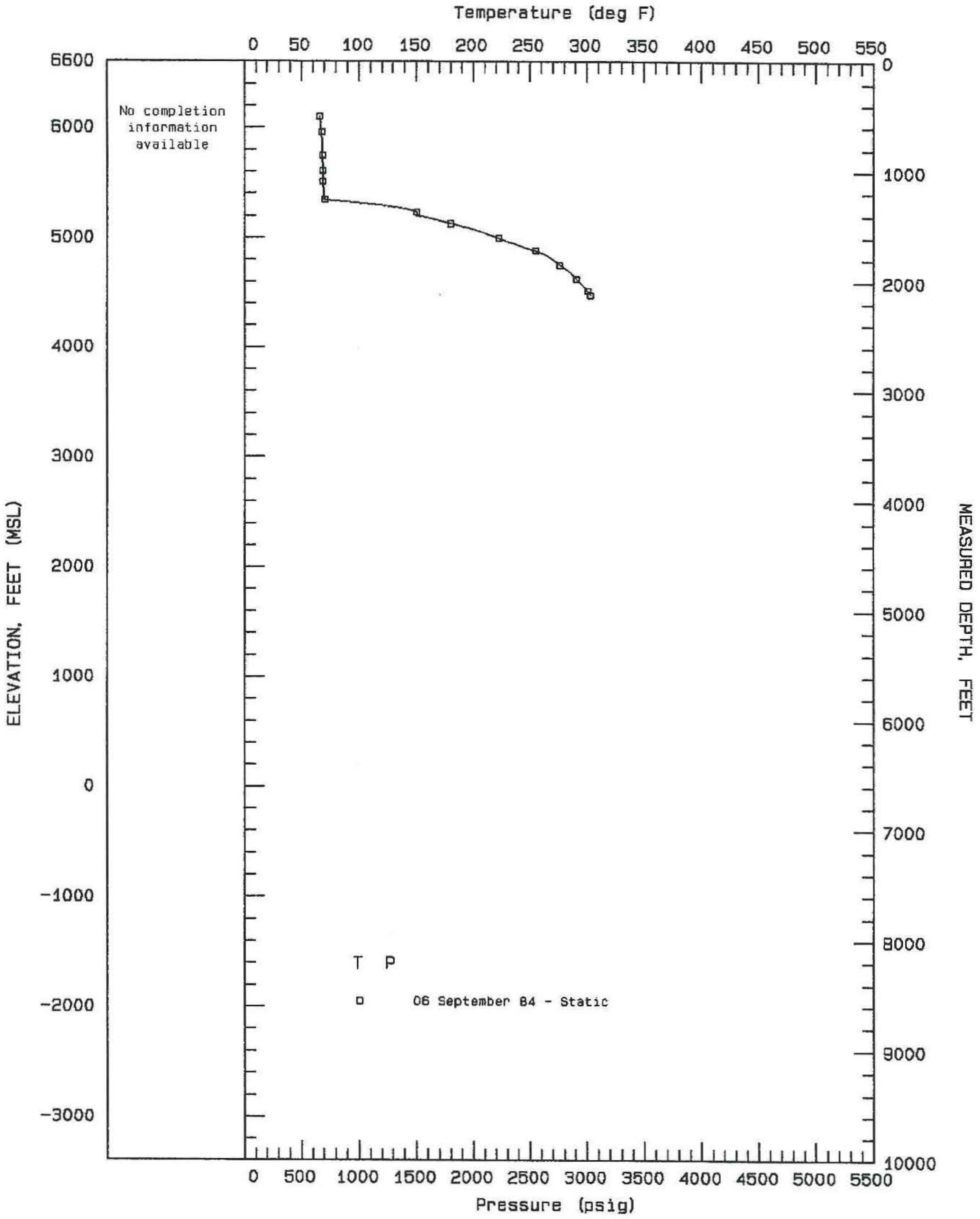
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 62-21



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