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Geothermal Resources International, Inc.

July 19, 1988

Chandler A. Swanberg, Ph.D.
Vice President — Earth Sciences

R. Jeffrey Hoyles
U.S. Department of Energy
785 DOE Place
Idaho Falls, ID 83402

Dear Mr. Hoyles:

Enclosed is our final report for contract DE-FC07-85ID12613. All basic data required under this contract has been forwarded to Dr. P.M. Wright of the University of Utah Research Institute, whose staff acted as our technical monitor for this project.

Since we have now encumbered funds in excess of the contracted amount, there is no need to keep the project open in order to plug and abandon the corehole. Therefore, GEO will assume full responsibility for this task. I have asked our finance department to submit to DOE a final billing to cover the contracted amount of $212,580.00.

Thank you very much.

Sincerely,

Chandler A. Swanberg

Chandler A. Swanberg

CAS/sb

cc R. Brown
J. Combs
C. Walkey

File: N-3
Oregon -
Newberry Volcano
Cascades Drilling.

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Cascade Geothermal Drilling/Corehole N-3

Submitted to The Department of Energy
Mr. R. Jeffrey Hoyles
Dated July 19, 1988

Final report for Contract DE-FC07-85ID12613

By

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8135 Hydrothermal Systems

CORE HOLE DRILLING AND THE "RAIN CURTAIN" PHENOMENON AT NEWBERRY VOLCANO, OREGON

C. A. Swanberg, (Geothermal Resources International Inc.,1825 S. Grant Street, Suite 900, San Mateo, Ca 94402) W. C. Walkey, J. Combs

Two core holes have been completed on the flanks of Newberry Volcano, Orgeon. Core hole GEO N-1 has a heat flow of 180 mWm-2 reflecting subsurface temperature sufficient for commerical exploitation of geothermally generated electricity. GEO N-3, which has a heat flow of 86 mWm-2, is less encouraging. Considerable emphasis has been placed on the"rain curtain" effect with the hope that a detailed discussion of this phenomenon at two distinct localities will lead to a better understanding of the physical processes in operation. Core hole GEO N-1 was cored to a depth of 1,387 m at a site located 9.3 km south of the center of the volcano. Core hole GEO N-3 was cored to a depth of 1,220 m at a site located 12.6 km north of the center of the volcano. Both core holes penetrated interbedded pyroclastic lava flows and lithic tuffs ranging in composition from basalt to rhyolite with basaltic andesite being the most common rock type. Potassium-argon age dates range up to 2 Ma. Difficult drilling conditions were encountered in both core holes at depths near the regional water table. Additionally, both core holes penetrate three distinct thermal regimes (isothermal (the rain curtain), transition, and conductive) each having its own unique features based on geophysical logs, fluid geochemistry, age dates, and rock alteration. Smectite alteration, which seems to control the results of surface geoelectrical studies, begins in the isothermal regime close to and perhaps associated with the regional water table.

on the gamma ray log (N-1, N-3) and the electrical conductivity log (N-1), (2) temperatures below surface ambient measured downhole with a maximum recording thermometer (MRT) during periodic pauses in drilling operations (N-1, N-3), and (3) drilling fluids whose chemistry does not reflect an influx of geothermal fluids (N-3). In contrast, the thermally conductive regime is characterized by (1) a high and variable response on the gamma ray log (N-1, N-3) and on the electrical conductivity log (N-1), (2) temperatures (MRT) measured downhole during pauses in drilling which are above ambient and which track in situ conditions (N-1, N-3), and (3) drilling fluids whose chemistry clearly reveals a geothermal component (N-3). The transition zone is characterized by major washouts in the caliper log (N-1, N-3), a major anomaly in the mercury content of the rocks (N-1), an extremely strong response on the gamma-ray log (N-1, N-3) and electrical conductivity log (N-1), and a major SP anomaly (N-1). Smectite alteration, which seems to control the results of surface geoelectrical studies, begins in the isothermal regime close to and perhaps associated with the regional water table.

INTRODUCTION

The Cascade Range, which consists of a series of Quaternary and late Tertiary andesitic volcanoes that extend from northern California to southern British Columbia, is a geologic province with immense potential for the generation of electricity from geothermal resources. The geothermal potential for the Cascades

Province may well be thousands if not tens of thousands of megawatts [Bloomquist, et al., 1985]. Yet to date, there are no geothermal power plants operating in the Cascades Province, and none are planned. Furthermore, except for the obvious heat sources represented by the active volcanoes, very little is known about the potential geothermal resources in the Cascades.

The geothermal literature is particularly sparse on such key parameters as the chemistry of geothermal fluids, the deep thermal structure of the geothermal systems, and the nature of reservoir host rocks in the Cascades. The Northwest Power Planning Council [1986], has not even included geothermal energy in their long-range power forecasts, stating that "Because the information regarding the character and extent of the regional geothermal resource areas used to prepare the estimates of cost and availability is very preliminary, this resource (geothermal) cannot be considered as available for the resource portfolio of this power plan."

The paucity of geothermal data in the Cascades Province and the consequent reluctance of the utility companies to plan for future geothermal development can all be traced to the single phenomenon known as the "rain curtain." This term refers to the zone of hydrologic disturbance where cool meteoric water percolates downward and spreads laterally, therefore masking the surface expression of geothermal activity. The rain curtain can severely complicate, if not render useless, the standard geophysical and geochemical techniques for locating and evaluating geothermal reservoirs. For example, hot springs are typically diluted or masked completely, temperature gradient holes may be isothermal to depths in excess of a kilometer, and surface geoelectrical studies must be designed to penetrate a kilometer or more of "noise" before geothermally useful data can be obtained. A case in point is Newberry Volcano, Oregon (Figure 1), where the rain curtain ranges in thickness from less than 300 m within the caldera [Black, et al., 1984] to about 1,000 m on the southern flank [Swanberg and Combs, 1986]. The cool meteoric zone overlies a geothermal system that is at least 265°C at a depth of 900 m [Sammel, 1981], yet supresses the surface manifestations of this system to the extent that only two small warm springs exist over the entire volcano. Various geoelectric and geoelectro-magnetic studies including magnetotellurics [D. Stanley, U.S. Geological Survey, Denver, Colo.; personal communication, 1986], Schlumberger soundings [Bisdorf, 1985], and transient geoelectromagnetic soundings [Fitterman and Neev, 1985] have shown the presence of electrically conductive zones both inside and outside the caldera, but the lack of drilling data has precluded a rigorous interpretation of these conductors [Fitterman and Neev, 1985, p. 409].

In recognition of this situation, the U.S. Department of Energy (DOE), Division of Geothermal and Hydropower Technologies (DGHT), initiated a Cascade Deep Thermal Gradient Drilling Program. The stated purpose of the program is to "support industry efforts in the Cascade Volcanic region" and the stated objectives are to "cost share with industry for the drilling of gradient holes which would penetrate the'rain curtain' and obtain deep thermal, lithologic, and structural data." In exchange for the cost sharing, the industry participant would "release [the data] to the public for the benefit of the geothermal industry and the scientific community," [Cascade Newsletter, 1986].

To date, GEO Operator Corporation (GEOOC) has cored and completed five core holes at Newberry Volcano two of which were drilled under the DOE Cascades Drilling Program. The first cost-shared core hole, GEO N-1, was completed in the fall of 1985 to a depth of 1,387 m on GEO leaseholds on the south flank of the volcano. Data and core from the upper 1,219 m are in the public domain [Cascade Newsletter, 1987]. The second cost-shared core hole, GEO N-3, was completed in the summer of 1986 to a depth of 1,220 m. Data and core from all of this core hole are in the public domain [Cascade Newsletter, 1987]. In the following sections, the basic data from these two core holes are presented with some preliminary observations which pertain to the understanding of the phenomenon of the rain curtain and its physical characteristics. We hope, the data and observations will lead to an enhanced understanding of the rain curtain; to subsequent refinements in geothermal exploration techniques for use in the Cascade Province; and finally, to an increased understanding of Cascade geothermal systems and their potential for economic exploitation.

GEOLOGY OF NEWBERRY VOLCANO

Newberry Volcano, covering roughly 1,300 km^2 in central Oregon, is one of the largest volcanoes in the conterminous United States and is one of a series of Quaternary bimodal volcanoes located to the east of the main Cascade Range trend (Figure 1). The volcano lies near the juncture of the Cascade Range with the Brothers Fault Zone, a northwest trending fracture system along which silicic volcanism and rhyolitic domes become progressively younger to the northwest [MacLeod, et al., 1975]. Considerable research has been conducted at Newberry during the past several years [Sammel, 1981; MacLeod, et al., 1981; MacLeod and Sammel, 1982; MacLeod, et al., 1982; Ciancanelli, 1983; Priest, et al., 1983, 1987], which update the earlier work of Williams [1935] and Higgins [1973]. Holes drilled within the caldera by the U.S. Geological Survey (USGS) and Sandia National Laboratories attained 265°C at 932 m [Sammel, 1981] and greater than 160°C at 424 m [Black, et al., 1984], respectively. The geothermal potential of Newberry Volcano has been estimated at 740 MWe for 30 years by the USGS [Muffler, 1979] and 1,551 MWe for 30 years by Bonneville Power Administration [Bloomquist, et al., 1985].

volcano in order to determine whether there is radial symmetry of the heat source. Core hole GEO N-1 was drilled near the neck of a very young basalt flow, the Surveyors flow whose age is probably comparable to the 5,835 ± 195 years B.P. date obtained for the near surface cinders at the drill site [Swanberg and Combs, 1986]. The core hole is also located near the center of a major soil mercury anomaly [Hadden, et al., 1982].

The average heat flow from GEO N-1 is 180 mWm^{-2} based on a least squares fit to temperature-depth data over the thermally conductive regime between 1,164 and 1,219 m and twelve (12) measurements of thermal conductivity representing the same interval (Table 1). Heat flow values of this magnitude imply temperatures in excess of 200°C at depths less than 3 km. Such temperatures are sufficiently high and accessible as to imply the possible commercial exploitation of geothermal resources for the generation of electricity utilizing either the single or double flash power conversion technologies, provided of course, that suitable production zones can be encountered in deep geothermal wells.

Geophysical Logging Program

The physical condition of core hole GEO N-1 caused deviation from a traditional geophysical logging program. Specifically, the interval 378 to 549 m was known to be associated with caving and sloughing. In order to minimize the risk of loosing a logging tool and possibly the entire core hole, it was decided to forego the geophysical logs over this interval. Therefore, after drilling to total depth, the rods were pulled to a depth of about 550 m, leaving the upper 550 m of the core hole, including the incompetent section, behind pipe. The remainder of the hole was open. The hole was then conditioned and a suite of logs were run from 550 m to total depth. After this first logging run, the rods were pulled out of the hole and the geophysical logs were run from the base of the surface casing at 143 m to the top of the incompetent section 378 m. The logging program called for temperature, induction, gamma-ray, caliper, sonic, BHC acoustic fraclog, and density logs; however, the density log was terminated because the tool would not freely penetrate the section.

Depth To Water Table

The depth/elevation of the water table is an important parameter in regional hydrologic studies of geothermal systems and is also useful in interpreting the results of experiments conducted at the surface or within the core hole. Unfortunately, the water table at GEO N-1 seems to be an elusive phenomenon. None of the geophysical logs indicate an obvious perturbation that might represent the water table. It is possible that the water table lies in the interval 378 to 550 m which never was logged. The driller routinely estimates and records the standing water level in the core hole and almost all such estimates fall within the unlogged interval, the most common estimate being about 490 m. This unlogged interval also represents the approximate depth at which smectite and other alteration products first occur within the subsurface section [Bargar and Keith, 1986]. These observations, coupled with the instability of the core hole (caving-sloughing), suggest a geologically plausible cause and effect relationship: i.e., geothermal fluids rising from depth spreading laterally near the water table and promoting hydrothermal alteration, which generally weakens the rocks. The closeness of the water table to physically incompetent rocks is noteworthy because it may allow difficult drilling conditions to be predicted, thus reducing the risks (drilling problems such as stuck rods and twist off) and costs.

The Temperature Log

The equilibrium temperature log is shown in Figure 3 and was taken ten (10) months after drilling. The data from all temperature logs over the interval 450 to 1,219 m are illustrated in Figure 4. At least three (3) distinct thermal regimes can easily be recognized on the logs (see Figure 3 or 4). The temperature log is isothermal at mean air temperature ($6^{o}C$) down at least to the water table at about 490 m and probably beyond. The interval 1,158 m to TD is a thermally conductive regime. Between the isothermal and conductive regimes lies a third interval over which the temperatures increase very rapidly with depth (see Figures 3 and 4).

