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GEOLOGIC AND HYDROLOGIC RESEARCH ON THE MOANA GEOTHERMAL SYSTEM WASHOE COUNTY, NEVADA

Final Report

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ABSTRACT

Combined geologic, geophysical, geochemical, and drilling exploration surveys were used to assess the Moana geothermal resource in Washoe County, Nevada, and to determine its relationship with nearby Steamboat Hot Springs. Moana is the largest single moderate-temperature resource in Nevada that supports geothermal space heating applications. Results show that the general geology and structure for the two systems is similar, but important differences exist with respect to reservoir rocks. Gravity data delineated the contact between important volcanic and sedimentary rocks in Moana, but contour trends did not correlate well with mapped faults. Fluid geochemistry data show major differences in bulk chemical composition, stable-light isotope ratios, and radiocarbon ages for Moana and Steamboat geothermal waters. Water level measurements in observation wells in Moana show simultaneous increasing and decreasing values in different sections of the geothermal area. Temperature-depth profiles changed little during the six-month monitoring period. Direct use of the resource is increasing and longer-lasting, more efficient down-hole heat exchangers are replacing previous equipment that was prone to scaling and corrosion. A computer program that calculates heat output for state-of-the-art heat exchangers is described. Recommendations for continued monitoring, heat exchanger design, and fluid reinjection studies are included. Data are available to government agencies responsible for regulation as well as local residents and potential developers to ensure prudent resource utilization.

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EXECUTIVE SUMMARY

This research program was formulated to assess the Moana geothermal resource and to make recommendations for prudent development. Resource assessment was based on geologic, geophysical, and geochemical exploration techniques that have been successfully employed in geothermal areas throughout the western United States. Recommendations for prudent development were made on the basis of resource characteristics, engineering principals, and legal and environmental issues.

Geologic investigations revealed two formations that represent the key to understanding the Moana geothermal resource. Most geothermal wells are completed in the Kate Peak andesite, which has been hydrothermally altered to a smectite clay, known locally as the "blue clay." The Sandstone of Hunter Creek overlies the andesite north and west of the principal development in Moana. Both the Kate Peak Formation and the Sandstone of Hunter Creek have been penetrated and displaced by north-trending faults that range in age from early to mid-Pleistocene (1 million to 100,000 years BP). Prior to this study, these faults were believed to be the principal conduits for thermal fluid migration, and drillers reported higher temperatures and permeabilities in fault zones. It is now clear that the stratigraphic contact between the Kate Peak Formation and the overlying Sandstone of Hunter Creek is an equally important controlling structure for fluid migration. In fact, wells recently completed in this area encountered water temperatures in excess of 100°C (212°F). These high temperatures, and reported high flow rates, were encountered at depths of approximately 400 m (1200 ft.). In these cases, the resource is used to heat more than one home. The extra cost of drilling a single deep well is balanced by the increased number of homeowners who can share the expense and benefit from lower heating bills. Present development in this area includes closely-spaced single family residences as well as apartments and condominiums. These factors favor the creation of small-scale geothermal space heating districts from a single well.

A gravity survey was conducted in the Moana area and south to Steamboat Hot Springs to delineate some of the basement structures and to determine the lateral extent of the Moana geothermal reservoir. The most significant structure observed in the gravity data is the sharp contact between the Kate Peak andesite and the Sandstone of the Hunter Creek. This sharp contact correlates well with a northeast trending fault as well as some of the highest temperature wells in Moana. In addition, the gravity data suggest that the Moana geothermal area is structurally isolated from Steamboat Springs, 12 miles south, by an irregularly-shaped block of andesite that trends east/west across the Truckee Meadows. This andesite block acts like the rim of a basin or sink; there are no reports of thermal wells within this block which is the effective southern boundary of the Moana geothermal area.

Although one major fault was identified in the gravity data, smaller faults with little or no vertical offset could not be identified because of lack of resolution with the survey equipment. The data agree with drill-hole data in the north-western portion of Moana and suggest that the Sandstone of Hunter Creek may attain a thickness in excess of 450 m (1500 ft.).

Chemical analyses of fluids throughout the Truckee Meadows revealed three major fluid groups: a low-temperature calcium-bicarbonate meteoric water; a sodium-sulfate rich thermal water, which is characteristic of Moana geothermal fluids, but occurs throughout the northern Truckee Meadows where hydrothermally altered volcanic rocks are exposed; and sodium-chloride rich fluids associated with the high-temperature geothermal resource at Steamboat Hot Springs. Significant mixing of thermal fluids from both Moana and Steamboat with meteoric waters is well documented and accounts for temperature and compositional variations in the near surface. Moana fluids do not appear to have a chemical genesis that is closely related to fluids from Steamboat Hot Springs. The two waters are, in fact, chemically different in every aspect except major cation proportions. Although both are ultimately composed of meteoric waters, stable light isotope ratios indicate that Moana thermal fluids were originally precipitated at a slightly higher elevation than Steamboat fluids. In addition, a significant oxygen-18 shift (4 per mil) was observed in Steamboat data, suggesting water/rock equilibrium temperatures in excess of 150°C (300°F). No corresponding O-18 shift was noted in the Moana data. Tritium analyses revealed significant mixing of recent meteoric waters with geothermal fluids in Moana; no mixing was seen in Steamboat fluids. Carbon-14 data suggest that Steamboat fluids range from 40,000 to 43,000 years in age. Moana fluids may be as old as 8,000 years.

Moana geothermal fluids do not pose a serious health hazard, but they are largely unsuitable as a source of potable water. Health officials in Nevada have set a strict limit of 1.8 parts per million (ppm) fluoride for drinking water. Levels of 3 to 5 ppm are found in Moana geothermal waters. In addition, levels of both sodium and sulfate in Moana fluids exceed the maximum permissible concentrations posted by the United States Public Health Service. However, because the range of chemical compositions for fluids sampled throughout Moana is large, some thermal fluids may qualify as potable sources of water.

Corrosion and scaling of metal parts in wells remains a problem. Calcium carbonate forms scale on steel casing and galvanized iron pipe. A metallic black-green scale, probably a sulfide, forms on copper tubing which is commonly used as a down-hole heat exchanger. Pitting corrosion is reported to occur in all metals causing leaks and system failure. There is some question, however, whether the leaks are the result of improper installation or actual corrosion.

To combat the threat of corrosion, fiberglass tubing is being routinely installed in newly completed wells. In addition, the copper and steel tubing used in older wells is being replaced with fiberglass.

Five observation wells were drilled to obtain reliable temperature and water level data in the important lithologic units of the Moana geothermal area. Following this, monitoring of temperature and water level in these wells was completed over a period of several months.

The highest recorded temperatures (70 to 85°C) were achieved and maintained in the Kate Peak Formation (blue clay). Wells completed in the Sandstone of Hunter Creek have lower temperatures at comparable depths, but also have constant and increasing temperature gradients, suggesting that the ultimate source of heat has not been reached. Temperature gradients in wells completed in the Kate Peak Formation generally become isothermal near the bottom of the hole, indicating that the geothermal reservoir has been encountered. An observation well drilled in the eastern part of Moana revealed a temperature reversal near the bottom of the well. This indicates that the thermal fluids are floating or perched on cooler groundwater below.

Minor changes in both temperature and water levels occurred in all observation wells over a six month monitoring period. Simultaneous increases and decreases in water levels (as much as 5 ft.) in different wells cannot be accounted for by changes in barometric pressure. These changes appear to be related to lithologies, bounding structures, and pressure transients that result from pumping within a bounded structure. The bounding structures are either fault planes or stratigraphic contacts and act like barriers to fluid flow. Thus, pumping from one bounded structure may not affect water levels in an adjacent block.

Temperatures throughout the well bores remained remarkably consistant throughout the monitoring period. Four of the five wells showed little or no change, remaining within 1 to 2°C of the original measured temperature. A temperature decrease of 6°C was recorded at a depth of 30 m (100 ft.) in one well, but the lower portion of the well remained unchanged.

Data for more than 140 geothermal wells in Moana were compiled and are listed in Appendix III. This number represents the minimum number of wells in Moana; the actual number may be 250 wells. In addition, 32 temperature-depth profiles are presented; these data were combined with the geological, geophysical and geochemical data from this investigation to produce a depth-to-temperature map of the geothermal area. The map divides the Moana resource into broad zones of expected depth to maximum temperature. Although the shape of the zones is general and subject to change with additional data, this map represents the first quantitative analysis of the lateral and vertical distribution of the Moana resource. It was designed to provide drillers and homeowners with accurate, objective data that can be used to estimate the cost of a geothermal space heating system.

Recent developments to improve geothermal resource utilization in Moana include use of fiberglass tubing as a down-hole heat exchanger and installation of convection tubes to distribute heat throughout the well bore, eliminating heat loss to low-temperature zones. In addition, the Division of Earth Sciences was instrumental in the completion and permitting of the first geothermal reinjection well in Moana. These developments have resulted in reduced operating and maintenance costs, as well as reducing the chances of surface contamination by geothermal fluids. Based on resource parameters and engineering principals, a computer code was developed to approximate heat output from a typical Moana geothermal heating system.

The monitoring program has demonstrated that the geothermal reservoir has not been stressed beyond its natural capabilities. At the present rate of development, approximately 2 new wells per month, the number of users will have doubled in 7 to 10 years. Continued monitoring is the recommended method for accurate prediction of reservoir performance.

INTRODUCTION

This report describes the results of an integrated geologic, hydrologic research program funded by the United States Department of Energy, San Francisco Operations Office (contract no. AC03-82RA50075), to assess the Moana geothermal resource and to make recommendations for present and future development.

The Moana area is the largest single low- to moderate-temperature geothermal resource in the State of Nevada presently employed for direct-use applications. Approximately 150 individual wells, representing a total estimated investment of $5 to $7 million, are presently used to provide heat and hot water to more than 130 private residences, several churches and two large motels. Although most of the wells are constructed to meet the heating needs of individual homes, a large-scale district space heating system, designed to supply heat to 60 houses from a single well, is now being developed. Usable temperatures range from 50° to 99°C (120° to 210°F); well depths range from 60 to 400 m (100 to 1300 ft.). The number of new wells coming on-line in Moana is two to three per month. Development of the resource has been largely unregulated and questions dealing with reported reservoir temperature and water level declines, loss of artesian flow, and fluid disposal have recently surfaced.

Moana is located 13 km north-northwest of Steamboat Hot Springs, a high-temperature, extensively studied geothermal resource that has been tentatively selected as a site for a geothermal electric power plant. Although significant differences exist, there is geochemical and geologic evidence to suggest a genetic relationship between Moana and Steamboat.

In October, 1982, a geologic and hydrologic research program began that was designed to provide detailed geothermal reservoir data, which would lead to better reservoir utilization, to present or prospective developers, as well as state, county and city government agencies. Several investigative techniques were employed in this program to determine if the two systems are closely related, secondarily related, or completely independent.

During the course of this investigation, research efforts were directed toward three major goals:

1) Characterizing the Moana geothermal area and determining its areal extent;
2) determining the relationship between Moana and Steamboat; and
3) provide data and recommendations for subsequent prudent development of the Moana geothermal resource.

The investigation consisted of the following tasks:

Task 1) <u>Collection of Existing Data:</u> All previous reports, maps, and data bases were assembled and compiled. In addition, a cooperative agreement was established with local drillers to obtain reliable subsurface lithologic, temperature, and water level data. This phase of the program proved most beneficial.

Task 2) <u>Conduct Gravity Survey:</u> Gravity surveys have been used successfully in many exploration programs to identify major geologic structures, such as basement configuration, as well as small-scale structures, such as fault trends. In this program a gravity survey was used, focused largely on Moana, to provide information on the depth-to-bedrock and to estimate the offset along faults that can be identified at the surface. These faults are thought to be the principal structural control on geothermal fluid migration. In addition, the survey was extended south to Steamboat to determine if the faults that control fluid flow in both ares are structurally related.

Task 3) Fluid Chemical Sampling Survey: This task included analyses of major, minor and trace constituents of thermal and non-thermal fluids to determine regional chemical patterns. Deuterium and oxygen-18 analyses were performed to identify possible recharge areas and high-temperature rock/water reactions. Selected fluids were also analyzed for tritium and Carbon-14 to determine, by means of radioisotope dating techniques, the age of the fluids.

Task 4) Drilling and Completion of Observation/Monitor Wells: This task consisted of drilling five, 122 m (400 ft.) temperature gradient holes in strategic locations throughout Moana. The wells were completed as small-scale water wells with steel casing, perforated at the bottom, and cement sealed. One well was cost-shared with a developer and completed to a depth of 800 feet. These wells were monitored on a regular basis from June through December, 1983. Monitoring included water level and temperature-depth measurements. In addition, lithologic logs constructed from drill chips were used to estimate the lateral extent of the Moana geothermal resource.

The combined geologic, geophysical and geochemical surveys, in conjunction with the observation/monitoring program, have resulted in a clear understanding of the relationship between the Moana and Steamboat geothermal systems. It has also provided a much larger data base on Moana. This information is presently provided to developers, well drillers and government regulatory agencies to ensure prudent utilization of the Moana geothermal resource by matching expected reservoir parameters, largely temperature and depth, with the intended use.

CONCLUSIONS AND RECOMMENDATIONS

The geologic assessment of the Moana area provided several different but related sets of data that delineated the size, shape, temperature distribution, and chemical characteristics of the geothermal reservoir. The assessment provided no evidence to support a near-surface relationship with Steamboat Hot Springs. Recent developments suggest that a major structure controlling the distribution of geothermal waters is the northward-dipping stratigraphic contact between the Kate Peak Formation and overlying Sandstone of Hunter Creek. Present use of the resource is largely limited to the shallow-depth (200-600 foot) wells that tap fluids that range in temperature from 50 to 95°C. Temperatures exceeding 100°C at a depth of 1200 to 1500 feet may be located to the north and west of the present development.

The most important result of this research program, however, is that, at present levels of use and within the limits of the monitoring period, no significant evidence of premature geothermal reservoir depletion was observed. It is also recognized that, since the geothermal aquifer is extremely variable in terms of its geometry, lithology, structure and temperature distribution, and since the source and rate of recharge are not known for certain, no available mathematical models can reliably predict future reservoir performance. Therefore, the first recommendation is that future geothermal development, especially if consumptive use (pumping) is involved, be coupled with a reservoir monitoring program.

Future growth in Moana will be similar to established patterns; single family dwellings will predominate followed by multiple family units and small commercial buildings. In order to accomodate options for geothermal energy resource utilization in Moana, a depth-to-temperature map, which divides the

Moana area into zones, was developed on the basis of presently available data. This map may be used by planners and developers to accurately estimate the three most important factors in an assessment of the economics of using geothermal energy: fluid temperature, resource location, and depth of well. Continued resource monitoring and data collection from newly completed wells can be used to expand or refine the boundaries and zones.

With increased use of convection tubes in recently completed wells, fewer wells are pumped and less geothermal fluid is wasted by surface discharge. Although some pumping may be required in certain zones, the practice should be discouraged and alternative uses, such as cascading a single flow to more than one home or fluid reinjection, should be advocated. If no such arrangement is suitable, fluid discharge to existing sewer lines represents the best alternative. This would depend largely on availability of sewer capacity in the Truckee Meadows.

The ultimate management of the Moana resource rests principally with the office of the State Engineer. Although no drilling permits are required for geothermal wells in Moana, if monitoring data suggest that the resource is in jeopardy of overuse, a drilling moratorium could be issued to either reduce the rate of drilling or eliminate further development.

The second most important result of this research, is that the development in Moana should be linked with a continued reservoir monitoring program to ensure prudent, conservative resource utilization. Monitoring should include the following specific tasks:

1) periodic temperature and water level measurements in existing observation wells,

2) continued collection of lithologic samples from new wells; if possible, measure temperature and water levels as well, as part of a cooperative agreement,

3) obtain chemical analyses of thermal fluids in areas that are not well represented in the data base,

4) delineate those portions of the Moana geothermal reservoir suitable for geothermal fluid reinjection, and

5) perform small scale fluid reinjection and tracer tests on existing observation wells.

Proper implementation of the monitoring program and continued recommendations for optional resource development will lead to enhanced, environmentally beneficial resource utilization. Present estimated savings of ten to twelve-thousand barrels of oil per year could double or triple with diligent management.

DESCRIPTION OF STUDY AREA

GEOGRAPHIC SETTING

The Truckee Meadows is located in southern Washoe County, Nevada, in a structural basin that includes the Cities of Reno and Sparks. The north trending valley is bound on the west by the Carson Range and on the east by the Virginia Range. Although the area is immediately adjacent to the Sierra Nevada, the entire region is within the Basin and Range geomorphic province.

The elevation of the valley is 4400 feet (Reno-Cannon International Airport). Elevations in the Carson Range exceed 10,000 feet and the average elevation in the Virginia Range is 7,000 feet. Bateman and Schiebach (1975) report a mean annual temperature of 9.7°C and a yearly precipitation of 17.8 cm (7 inches).

The Truckee River is the principal drainage in the area. This river drains Lake Tahoe and flows generally east and north through the Truckee Meadows to Pyramid Lake, located approximately 35 miles northeast of Reno.

Several geothermal areas occur within the Truckee Meadows including Steamboat Hot Springs, Zolezzi Springs, Moana, the Wedikind Mining District, and Lawton Hot Springs (fig. 1).

This study focuses largely on the Moana area, a moderate temperature geothermal resource (50 to 97°C) that is presently being used for space heating applications. The nearby Steamboat system is a high-temperature resource (>200°C) that has been extensively studied and has been selected as a site for geothermal electric power production. Lawton Hot Springs has been used as a geothermal spa and there is no reported use of geothermal fluids in the Wedikind District.

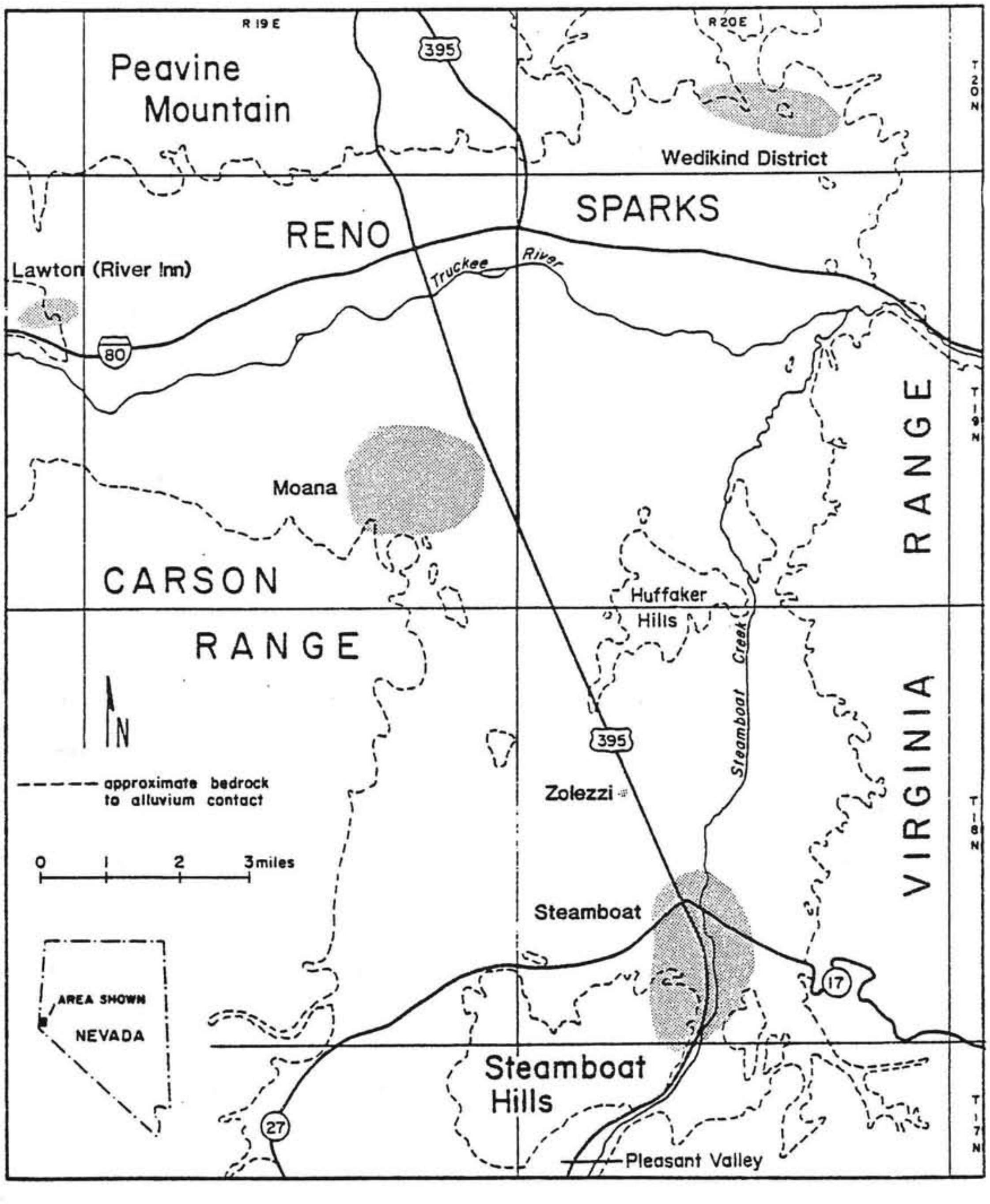


Figure 1. Location map showing geothermal areas in the Truckee Meadows. (modified after Bateman and Schiebach, 1975)

Previous work in this area includes both regional mapping (Bonham, 1969) as well as 15 and 7.5 minute geologic quadrangle maps (Thompson, 1956; Bonham and Bingler, 1973; and Bonham and Rogers, 1983). Detailed geologic mapping and structural interpretation was completed at Steamboat (Thompson and White, 1964; White and others, 1964) and for Quaternary deposits and structures in the Truckee Meadows (Bingler, 1975).