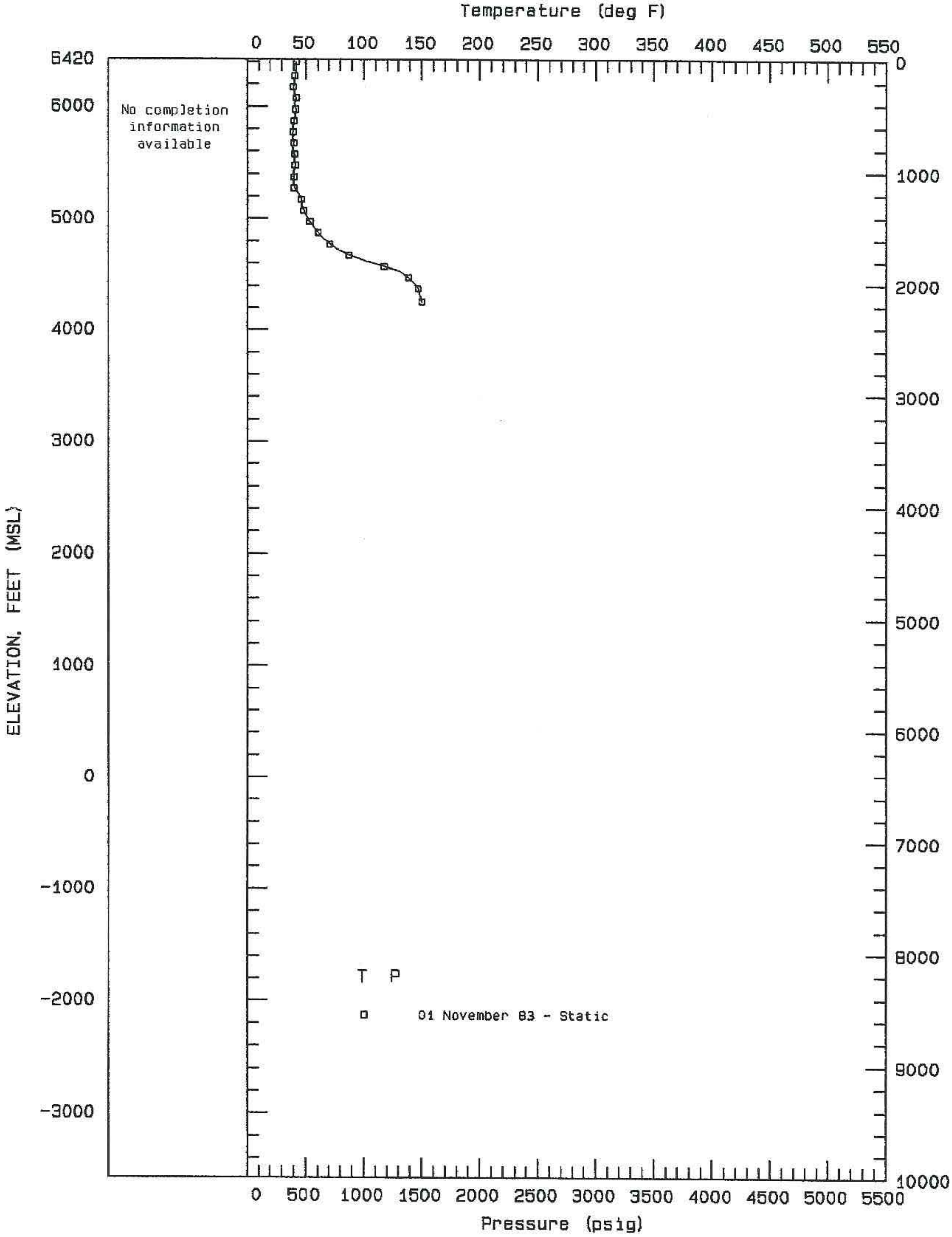
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 65-26



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