The nature and extent of the uppermost isothermal section (the rain curtain) has been the subject of debate among several workers who have examined the temperature logs. There is no doubt that the rain curtain extends at least to the water table (about 490 m), but there is a question as to whether the isothermal temperatures measured for several hundred meters below the water table indicate a rain curtain, or merely water percolating downward in the annulus between the completion tubing and the walls of the core hole.

One scenario has the rain curtain extending to an approximate depth of 1,005 m., at which point the downward percolating groundwater exits the volcano along the highly permeable horizons depicted on the geophysical well logs (Figure 5). In this first model, the rain curtain is located in a suite of volcanics whose geological character (including porosity and permeability) is distinct from the suite of rocks lying below. This model is favored by the fact that the volcanic section does in fact change character at depths near the bottom of the isothermal section (Figure 5), and also by the fact that temperatures measured during pauses in drilling operations were never above ambient until depths of 500 meters below the water table.

A second scenario [Blackwell and Steele, 1987] has the rain curtain extending to a depth of 350 to 400 m, while the remaining isothermal interval is a consequence of intra-hole fluid flow. In this second model, the rain curtain would coincide with the region above the water table. This model is favored by its simplicity and by the observation that an extrapolation upwards of the deep temperatures intersect mean air temperature at a depth which is not incompatible with the water table.

A third (preferred) hybrid possibility would accommodate limited groundwater flow within the annulus over the interval 1,005 to 1,158 m. The first or third model is favored on the assumption that the temperatures measured during drilling are diagnostic, if not highly accurate, thus precluding the second model, which associates the rain curtain with the water table. Also, the first and third models are more compatible with the fluid geochemistry data from GEO N-3 which are discussed below.

The Mercury Log

Core hole GEO N-1 was sited on one of the major soil mercury anomalies of Hadden, et al. [1982], as was the USGS core hole NB-2, which was located near the center of the volcano, and which encountered temperatures of 265°C at 932 meters [Sammel, 1981]. Because soil mercury surveys are routinely used as a surface manifestation of sub-surface geothermal conditions, it was decided to attempt a detailed mercury survey of the rocks penetrated by core hole GEO N-1 in the hopes of learning more about the migration of mercury from a geothermal reservoir to the surface. The sampling procedure was to randomly select several core fragments from each 3-m interval, pulverize and sieve the aggregate to the same mesh as typically used in soil mercury surveys, and analyze the resulting powdered core sample for mercury content. The results of the survey are shown in Figures 5 and 6. The upper part of the core hole failed to yield detectable levels of mercury so the sampling technique was modified to emphasize altered zones and fractures. This technique also failed to yield detectable mercury. However, once the hydrologically disturbed zone between 945 and 1,000 m was entered, a major mercury anomaly was encountered. This anomaly has been verified by resampling and laboratory analysis by an independent laboratory. The mercury anomaly is shown in Figure 5 in relation to other core hole data sets and the correlation among the mercury anomaly, the rapid temperature buildup, and the "washouts" in the caliper log are quite obvious. Clearly, geothermal fluids relatively enriched in mercury are migrating through this interval. But, the relationship between this mercury anomaly within the core hole and soil mercury anomaly at the surface remains unclear. None of the other fracture or rubble zones in the core hole are enriched in mercury, and the low background levels of mercury throughout the core hole would seem to preclude the volcanic pile itself as the source of the soil mercury anomaly. These data are consistent with the standard concept that soil mercury anomalies result from clay entrapment of mercury ascending along fractures from depth. However, it is not possible to prove that the mercury anomaly at depth is the origin of the soil mercury anomaly observed at the surface.

Geophysical Logs: Electrical Conductivity

A generalized electrical conductivity log derived from the induction log for core hole GEO N-1 is shown in Figure 5. It was prepared by averaging the log over 30-meter intervals and plotting the resulting average at the midpoint of the 30-meter section. Thus, any anomalous point in this log may be reflecting changes up to 15 meters on either side of the depth at which the point is plotted. The logic behind this type of presentation is the expectation that gross changes in the electrical properties of the volcanic pile might be detected from the ground surface using traditional geoelectric or geoelectromagnetic surveys. Examination of the generalized electrical conductivity log (Figure 5) shows the volcanic pile to be of generally constant conductivity down to a depth of 945 m. This interval of uniform conductivity coincides very well with the rain curtain as defined by the five temperature data sets (Figure 4). The conductivity log shows no obvious perturbations at the water table (490 m), at the onset of smectite alteration (Figure 5, Column 2), or at the depths at which smectite alteration becomes ubiquitous (Figure 5, Column 2). Below 945 m, the volcanic pile becomes significantly more conductive and more variable in its electrical conductivity. The increased electrical conductivity may result as a direct consequence of higher temperature or from the effects of increasing rock alteration (Figure 5). In either case, the increased conductivity represents a marked change in the physical properties of the volcanic pile which is related to geothermal activity and which at least in theory, should be detectable from the surface. Fitterman and Neev [1985] have published the results of a one-dimensional geoelectrical model based on a transient geoelectromagnetic sounding (TS) located at the GEO N-1 site. This model is reproduced in Figure 5, Column 1 as "TS Resist Section Ω -M." Unfortunately, the model appears to reflect smectite alteration and not the geothermal system. A similar conclusion has been published by Wright and Nelson [1986], also based on analyses of data from core hole GEO N-1.

Geophysical Logs: Gamma Ray

A generalized gamma ray log for core hole GEO N-1 is presented in Figure 5. It was prepared in a manner analogous to the electrical conductivity log, i.e., averaged over 30-meter sections and plotted at the midpoint. The generalized gamma ray log is fairly uniform from the surface to a depth of 945 m, below which the rocks become significantly more potassic (see stratigraphic column, Figure 6).

It is interesting to note that the gamma ray and electrical conductivity logs are inversely correlated throughout the nonisothermal section of the core hole (i.e., below 945 m), but not in the isothermal section (i.e., 0-945 m). A thermal origin for this inverse correlation is suggested and probably reflects the manner in which laterally migrating geothermal fluids promote rock alteration. Apparently, the more mafic glass-rich basalts are more prone to undergo alteration to highly conductive clay minerals such as smectite than are the more potassic rocks which show the strong gamma ray signature (from K^{40}). The lack of the inverse correlation throughout the isothermal section would, therefore, reflect a lack of migrating geothermal fluids (see Figures 3, 4), a general lack of felsic volcanics (see Figure 6), or a combination of both.

Geophysical Logs: Caliper

The core hole diameter over the interval 550 to 1,045 m as depicted by the caliper log is presented in Figure 5. The three lower washouts and their association with the rapid temperature increase and other anomalous features of the core hole have already been discussed. The four washouts further up the core hole do not appear to reflect migration of geothermal fluid (i.e., they are in the rain curtain).

Geophysical Logs: SP

The SP log (Figure 5) undergoes a drop of 70 mV over the interval from about 1,000 to 1,020 m. This feature probably reflects fluid movement, and is the only such feature on the SP log.

Rock Alteration

Bargar and Keith [1986] have studied the alteration mineralogy of core hole GEO N-1. A generalized depiction of smectite alteration, taken directly from Bargar and Keith [1986], is shown in Figure 5. The relationships among alteration mineralogy, the electrical conductivity log, and surface geoelectromagnetic studies are discussed elsewhere in this report.

Potassium Argon (K-Ar) Age Dates

K-Ar age dates representing surface samples collected from around Newberry volcano are presented in Figure 2 and typically are less than 2 Ma although ages as old as 5 to 7 Ma are reported for the outer flanks of the volcano. Age dates representing samples taken from core hole GEO N-1 increase systematically with increasing depth from values of 27,000 and 29,000 years B.P. at 481 and 491 meters, respectively, to 1.63 Ma at 1,081 meters (Figure 7, Table 2). In addition, in an earlier report, Swanberg and Combs [1987], reported the results of a single C^{14} age date based upon charcoal discovered while digging the mud sumps. This date of 5835 ± 195 years B.P. establishes the age of the basaltic cinders at the surface near the core hole.

Whenever age dates are determined in a geothermal environment, the possibility always exists of nonrepresentative ages due to argon diffusion and subsequent resetting of the K-Ar clock. Perhaps the best testament to the reliability of the age dates presented in Table 2 and Figure 7 is the fact that they are geologically reasonable. The dates are generally compatible with those determined from surface samples throughout the volcano. The dates increase systematically with depth throughout the core hole and there is no radical departure from this trend upon encountering the zone of ubiquitous smectite alteration near 700 meters (Figure 5) or encountering the zone of rapid temperature buildup near 1,000 meters.

Chemistry of Formation Fluids

During drilling operations, fluid samples were episodically selected for chemical analysis. Although such samples would be severely contaminated with drilling mud, it was felt that various geothermal constituents might be detectable above the background and if so, would serve to indicate any environmental problems that might be encountered during eventual production. The results of silica analyses as a function of depth are presented in Figure 8. Representative samples of the drilling fluid are also shown. Analyses of other chemical constituents are even less revealing than silica and are not reported here.

The Rain Curtain as a Lithologic Discontinuity

The coincidence that the generalized gamma ray and electrical conductivity logs both change character at a depth (945 m, Figure 5) which is compatible with the rain curtain as defined by the five temperature data sets (Figure 4) suggests the possibility that the rain curtain may represent a lithologic discontinuity. An intriguing (but speculative) extension of this logic is to associate such a discontinuity with the transition between pre- and post-Newberry strata. The pre-Newberry strata are generally more felsic than the Newberry pile [Ciancanelli personal communication, 1987], so that the pre/post Newberry transition might well produce a generalized gamma ray signature similar to that shown in Figure 5. MacLeod and Sherrod [this issue] confine the Newberry section to those normally polarized strata younger than 0.73 Ma. The K-Ar age dates shown in Figure 7 are compatible with a pre/post Newberry transition at 945 m. In fact, using selective license with the error bars on the K-Ar age dates (Table 2), indicates that all age dates shallower than 945 m are 0.737 Ma or less, while all age dates deeper than 945 m are older than 0.73 Ma. At present, however, the data do not totally support the postulation of a depth or even the existance of a pre/post Newberry discontinuity. Any K-Ar age date for extremely young, potassium poor rocks located in a geothermal regime are subject to question and although the age dates presented in Table 2 and Figure 7 are considered reliable, this issue should be tabled until the paleomagnetic studies have been completed and the K-Ar age dates have been verified.

CORE HOLE N-3

Core hole GEO N-3 was drilled at a surface elevation of 1,753 m on the north flank of the volcano at a distance of 12.6 km from the center of the volcano (see Figure 2). Of all of the Newberry core holes, GEO N-3 is the most distant from the center of the volcano. Heat flow from GEO N-3 is 86 mWm^{-2} based on a least squares fit to the temperature-depth data over the thermally conductive region between 1,170 and 1,220 meters and nine (9) measurements of thermal conductivity representing the same interval (Table 1). This value is typical of heat flow values found throughout the non-geothermal areas of the Cascade Range [Blackwell and Steele, 1987] and, therefore, does not indicate the presence of an exploitable geothermal resource. This core hole, located 12.6 km from the center of the volcano, apparently constrains the radial extent of the major geothermal system associated with the core of Newberry Volcano. If geothermal resources are to be located at such large distances from the center of the volcano, they must be associated with heat sources which are separate from the main volcanic heat source.

Geophysical Logging Program

As in core hole GEO N-1, the integrity of core hole GEO N-3 forced modifications to the geophysical logging program. Specifically, at a depth of about 520 m the rods became stuck in the core hole and were cemented in place, causing a reduction in hole size. To compound the problem, the induction tools and gamma-ray tools, required to penetrate the smaller diameter hole all failed. The gamma-ray log was recovered from the surface to total depth, since this log could be run through the completion tubing, but the induction log was lost. The temperature log and the neutron density log were also run from surface to total depth but the caliper log and BHC acoustic fraclog could only be run from 520 m to total depth. The casing schematic for core hole, GEO N-3 is shown in Figure 9.

Depth To Water Table

The depth to the regional water table is just as elusive as in GEO N-1. The standing water level in the core hole as estimated by the drillers ranges from about 455 to 565 m with a modal value of 525 m. Thus, the water table may well lie close to, and perhaps exactly at, the depth at which the drilling problems were encountered which forced the cementing of the rods in place. Therefore, the failure of the geophysical logs to clearly reveal the water table may well result from the complicating effects of the metal rods and the cement.

The Temperature Log

The final temperature log for core hole GEO N-3 is shown in Figure 10 and compared with other data sets in Figure 9. A composite of all temperature logs measured in this core hole is presented in Figure 11. At first glance, the final temperature log appears to differ significantly from the corresponding log for core hole GEO N-1 (Figure 3). Closer examination, however, reveals that the two logs contain the same basic elements. Specifically, like GEO N-1, core hole GEO N-3 is isothermal to the water table and probably beyond, it has a thermally conductive zone near the bottom, and the isothermal and conductive zones are separated by a transition region exhibiting considerable hydrologic disturbance.