The following summary of the regional geology and structure is based on previous work as well as reconnaissance in the Moana and Steamboat areas. Most of the geologic structures and formations, as well as the geothermal areas, are located on the Reno and Mt. Rose, N.E. 7.5 minute quadrangle maps. Figure 2 shows the location of these maps and other features in the study area.

REGIONAL GEOLOGY

The oldest rocks exposed in the study area are Triassic and Jurassic-age metamorphic volcanic and sedimentary units, known as the Peavine sequence, that have been mapped as roof pendants in the underlying Cretaceous-age granodiorite. Metasedimentary rocks associated with the Peavine sequence include phyllites, greywackies, quartzites, and recrystallized limestone, which are exposed in the Steamboat Hills and southern Virginia Range. Smaller outcrops of metavolcanic rocks, including volcanic flows, breccias, and pyroclastic units are exposed in the Truckee River Canyon in the northern Virginia Range.

The lower Mesozoic metamorphic rocks were intruded by rocks associated with the Cretaceous granodiorite of the Sierra Nevada. Extensive outcrops occur in the Carson Range to the southwest, Peavine Mountain to the northwest, and in the Steamboat Hills and Virginia Range to the south. Granodiorite and quartz monzonite represent the most abundant rock types, but rocks ranging in composition from gabbro to pegmatite-aplite dikes have been reported. Complete

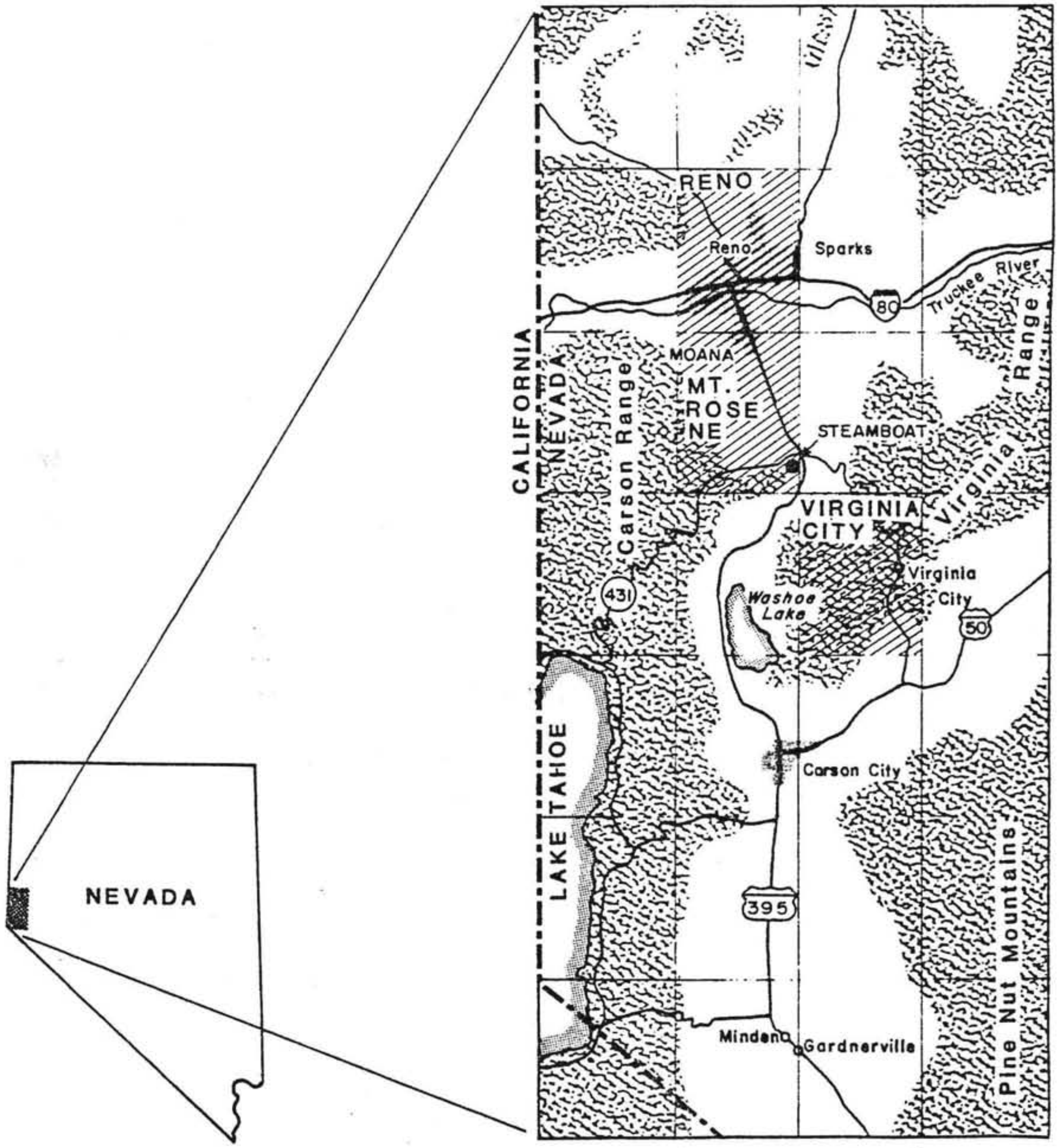


Figure 2. Reno, Mt. Rose, N.E., and Virginia City 7½ minute quadrangle maps: index.

petrographic and petrologic descriptions, as well as bulk chemical analyses of the metamorphic and plutonic rocks have been described by previous workers (Thompson, 1956; Thompson and White, 1964; White and others, 1964; and Bonham, 1969).

Tertiary-age rocks constitute the most extensive exposures throughout the study area. The Alta Formation, of Miocene age, overlies a complex sequence of at least six ash-flow tuffs that range in age from 22 to 28 million years (Bingler, 1978). These formations nonconformably overlie Cretaceous-age granodiorites. The Alta Formation consists of andesite flows, breccias and pyroclastics. These rocks are often hydrothermally altered and constitute the principal host rock for gold-silver deposits of the Comstock Lode mining district beneath Virginia City (Bonham, 1969). Directly overlying the Alta is the lower Pliocene Kate Peak andesite, which consists of volcanic flows, flow breccias, mudflow breccias, and agglomerates that range in composition from pyroxene dacite to rhyolite (Bonham, 1969).

Pliocene sedimentary rocks, Sandstone of Hunter Creek (Bingler and Bonham, 1976) overlie the Kate Peak andesite and consist of a lower greywacke member, a thick sequence of diatomaceous siltstone, and upper member of well rounded sandstone. Although extensive exposures of both the andesite and sandstone occur throughout the Truckee Meadows, a conformable sedimentary contact between these two units has not been reported. Tertiary volcanic and sedimentary rocks are exposed throughout the Moana area and will be discussed in detail in a following section.

Quaternary deposits are widespread and consist of approximately 13 distinct formations. Major unconformities separate rocks of Tertiary and Quaternary age. Bingler, (1975) recognized three major categories of Quaternary deposits:

1) Main stream gravel deposits of the Truckee River associated with Illinoisan and Wisconsin Glaciation,

2) Alluvial fan deposits that range in age from early Quaternary to Holocene, and

3) Reworking of older deposits and deposition of relatively fine-grained clastics in the central Truckee Meadows.

In addition, Silberman and others (1979) have documented the history of silicious sinter deposition in the Steamboat Springs area and have suggested that hydrothermal activity there has occurred for more than 2.5 million years.

REGIONAL GEOLOGIC STRUCTURES

Two major deformational episodes were recognized and described for rock units throughout the Truckee Meadows (Thompson, 1956; Thompson and White, 1964; White and others, 1964). During the Late Mesozoic, sedimentary and volcanic rocks that were deposited in a eugeosyncline were subjected to greenschist facies regional metamorphism by intrusion of granodiorite plutons associated with the Sierra Nevada Batholith. This resulted in the formation of slates, phyllites, and recrystallized limestones that are exposed as roof pendants in the Carson and Virginia Ranges. The second major period of deformation began in middle to late Tertiary and continues to the present. This phase consists of normal faulting, tilting of fault blocks, warping, wrench faulting, and related folds that are believed to be the result of extensional tectonics throughout the Basin and Range. This phase is responsible for existing topographic features. Offset along the major range bounding faults is estimated to be 3000 to 5000 feet, based on exposures of key pre-Tertiary metasedimentary units.

The area of investigation is located within a transition zone of the Basin and Range Province and Sierra Nevada. The Truckee Meadows is considered an intermontane structural trough (Thompson and White, 1964) located between the Carson Range on the west and the Virginia Range on the east. The Truckee Meadows is constricted and divided into two smaller basins at Huffaker Hills, a transverse range that trends east-northeast consisting largely of Kate Peak andesite.

The Moana and Steamboat Hot Springs geothermal areas are located along the eastern flank of the Carson Range in the Truckee Meadows. Steamboat Springs is located on the eastern edge of Steamboat Hills, which trends northeast and consists of pre-Tertiary metamorphic and igneous plutonic rocks capped by a complex sequence of Tertiary and Quaternary volcanic rocks and Quaternary alluvial deposits. Thompson and White (1964) recognized three systems of normal faults in the Steamboat Hills area:

1) A northeast trending system that parallels the axis of the Carson Range; many are antithetic.
2) A northwest trending system that is orthogonal to system 1.
3) A north-trending system, which is very prominent in the Steamboat Hot Springs area and which appears to be most recently active.

Structural deformation appears to be genetically related to the large episodes of Cenozoic volcanism, which was centered in ranges throughout southern Washoe County. A volume of 100 cubic miles of volcanic rocks and sediments derived from volcanic rocks was estimated by Thompson and White (1964).

The dominant faults in the Moana area are normal faults that are antithetic in their sense of displacement (mountain side down). These faults are also common in the Peavine Mountain area to the north and are believed to be related to the dome-like structure of the northern Carson Range. Two fault trends in Moana are recognized. One set trends approximately north 20 east and the other trends north 10 west. Both sets appear to be related to similar fault sets mapped in the Steamboat Springs area further south. Moana area faults do not offset the more recent Quaternary or Holocene age alluvial formations and are considered inactive (Bingler and Bonham, 1976).

GEOTHERMAL AREAS

Thermal fluids occur throughout the Truckee Meadows and include Steamboat Hot Springs, Moana, the Wedikind mining district, and Lawton Hot Springs. In addition, warm water has also been reported near Huffaker Hills and at Zolezzi Lane a warm spring flows intermittantly. These last two, however, represent lateral extension of the Steamboat Springs geothermal system.

Steamboat Hot Springs is one of the most extensively explored geothermal systems in the world. Studies conducted by the U.S. Geological Survey from 1942 through 1964 (Thompson and White, 1964; White and others, 1964; and White, 1964) summarized the geologic history, described previous exploration and development, and calculated a reservoir temperature of 175°C, based on the chemical and isotopic composition of the fluid discharge. In addition, the authors proposed that the heat source is a shallow magma body that has maintained high thermal gradients over an extensive area, by convection within the magma chamber, for a minimum of 1 million years. The authors also estimated that heat flow from the Steamboat system is a minimum of 2.5 times background, or at least 35×10^6 cal/sec.

Subsequent studies by Schoen and White (1967) describe the extent of hydrothermal alteration of volcanic and other rocks at Steamboat. Silberman and others (1979) detailed the age relationships of the silicious sinter deposits and recent volcanic rocks and proposed that the hydrothermal system has been active for 3 million years. Nehring (1980) conducted a detailed fluid geochemistry survey at Steamboat and concluded that the reservoir was recharged largely by meteoric fluids in the Carson Range at an estimated average elevation of

1920 m (6300 feet). In addition, the chloride versus enthalpy data suggested a reservoir temperature of 230°C. The ^{18}O shift of nearly 4°/oo supports a water/rock interaction at temperatures in excess of 150°C.

Temperatures of surface fluids range from 30 to 97°C. Phillips Petroleum Corporation completed a well to an estimated depth of 1000 m (3300 feet) and encountered temperatures in excess of 200°C (400°F). Surface fluid discharge is confined to two large areas, covered with silicious sinter deposits, known as the lower and upper terrace (White and others, 1964). The main terrace is located in an area east of Steamboat Hills that is extensively faulted. Fractures here may be as wide as .3 m (1 foot) and most of the hot springs and fumaroles discharge from these fractures. Some wells were drilled to support attempts at commercial development; several are prone to geysering. On August 4, 1983, a well located in the Steamboat Area began to geyser on a continuous basis. The discharge is largely steam and the continuous eruption may have been initiated by a small earthquake (Richter mag. 3.2) that occurred near Zolezzi Spring, 5 miles to the north in July, 1983.

The Moana geothermal area is the largest low- to moderate-temperature (35 to 150°C) resource in the state of Nevada presently employed for direct-use applications. There is no natural surface discharge of thermal fluids in Moana, although flowing springs were reported (Cohen and Loeltz, 1964) in addition to several artesian wells. Presently, there are no flowing springs and a single artesian well (Gadda well, record #57, Ghusn, 1982) ceased to flow in February, 1982.

The approximate geographic center of the known thermal area is close to the intersection of Manzanita Lane and Plumas Street (fig. 3). Fluid temperatures range from 97°C in the west to about 30°C in the east. This temperature decline, which is the result of mixing with cool groundwater in Truckee

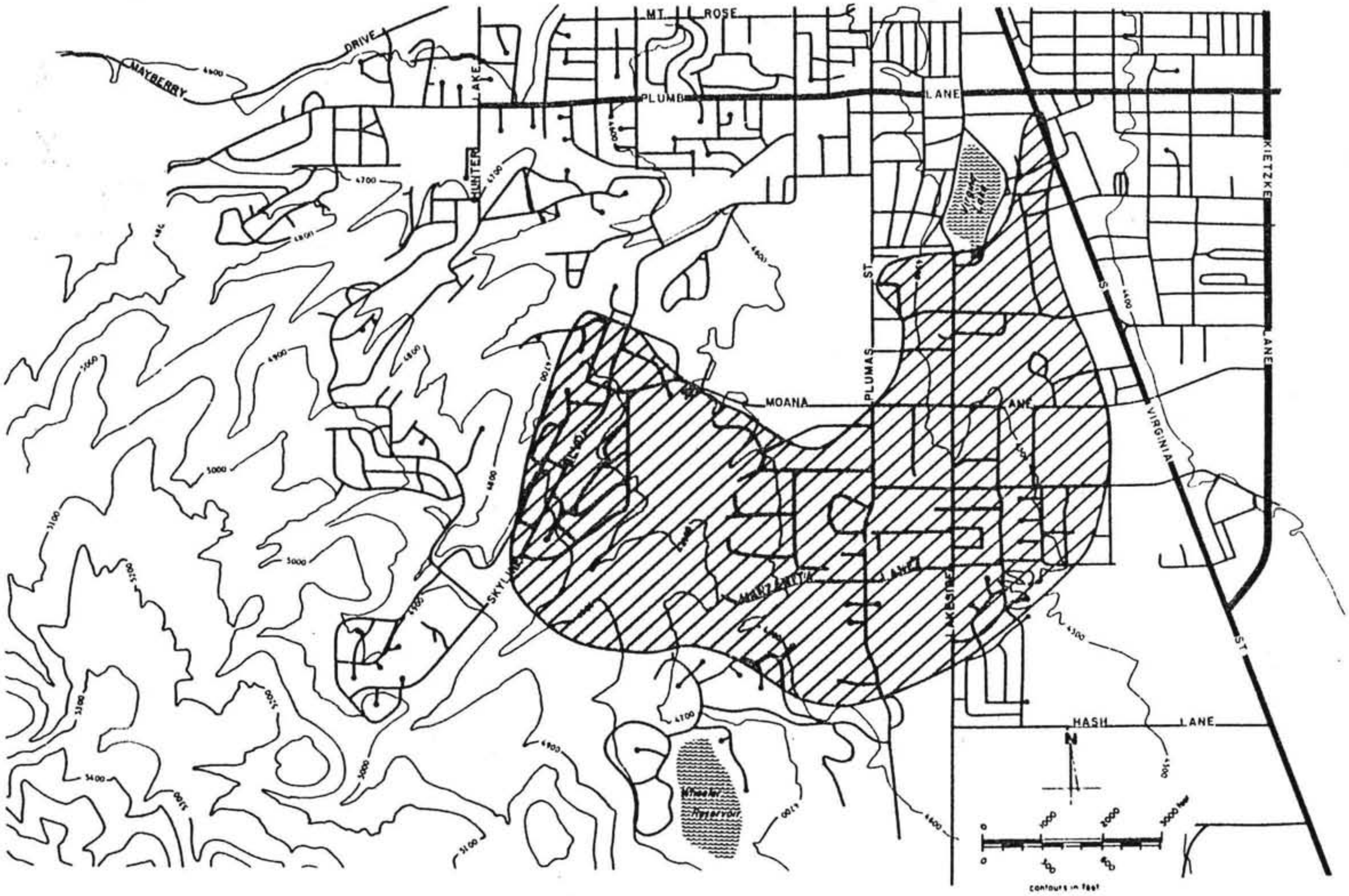


Figure 3. Approximate areal extent of the Moana geothermal resource.

Meadows, is accompanied by a general decrease in total dissolved solids. The northern, southern and eastern boundaries are fairly well defined by substantial temperature decreases and measurable drop in total dissolved solids.

Prior to this study, little was known about the nature of the reservoir rock in Moana. Bateman and Scheibach (1975) reported an association of thermal water with a "blue" clay which was encountered during drilling. The blue clay was not discussed in detail but lithologic logs indicate that it is located above the altered Kate Peak andesite and beneath the alluvial deposits at the surface. Figure 4 is a generalized geologic map of Moana and illustrates the relationships between the Sandstone of Hunter Creek and the underlying Kate Peak andesite. In addition, mapped faults, discussed previously, are also shown.

In this investigation, samples of blue clay were collected from several drill holes and from various depths. X-ray diffraction analyses reveal that the blue clay is composed almost entirely of smectite, a structurally disordered clay, and no other clay minerals. Smectite is commonly formed by hydrothermal alteration of volcanic glass. In addition, minor hornblende, K-feldspar, gypsum and calcite were also identified. Partial chemical analyses of the drill chips revealed a compositional similarity to the andesite and also showed anomalous levels of gold, silver, thallium and antimony, further suggesting the presence of mineralizing solutions. The data indicate that the blue clay is the hydrothermal alteration product of a vitrophyre member of the Kate Peak andesite, which is exposed in the hills south and west of Moana and in drill chips obtained from other wells.