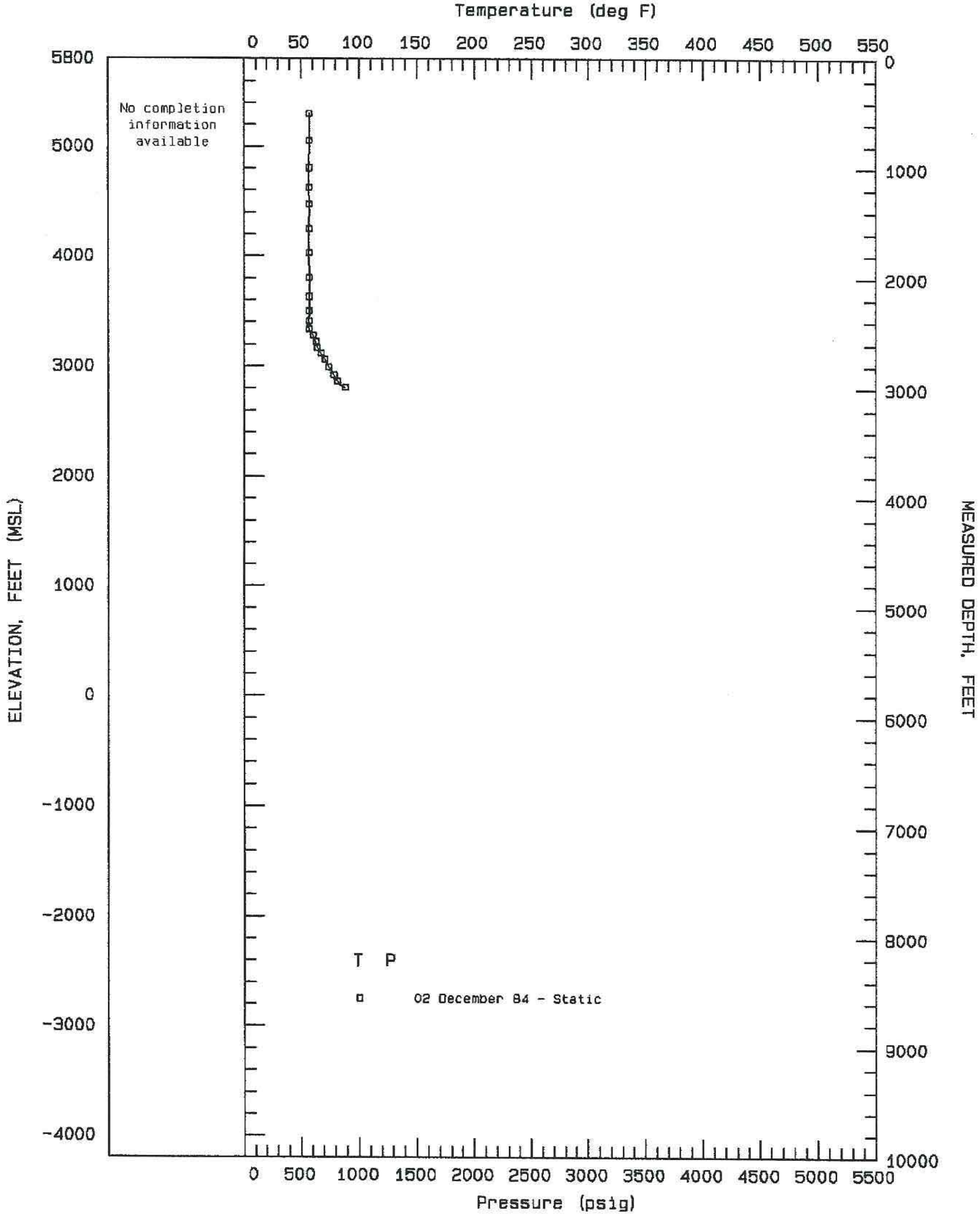
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 27-27



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