The interval between the upper isothermal and lower conductive sections of core hole GEO N-3 is a complicated region because it represents two separate and overlapping patterns of groundwater circulation, one of which was induced by drilling operations. Several obvious features of the temperature log are the rapid buildup of temperature at about 580 to 610 m, the smaller temperature buildup at about 1,160 m, and the interval between them which is very nearly isothermal at 52°C. These observations are the result of artesian water ascending the annulus of the core hole. Geothermal fluids under artesian pressure appear to enter the core hole at a depth of about 1,160 m. This same depth is charactered by a significant washout as observed on the caliper log (Figure 9) and also by a thermal pulse as detected by the maximum recording thermometers (MRTs) which were run into the core hole during pauses in the drilling operations (Figure 11). The geothermal fluids appear to exit the core hole annulus at a depth of about 575 to 585 m. This zone is a major washout area as shown by the caliper log (Figure 9). It is significant that the ascending geothermal fluids seem to ignore the numerous washouts throughout the core hole interval 610 to 1,100 m (Figure 9) and choose instead to exit the core hole annulus at a washout located at or near the regional water table estimated at about 455 to 564 m. If a man-induced vertical conduit such as a core hole will cause artesian fluids to rise and spread laterally near the water table, it might be expected that a natural conduit such as a vertical fracture might also cause the same phenomenon. If so, geothermal fluids migrating laterally near the water table are likely to promote hydrothermal alteration, reduce the mechanical strength of the rocks, and help explain why there seem to be difficult drilling conditions coincident with the water table.

The remaining unexplained feature of the GEO N-3 temperature log is the nature of the thermal regime which existed before the artesian breakthrough. The germane data are the temperatures taken during drilling by maximum recording thermometers (MRTs, Figures 9 and 11). As was the case for GEO N-1, these temperatures showed no tendency to increase near the water table and in fact, readings did not exceed ambient temperatures until a depth of about 935 m. On this basis, it is suggested that the rain curtain extends to an approximate depth of 915 to 975 m at which point the section becomes significantly more potassic as indicated by the gamma ray and lithologic logs (Figures 9 and 12). Having the rain curtain extend to a signficant depth below the water table is supported by the close association between washouts as depicted by the caliper log and small temperature anomalies measured by the MRTs during drilling operations. Careful inspection of Figure 9 shows that below 915 m, the MRT readings taken at or near the washouts are slightly but consistently elevated relative to the remaining MRT values: as if thermal fluids were moving through these horizons. Above 915 m no such correlation exists. If the washouts above 915 m represent horizons which permit lateral flow of groundwater, it is not thermal fluid that is migrating through these horzions but rather cold, descending groundwater, i.e., the rain curtain. As a final comment for those researchers who prefer to associate the rain curtain with the region above the water table, it can be noted that an upward extrapolation of temperature from the thermally conductive region, intersects the mean annual air temperature at a depth which is not incompatible with the water table.

Ages Dates

The seven K-Ar age dates from core hole GEO N-3, range from 0.1 to 1.5 Ma and are presented in Figure 13 and Table 2. These dates are similar to those measured in core hole GEO N-1 (Figure 7) and throughout the volcano (Figure 2). There is also a tendency for the age dates to increase with depth although the date of 1.5 Ma at 324 m is contrary to this trend.

Chemistry of Formation Fluids

During the drilling operations for core hole GEO N-3, fluid samples were systematically collected from the core hole for routine chemical analyses. As was the case for GEO N-1, these samples were not collected to provide reliable geochemical data of formation fluids, but rather to try to detect the presence of geothermal fluids and any associated chemical species that may require special treatment during eventual production. The results of silica concentration, a typical indicator of geothermal fluid, is shown as a function of depth in Figure 14. As shown in Figure 14, the bottom four (4) samples, which were collected from depths below 1,050 m, are greatly enriched in silica relative to samples taken at other depths and this enrichment reflects the strong presence of geothermal fluids near the bottom of the core hole. Vertical zonation of the silica content of fluids sampled from GEO N-3 is an interesting feature of the core hole that may relate directly to the depth of the rain curtain. To examine the phenomenon further, a composite of all anomalous chemical constituents was prepared and their distribution with depth was plotted in histogram form (Figure 15). Also shown in Figure 15 is a histogram of sample depth and a comparison of the two histograms should reveal the depths at which the anomalous chemical constituents are located. As can be seen in Figure 15, the anomalous constituents are found primarily below the arbitrary depth of 915 m and reflect the presence of geothermal fluids below this depth. Above 915 m, nearly all samples collected are depleated in almost every chemical constituent analyzed and these samples are thought to represent the cold descending groundwater of the rain curtain. A comparison of the data in Figure 15 with that in Figures 9 and 11 shows the anticipated result that the depths at which the chemically anomalous (geothermal) fluids were sampled are precisely the same depths at which the highest temperatures were recorded during drilling operations. This almost trivial observation would probably not be worth reporting were it not for the important role played by the rain curtain in the exploration for and evaluation of geothermal resources.

SUMMARY

In the preceding sections, the data and some observations for two core holes on the flanks of Newberry Volcano, Oregon have been presented. Particular emphasis has been placed on the rain curtain with the purpose that a detailed discussion of this phenomenon at two discrete localities will lead to a better understanding of the physical processes in operation. It is further expected that the data will spark scientific debate and additional research on the rain curtain phenomenon, with emphasis directed towards surface geophysical techniques that can "see through" the rain curtain and provide valuable exploration information on the underlying geothermal reservoirs. Unfortunately, most geoelectric and geoelectromagnetic surveys to date have been strongly affected by smectite alteration which prevails at depths that are shallower than the geothermal reservoir (Figure 5; see also Fitterman and Neev, 1985; Wright and Neilson, 1986) Wright and Neilson [1986] have noted that "delineation of the high temperature (geothermal) system by electrical surveys may be difficult or impossible because of effects from altered rocks." While the problem is formidable, sufficient documentation has been provided that the rain curtain and the underlying geothermal systems are sufficiently different in their physical characteristics to justify continued search for a surface geophysical technique or a combination of techniques which will detect and provide information on geothermal systems, in spite of the complicating effects of the rain curtain and the smectite alteration. The goal is certainly worthwhile, since mile-deep core holes are rather expensive for reconnaissance exploration.

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TABLE 1

HEAT FLOW - NEWBERRY VOLCANO, OREGON

Depth Range (meters)	Gradient ($^{o}C/km$)	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Number of Samples	Heat Flow (mWm^{-2})
		GEO N-1		
1,164 - 1,177	122.7	1.76 ± 0.40	5	216
1,180 - 1,192	86.7	2.01	1	174
1,195 - 1,219	74.9	2.00 ± 0.08	6	150
			AVERAGE =	180
		GEO N-3		
1,172 - 1,220	54.3	1.59 ± 0.14	9	86

TABLE 2

K-Ar AGE DATES - NEWBERRY VOLCANO, OREGON

feet	Depth (meters)	Age (Ma)	Description
		GEO N-1	
1213	370	0.306 ± 0.075	Basaltic andesite
1578	481	0.027 ± 0.009	Basaltic andesite
1610	491	0.029 ± 0.081	Basaltic andesite
2299	701	0.090 ± 0.026	Basaltic intrusive
2375	724	0.847 ± 0.110	Basaltic andesite
2926	892	0.768 ± 0.147	Basalt
2995	913	0.746 ± 0.110	Basalt
3238	987	0.943 ± 0.053	Andesite
3261	994	0.997 ± 0.050	Andesite
3546	1,081	1.630 ± 0.13	Basaltic andesite
		GEO N-3	
1062	324	1.50 + 0.63	Phyric basalt
	594	0.911 + 0.188	Phyric basaltic andesite
	769	0.109 + 0.081	Lithic tuff
	853	0.819 + 0.113	Basalt
	1,010	1.04 + 0.03	Rhyodacitic flow
	1,100	1.54 + 0.05	Rhyodacitic flow
	1,207	1.18 + 0.30	Basalt

FIGURE CAPTIONS

FIGURE 1 Index map showing the location of Newberry Volcano in relation to the Oregon Cascades (stippled area).

FIGURE 2 Potassium Argon age dates (Ma) for surface samples at Newberry Volcano, Oregon. Data from Fiebelkorn, et al. [1982] are plotted as age dates with the plot point representing the decimal point. Two GEO determinations are presented with errors indicated. The location of the Newberry Flank Federal Geothermal Unit (area between the two boundaries), The Newberry Known Geothermal Resource Area (KGRA - inside the inner boundary), and the location of the two small lakes inside the crater are also shown.

FIGURE 3 Equilibrium temperature log for GEO N-1. Original data were collected (9/25/86) by D. D. Blackwell and R. E. Spafford and were measured at 2-m intervals with a precision of 0.01°C. Data plotted at 10-m intervals.

FIGURE 4 Summary of all temperature data below 500 m for GEO N-1. Plotted points labeled "1" represent maximum recording thermometers (MRTs) which were allowed to sit on bottom for roughly 10 minutes without circulation. Logs 2 through 4 were obtained by Geotech Data and represent discrete measurements at 3-m interval with a precision of 0.01°C. Log 5 is the same as that presented in Figure 3.

FIGURE 5 Comparison of GEO N-1 logs. From left to right: (1) the one dimensional geoelectric section determined from the surface measurements of Fitterman and Neev [1985] using transient geoelectromagnetic soundings (TS), (2) smectite alteration from Bargar and Keith [1986], (3) generalized electrical conductivity (see text for discussion), (4) generalized gamma ray log (see text for discussion), (5) the location of the SP anomaly, (6) mercury log (see Figure 6 for detail), (7) location of washouts below 500 m as determined by the caliper log, (8) the bottom part of the temperature log shown in Figure 3, and (9) the core hole completion. Note the unlogged section (conductivity log) which reflects the depth interval of difficult drilling conditions and also the relationship between the zone of rapid temperature buildup and anomalies in the other geophysical logs.

FIGURE 6 Generalized litholgic log and detailed rock mercury analyses for GEO N-1. The detection thresholds for the Cascadia and Bondar-Clegg analyses are 1 and 5 ppb, respectively.

FIGURE 7 Potassium-argon age dates from GEO N-1. Note the agreement with the surface data shown in Figure 2.

FIGURE 8 Silica content of fluids recovered from GEO N-1. Surface samples depicted as open symbols while downhole samples are shaded symbols. Note that all downhole samples are contaminated with drilling fluid.

FIGURE 9 Comparison of the temperature data from GEO N-3 with the generalized gamma ray log and the washouts as depicted by the caliper log. Note: (1) the relation between the large washout in the caliper log and the intermediate drill string (drill rods cemented in place) reflecting the difficult drilling conditions, (2) the anomalous temperatures measured during drilling (triangles) and the washouts at depths below 915 m, and (3) the washouts which allow the artesian fluids to enter and exit the annulus of the core hole. The detailed temperature log is reproduced in Figure 10. Core hole completion presented on the far right.

FIGURE 10 Detailed equilibrium temperature log of GEO N-3. Measurements were taken every 6 m with a precision of 0.01^{o}C by Geotech Data on 8/18/86. Data plotted at 10-m intervals.