Thermal fluids are not restricted to the blue clay. To the east, many wells are completed in alluvial sediments of Quaternary age which overlie the blue clay. These fluids are generally cooler and more dilute than fluids

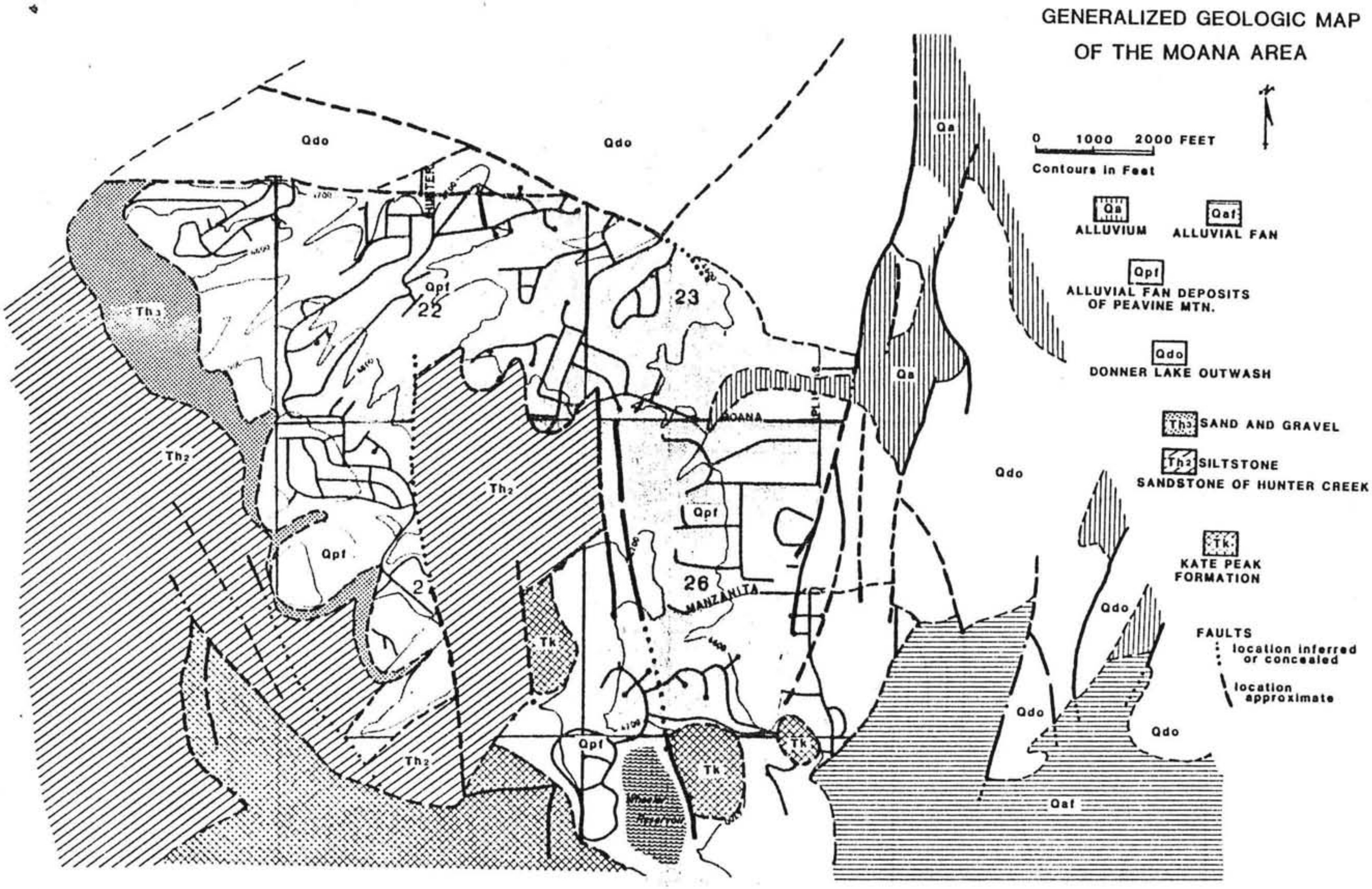


Figure 4. Generalized geologic map of the Moana area. (modified after Bonham and Rogers, 1983)

further west and illustrate the extent of mixing. To the west, thermal fluids occur in portions of the Sandstone of Hunter Creek, which overlies the Kate Peak andesite and attains a thickness of nearly 2000 feet in western Reno. The principal conduit of thermal fluids here appears to be the contact between the sedimentary and volcanic rocks. Wells drilled west of the center of Moana encounter warm water that is mixed and derives its heat by conduction. Wells that penetrate the sedimentary rocks show sharp temperature increases that correlate with the contact. A temperature of 95°C (203°F) has been recorded in a well drilled to a depth of 244 m (800 feet) near Skyline Boulevard (fig. 3). It is unlikely that thermal fluids rising through faults near the central Moana area flow laterally up the piezometric surface to the west. A more likely explanation of the high temperature to the west is a combination of faults and stratigraphic controls on the lateral migration of fluids. There are many faults to the west and any one, or combination, could yield high temperature fluids.

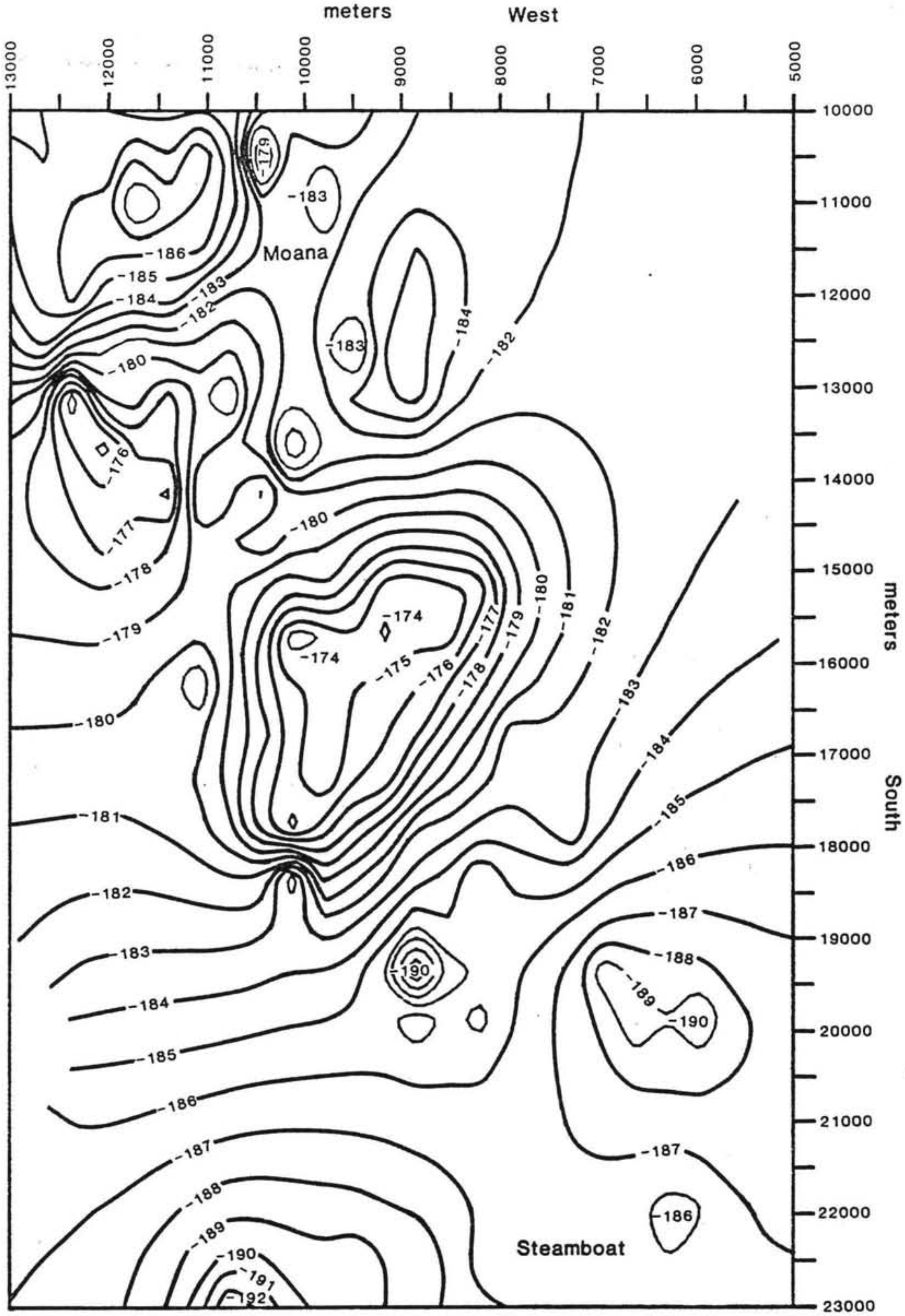
GRAVITY SURVEY

A survey of anomalies in the Earth's gravity field due to density differences in rocks was used to roughly delineate the basement structure from Steamboat north through Moana. Three hundred fifteen stations were occupied including eighty five stations for which the elevations were already known and two hundred thirty stations whose elevations were obtained by surveying. Gravity measurements were made with a LaCoste-Romberg Gravimeter capable of a .01 mgal resolution and 5500 mgal range. The gravity reference is the U.S.A.F. gravity base station ACIC 0454-1 located in the Scrugham Engineering-Mines Building at the University of Nevada, Reno. The base station has an absolute gravity value of 979.6884 gals. Gravity data are presented in Appendix I.

Reduction of these data included calculation of the simple Bouguer anomaly according to the 1939 International Gravity Formula using an assumed density of 2.67 for basement rocks. Complete bouguer anomalies were computed using terrain corrections calculated for representative points and applied to all points. From the resulting irregularly spaced values, a uniform 160 x 160 meter grid of values was interpolated using cubic splining techniques. A contour map and isosurface plot were created from this grid (fig. 5 & 6). In Figure 6, the surface is inverted; a gravity high appears as a depression, and gravity lows appear as domes.

In addition, a residual gravity map was calculated for the Moana area using the 1:250,000 Reno Gravity Map as the regional gradient (fig. 7).

All the figures show relative gravity highs near outcrops or shallow occurrences of the Kate Peak andesite. This rock has a density of approximately 2.7 g/cc and produces gravity highs relative to the Sandstone of Hunter Creek or the Quaternary alluviums with densities in the 1.5-1.8 g/cc range.



MOANA BOUGUER GRAVITY MAP

Figure 5. Bouguer gravity map of Moana and Steamboat geothermal areas.

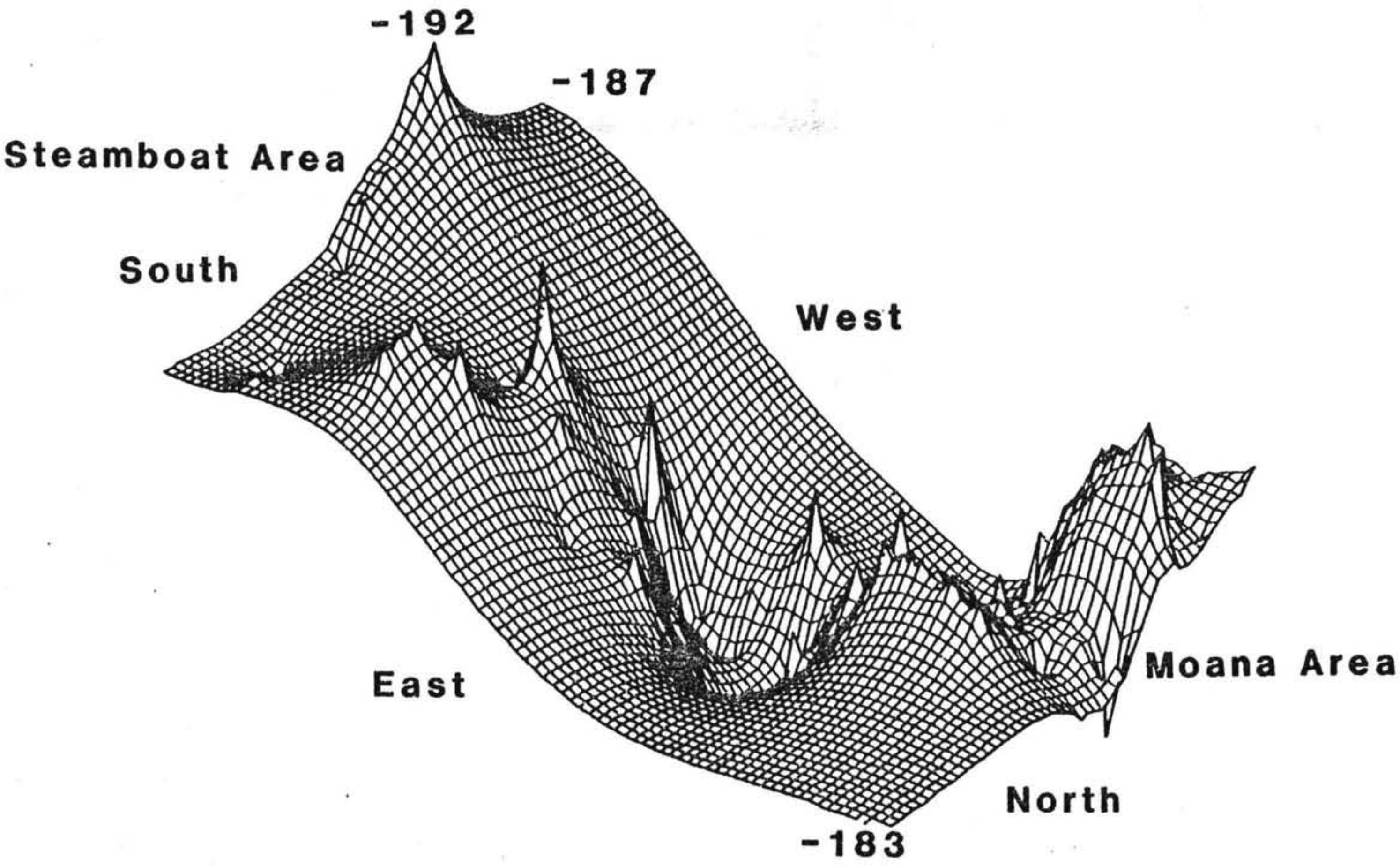


Figure 6. Three-dimensional isosurface gravity map of Moana and Steamboat geothermal areas.

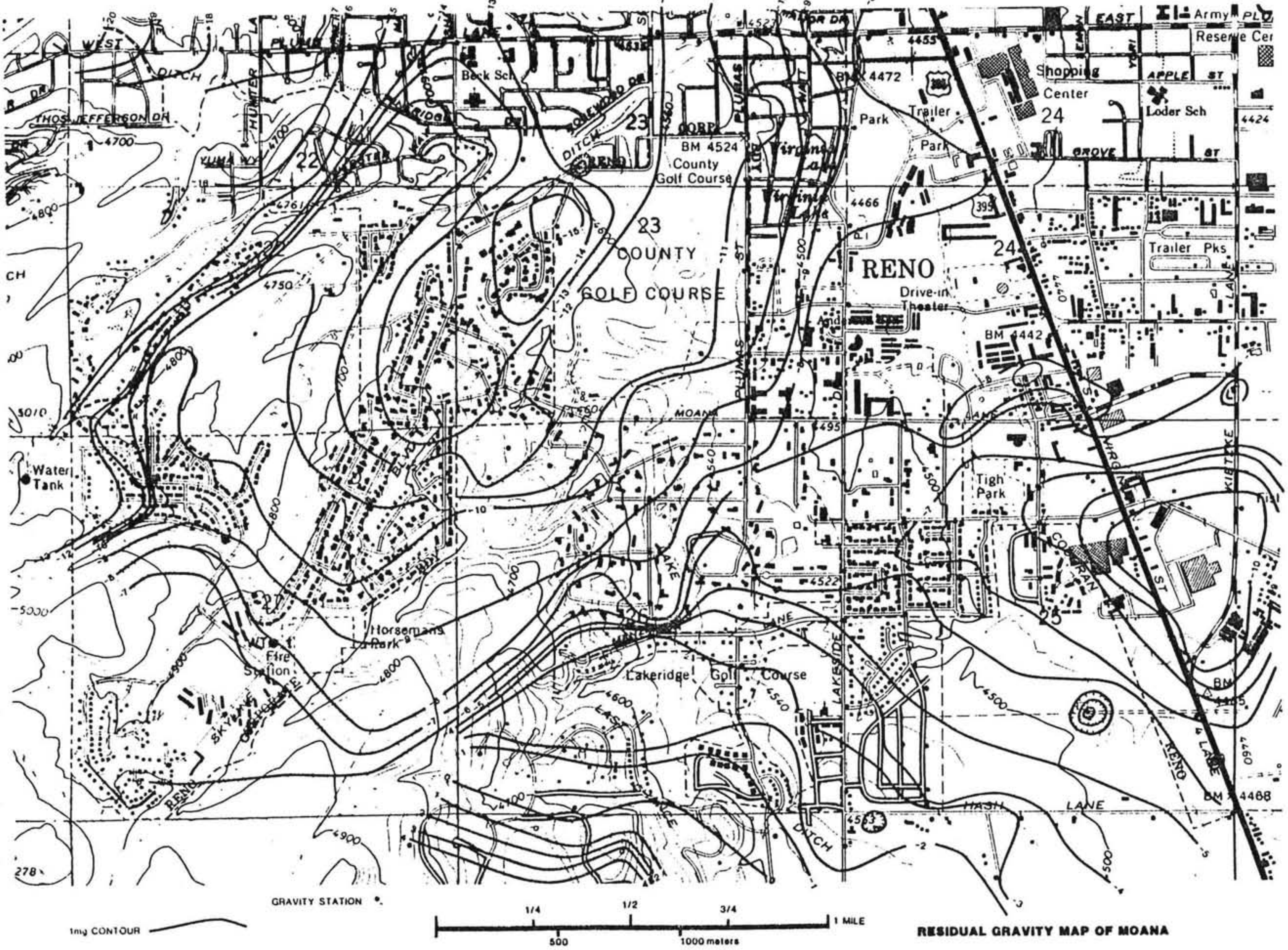


Figure 7. Residual gravity map of Moana area.

The most striking anomaly is a dome-like high of 10 mgal in the center of the map in the Huffaker Lane area (fig. 5). This feature is probably the result of a shallow occurrence of andesite which outcrops to the east and south. This gravity high does not correlate with known geothermal wells. There are few mapped faults in the area (Bonham and Rogers, 1983), perhaps due to a combination of farming, construction, and other cultural activities, and deposition of young alluvial material. For the purposes of this study, this anomaly was considered insignificant as an indicator of a geothermal reservoir; however, it appears to represent a major physical barrier between the Steamboat and Moana geothermal systems.

In the southern portion of this study, there are several small "spike" anomalies of 3 to 5 mgal which may indicate local thickening of the alluvium or artifacts of the irregularly spaced data (fig. 5 & 6). The anomaly on the southern boundary probably shows thickening of the alluvium; other spikes are likely artifacts. Since the focus of this study was the Moana area, more than 50% of the stations are in the northern survey area. The gravity data south of 15,000 m shows a general thickening of valley fill to the east, but this and any other interpretations from these data must be considered with caution.

Additional gravity data are available from the 1:250,000 Reno Bouguer Gravity Map (Erwin and Berg, 1977) which confirms the range of Bouguer anomaly values determined in this study. The scale, however, is too small to assist interpretation.

In the Moana area, the complete Bouguer gravity map and the isosurface plot (fig. 5 & 6) show an area of low gravity in the southeast, a gravity high ("ridge") curving from west to north through the center of Moana, and another area of low gravity to the northwest. The "ridge" roughly corresponds to outcrops and shallow occurrences of the Kate Peak andesite. The gravity lows are coincident with the greatest thicknesses of the Sandstone of the Hunter Creek to the northwest and increasing thicknesses of Quaternary alluvium to the east and northeast. The trend of the gravity contours do not correlate well with faults mapped by Bonham and Rogers (1983) or Bonham and Bingler (1973). Most of these faults trend north-south, across the isogals in the center of the area. A comparison of the residual gravity map (fig. 7) and the geology map (fig. 4) illustrates the poor correlation of faults and isogals in the center of the map.

There is a fault mapped in the eastern portion of the area trending parallel to the isogals; although not mapped as continuing to the northeast, this fault may represent the boundary between the Kate Peak Formation (Tk) and the Sandstone of Hunter Creek (Th_2). The fault may be obscured by drainage, topography, or human activities. Figure 8 illustrates a structural model in which faults to the northeast and southwest bound an upthrown block of Kate Peak andesite. Assuming this subsurface configuration is real, the faults are hinged near the south end of Virginia Lake producing approximately 12 m (40 feet) of downward offset at the north end of the lake and 400- 500 feet of upward offset in the area of the Warren Estates.

Another possible explanation does not require faulted boundaries; instead simple contacts are used (fig. 9). The andesite is ridge-shaped plunging to the northeast, possibly a buried topographic high. Faults cut through the formations but are not major structural features. Without additional subsurface data, either model may be valid.

Based on drill hole data, the highest temperature fluids are located within the hydrothermally altered Kate Peak andesite. The depth to the andesite is important to an individual who wishes to drill a geothermal well.