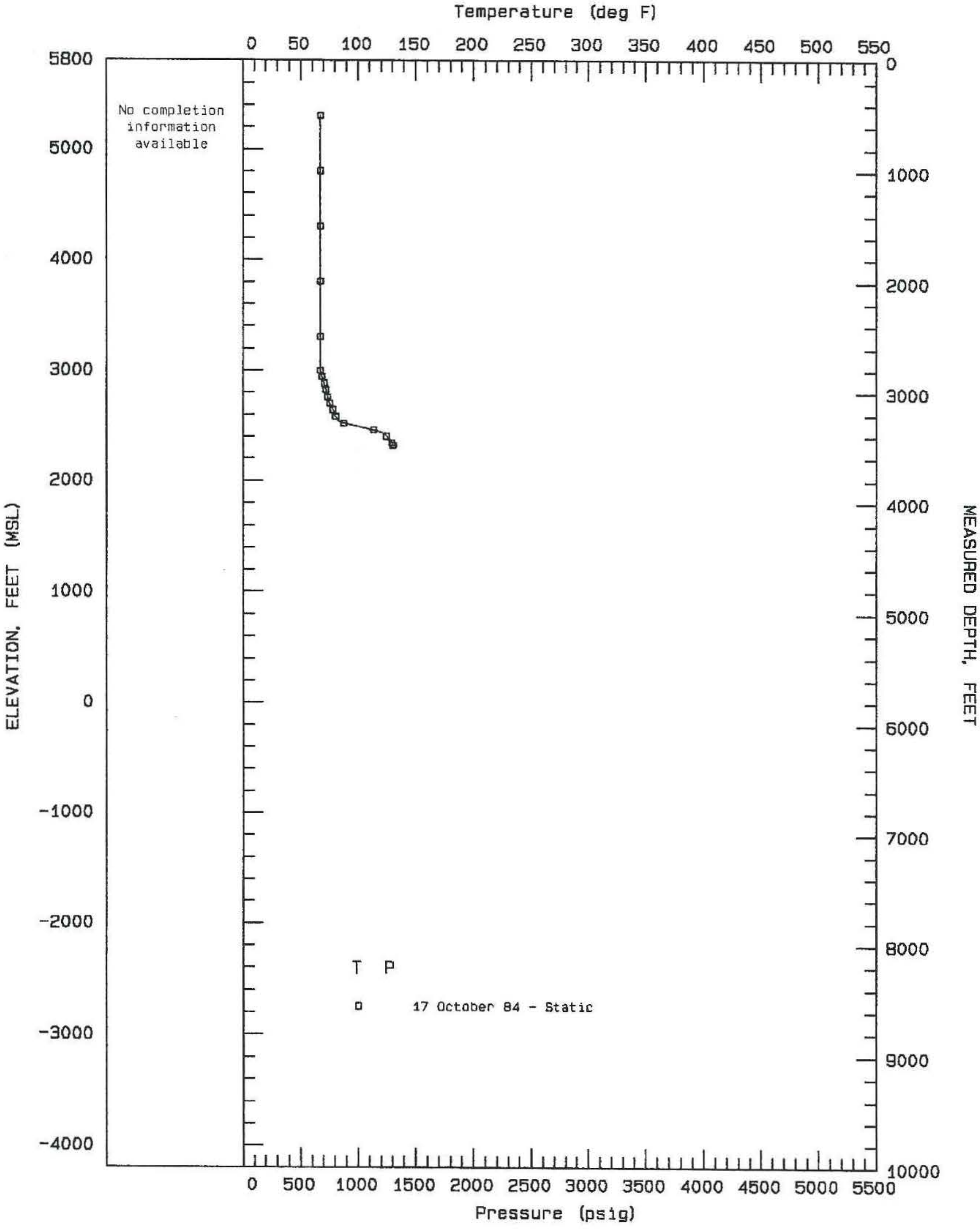
DOWNHOLE SUMMARY PLOT, GLASS MOUNTAIN WELL 18-34



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