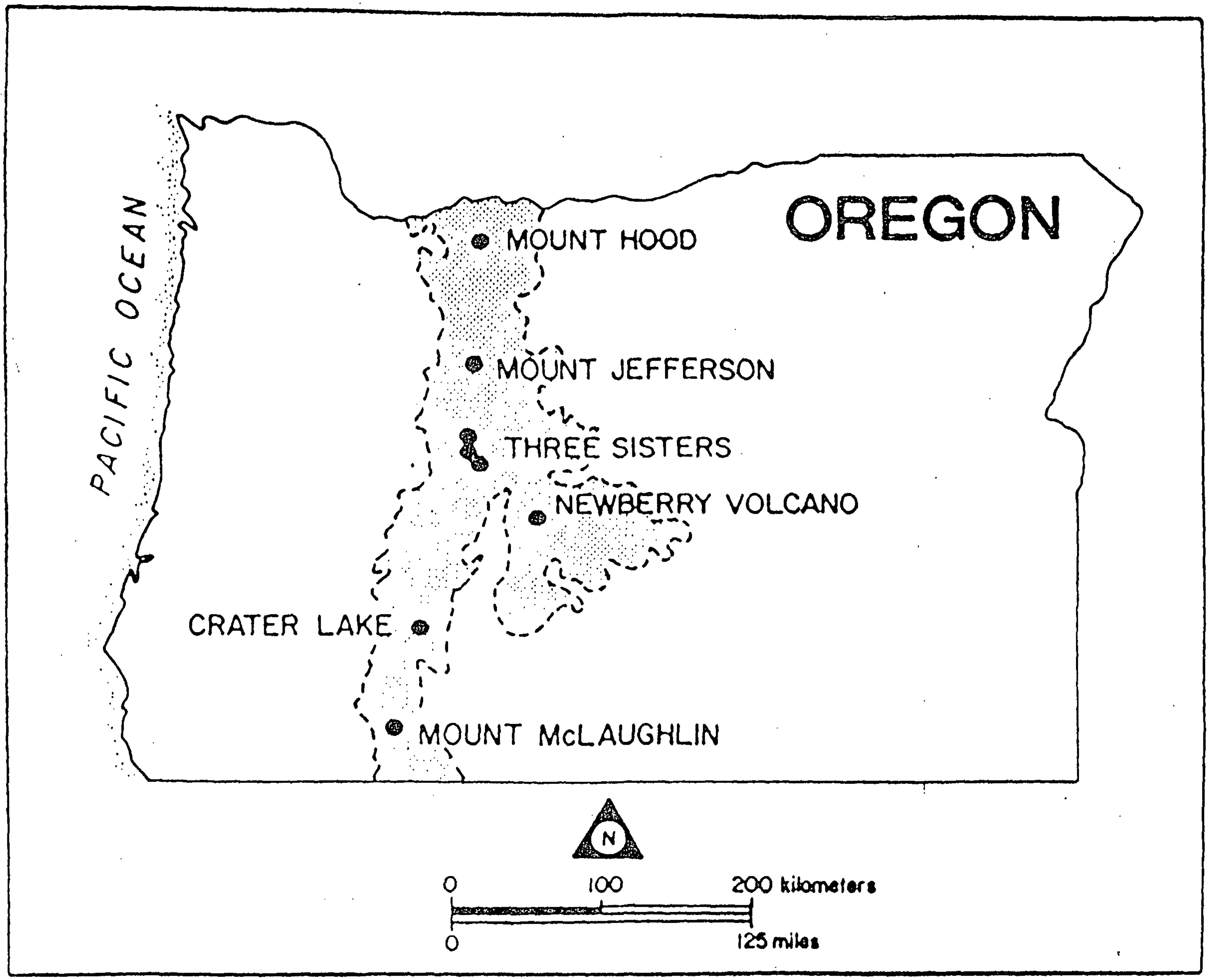
FIGURE 11 Summary of all temperature data obtained below 500 m in GEO N-3. Note the highest MRT temperature reading coincides with the artesian aquifer (compare Figure 9).

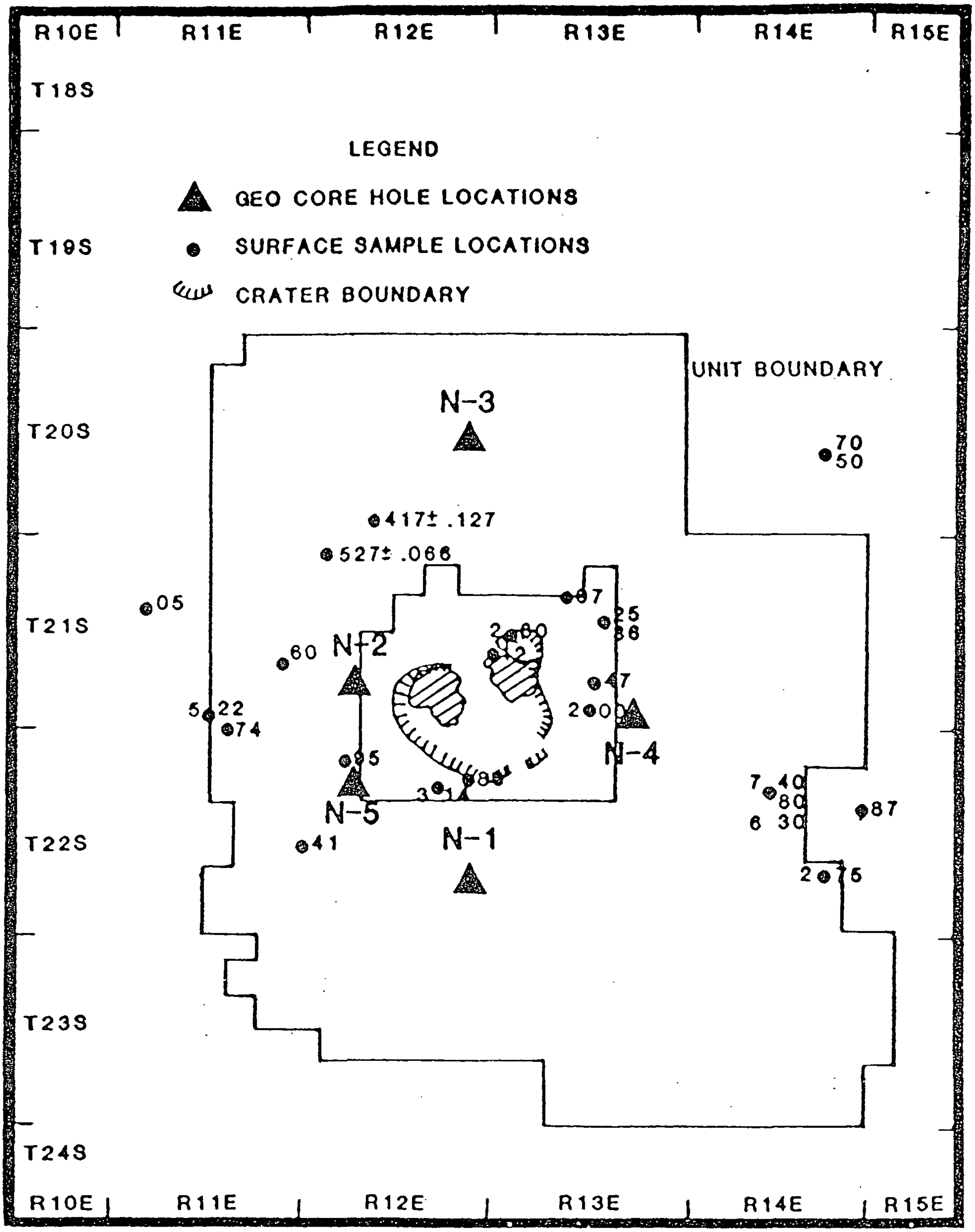
FIGURE 12 Thermal conductivity from GEO N-3. Note the generalized lithologic log shows a rhyodacitic flow unit centered at 1,100 m (compare Figure 9) and that the remainder of the core hole is essentially a series of basaltic andesite flows. Data from Geotech Data.

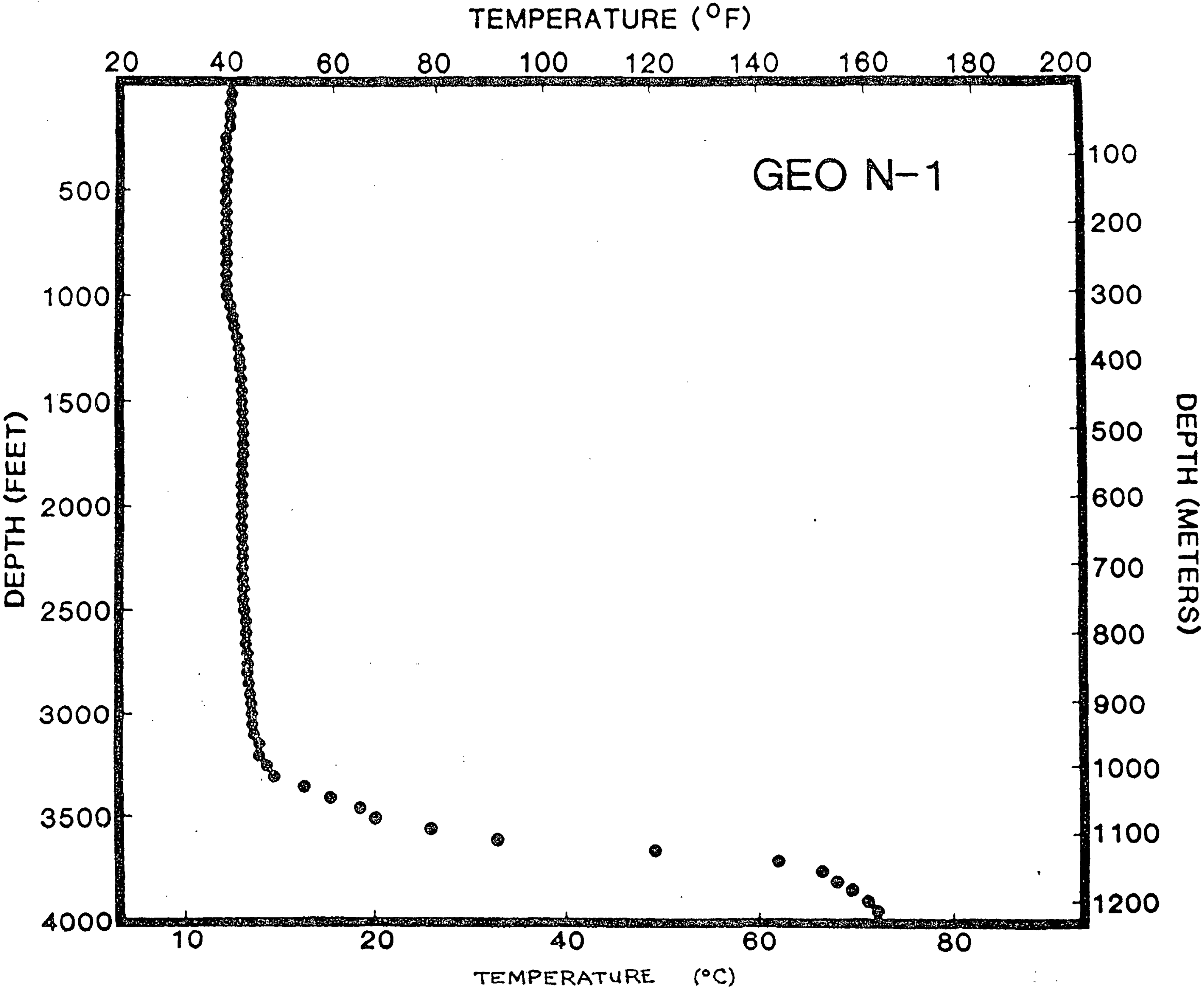
FIGURE 13 Potassium-argon age dates from GEO N-3. Note the agreement among these dates and those from GEO N-1 (Figure 7) and the surface samples (Figure 2).

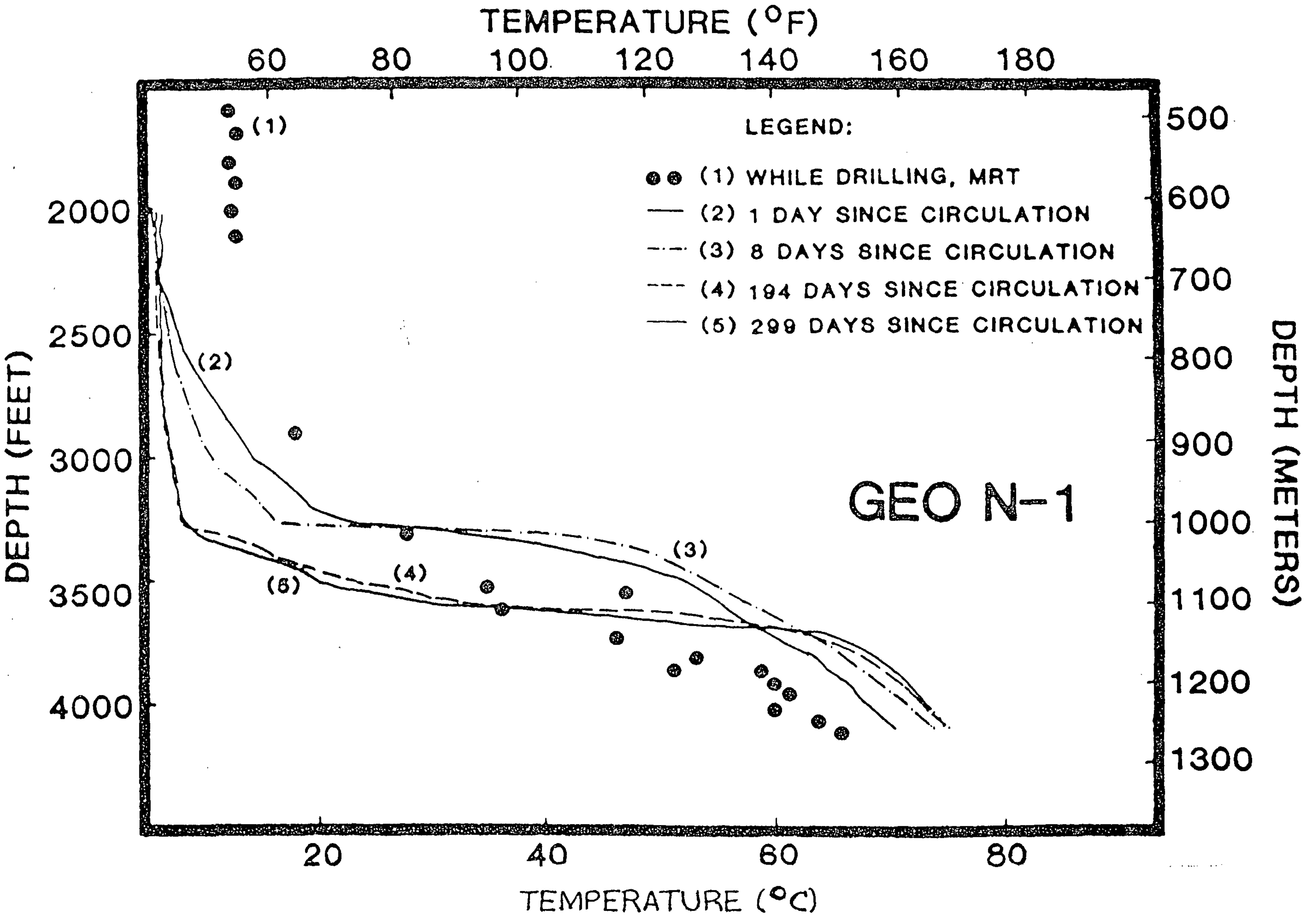
FIGURE 14 Silica content of fluids taken from GEO N-3. Note the increase in silica below 1,100 m and that all downhole samples are contaminated by drilling fluids.