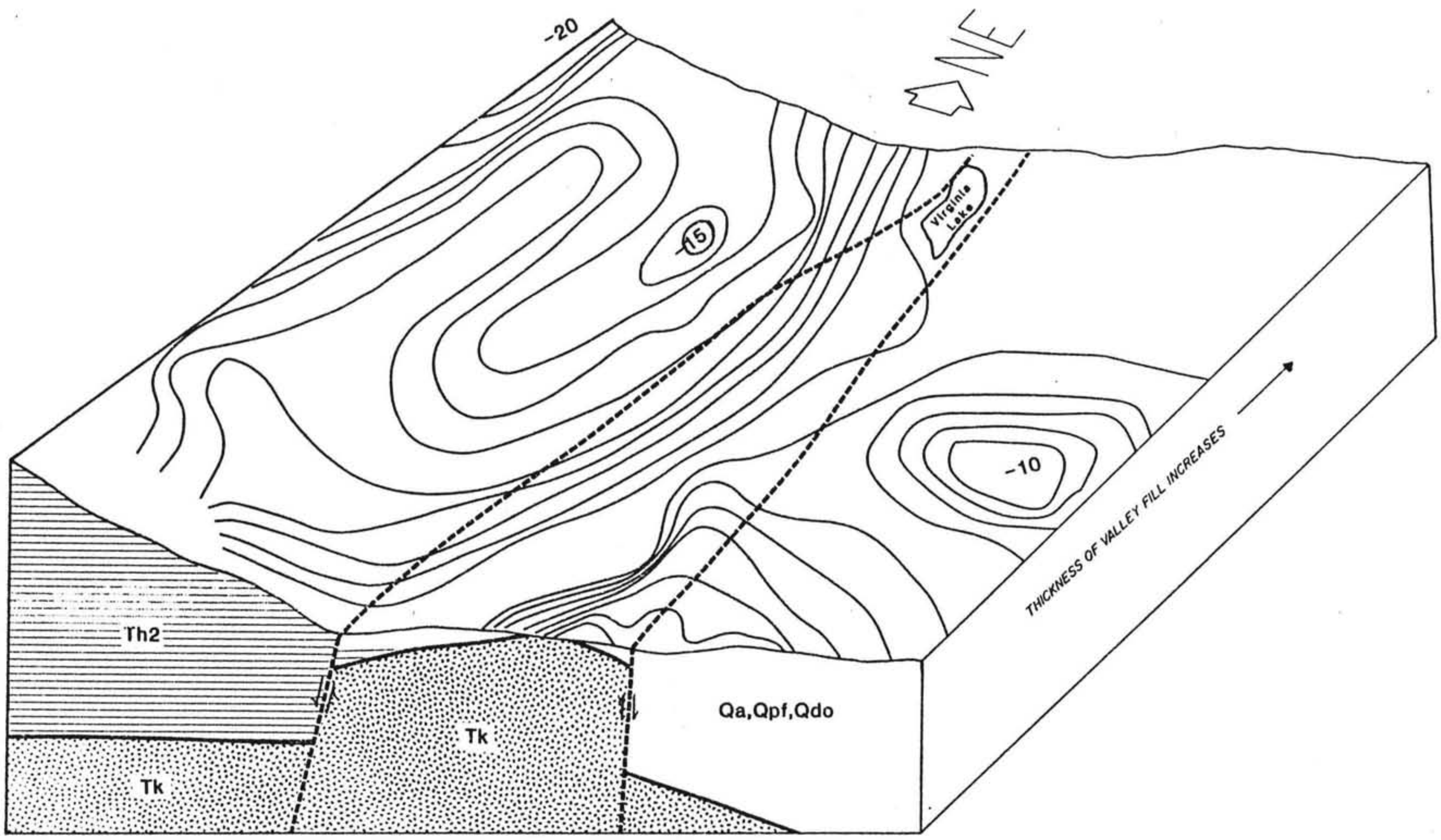


Figure 8. Fault-block model of Moana area.

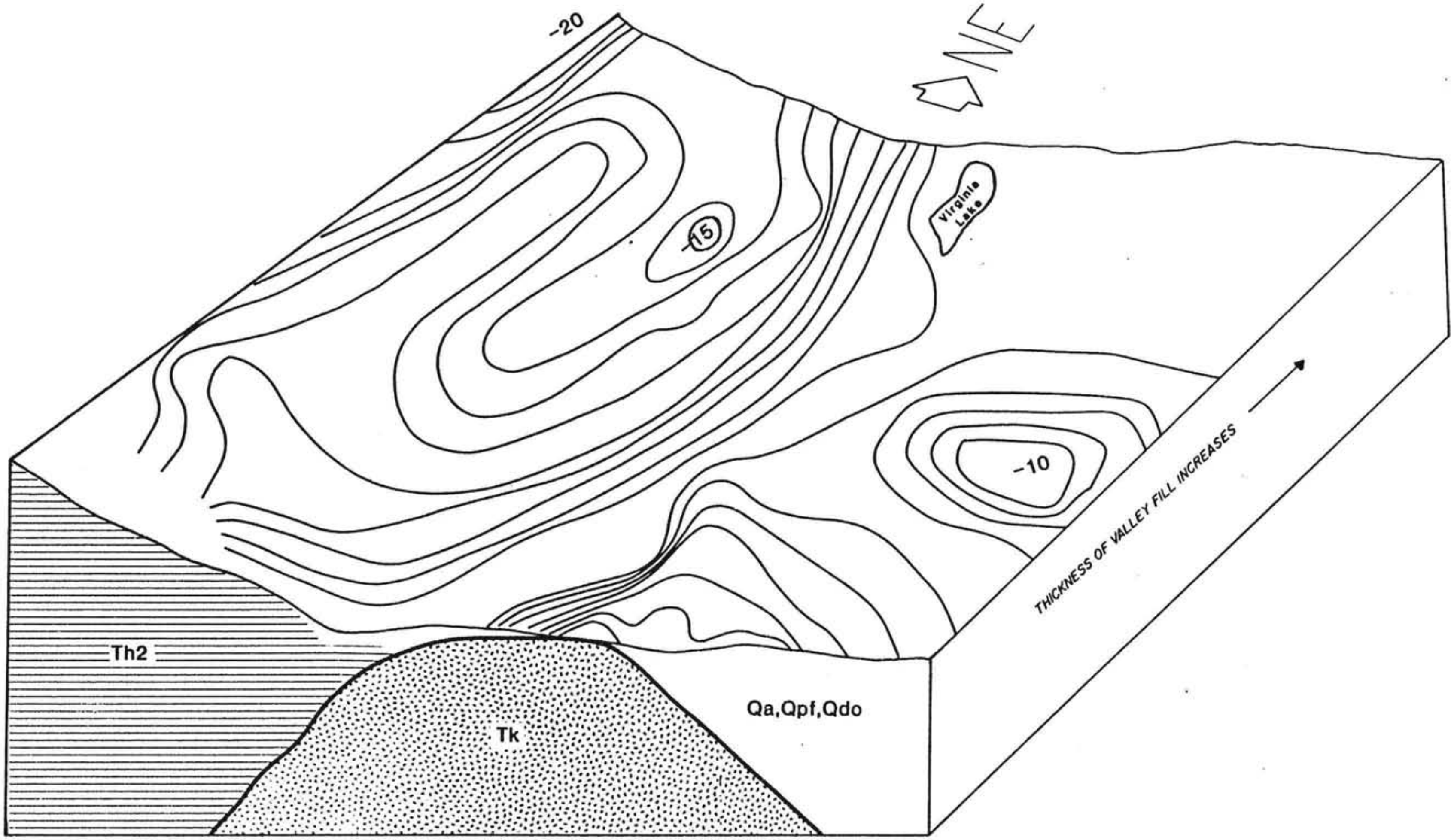


Figure 9. Simple contact model of Moana area.

Depth to the andesite or thickness of the lower density sandstone or alluvium may be estimated from the expression:

$$T = A/(.013\ S)$$

where A is the residual anomaly, S is the density contrast (assumed equal to 1.0 for this case), and T is the thickness (or depth) in feet. (This equation is based on the potential field of an infinite slab, Thompson and Sandberg, 1958.) This formula yields a thickness which correlates well with data from the Skyline Boulevard area and the area east of Lakeside Drive. At the location of the Warren Estates well, this equation predicts a thickness of 630 feet (192 m) using a density contrast of 1.1. The actual thickness of alluvium and sandstone is 600 feet (183 m). However, in the Manzanita Lane area, the equation gives a value of 209 feet (64 m); the actual measurement was 138 feet (42 m). In the area of DES #4, in the center of Sec. 25 (fig. 4), the equation results in a value of 384 feet (117 m); the actual top of the Kate Peak andesite was at 380 feet (116 m). To the north, just east of the center of the Washoe County Golf Course (fig. 7), thickness of the alluvium and sandstone is estimated at 630 feet (192 m), but a well 1500 feet (457 m) deep reportedly never encountered the Kate Peak Formation. As with all geophysical techniques, this equation must be used with caution, but may be valuable for rough estimates of the thickness of alluvium and/or sandstone in areas with few wells.

FLUID GEOCHEMISTRY

SAMPLE COLLECTION AND ANALYTICAL TECHNIQUES

Fluid chemistry analyses represent one of the most important aspects of understanding the dynamics and potential utilization of geothermal resources. Dissolved constitutents are used in general to characterize and differentiate thermal and non-thermal fluids, determine the extent of mixing, and to estimate reservoir temperatures. Isotopic studies may provide the same information, as well as data on recharge area and age of the fluids.

During the course of this investigation, 20 fluid samples were collected from surface, subsurface, thermal and non-thermal sources. Fluid sample sites are shown on Figure 10. Most of the samples were collected from geothermal wells in Moana. Several samples were collected in the Steamboat area as well as one from Lawton Hot Springs (River Inn #13).

Two groups of ten samples were collected during this phase of the investigation. In February, 1983, the first ten samples (1-10) were collected for analyses of the following: major, minor and trace constituents; deuterium and oxygen-18; tritium; and carbon-14. A second set of samples (11-20) was collected in July, 1983, and included only major, minor, and trace constituents and deuterium/oxygen-18 analyses.

Fluids collected for analysis of both major, minor and trace constituents and deuterium/oxygen-18 were pressure-filtered through a 0.8 micron polycarbonate membrane. Samples collected for bulk chemistry were then placed untreated in screw-top 250 ml polyethylene bottles. Stable isotope samples were placed untreated in screw-capped 100 ml glass bottles sealed at the top with wax to reduce the chances of re-equilibration with atmospheric isotopes. Samples collected for analysis of tritium were placed unfiltered and untreated in Teflon-

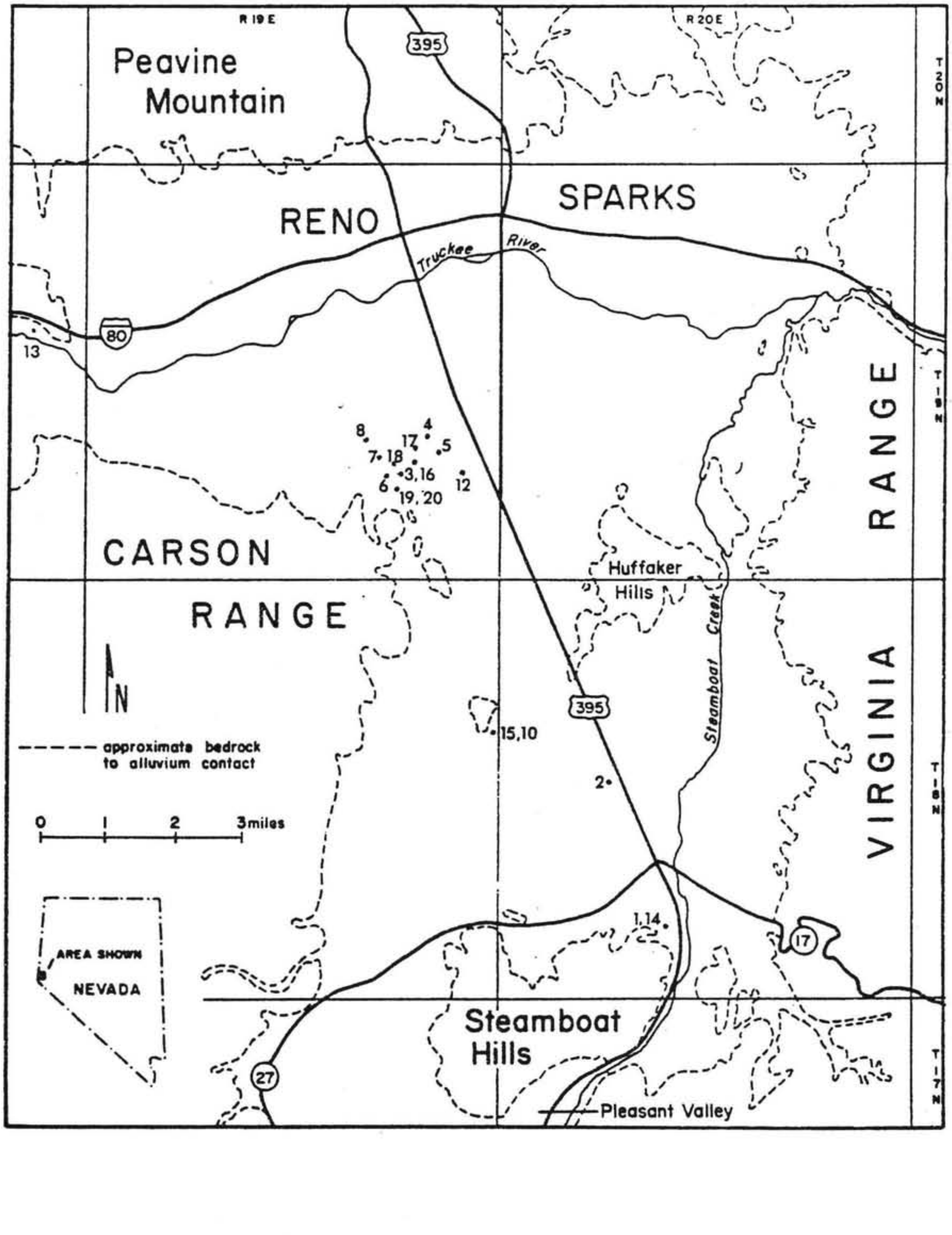


Figure 10. Fluid geochemistry sample sites. Numbers correspond to sample names and numbers in subsequent Tables. Sample site 14 is off this map. (map base modified after Bateman and Schiebach, 1975)

sealed screw-capped 1 liter glass bottles. A complete description of sampling and preparation of fluids for analysis of carbon-14 is presented in a subsequent section.

Analyses for major, minor and trace constituents were performed by AMTECH, a commercial laboratory in San Diego, California, and included colorometric, electrical, atomic absorbtion, and induction-coupled plasma methods. The laboratory guarantees an ionic balance of ± 10%. Deuterium and oxygen-18 samples were analyzed at the Laboratory of Isotope Geochemistry, University of Arizona, Tucson. Analyses were performed with a mass spectrometer with a reproducibility of ± 0.1% for oxygen-18 and ± 1.0% for deuterium. Tritium samples delivered to the Water Resources Center, Desert Research Institute, University of Nevada-Reno, were first enriched for one month by electrolysis. Tritium is then measured in a liquid scintillation counter. The sample preparation and analytical techniques for carbon-14 are discussed in a following section.

ANALYTICAL RESULTS

Major Constituents

This section focuses largely on the Moana resource. Because the Steamboat geothermal system has been thoroughly studied, reference to Steamboat is included to demonstrate the differences between the two adjacent geothermal areas. Investigative methods are similar for both areas.

Fluid samples collected in the Truckee Meadows can be classified into three groups based on temperature and chemical composition:

Fluid Type	Description
Non-thermal	$Ca\text{-}HCO_3$, low-temperature, neutral pH, dilute
Steamboat	NaCl, high temperature, 4000-8000 TDS
Moana	$NaSO_4$, moderate temperature 500-1200 TDS

Thermal fluids from both Steamboat and Moana have a wide temperature range. Although fluid compositions are internally consistent, some spatial variation in chemistry can be observed in both areas. Analyses of major, minor and trace constituents are consistent with previous reports (Cohen and Loeltz, 1964; Bateman and Schiebach, 1975; Nehring, 1980; and Ghusn, 1982). The analytical results for major and minor constituents are shown in Table 1 and 2.

As mentioned previously, Steamboat Hot Springs is one of the most thoroughly studied geothermal systems in the world. White (1968) concluded on the basis of nearly 20 years of investigation that Steamboat water derived all of the heat and as much as 5% of the fluids from a shallow-depth cooling magma body, associated with the recent volcanics in the Steamboat Hills. On a regional scale, Steamboat appears to be related to geothermal fluids that occur throughout an area of more than 24,000 km^2 (9000 mi.) in northwest Nevada. This large area is west of the Battle Mountain heat flow high and also contains a large volume of recent volcanic rocks.

Nehring (1980), applying advanced methods of analysis and interpretation to geothermal fluids investigations at Steamboat, reported data that indicated a reservoir temperature of 230°C. The data also supported previous investigators (Thompson and White, 1964; White and others, 1964; White, 1964; and Silberman and others, 1979) that presume a shallow-depth magmatic heat source recharged largely by meteoric fluids.

The data base for the Moana resource has been greatly expanded as a result of increased activity and interest in geothermal utilization. A better understanding of Moana fluids can be gained by analysis of fluid chemistry in conjunction with whole rock chemistry and mineralogy.

Sodium is the dominant cation in both Moana and Steamboat. This may seem unusual in Moana because of the presence of large volumes of calcium-rich

Sample	Designator	NUM	TEMP (C)	pH	Ca	Mg	Na	K	Li	HCO_3	Cl	SO_4	F	NO_3	B	SiO_2
Steamboat	MB-1	1	96.0	7.42	4.75	.13	677.0	76.3	8.10	296.0	771.0	151.0	2.62	4.64	60.20	322.0
Zolezzi	MB-2	2	27.0	7.44	17.10	8.12	54.9	14.6	.75	226.0	32.8	7.1	.32	.06	2.40	108.0
Miles	MB-3	3	89.0	8.37	24.60	.21	259.0	11.2	.26	106.0	48.0	449.0	5.57	.30	2.25	120.0
Moana Ln.	MB-4	4	40.0	8.16	20.90	.14	235.0	8.4	.22	184.0	39.5	386.0	4.06	1.05	1.80	81.0
McKay	MB-5	5	54.0	8.47	14.30	.61	158.0	9.0	.12	168.0	25.0	221.0	3.32	.25	1.18	105.0
Desjarden	MB-6	6	77.5	8.22	24.70	.10	257.0	12.2	.25	93.0	47.0	459.0	5.15	.30	2.55	113.0
Warren Est.	MB-7	7	87.0	8.18	24.20	.04	276.0	11.9	.26	106.0	51.3	459.0	5.57	.28	2.45	127.0
Newburg	MB-8	8	33.3	7.20	49.50	5.45	279.0	14.9	.29	193.0	42.2	553.0	1.91	.32	1.98	124.0
Gadda	MB-9	9	90.0	8.29	25.20	.07	241.0	11.6	.26	114.0	46.5	459.0	5.36	.12	2.24	110.0
Thomas Crk.	MB-10	10	6.0	7.38	7.80	3.40	3.2	3.0	-	65.7	.5	2.0	.19	.09	.01	42.5

Table 1. Analytical results of major and minor chemical constituents, samples 1 through 10.

Sample Designator		NUM	TEMP (C)	pH	Ca	Mg	Na	K	Li	HCO_3	Cl	SO_4	F	NO_3	B	SiO_2
Farad	MB-11	11	34.0	7.50	24.50	.68	253.0	14.0	1.15	130.0	330.0	89.0	4.10	.01	13.30	73.0
Quillicy	MB-12	12	34.0	7.88	10.10	.89	114.0	6.0	.10	200.0	15.0	107.0	3.50	2.20	.80	97.4
River Inn	MB-13	13	58.0	8.44	22.60	2.06	117.0	2.0	.18	174.0	10.0	162.0	2.30	.15	2.10	46.8
Steamboat	MB-14	14	98.0	7.44	4.67	.07	684.0	76.0	8.80	320.0	930.0	102.0	2.50	-.01	61.70	339.0
Thomas Crk.	MB-15	15	7.0	7.17	5.99	2.28	2.5	2.0	-.01	65.0	10.0	10.0	.06	.10	2.30	38.1
Miles	MB-16	16	83.0	8.18	25.90	.12	247.0	8.0	-.01	125.0	50.0	455.0	5.20	.01	2.40	118.0
Edmiston	MB-17	17	46.0	8.88	16.70	.01	245.0	6.0	-.01	133.0	30.0	445.0	4.40	.01	2.10	54.5
Dicapprio	MB-18	18	80.0	7.54	13.10	1.18	43.2	2.0	.05	50.0	10.0	74.0	1.00	.10	.30	27.8
S. Bermuda	MB-19	19	81.0	8.09	26.70	.04	240.0	6.0	-.01	120.0	20.0	450.0	5.20	.01	2.40	81.8
N. Bermuda	MB-20	20	88.0	7.87	27.00	.09	239.0	8.0	-.01	120.0	20.0	460.0	5.10	.01	2.40	110.0

Table 2. Analytical results of major and minor chemical constituents, samples 11 through 20.

andesites and basaltic andesites. Dacite and rhyodacite occur in equal abundance in Moana and partial chemical analyses of drill chips of the volcanics show very nearly equal proportions of sodium and calcium (Table 3).

X-ray diffraction patterns of three samples of altered Kate Peak andesite are shown in Figure 11. Analysis of these data revealed that smectite was the only clay mineral and constituted between 70% to 90% of the samples (Dr. David Bish, Los Alamos National Lab., personal commun., 1983). Smectites are structurally dissordered clays that are often the product of hydrothermal alteration of volcanic glass. In Moana, the Kate Peak andesite includes a rhyodacite vitrophyre which appears to be the source of the smectite.

Smectites commonly occur in areas of low-temperature hydrothermal alteration. Base-exchange is commonly encountered in smectites and calcium may be preferentially absorbed by the clays from surrounding thermal fluids. In addition, hydrolytic reactions involving production of both sericite and kaolinite, plus quartz, at the expense of andesine yield an ionic ratio of 2:1 for Na:Ca (Hemley and Jones, 1964). Although smectite is the only clay product in Moana, a similar mechanism may account for some of the sodium in solution.

In the presence of excess sulfate, calcium may precipitate as gypsum. Moana thermal fluids contain 450 to 500 PPM sulfate and, although the solution may not be saturated, gypsum was identified in one sample (fig. 11, no. 3) from Moana.

Potassium levels in Moana fluids are low and may also reflect base exchange reactions. Potassium ions fit readily into clay structures and potassium fixation is favored in many clays. Magnesium is rarely a major constituent in thermal fluids. It occurs in higher concentrations in non-thermal waters.

Sulfate is the dominant anion in thermal waters in Moana and may be related to oxidation of sulfides in the volcanic rocks and clays. Well-formed

	1	2	3	4	5	6
SiO_2	5.650	58.500	55.500	66.700	61.40	58.900
Al_2O_3	8.090	7.010	6.150	5.140	3.18	6.940
Fe_2O_3	5.720	6.430	4.630	5.720	6.29	5.150
MgO	1.010	.830	.450	.480	.33	0.730
CaO	1.580	3.430	2.570	.630	.49	2.640
Na_2O	1.980	2.250	.880	.580	2.01	2.560
K_2O	1.000	1.340	.390	.340	1.04	1.040
MnO	.062	.069	.054	.125	.03	0.081
S	.070	.070	3.600	-	-	.100

1. Kate Peak andesite (altered), 1160 Manzanita, 210 ft.
2. Kate Peak andesite (altered), 1160 Manzanita, 255 ft.
3. Pyrite clay, 3705 Lakeside, 255 ft.
4. Diatomaceous siltstone, surface, near Mt. Rose substation
5. Diatomaceous siltstone, 2690 Monterey, 100 ft.
6. Kate Peak andesite (rhyodacite vitrophere - altered), Lakeside, 300 ft.

Table 3. Partial chemical analyses of surface and subsurface rock samples in Moana area.

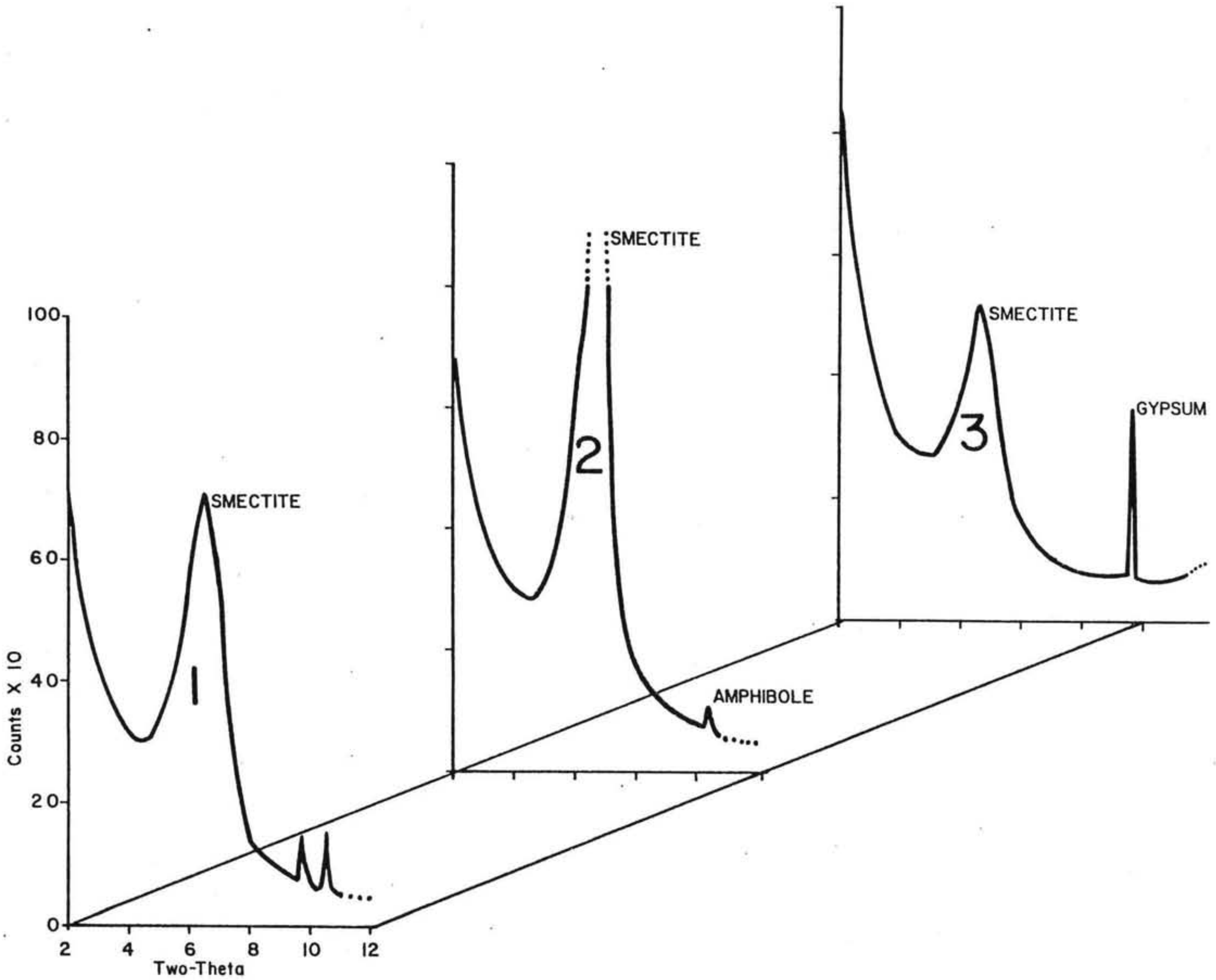


Figure 11. X-ray diffraction patterns of selected drill chips in geothermal wells, Moana area.

pyrite crystals were identified in drill cuttings from a well in north-east Moana. Sulfate waters are common throughout the Truckee Meadows. Most of the moderate temperature geothermal waters in western Nevada are high in sulfate.

Chloride occurs at relatively low levels in Moana thermal fluids, possibly reflecting a low or zero contribution from a magmatic source. Precipitation, believed to be the ultimate source of Moana fluids, generally contains 1 ppm chloride in this area.

Bicarbonate accounts for 15 to 35% of the total anions and its concentration is, in general, inversely proportional to temperature. The highest temperature fluids contain the least amount of bicarbonate. Carbonate is not detected in high pH waters.

Graphical representations are used in water chemistry investigations to classify waters and to identify possible mixing modes. Figure 12 is a trilinear or Piper Diagram (Piper, 1944) based on the relative percent of equivalents of major dissolved species. The small triangles represent relative proportions of cations and anions for a single fluid.

The figure shows that all thermal fluids are predominantly sodium rich. Only non-thermal waters contain appreciable amounts of calcium and magnesium.

The triangle to the right shows three distinct fluid types: high chloride-Steamboat; high sulfate-Moana; and high bicarbonate-non thermal. In addition, mixing of bicarbonate with both Moana and Steamboat fluids can be seen by the compositional variations from the sulfate and chloride species.

The center diagram represents the projection of the data on the adjacent triangles. Unfortunately, due to the nature of this graphic projection, the distinction between Steamboat and Moana fluids is not clear.

An alternate method, which illustrates regional fluid chemistry, is shown in Figure 13. These symbols, known as modified St$\overset{ff}{\text{ill}}$ Diagrams (Stiff, 1953),

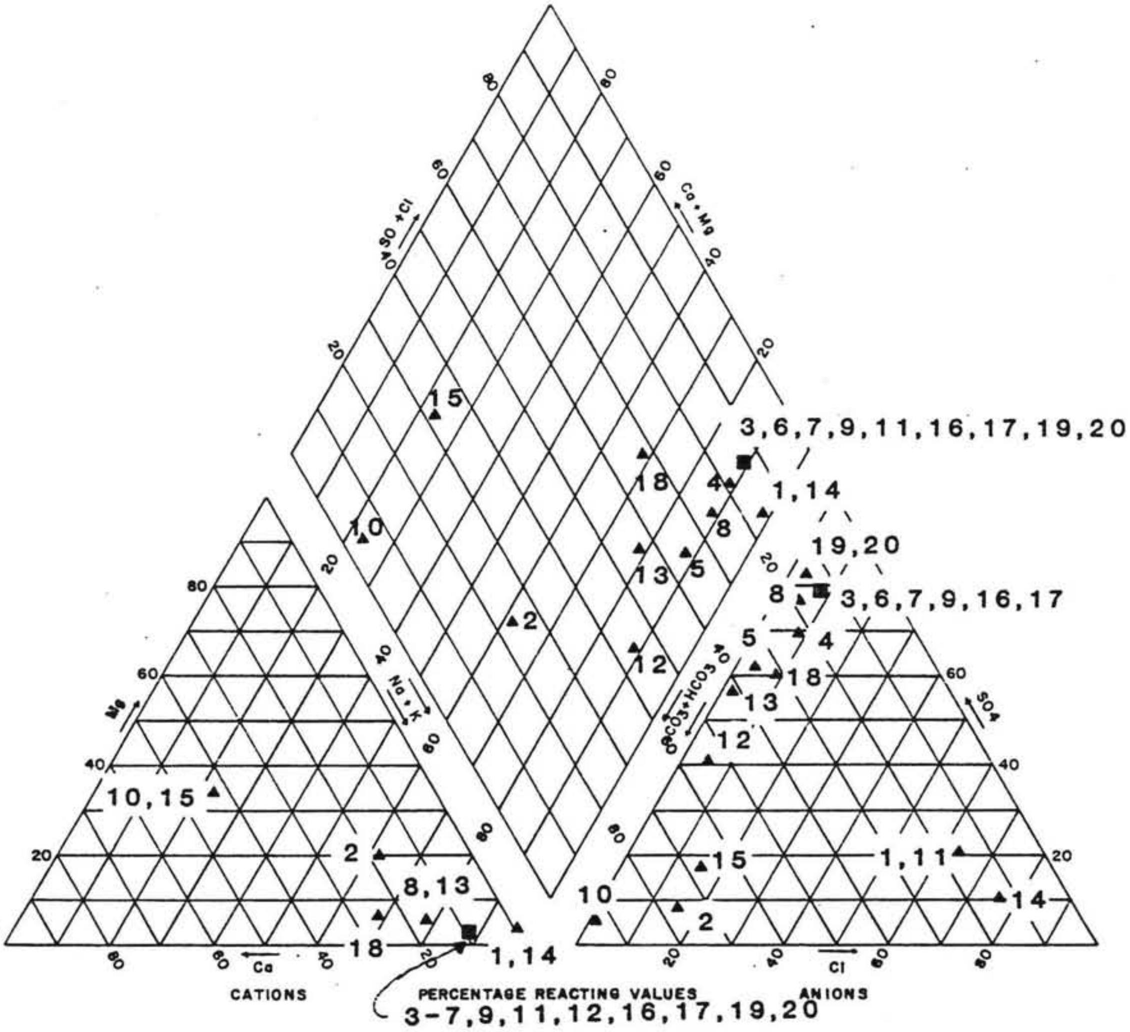


Figure 12. Trilinear diagram showing major chemical characteristics of fluids sampled in Truckee Meadows. (base modified after Piper, 1944)

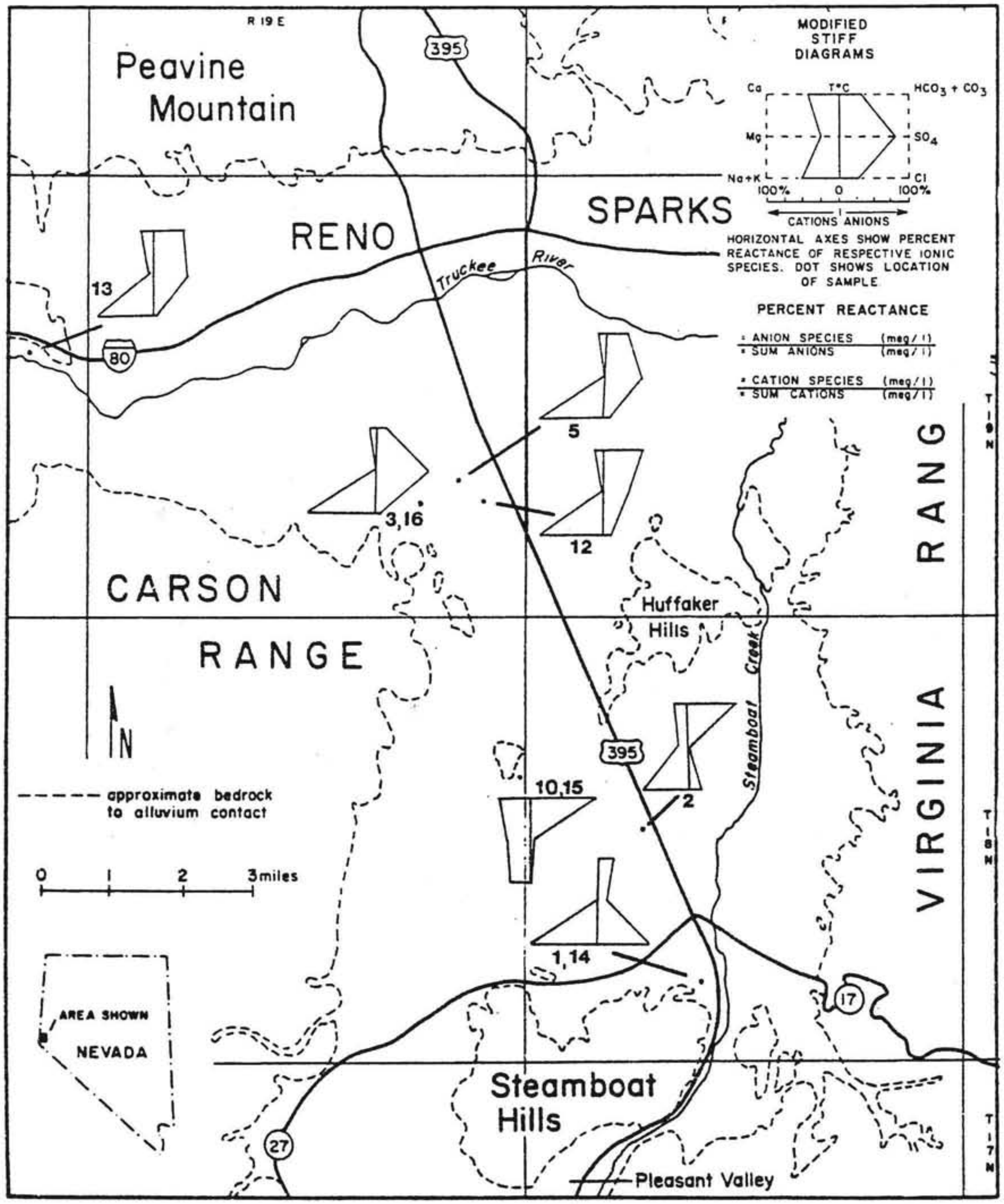


Figure 13. Regional chemical characteristics of thermal and non-thermal fluids in the Truckee Meadows. (diagrams modified after Stiff, 1953; base map modified after Bateman and Schiebach, 1975)

also illustrate the three major water types in the Truckee Meadows. Sodium-chloride-rich waters (1, 14) dominate Steamboat but become more dilute (2) as they mix with calcium-bicarbonate-rich surface waters (10, 15). In Moana, sodium sulfate-rich waters (3, 16) also become more dilute as they flow from west to east and mix with bicarbonate-rich groundwaters (5, 12).

Data from 12 thermal wells in Moana were used to detail the spatial variations in chemical composition. Figure 14 illustrates the variations in sodium and sulfate. In general, both values decrease from west to east. In addition, sodium values appear to be concentrically arranged around a core area that is characterized by high temperature wells. This area also coincides with near-surface water levels. Figure 15 shows the variation in total dissolved solids and boron throughout Moana. These diagrams show a nearly identical contour configuration as Figure 14.

Silica and Chemical Geothermometers

Dissolved silica deserves special attention because it is a major constituent of thermal fluids and may be used to estimate maximum expected reservoir temperatures. Chemical analyses for silica, listed in Tables 1 & 2, show that Moana fluids range from 50 to 120 PPM. Steamboat fluids, by comparison, contain nearly 340 PPM silica.

Figure 16 plots values of silica, shown as log molality SiO_2, against temperatures of fluid samples. Most of the samples from Moana plot in the stability field between alpha and beta cristobalite. This indicates that the fluids are saturated with respect to alpha cristobalite and undersaturated with respect to beta crystobalite, the more soluble of the two polymorphs. Steamboat fluids contain far more silica and are saturated with respect to beta

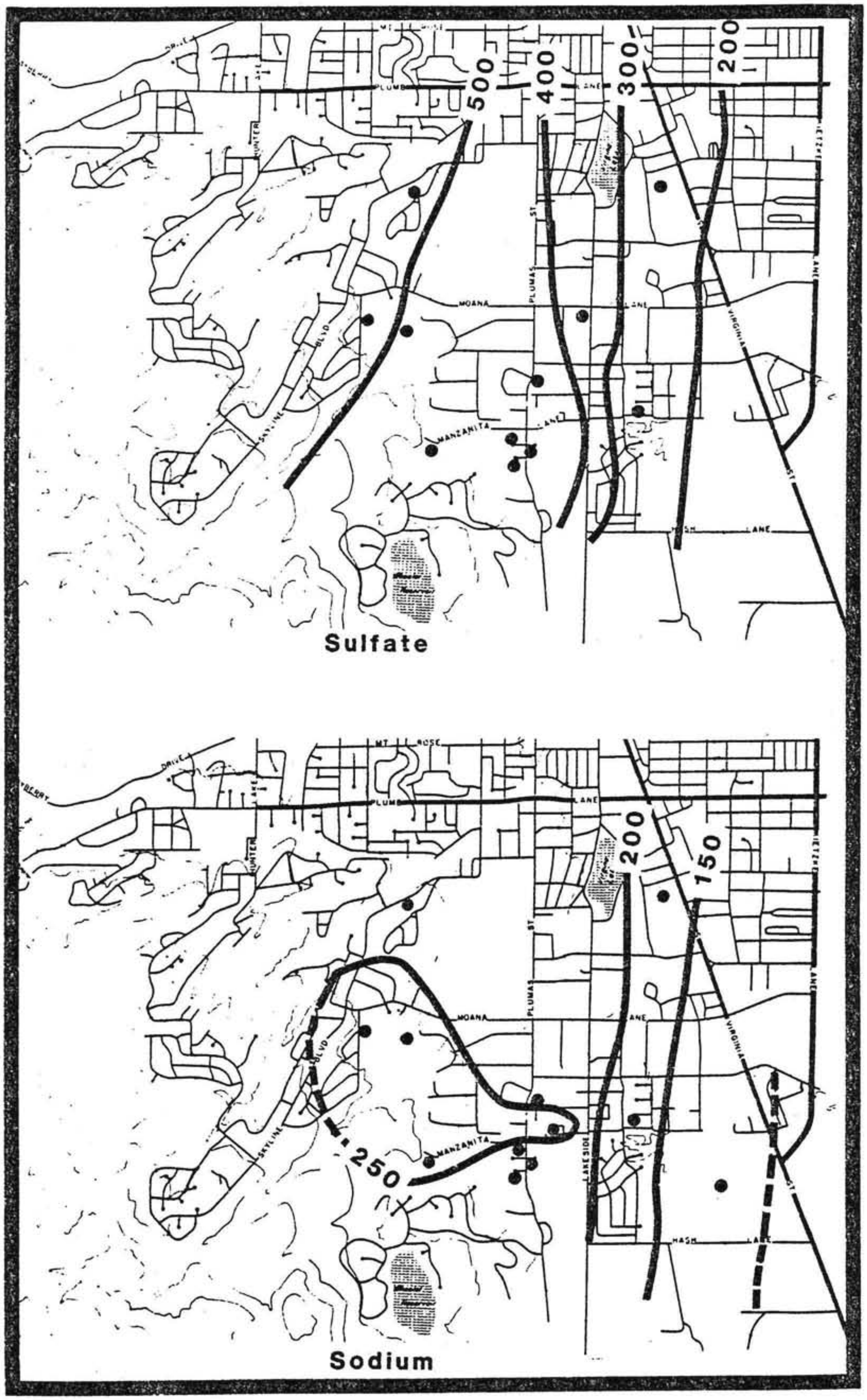


Figure 14. Areal distribution of sulfate and sodium concentrations (ppm) in Moana geothermal fluids.