FIGURE 15 Distribution of anomalous constituents of fluids taken at intervals of about 75 m from GEO N-3. Chemical species used in constructing this figure are Si, Hg, K, Al, Sr, B, and F. The highest 10% of each of the species are considered anomalous and their distribution plotted as a function of depth in histogram form. The shaded area reflects the depth distribution of sample depths. The difference between the two should qualitatively reflect drilling fluids mixing with formation fluids. Note that effects of geothermal fluids are basically lacking above 915 m (compare with Figure 9).

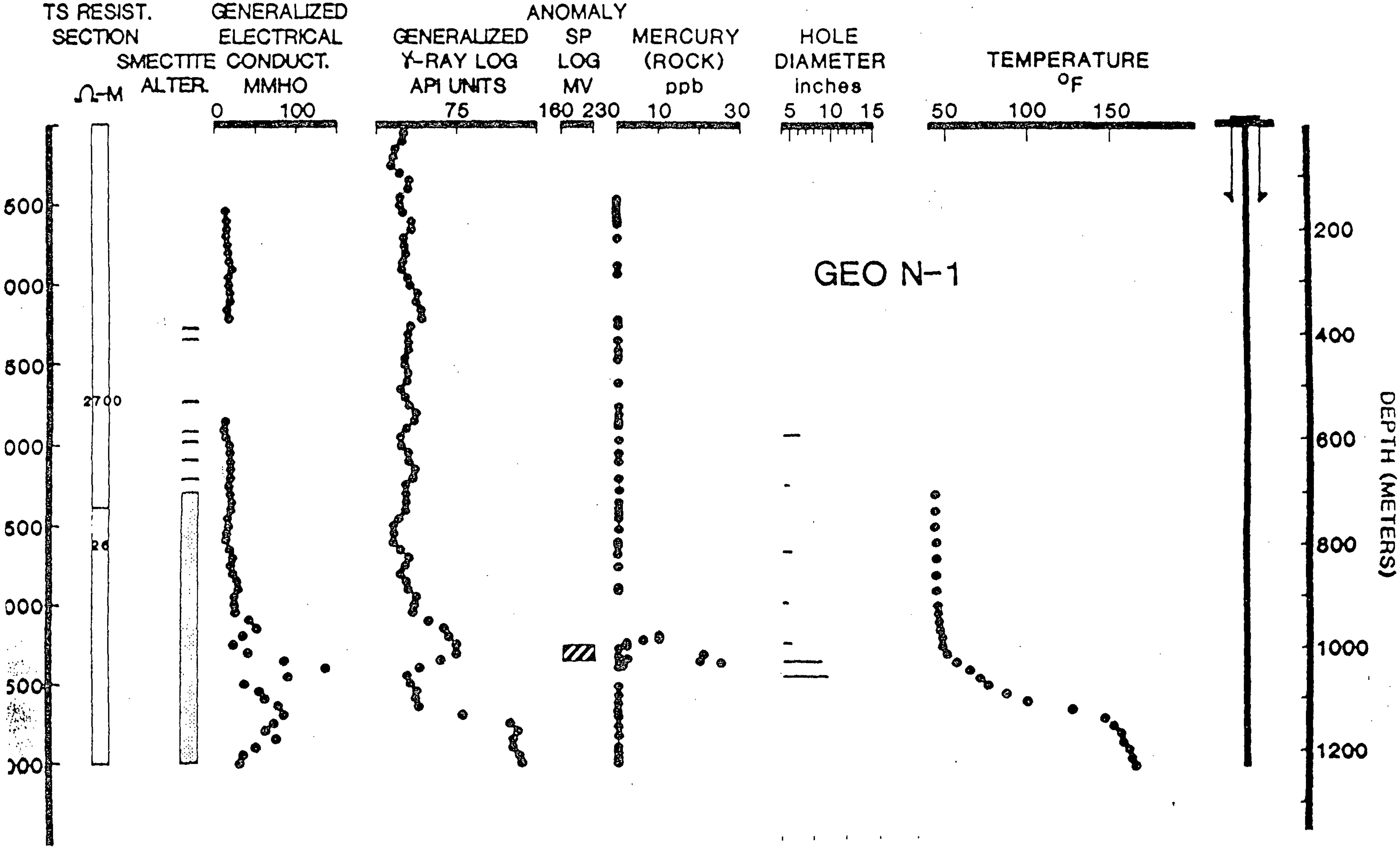

OREGON
PACIFIC OCEAN
MOUNT HOOD
MOUNT JEFFERSON
THREE SISTERS
NEWBERRY VOLCANO
CRATER LAKE
MOUNT McLAUGHLIN
N
0
100
200 kilometers
0
125 miles

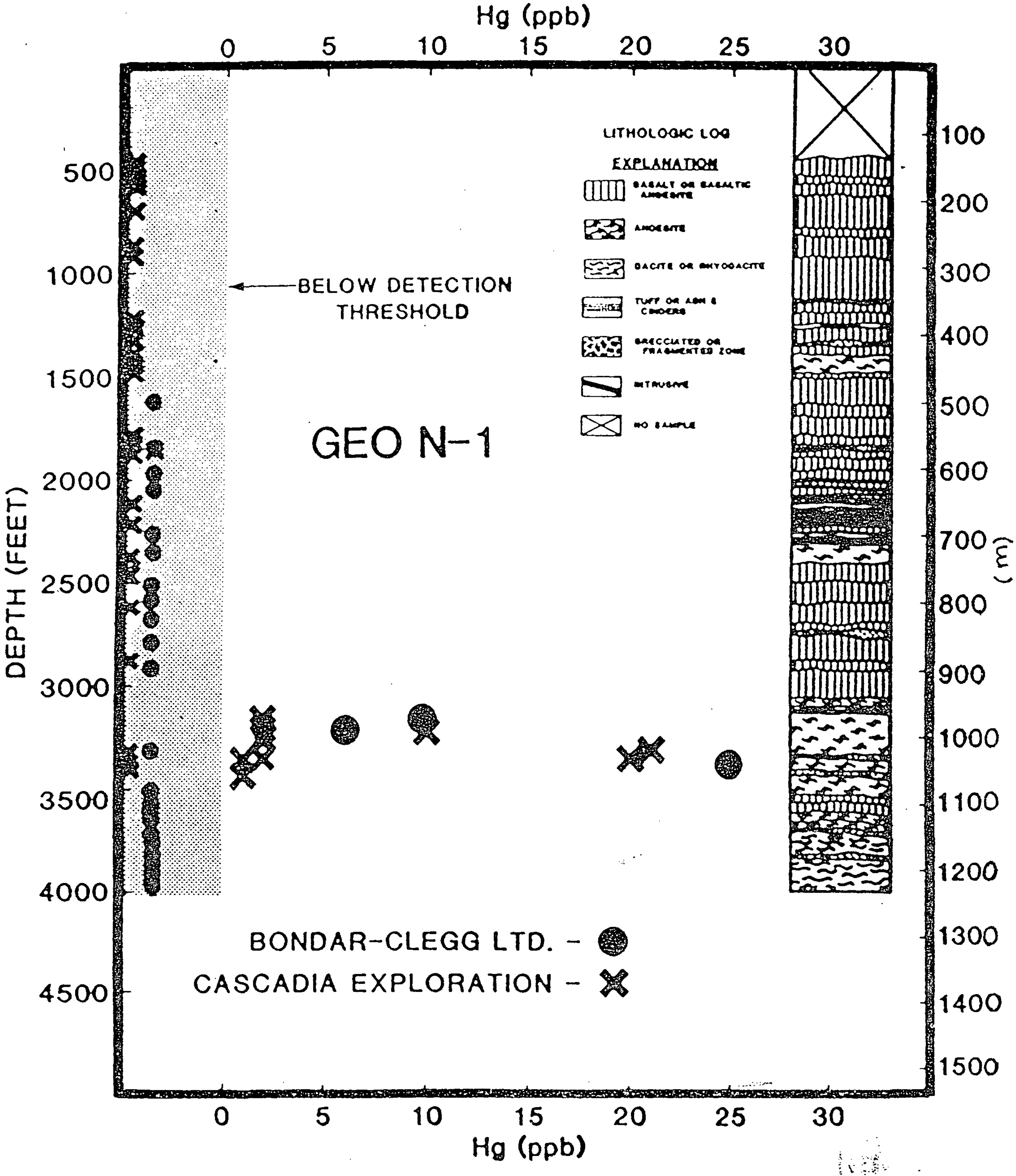

R10E
R11E
R12E
R13E
R14E
R15E
T18S
T19S
T20S
T21S
T22S
T23S
T24S
LEGEND
▲ GEO CORE HOLE LOCATIONS
● SURFACE SAMPLE LOCATIONS
CRATER BOUNDARY
UNIT BOUNDARY
N-3
N-2
N-5
N-1
N-4
.417± .127
.527± .066
.05
.60
.522
.74
.95
.41
.387
.25
.36
.280
.2
.47
.200
.331
.885
.70
.50
.740
.680
.630
.87
.275
R10E
R11E
R12E
R13E
R14E
R15E