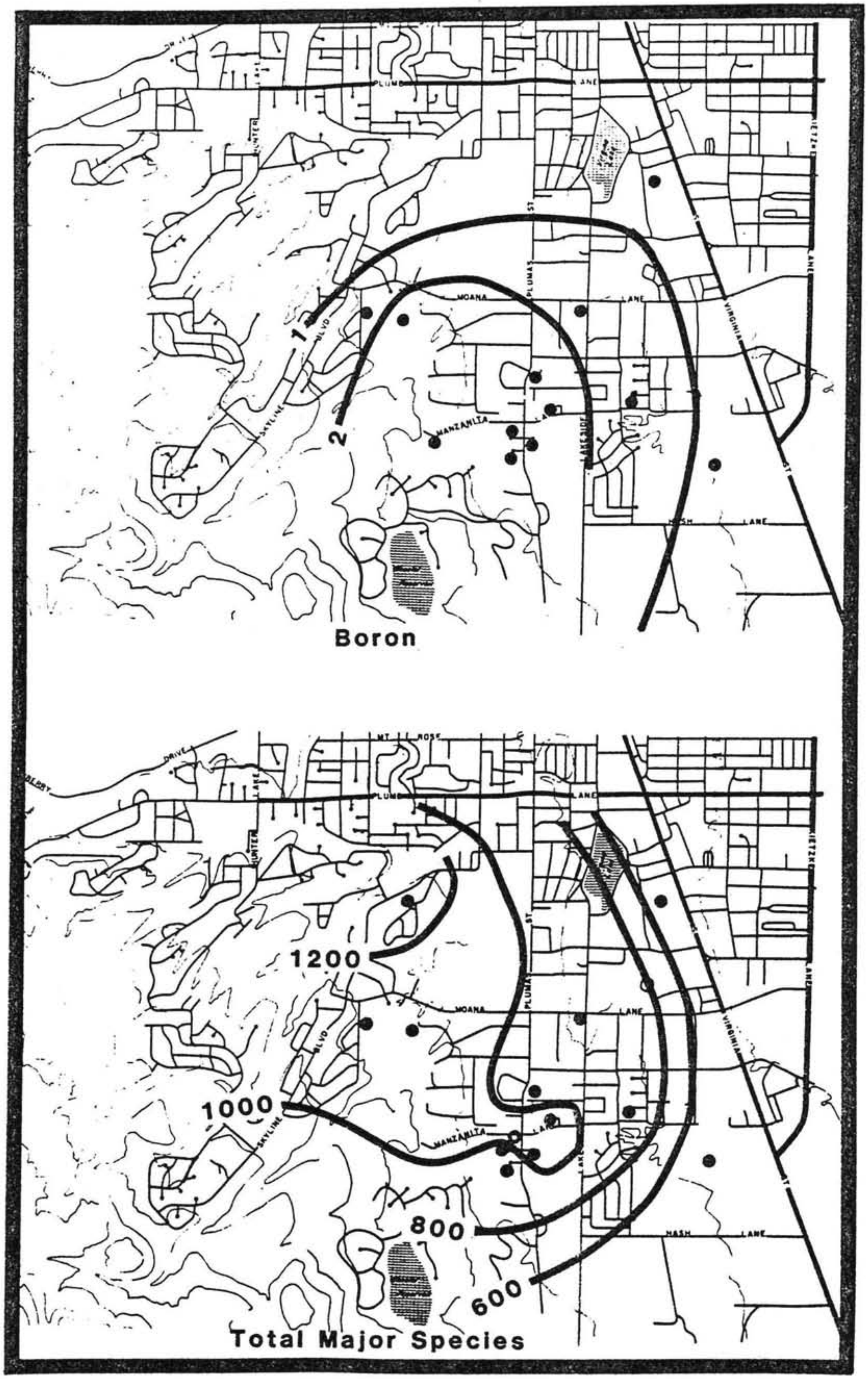


Figure 15. Areal distribution of boron and total major species concentrations (ppm) in Moana geothermal fluids.

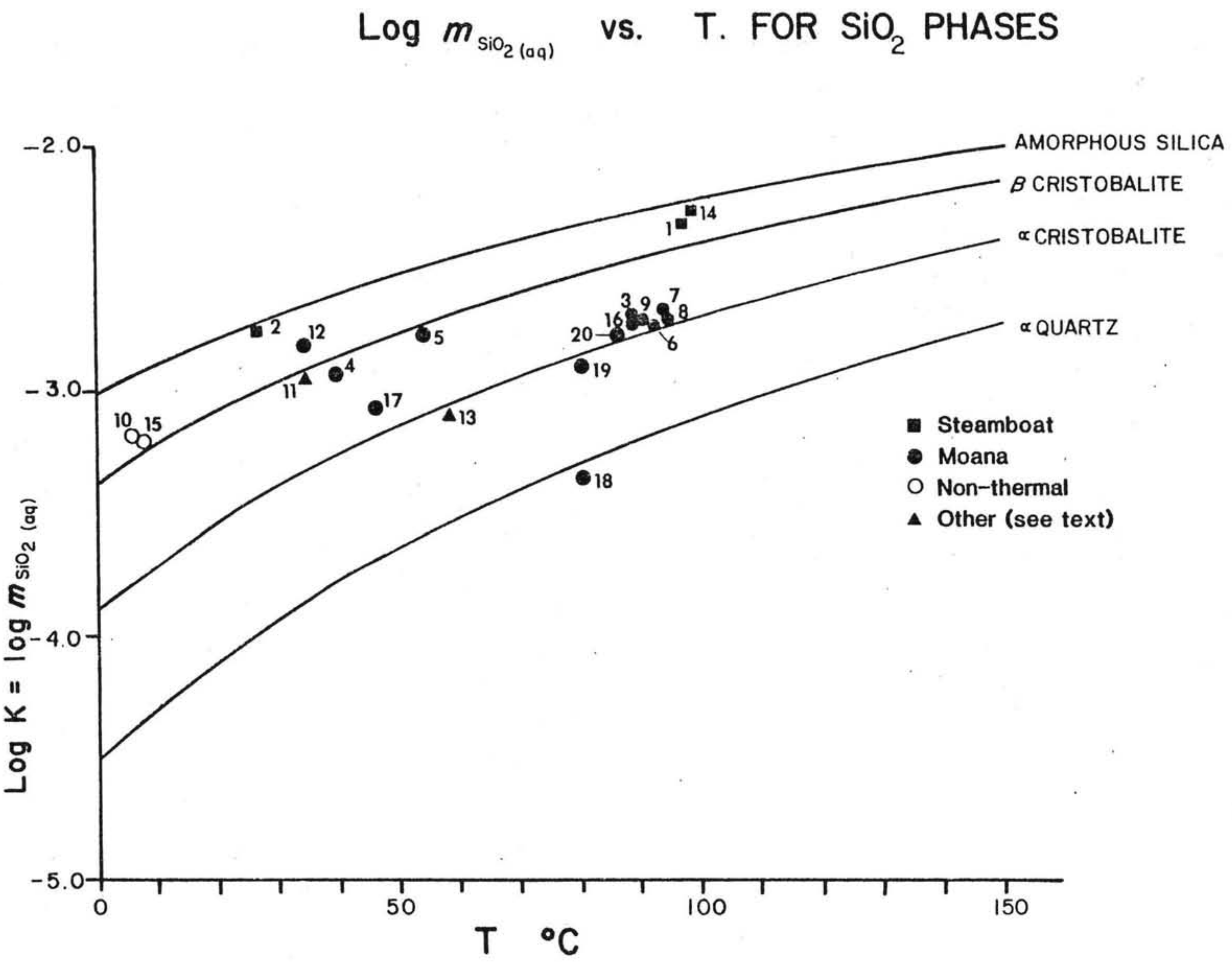


Figure 16. Silica polymorph solubility/temperature curves and fluid sample plots. (diagram modified after Walther and Helgeson, 1977)

crystobalite and undersaturated for amorphous silica, which is the most soluble of all silica species.

The spatial distribution of silica in Moana fluids (fig. 17) is similar to sodium and boron (fig. 14 & 15). The highest values coincide with high temperatures and near-surface fluids. The concentric contours suggest mixing of non-thermal fluids around a point or line-source.

Several chemical geothermometers, based on dissolved silica and polymorph stability, were used to estimate reservoir temperatures for both Moana and Steamboat (Tables 4 & 5). The geothermometers used are: A. quartz, no steam loss; B. quartz, maximum steam loss; C. chalcedony; D. amorphous silica; and E. Na-K-Ca. The data for amorphous silica (D) show inconsistent, often negative, temperatures and should be disregarded. For Moana fluids, the silica geothermometers (A, B, C) predict temperatures ranging from 120 to 150°C. A broader temperature range (85 to 150°C) is suggested by a cation-geothermometer (E) (Fournier and Truesdell, 1973). Although the Moana fluids are mixed with non-thermal fluids, an ultimate fluid temperature of 125° to 130°C appears reasonable. The chemical geothermometers for Steamboat fluids predict reservoir temperatures of 200° to 230°C, which agree very well with previous investigations (White, 1964; Nehring, 1980).

Minor and Trace Constituents

Boron, fluoride and lithium are included as minor constituents, although boron concentrations in Steamboat fluids are 60 ppm (Table 6). All three elements occur commonly in the Earth's crust, but are found in greater abundance in thermal waters associated with recent volcanism. Boron, for example, is a common constituent of volcanic gas and may condense as orthoboric acid (H^3BO^3) in thermal waters. Fluoride and lithium are abundant in igneous rocks and are

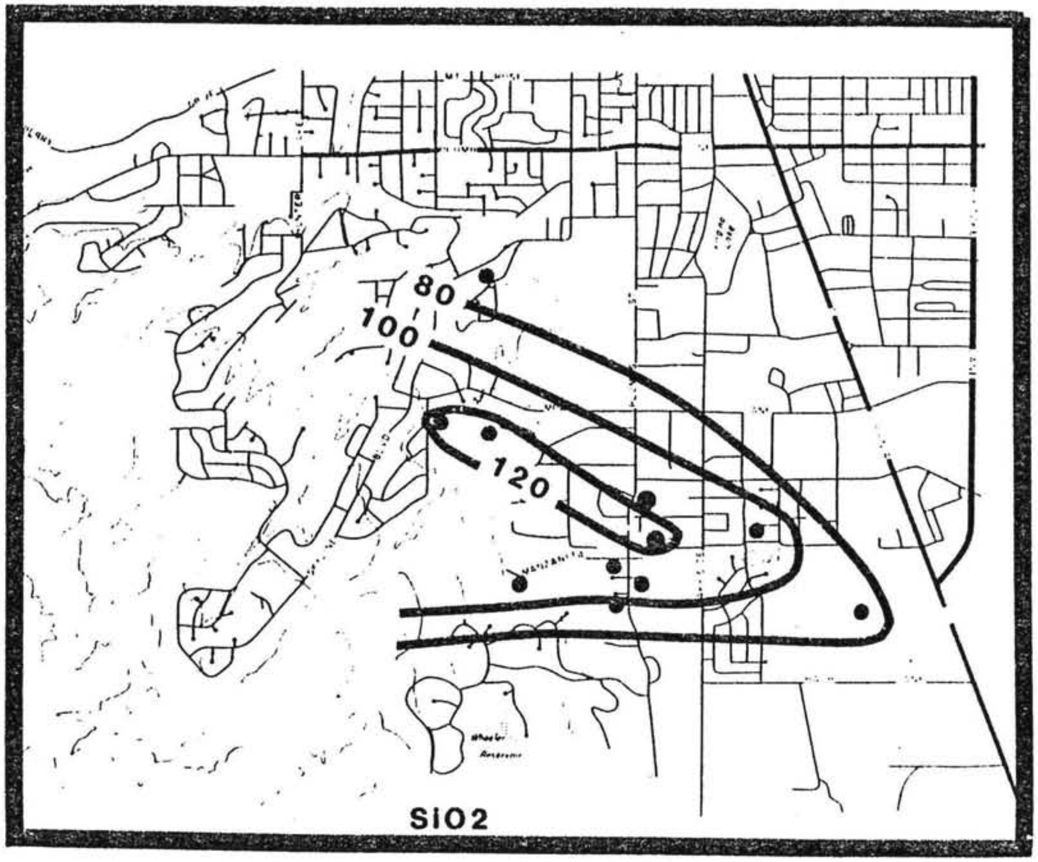


Figure 17. Areal distribution of silica concentrations (ppm) in Moana geothermal fluids.

SAMPLE DESIGNATOR	NUM	SUM CATIONS	SUM ANIONS	IONIC BALANCE	RELATIVE PERCENTS (EQUIVALENTS)						Chalcedony Na-K-Ca CHEMICAL GEOTHERMOMETERS					
					Ca	Mg	Na+K	CO_3+HCO_3	Cl	SO_4	A	B	C	D	E	BETA
Steamboat MB-1	1	32.813	29.985	1.095	.749	.034	99.217	16.310	73.120	10.570	214.9	196.3	199.8	90.1	229.9	1.0
Zolezzi MB-2	2	4.389	4.795	.915	19.924	15.597	64.478	77.529	19.367	3.103	141.5	136.4	115.3	20.8	217.4	1.0
Miles MB-3 (depth 30 m)	3	12.833	12.737	1.008	9.592	.135	90.273	13.963	10.884	75.152	147.6	141.5	122.1	26.3	144.0	1.0
Moana Lane MB-4 (depth 50.3 m)	4	11.523	12.397	.930	9.074	.100	90.825	24.784	9.158	66.058	125.8	123.0	97.9	6.8	135.6	1.0
McKay MB-5 (depth 69.5 m)	5	7.885	8.238	.957	9.068	.638	90.294	34.159	8.750	57.091	139.9	135.0	113.5	19.4	153.9	1.0
Desjarden MB-6 (depth 89.5 m)	6	12.766	12.682	1.007	9.681	.065	90.255	12.283	10.686	77.031	144.1	138.5	118.2	23.2	148.2	1.0
Warren Est. MB-7 (depth 254 m)	7	13.557	13.038	1.040	8.931	.024	91.044	13.633	11.358	75.009	151.0	144.3	125.9	29.4	145.0	1.0
Newburg MB-8 (depth ≈150 m)	8	15.486	15.972	.970	16.003	2.905	81.093	19.933	7.502	72.565	149.6	143.1	124.3	28.1	149.6	1.0
Gadda MB-9 (depth 30 m)	9	12.079	13.020	.928	10.442	.048	89.510	14.667	10.298	75.035	142.6	137.2	116.5	21.8	147.7	1.0
Thomas Crk. MB-10	10	.883	1.144	.772	43.988	31.610	24.402	95.053	1.270	3.677	94.4	96.1	63.9	-20.3	45.7	4.0

Table 4. Relative percents (equivalents) of major ions and chemical geothermometers for fluid samples 1 through 10. See text for geothermometer key.

SAMPLE DESIGNATOR		NUM	SUM CATIONS	SUM ANIONS	IONIC BALANCE	RELATIVE PERCENTS (EQUIVALENTS)						CHEMICAL GEOTHERMOMETERS Chalcedony Na-K-Ca					
						Ca	Mg	Na+K	CO_3+HCO_3	Cl	SO_4	A	B	C	D	E	BETA
Farad	MB-11	11	12.806	13.507	.948	9.671	.443	89.886	16.027	70.032	13.941	120.3	118.4	91.9	2.0	155.3	1.0
Quillicy	MB-12	12	5.702	6.148	.928	8.858	1.287	89.855	55.285	7.137	37.578	135.7	131.5	108.9	15.6	99.3	4.0
River Inn	MB-13	13	6.462	6.630	.975	17.518	2.632	79.849	43.825	4.335	51.840	98.8	99.9	68.6	-16.6	48.0	4.0
Steamboat	MB-14	14	33.201	33.731	.984	.730	.018	99.252	15.608	78.072	6.320	219.0	199.6	204.7	94.2	229.4	1.0
Thomas Creek	MB-15	15	.643	1.560	.412	46.244	29.018	24.737	68.476	18.137	13.387	89.5	91.9	58.8	-24.4	37.5	4.0
Miles	MB-16	16	12.248	13.206	.927	10.550	.081	89.370	15.839	10.906	73.255	146.7	140.6	121.0	25.4	96.3	4.0
Edmiston	MB-17	17	11.642	12.713	.916	7.156	.007	92.836	18.987	6.780	74.233	105.9	106.1	76.3	-10.5	96.4	4.0
Dicapprio	MB-18	18	2.687	2.696	.997	24.382	3.621	71.997	31.005	10.677	58.318	76.3	80.3	44.8	-35.5	48.8	4.0
S. Bermuda	MB-19	19	11.926	12.173	.980	11.169	.028	88.803	16.525	4.741	78.735	126.3	123.5	98.4	7.2	85.2	4.0
N. Bermuda	MB-20	20	11.953	12.376	.966	11.270	.062	88.668	16.240	4.659	79.100	142.6	137.2	116.5	21.8	94.9	4.0

Table 5. Relative percents (equivalents) of major ions and chemical geothermometers for fluid samples 11 through 20. See text for geothermometer key.

Sample Name	Sample #	As	Ba	Fe	Mn	Sr
Steamboat	1	1780	50	<50	<10	800
Zolezzi	2	85.8	130	<50	<10	210
Miles	3	33.8	<20	<50	10	490
Moana Lane	4	22.7	<20	<50	10	240
McKay	5	27.4	<20	50	<10	180
Desjardin	6	27.4	<20	<50	<10	550
Warren Est.	7	29.0	<20	<50	<10	500
Newberg	8	12.0	40	280	960	540
Gadda	9	31.2	<20	<50	20	520
Thomas Crk.	10	<1.0	30	60	<10	100
Farad	11	1100	<20	<50	<10	70
Quillicy	12	<1.0	<20	<50	<10	150
River Inn	13	<1.0	10	<50	<10	110
Steamboat	14	3200	60	10	<10	900
Thomas Crk.	15	<1.0	30	20	<10	100
Miles	16	<1.0	20	30	10	500
Edmiston	17	<1.0	30	10	<10	470
Decapprio	18	<1.0	20	50	10	260
S. Bermuda	19	<1.0	30	680	<10	390
N. Bermuda	20	<1.0	30	190	<10	530

*All units PPB.

Table 6. Trace element concentrations in fluid samples (ppb)

highly soluable. Concentrations of both boron and lithium in Steamboat fluids far exceed respective Moana values. On the other hand, Moana fluids contain far more fluoride than Steamboat. These data suggest two different source rocks for these fluids. Physiological damage to bones and teeth in humans has been directly related to high fluoride concentrations in water. For this reason, it is important to consider fluoride levels in direct use of geothermal fluids. In Washoe County, Nevada, levels exceeding 1.8 ppm are considered unsafe. In Moana, fluoride concentrations range from 3 to 5 ppm.

Arsenic is also an important constituent to consider because it is highly toxic in even very low concentrations. For the Reno area, a concentration of 0.05 ppm is considered unsafe. None of the Moana fluids have arsenic concentrations in excess of 0.034 ppm. Fluids sampled in the Steamboat area have arsenic concentrations of .86 to 1.78 ppm.

Arsenic and lithium concentrations for the second set of Moana samples (11-20) are much lower than the first set. As an example, the Miles well (MB-3 and MB-16) had .26 ppm lithium and .34 ppm arsenic for the February analyses (MB-3). In July, the respective values for the same well (MB-16) dropped to <0.01 and <0.001 ppm. This appears to be the situation for all these fluids and may simply be analytical errors associated with the second sampling.

Strontium is a trace element common in igneous rocks. It is chemically similar to calcium and in Moana, high concentrations of strontium appear to be directly related to high temperatures. Lower concentrations of strontium are found in cold waters and intermediate concentrations are found in what appears to be mixed thermal and non-thermal fluids. Barium, iron, and manganese are found in trace and relatively insignificant concentrations in thermal and non-thermal fluids in both Steamboat and Moana.

Stable Light Isotopes

Analysis of stable light isotope compositions (δD and $\delta^{18}O$), in conjunction with chemical analyses, provides information on fluid recharge and thermal processes. Isotopic studies rely principally on fractionation processes that occur in natural water. Evaporation, boiling, and high-temperature rock/water interaction may be detectable in geothermal fluids by analyzing ratios of deuterium and oxygen-18. Water is isotopically "heavy" if it becomes enriched in deuterium and oxygen-18. Depletion of these isotopes yields an isotopically "lighter" fluid.

Craig (1963) analyzed several thousand water samples for deuterium and oxygen-18 content relative to Standard Mean Ocean Water (SMOW). By graphic analysis, Craig found that most meteoric water plotted along a line such that $\delta D = 8\,\delta^{18}O + 10^{\circ}/oo$. Deviations along this line could be accounted for by differences in elevation of precipitation and by periods of prolonged evaporation. Heavier isotopes are, in general, the first to precipitate and the last to evaporate. All isotopic analyses are now compared to the worldwide meteoric line of Craig (1963).