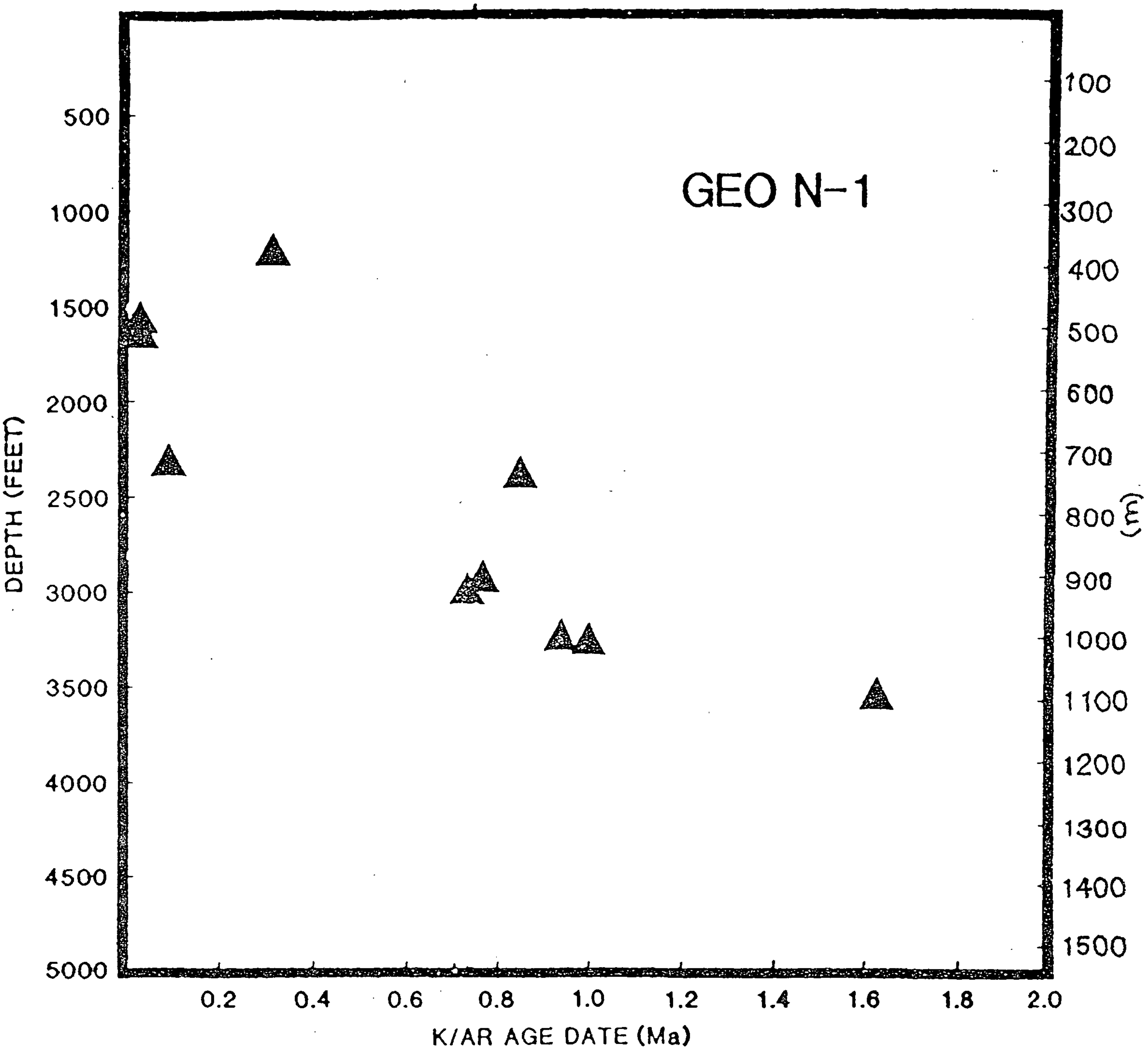

TEMPERATURE (°F)
20
40
60
80
100
120
140
160
180
200
GEO N-1
DEPTH (FEET)
500
1000
1500
2000
2500
3000
3500
4000
DEPTH (METERS)
100
200
300
400
500
600
700
800
900
1000
1100
1200
10
20
40
60
80
TEMPERATURE (°C)

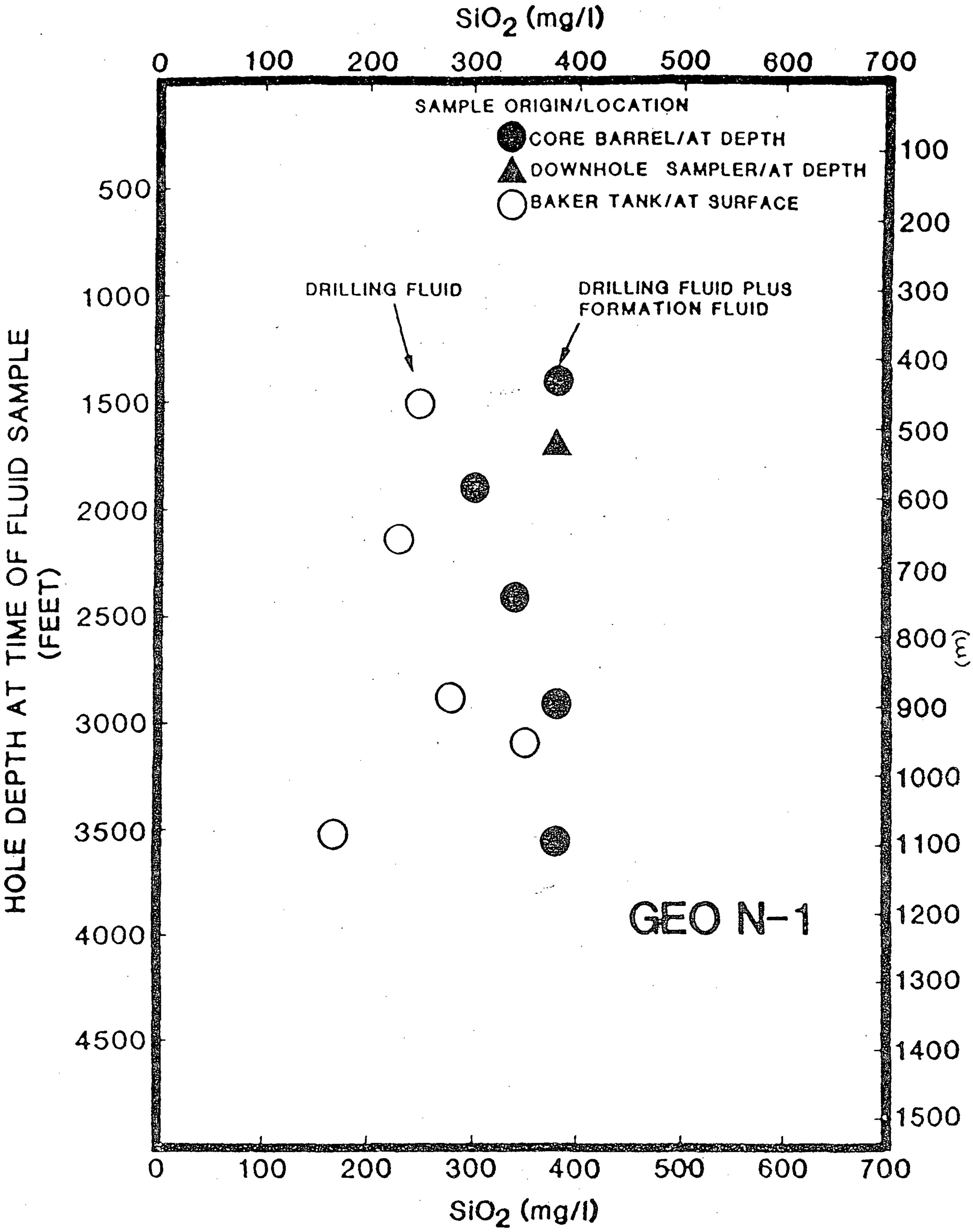

TEMPERATURE (°F)
60
80
100
120
140
160
180
LEGEND:
●● (1) WHILE DRILLING, MRT
(2) 1 DAY SINCE CIRCULATION
(3) 8 DAYS SINCE CIRCULATION
(4) 194 DAYS SINCE CIRCULATION
(5) 299 DAYS SINCE CIRCULATION
(1)
(2)
(3)
(4)
(5)
GEO N-1
DEPTH (FEET)
2000
2500
3000
3500
4000
DEPTH (METERS)
500
600
700
800
900
1000
1100
1200
1300
20
40
60
80
TEMPERATURE (°C)

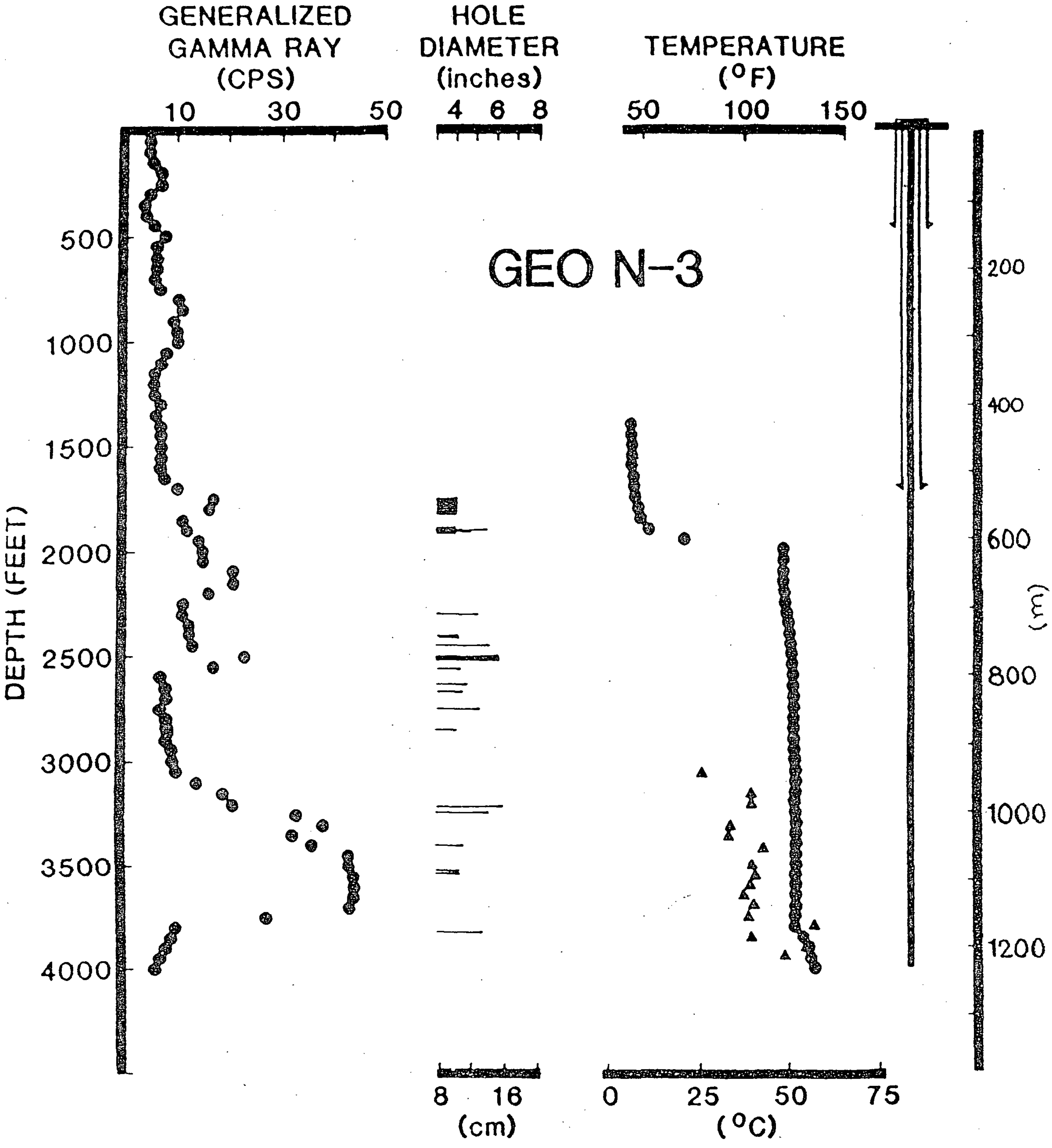
4

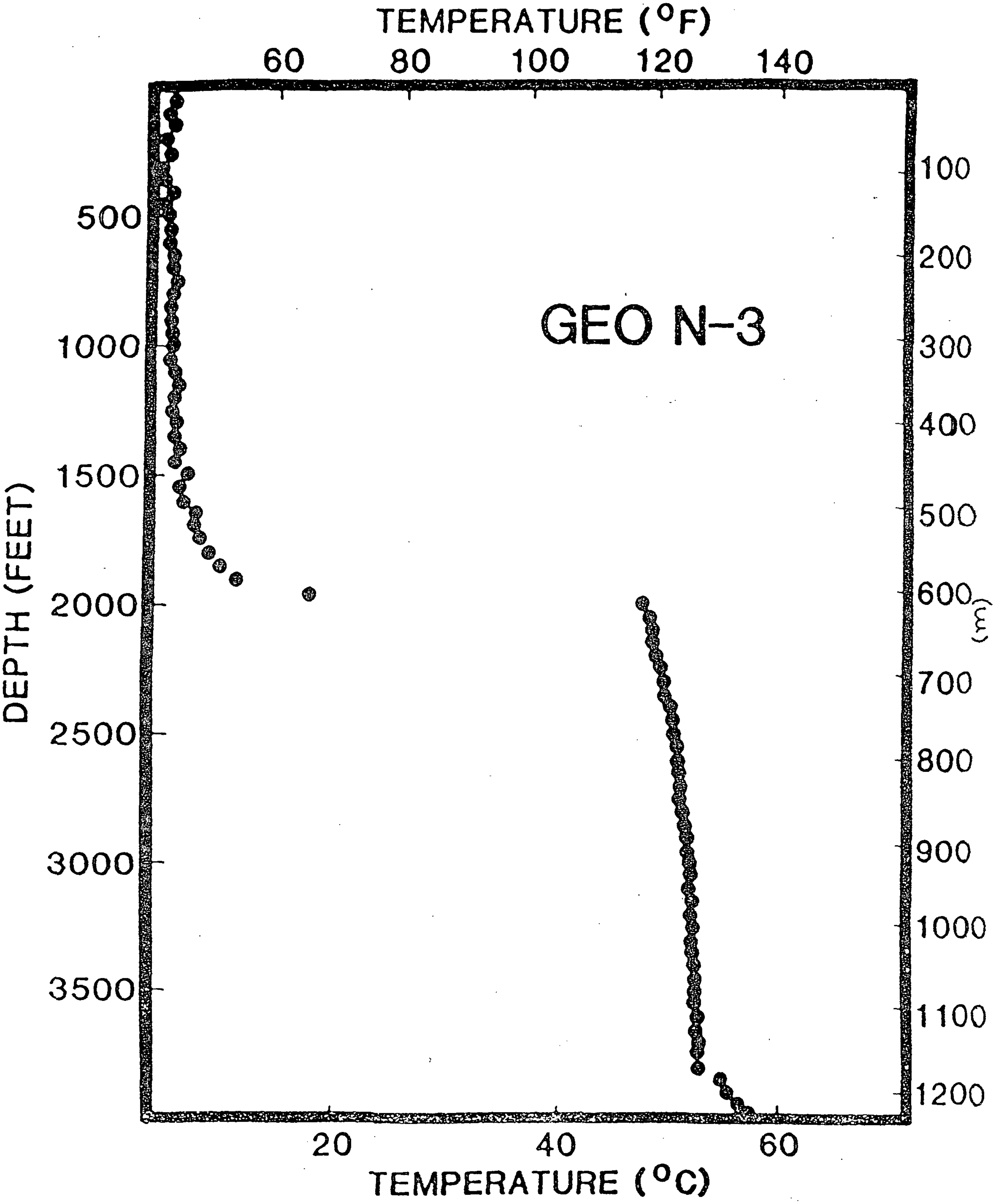

TS RESIST. SECTION
Ω-M
SMECTITE ALTER.
GENERALIZED ELECTRICAL CONDUCT. MMHO
0
100
GENERALIZED Y-RAY LOG API UNITS
75
ANOMALY SP LOG MV
160
230
MERCURY (ROCK) ppb
10
30
HOLE DIAMETER inches
5
10
15
TEMPERATURE °F
50
100
150
GEO N-1
2700
26
500
000
500
000
500
000
500
000
200
400
600
800
1000
1200
DEPTH (METERS)

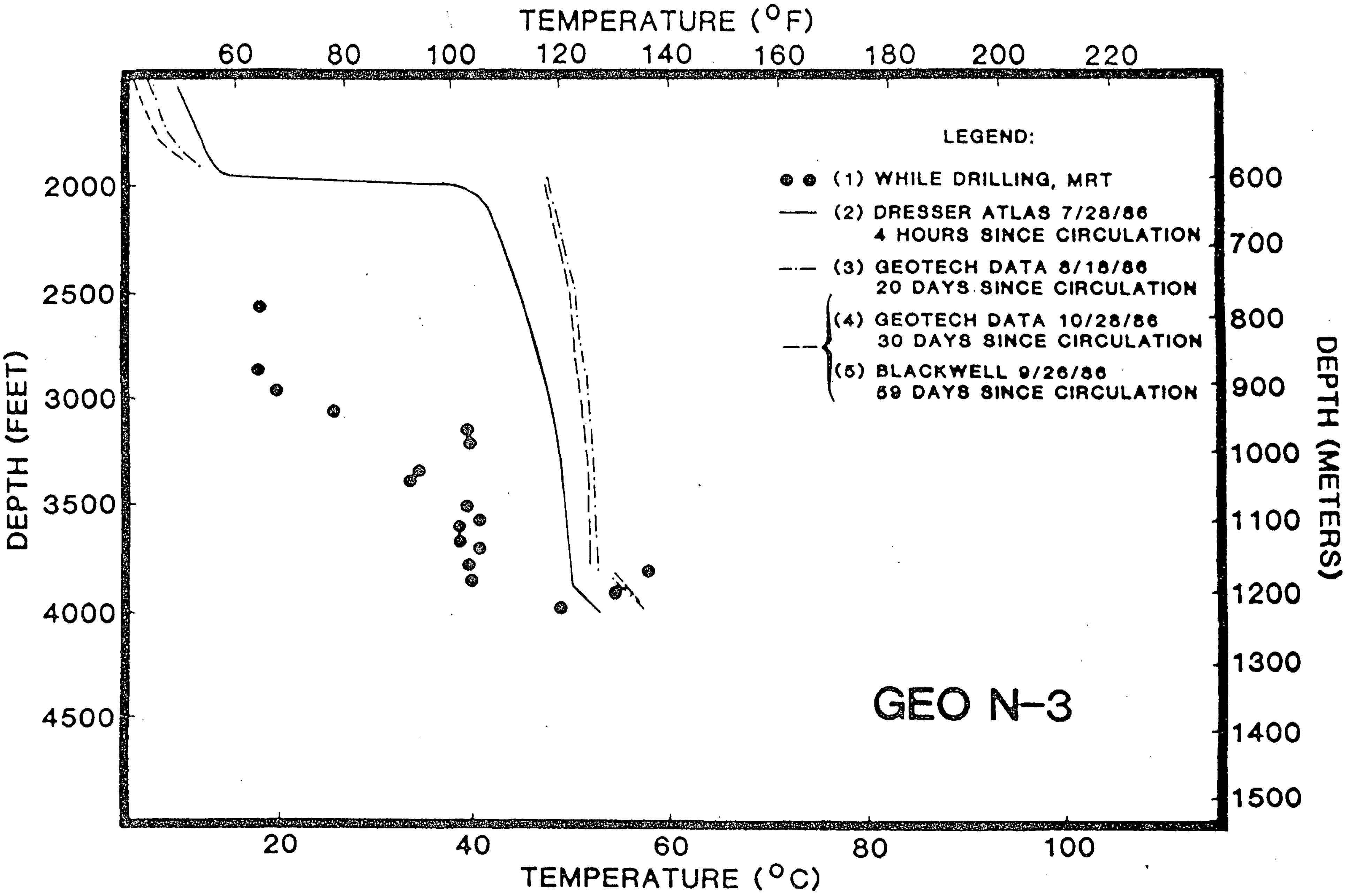
Hg (ppb)
0
5
10
15
20
25
30
DEPTH (FEET)
500
1000
1500
2000
2500
3000
3500
4000
4500
(m)
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
BELOW DETECTION THRESHOLD
GEO N-1
LITHOLOGIC LOG
EXPLANATION
BASALT OR BASALTIC ANDESITE
ANDESITE
DACITE OR RHYODACITE
TUFF OR ASH & CINDERS
BRECCIATED OR FRAGMENTED ZONE
INTRUSIVE
NO SAMPLE
BONDAR-CLEGG LTD. - ●
CASCADIA EXPLORATION - ✕

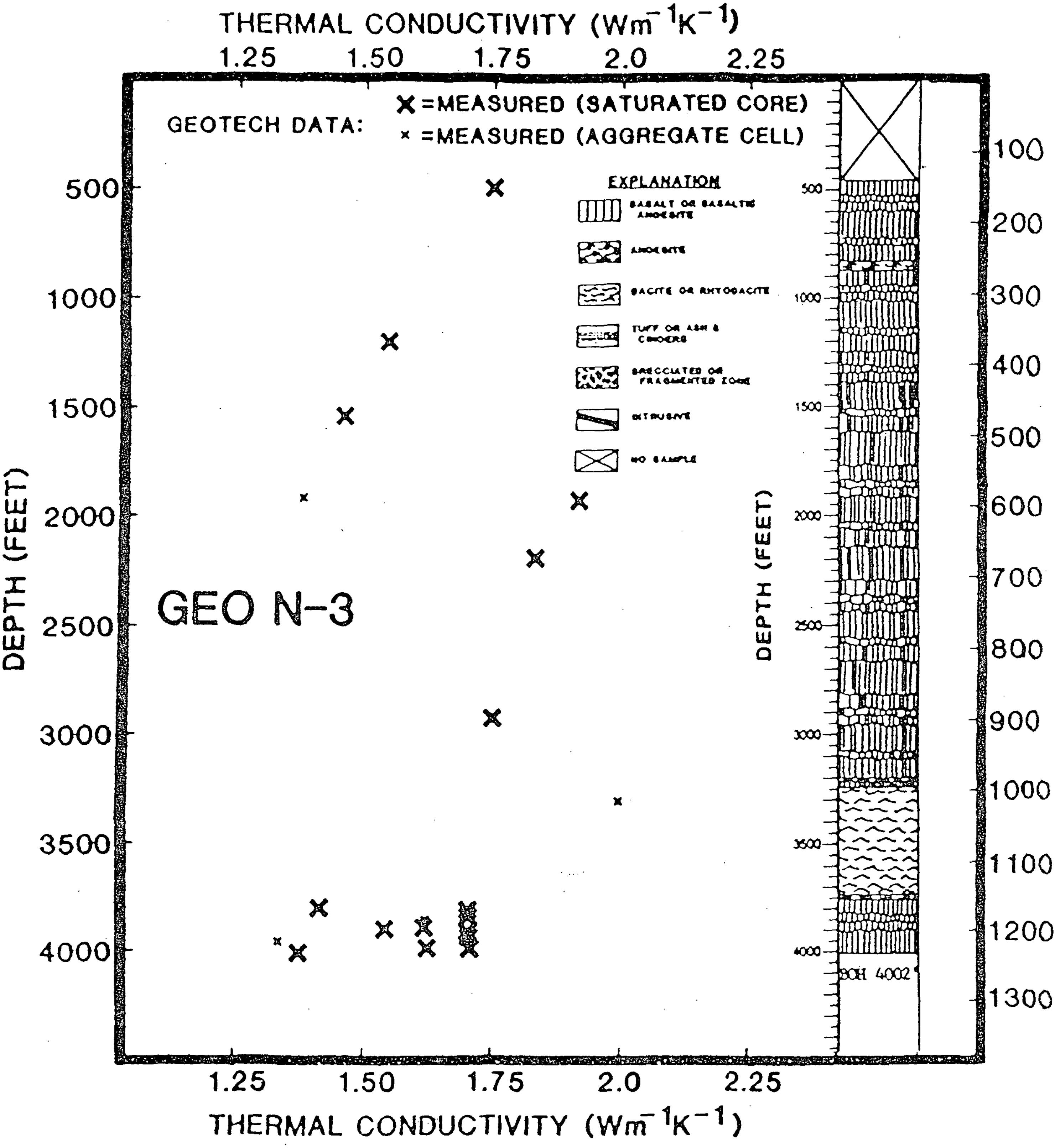

GEO N-1
DEPTH (FEET)
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
(m)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
K/AR AGE DATE (Ma)


SiO2 (mg/l)
0
100
200
300
400
500
600
700
SAMPLE ORIGIN/LOCATION
● CORE BARREL/AT DEPTH
▲ DOWNHOLE SAMPLER/AT DEPTH
○ BAKER TANK/AT SURFACE
DRILLING FLUID
DRILLING FLUID PLUS FORMATION FLUID
GEO N-1
HOLE DEPTH AT TIME OF FLUID SAMPLE (FEET)
500
1000
1500
2000
2500
3000
3500
4000
4500
(m)
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500