Isotopic data obtained during this study are listed in Table 7 and shown graphically in Figure 18. Three important groups of water can be identified in this diagram. Group I represents local meteoric fluids and mixed geothermal fluids from the Truckee Meadows. This group includes surface non-thermal waters as well as most of the lower temperature Moana geothermal fluids. Group II consists largely of the high temperature (>75°C) Moana fluids and is isotopically "lighter" than group I. This distinction is the result of elevation differences of the initial precipitation. For example, fluids from group I are derived from precipitation that fell at an elevation of approximately

Sample, Name, Temperature	$\delta^{18}O$ °/oo	δD °/oo
M1 Steamboat, 96°C	-12.0	-115.3
M2 Zolezzi, 27°C	-10.5	-93.9
M3 Miles, 89°C	-15.9	-130.5
M4 Moana Lane, 40°C	-14.4	-113.2
M5 McKay, 54°C	-14.2	-108.8
M6 Desjardin, 77°C	-16.0/-15.8	-122.4
M7 Warren Estates, 87°C	-16.1	-128.9
M8 Newburg, 95°C	-15.8	-128.0
M9 Gadda, 90°C	-15.9	-122.9
M10 Thomas Creek, 6°C	-15.1	-114.0
M11 Farad Spring, 35°C	-13.5	-114.8
M12 Quillicy Well, 34°C	-13.8	-110.5
M13 River Inn, 58°C	-14.9	-115.4
M14 Steamboat Springs	-11.6	-115.5
M15 Thomas Creek, 7°C	-14.8	-114.0/-113.3
M16 Miles, 90°C	-15.6	-125.4
M17 Edmiston, 46°C	-15.5	-110.1
M18 Decapprio, 80°C	-12.3/-12.5	-96.9
M19 S. Bermuda, 81°C	-15.8	-115.5
M21 Steamboat, blow well 90°C	-10.9	-107.9
B1 Barnett, 30°C	-13.1	-111.0
B2 Barnett, 30°C	-13.3/-13.1	-107.0
G1 Gadda, 90°C	-15.0	-122.0
G2 Gadda, 90°C	-15.1	-114.0
M1 Miles, 90°C	-15.6	-114.0
P1 Peppermill	-13.3	*-84.0/-85.0
P2 Peppermill	-14.8	-110.0/-111.0

(* "suspect data")

Table 7. Deuterium and oxygen-18 analytical results for fluid samples 1 through 21. Additional samples from Ghusn, 1982.

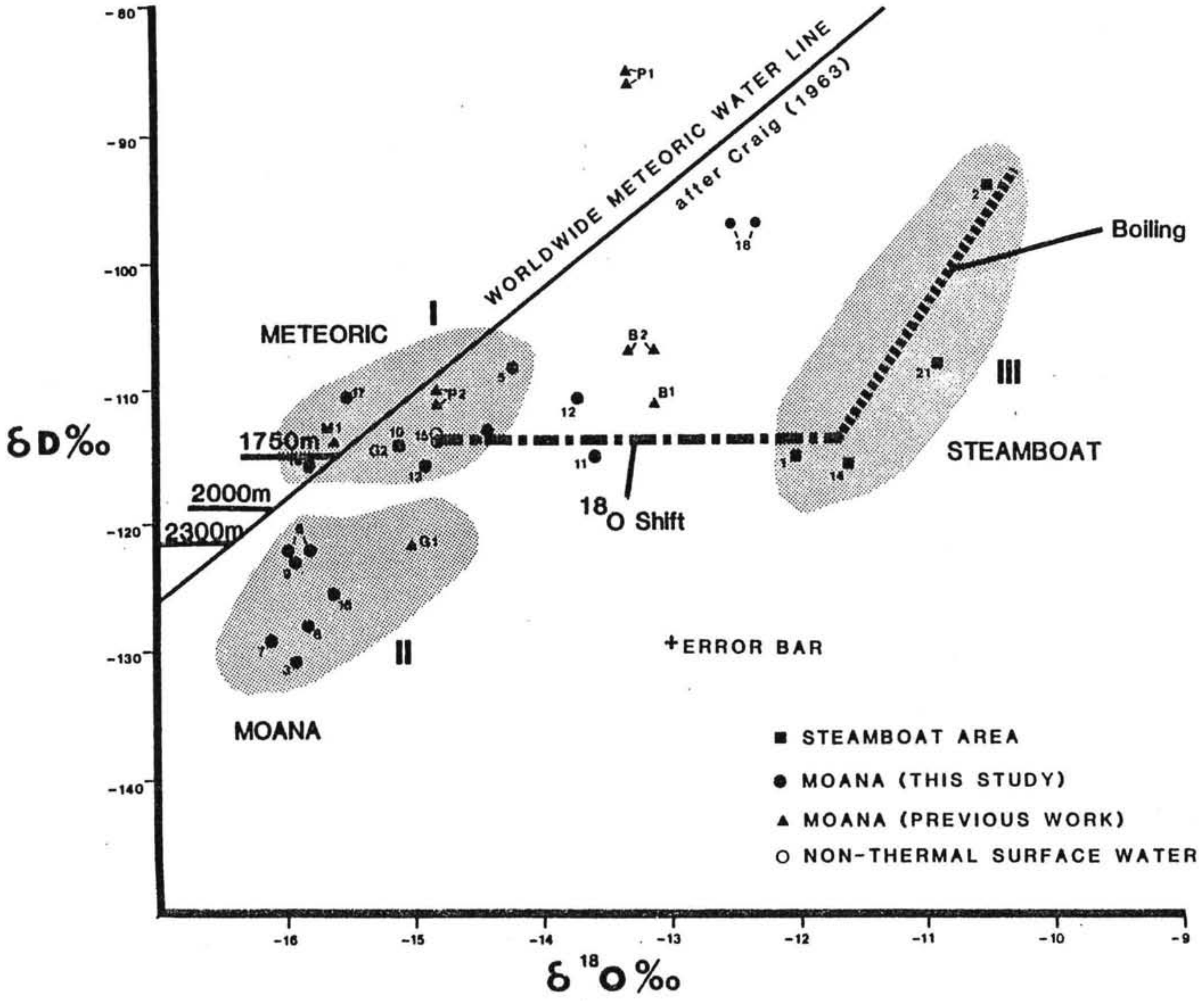


Figure 18. Deuterium and oxygen-18 ratios of fluid samples vs. worldwide meteoric water line (modified after Craig, 1963).

1750 m (5740 ft.) above sea level. Group II fluids are derived from precipitaeion that fell at an elevation of approximately 2300 m (7500 ft.). Koenig and others (1981) demonstrated that fluids sampled from a single stream at different elevations within a 24 hour period became progressively enriched in deuterium and oxygen-18. This suggests that fractionation continues at the surface and that isotopic signatures can be retained only if the precipitation penetrates into the subsurface immediately.

Group III includes Steamboat Hot Springs fluids only. These data illustrate a complex process known simply as the oxygen-18 (isotope) "shift". The Steamboat fluids (1, 14) have essentially the same deuterium content as do meteoric waters (10, 15), but they differ in oxygen-18 by more than 3°/oo. The oxygen-18 shift occurs in high temperature geothermal fluids throughout the world. Simple mixing cannot account for constant deuterium in each foreign fluid. This shift was explained by Craig and others (1956) as a process of isotope exchange between geothermal fluids and rocks at elevated temperature. Under these conditions, oxygen-18 in the fluid and rock are exchanged. This generally results in higher oxygen-18 values for water and lower values for rock. A shift in deuterium is generally not evident because most rock-forming minerals contain insignificant amounts of hydrogen relative to oxygen. The magnitude of the oxygen-18 shift depends on initial isotope ratios in fluids and rock, temperature, and duration of contact. Nehring (1980) suggested a minimum temperature of 140°C to account for the oxygen-18 shift in Steamboat fluids.

The results of this analysis show that Moana fluids can be distinguished from Steamboat fluids on the basis of both chemical and isotopic composition. Nehring (1980) proposed, on the basis of isotopic analyses from fluids collected at various elevations in the Carson Range, that the recharge area for Steamboat Springs extended from Evan's Creek south to Thomas Creek at an average elevation of 1920 m (6300 ft.) (fig. 19). Based on the same elevation data, Moana fluids recharge from precipitation that falls at an elevation in excess of 2400 m (8000 ft.).

Figure 20 shows the extent of mixing of thermal and non-thermal fluids in Moana on the basis of isotopic composition. The contours show essentially the same dispersion pattern as seen for other dissolved constituents and support the hypothesis of point or line source thermal fluid discharge.

Tritium

Tritium (^3H) is the radioactive isotope of hydrogen (H) and has a half-life of 12.26 years. It is commonly used in well tracer studies and for semi-quantitative estimates of the age of waters.

Tritium is produced naturally in the upper atmosphere by cosmic ray spallation and by the interaction of fast neutrons with nitrogen (Fairbridge, 1972). Between 1952 and 1963, atmospheric thermonuclear testing greatly increased pre-bomb tritium levels. Pre-bomb measurements suggest that natural tritium levels ranged from 4 to 25 T.U. ($1 \text{ T.U.} = {}^3H/H = 10^{-18}$) depending on hemisphere, latitude, and precipitation. For northern hemisphere, mid-latitude precipitation, Fairbridge (1972) estimates that the pre-bomb tritium level was approximately 10 T.U.

Since 1952, there have been three major episodes of atmospheric thermonuclear detonations which produced 3 major peaks in tritium concentrations for precipitation in the northern hemisphere: 1000 T.U., 1954; 1700 T.U., 1959; and 2200 T.U., 1963 (Fritz and Fontes, 1980). In addition, many minor peaks as well as seasonal variations have been identified. These inconsistent levels of tritium since 1952 have essentially ruled out its use as an absolute age of

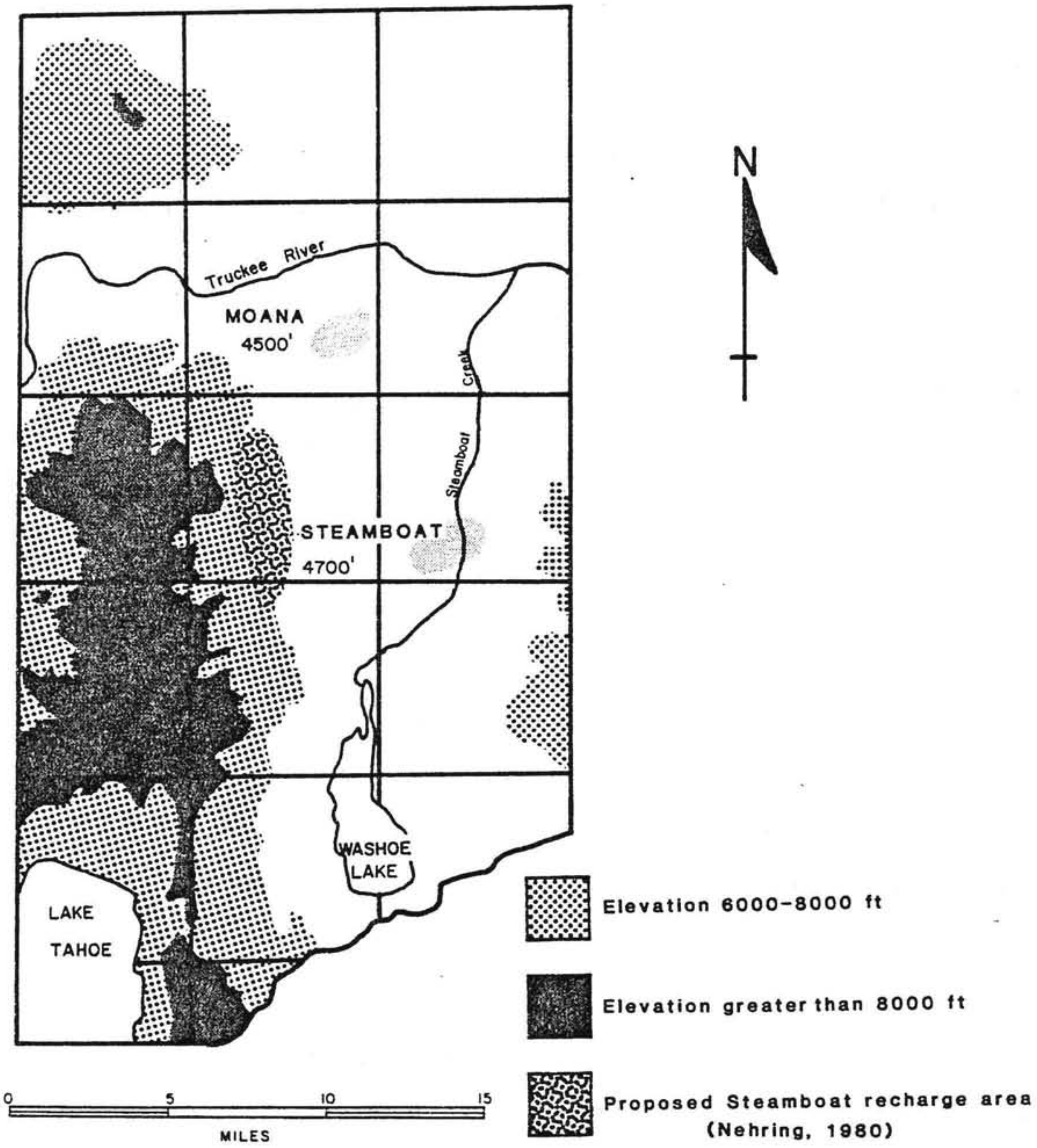


Figure 19. Possible recharge areas for Steamboat and Moana geothermal fluids.

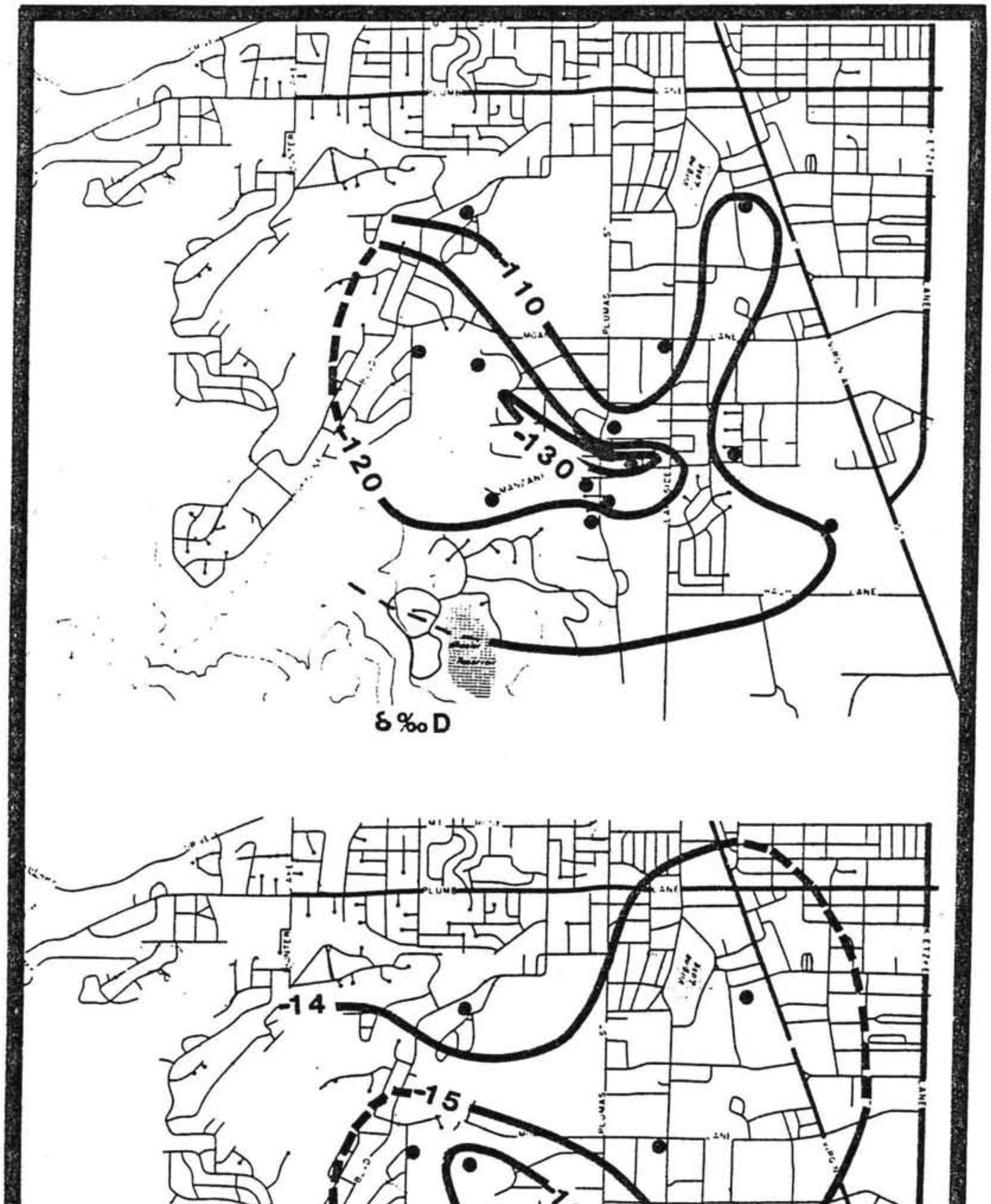
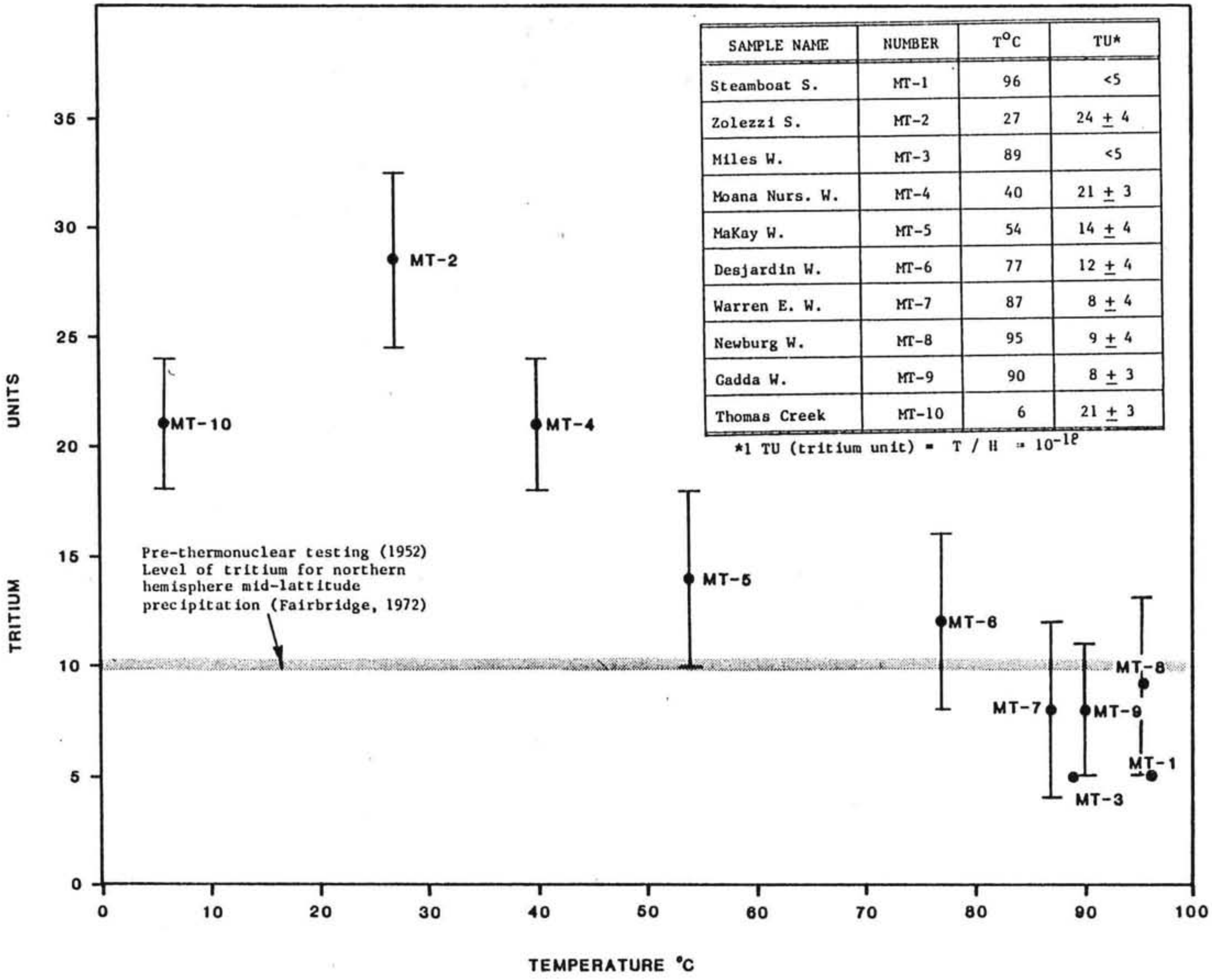


Figure 20. Areal distribution of deuterium and oxygen-18 concentrations (per mil) in Moana geothermal fluids.

fluids. Instead, tritium is most often used in conjunction with carbon-14 dating techniques to identify "contamination" by modern, carbon-bearing waters in older geothermal fluids.

Tritium analyses were completed for 10 fluid samples collected in the Truckee Meadows. The analytical results are tabulated in Figure 21 and are also shown graphically with respect to fluid temperature. The data suggest a simple, near-linear relationship of increasing T.U. and decreasing fluid temperature. However, since it is not possible to determine the initial level of tritium in the fluid due to the tremendous variations in the past, current tritium levels cannot be used to estimate a unique fluid age by standard radioisotope decay techniques.