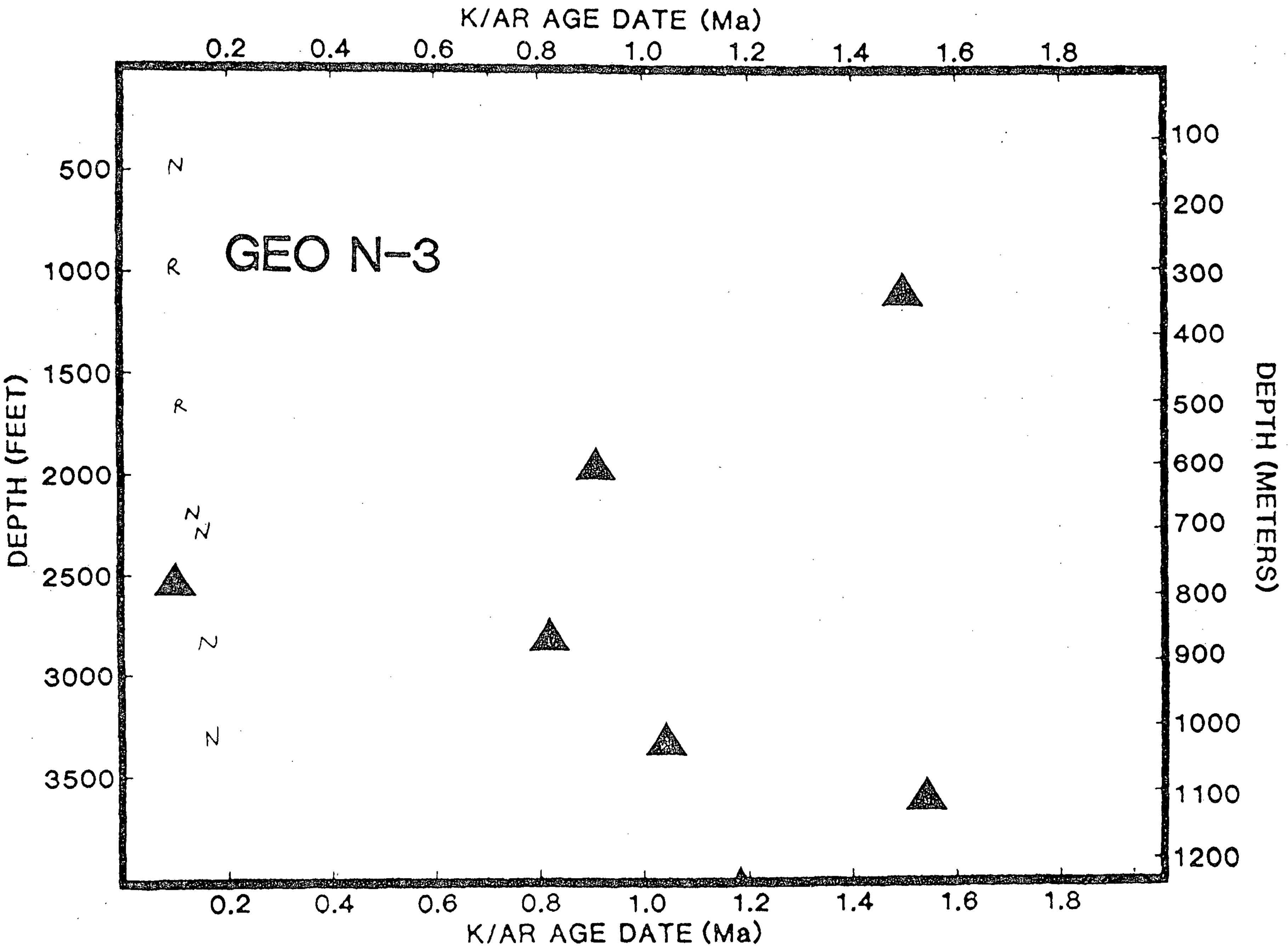

GENERALIZED GAMMA RAY (CPS)
10
30
50
HOLE DIAMETER (inches)
4
6
8
TEMPERATURE (°F)
50
100
150
GEO N-3
DEPTH (FEET)
500
1000
1500
2000
2500
3000
3500
4000
8
16
(cm)
0
25
50
75
(°C)
200
400
600
800
1000
1200
(m)

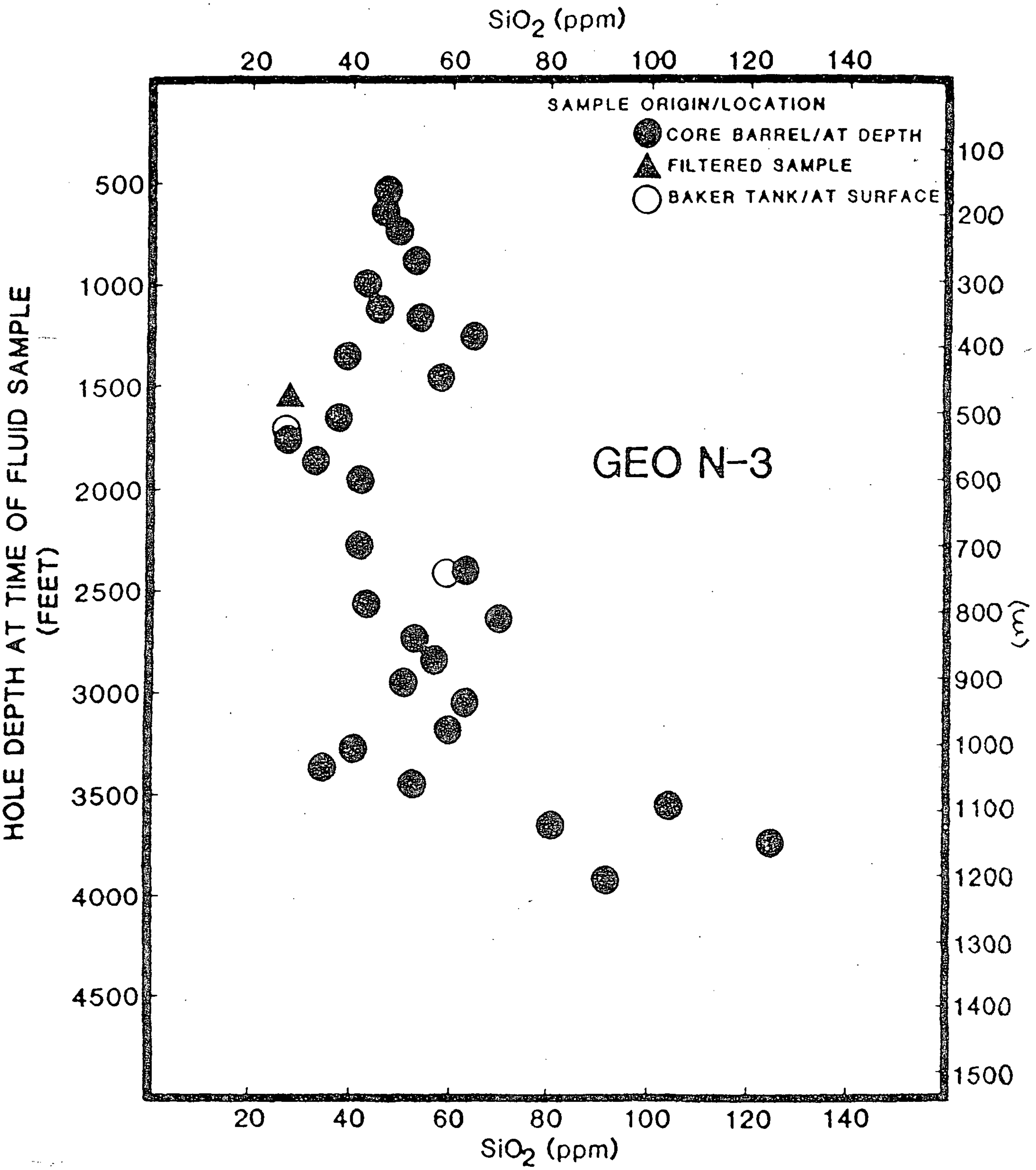

TEMPERATURE (°F)
60
80
100
120
140
GEO N-3
DEPTH (FEET)
500
1000
1500
2000
2500
3000
3500
100
200
300
400
500
600
700
800
900
1000
1100
1200
(m)
20
40
60
TEMPERATURE (°C)

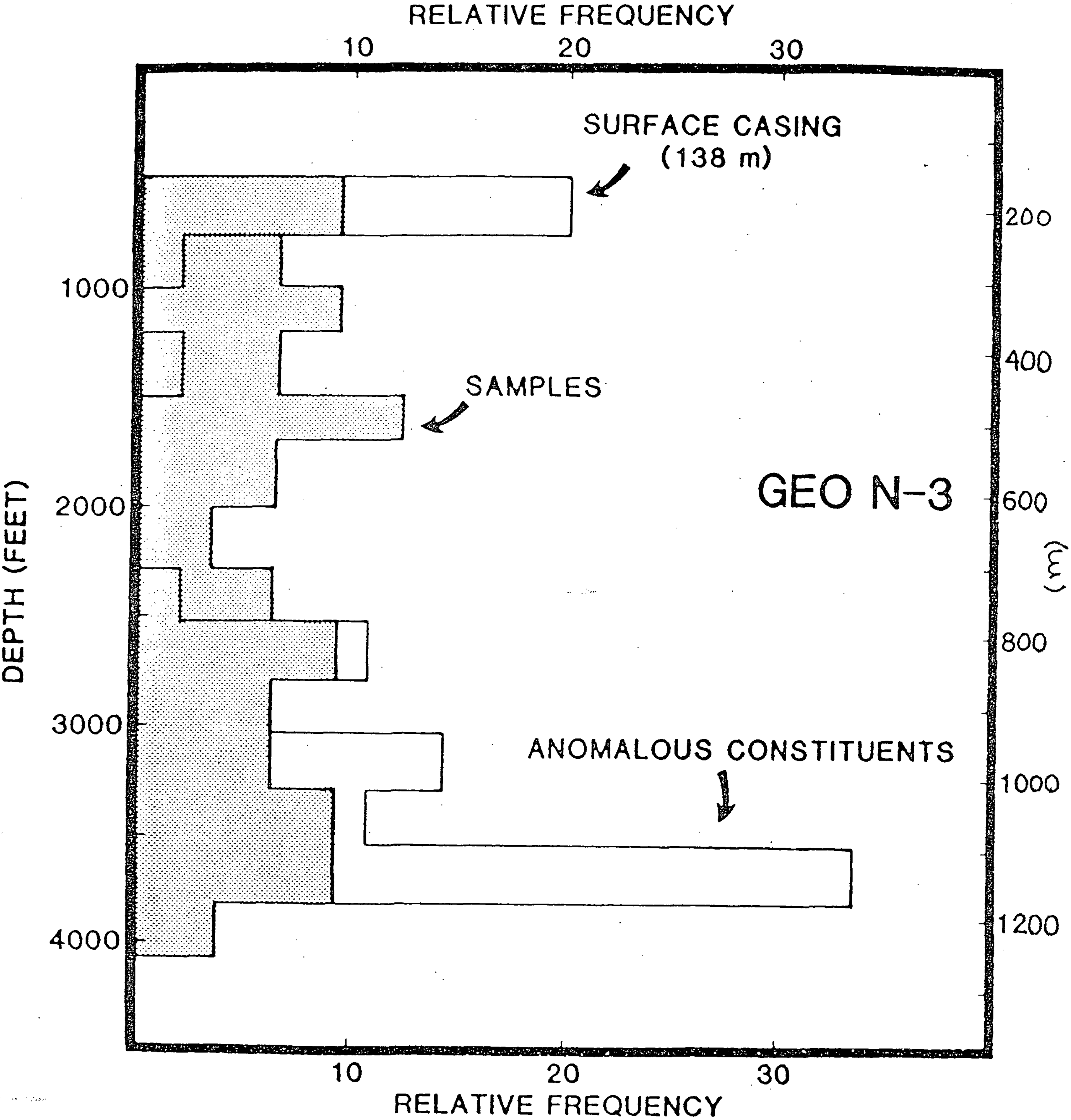

TEMPERATURE (°F)
60
80
100
120
140
160
180
200
220
LEGEND:
●● (1) WHILE DRILLING, MRT
—— (2) DRESSER ATLAS 7/28/86
4 HOURS SINCE CIRCULATION
—·— (3) GEOTECH DATA 8/18/86
20 DAYS SINCE CIRCULATION
(4) GEOTECH DATA 10/28/86
30 DAYS SINCE CIRCULATION
– – (5) BLACKWELL 9/26/86
59 DAYS SINCE CIRCULATION
GEO N-3
DEPTH (FEET)
2000
2500
3000
3500
4000
4500
DEPTH (METERS)
600
700
800
900
1000
1100
1200
1300
1400
1500
20
40
60
80
100
TEMPERATURE (°C)


THERMAL CONDUCTIVITY (Wm⁻¹K⁻¹)
1.25
1.50
1.75
2.0
2.25
GEOTECH DATA:
X =MEASURED (SATURATED CORE)
× =MEASURED (AGGREGATE CELL)
EXPLANATION
BASALT OR BASALTIC ANDESITE
ANDESITE
DACITE OR RHYODACITE
TUFF OR ASH & CINDERS
BRECCIATED OR FRAGMENTED ZONE
INTRUSIVE
NO SAMPLE
DEPTH (FEET)
500
1000
1500
2000
2500
3000
3500
4000
GEO N-3
DEPTH (FEET)
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
BOH 4002
1.25
1.50
1.75
2.0
2.25
THERMAL CONDUCTIVITY (Wm⁻¹K⁻¹)

F12


K/AR AGE DATE (Ma)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
DEPTH (FEET)
500
1000
1500
2000
2500
3000
3500
DEPTH (METERS)
100
200
300
400
500
600
700
800
900
1000
1100
1200
GEO N-3
N
R
R
N
N
N
N
K/AR AGE DATE (Ma)


SiO2 (ppm)
20
40
60
80
100
120
140
SAMPLE ORIGIN/LOCATION
● CORE BARREL/AT DEPTH
▲ FILTERED SAMPLE
○ BAKER TANK/AT SURFACE
GEO N-3
HOLE DEPTH AT TIME OF FLUID SAMPLE (FEET)
500
1000
1500
2000
2500
3000
3500
4000
4500
(m)
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
20
40
60
80
100
120
140
SiO2 (ppm)


RELATIVE FREQUENCY
10
20
30
SURFACE CASING
(138 m)
SAMPLES
GEO N-3
ANOMALOUS CONSTITUENTS
DEPTH (FEET)
1000
2000
3000
4000
200
400
600
(m)
800
1000
1200
10
20
30
RELATIVE FREQUENCY