However, the presence of any tritium in these fluids does represent an influx of "modern" (<30 years old) water. All but two samples contain detectable quantities of tritium. Samples MB-1 and MB-3 contain fewer than 5 T.U., which is the quoted resolution of the equipment used in the analysis. Based on this understanding of tritium, it appears that samples MB-1 and MB-3 contain no modern water. Sample MB-1 is from a flowing spring at Steamboat. Sample MB-3 is from a nearly constantly pumped thermal well in Moana. Figure 22 is a contour diagram of tritium concentrations from sampled wells in Moana. The configuration of the contours is identical to similar diagrams of chemical and stable light isotope concentrations. MB-3 appears to be at or near the location of the springs that ceased to flow in Moana. All other samples contain various amounts of tritium and have, to a greater or lesser degree, mixed with "modern" meteoric waters.



SAMPLE NAME	NUMBER	T°C	TU*
Steamboat S.	MT-1	96	<5
Zolezzi S.	MT-2	27	24 ± 4
Miles W.	MT-3	89	<5
Moana Nurs. W.	MT-4	40	21 ± 3
MaKay W.	MT-5	54	14 ± 4
Desjardin W.	MT-6	77	12 ± 4
Warren E. W.	MT-7	87	8 ± 4
Newburg W.	MT-8	95	9 ± 4
Gadda W.	MT-9	90	8 ± 3
Thomas Creek	MT-10	6	21 ± 3

*1 TU (tritium unit) = T / H = 10^{-18}

Pre-thermonuclear testing (1952) Level of tritium for northern hemisphere mid-lattitude precipitation (Fairbridge, 1972)

Figure 21. Analytical results and plot of tritium vs. fluid temperatures for samples 1 through 10.

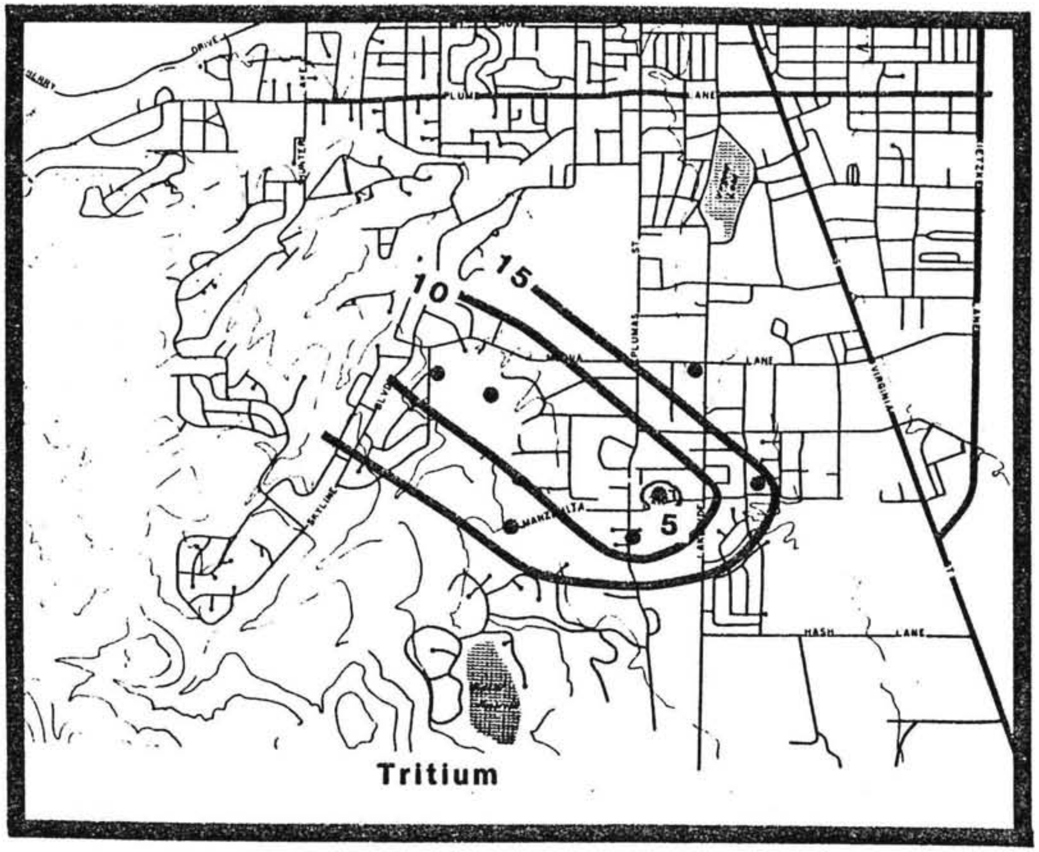


Figure 22. Areal distribution of tritium concentrations (T.U.) in Moana geothermal fluids.

Carbon Isotopes

Sample Collection

Ten fluid samples were collected and analyzed for carbon isotopes to obtain additional information on geothermal water origin in the Moana thermal area. A complete discussion of the theory of groundwater dating by carbon-14 methods is given in Appendix II. Thermal fluids sampled included two springs and seven shallow-depth wells. A mountain creek was sampled for the purpose of obtaining $\delta C^{13}/12$ and $\delta C^{14}/12$ values.

Waters that were sampled for carbon isotopes required special treatment. These fluids were first collected and analyzed for bicarbonate and carbonate. Since a minimum of two grams of carbon is required for both $\delta C^{13}/12$ and $\delta C^{14}/12$ analysis, the volume of water needed to precipitate 10 grams of $SrCO_2$ (2g of C) was calculated for each sample by:

$$\text{Volume (liters)} = \left[10{,}000 \text{ mg } CO_3^{=}\right] / \left[HCO_3^{-} + CO_3^{=} \text{ in PPM}\right] \quad \text{(IAEA, 1971)}$$

Thermal fluid volumes ranged from 33 liters (9 gallons) to 108 liters (28 gallons); 152 liters (40 gallons) were required for Thomas Creek. This is a minimum volume; approximately 30% more water should be collected. In addition, "older" waters which have proportionately less carbon-14 require significantly more sample fluid to accurately measure the carbon-14 activity (Teledyne Isotopes, 1979). Approximately 132 liters (35 gallons) were collected from each thermal source and 265 liters (70 gallons) from Thomas Creek to ensure accurate C-14 activity measurement.

Samples MB-1 and MB-2 were collected and precipitated on February 22, 1983. Sample MB-1 (Steamboat) was collected at a seep location which is probably the same location as sample 21n described by Nehring (1980). Samples

MB-3, MB-4, and MB-5 were collected on February 23, 1983. Samples MB-7, MB-8, and MB-9 were collected on February 24, 1983, and MB-6 and MB-10 (Thomas Creek) were collected on February 25, 1983.

Sample MB-1 was precipitated at the sample location; all other samples were transported in a "sealed drum" to a laboratory for precipitation which resulted in a maximum of 45 minutes between collection and initial precipitation. Longer lag time before precipitation would result in CO_2 degassing which may alter sample chemistry. To ensure collection of fresh groundwater samples, all thermal well samples were collected after the well was pumped for approximately 15 minutes.

Sample Precipitation

The procedure used for precipitation of carbonate from samples consists of placing the water into a container sealed from the atmosphere, raising the pH to convert bicarbonate species to carbonate species, followed by addition of strontiium chloride to precipitate $SrCO_2$.

The apparatus used to precipitate carbonate consists of a stainless steel funnel with a working volume of 132 liters (35 gallons). The inverted pyramid-shaped funnel is supported by a wood frame. The top of the funnel has a foam seal and a large piece of plexiglass as a lid (see fig. 23). The plexiglass has a center hole through which a shaft and mixing paddle are attached. The solution is agitated with a hand-crank. Additional holes in the lid supply pressurized nitrogen for evacuating air above the water, a vent hole, and a hole for supplying chemicals.

The three-inch diameter valve at the bottom of the funnel has been modified to accomodate a two liter bottle to collect the precipitate. The bottles are made of linear polyethylene, necessary to reduce CO_2 exchange between the

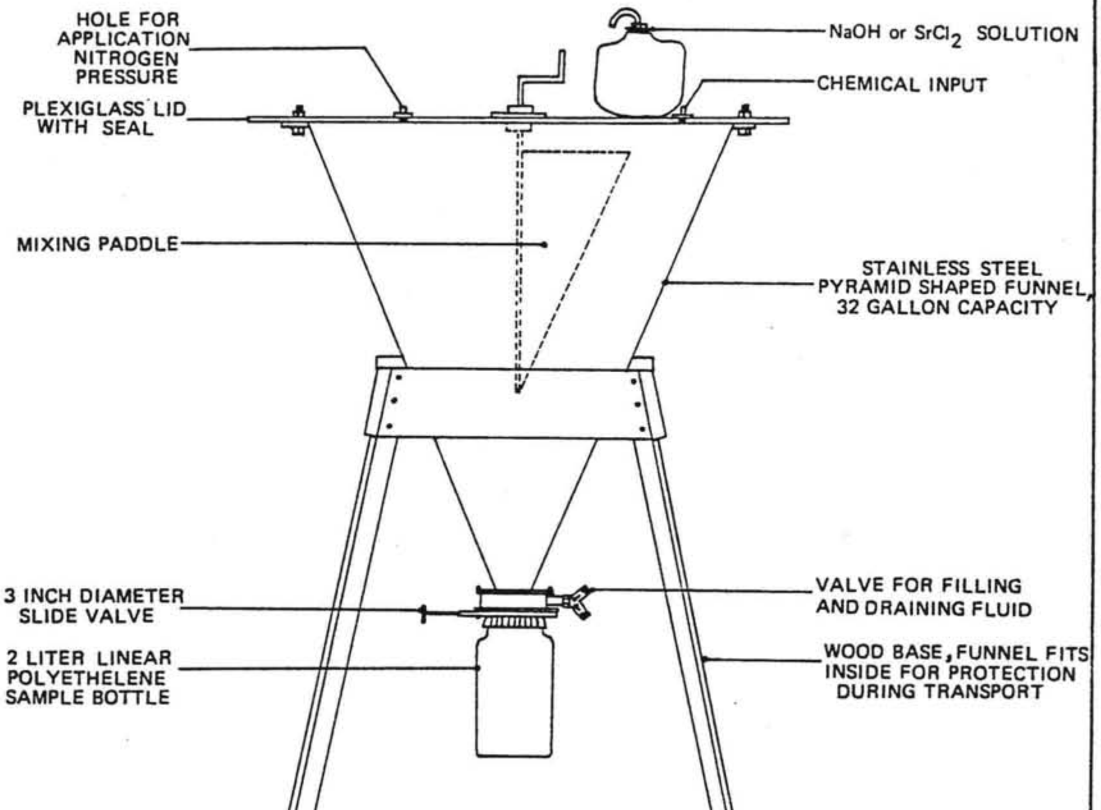


Figure 23. Schematic of carbonate precipitator used in this study.

sample and the atmosphere. The precipitator was on loan from the Water Resources Division, U.S. Geological Survey in Carson City, Nevada.

The procedure for precipitation consists of first slowly filling the precipitator with sample water with a minimum of agitation. The plexiglass lid is then installed and nitrogen is introduced to remove air from inside the precipitator and minimize CO_2 exchange of sample with air. Unfortunately, the temperature of the thermal fluids was often high enough to cause the plexiglass cover to melt. The cover was only used for samples MB-2, MB-4, MB-8 and MB-10. A floating precipitate formed on those samples without a lid, probably from atmospheric CO_2 dissolving in the water. This precipitate was skimmed off and not allowed to enter the sample bottle. Vogel (1967) analyzed two samples from the same source where air was bubbled continuously through one during collection. The $\delta^{14}C$ values were within 0.2°/oo and the $\delta^{13}C$ within 0.05°/oo of one another, which suggested little problem due to air contamination. Two chemicals are needed for precipitation:

(1) A 6N, carbonate-free, sodium hydroxide solution. This is prepared by using boiled, distilled, deionized water to remove carbonate. A small amount of the $SrCl_2$ solution is added to precipitate out any carbonate left, and only the clear NaOH solution is siphoned into cubitainers. Ten liters were prepared for the 10 samples.

(2) A strontium chloride solution. This is prepared by dissolving 454 grams of $SrCl_2 6H_2O$ in one liter of distilled, deionized water. Again, a small amount of NaOH solution is added to precipitate any remaining carbonate, and the clear supernatant solution is siphoned into cubitainers (adapted after Pearson, 1970). Ten liters were prepared for the 10 samples. Both chemicals were prepared by the Desert Research Institute, Water Resources Center Analytical Laboratory.

Approximately 500 to 1000 ml of the NaOH solution is necessary to raise the pH of the sample water to 12, converting virtually all carbonate species to carbonate. 1000 ml of NaOH were added to MB-1, MB-2, and MB-6; 500 ml were added to all other samples. The pH was checked with pH indicator paper. Approximately 1000 ml (500 ml added to MB-1, MB-2, and MB-5) of the $SrCl_2$ solution was then added to create the following spontaneous chemical reaction:

$$CO_3^{-2} + Sr^{+2} \text{<>} SrCO_3$$

The precipitated strontium carbonate was collected in the sample bottle. Precipitation did not occur immediately in sample MB-6 and fifteen grams of $FeSO_4 \cdot 7H_2O$ were added, producing coarse agglomerates upon which $SrCO_3$ crystallized. This resulted in the precipitation of $SrCO_3$. Nehring (1980) suggested adding a few grams of cadmium chloride, releasing H_2S which acts as a flocculating agent. This should be added before the NaOH and $SrCl_2$ solutions.

Most samples were allowed to precipitate for 2 to 6 hours. The fluid was stirred intermittantly. Sample MB-5 was precipitated for 17 hours. Additional $SrCl_2$ solution was added to ensure complete $SrCO_3$ precipitation. When precipitation was completed, the valve at the bottom of the funnel was closed, and the precipitate removed. This equipment can accomodate enough water to precipitate two grams of carbon from samples with a bicarbonate content as low as 80 ppm. Two volumes of water were necessary for Thomas Creek (MB-6). This was accomplished by closing the bottom sample valve, draining off the water, and reprecipitating more water.

Analytical Techniques

All ten carbon isotope samples were sent to the Radiocarbon Dating Laboratory, Washington State University, Pullman, Washington, for analysis of carbon-14 activity, and δC13/12.

Pre-analysis treatment of the samples consisted of filtering the strontium carbonate and drying. After pretreatment, CO_2 is generated from the carbonate samples by acidification. The CO_2 is then purified in a vacuum system to remove halides, sulfur compounds (such as $FeSO_4$), oxides of nitrogen, and electronegative species which affect the counting characteristics of the gas. Radon is extracted routinely and the purified CO_2 is ready for counting (Teledyne Isotopes, 1981).

Actual radiometric measurement is made by proportional counting of the CO_2 gas housed in a lead and steel shield. Sample purity is monitored by noting the counting characteristics of an external gamma radiation source at low voltage. All samples were counted two to three times, 1000 minutes each time (Currie, 1972), to eliminate the possibility of error due to traces of residual contamination by radioactive radon gas, and to produce greater precision and sensitivity. Samples could be accurately counted in 8 minutes if an anti-coincedence circuit is employed (Faure, 1977). Data are reported as deviation in parts per thousand from the oxalic acid standard.

All samples were also analyzed for δC13/12, which is accomplished with a mass spectrometer using a technique similar to oxygen and hydrogen stable isotope analysis. The δC13/12 reproducibility is about ± 0.7% (Fritz, Suzuki, Silva and Salati, 1981).

Analytical Results and Discussion

Analytical results for the ten samples collected from the Moana and Steamboat thermal areas, are presented in Table 8. Carbon-14 activities are presented as percent modern carbon (PMC%), which can be compared to modern carbon (100% PMC). Two separate methods for correcting the carbon-14 activity were used in this study. The first method assumes a single recharge area and single "dead" carbon dilution source. In this case, photosynthetic plants in the recharge area produce soil-CO_2 (^{13}C=-25%); "dead" carbon is assumed to have a ^{13}C = +0.0%. This method (footnotes 3-6 on Table 8) produces corrected carbon-14 ages that are believed to be unrealistically young (Wigley, 1975; Payne, 1972). Because many of the corrected activities exceed 150% PMC, these values probably represent a minimum corrected age. Sample MB-10 (Thomas Creek) was not corrected with this method because the CO_2 is derived from the atmosphere (δC = -6.4%) and is not plant-produced CO_2.

The second correction method presented assumes two recharge sources; plant-CO_2 (^{13}C = -6.4%) and either atmospheric CO_2 (^{13}C = -6.4%) or arid plant-CO_2 (^{13}C = -12%). The net effect is a mixture of -25% and (-6.4% or -12%) which produces a mixture of ^{13}C = -17.1%. A value of -17.1% was used in this study because sample MB-2 represented a sample with little or no dead carbon (C-14 = 105% PMC, and modern tritium activity). In Carson City, Nevada, Szecsody (1982) used -17.3%; in Fallon, Nevada, Glancy (1980) used a value of 15%. Corrected carbon-14 ages with use of -17.1% probably represent the maximum corrected age. The plus and minus values represent laboratory error.

A third method was evaluated in the calculation of corrected carbon-14 ages. This method (Pearson and White, 1967) assumes a single recharge source (-25%) and "dead" carbon dilution source. With this method, individual samples produce the same corrected ages as the first method described and, by grouping

			1	2		3	4	5	6	7	8	9	6
SAMPLE	TEMP (^{o}C)	^{3}H TRITIUM (TU)	δ^{14}C (‰)	C-14 ACTIV. (PMC%)	δ^{13}C (‰)	P (FRACTION)	1-P (%)	CORRECTED C-14 ACTIV. Ac (PMC%)	CORRECTED MIN. AGE Ka	P' (FRACTION)	1-P' (%)	CORRECTED C-14 ACTIV. Ac' (PMC%)	CORRECTED MAX. AGE Ka
MB-1 Steamboat	96	<5	-998 ± 648	.200 ± 32%	-6.2	.248	75%	0.806%	39.85	.376	62%	.532%	43.30 ± 24.0
MB-2 Zolezzi	27	24 ± 4	+46 ± 0.3	104.6 ± .03%	-17.1	.684	32%	152.9%	RECENT	1.000	0%	100.00%	RECENT
MB-3 Miles	89	<5	-776 ± 26	22.4 ± 2.6%	-10,1	.404	60%	55.4%	4.88	.591	41%	37.90%	8.02 ± .45
MB-4 Moana Lane	40	21 ± 3	-188 ± 1	81.2 ± 0.1%	-15.5	.620	38%	131.0%	RECENT	.906	9%	89.60%	.91 ± .003
MB-5 McKay	54	14 ± 4	-337 ± 3	66.3 ± 0.3%	-13.9	.556	44%	119.0%	RECENT	.812	18%	81.60%	1.68 ± .037
MB-6 Desjarden	77	12 ± 4	-552 ± 24	44.8 ± 2.4%	-11.2	.448	55%	100.0%	RECENT	.655	35%	68.40%	3.14 ± .10
MB-7 Warren Est.	87	8 ± 4	-885 ± 84	11.5 ± 8.4%	-10.3	.412	59%	27.9%	10.55	.602	40%	19.10%	13.68 ± 1.73
MB-8 Newburg	33	9 ± 4	-987 ± 116	1.30 ± 6.45%	-6.6	.264	74%	4.9%	24.89	.386	61%	3.37%	28.03 ± 7.38
MB-9 Gadda	90	8 ± 3	-782 ± 13	21.8 ± 1.3%	-11.8	.472	53%	46.2%	6.39	.690	31%	31.60%	9.53 ± .18
MB-10 Thomas Crk.	6	21 ± 3	+208 ± 6	120.8 ± 0.6%	-5.0	(.781)[10]	-	(155.0%)	(RECENT)	-	-	-	-

1) $\delta^{14}C\,‰ = \left(\frac{A\ \text{sample}}{A\ \text{standard}} - 1\right) 1000$

2) $A(PMC\%) = \frac{\delta^{14}C\,‰ \cdot A_o}{1000} + A_o$ where $A_o = 13.56$ dPM/g

3) $P = \delta^{13}C$ sample/-25 = fraction datable, from recharge area assuming single recharge source.

4) 1-P = approximate dead carbon dilution

5) $Ac = \frac{A}{P}$ only when activity is reported in dPM/g or PMC

6) $t = -8267\ LN\left[\frac{A}{A_o}\right] = -8267\ LN\left[Ac(PMC)\right]$ with T½ = 57.3 Ka, and A(PMC) reported as a fraction not percent ± represents laboratory error (± 2s). Ka = 1000 years

7) $P' = \delta^{13}C$ sample/-17.1, see text

8) 1-P' = approximate dead carbon dilution

9) $Ac' = \frac{A}{P'}$, only when sample activity is reported in dPM/g or PMC

10) Surface water sample; $P_s = \delta^{13}C$ sample/-6.4

Table 8. Analytical results and corrected ages for carbon isotopes in samples 1 through 10. (Ka = 1000 yrs.)

samples, corrected ages were only slightly different from the first method. Therefore, results from this analysis were not included in this report.

Table 8 also lists the results of the corrections. Ages for the thermal waters ranged from recent (<.5 Ka) to 43.3 Ka (Ka = 1000 years). There was some correlation of measured temperature with estimated age (fig. 24).

Steamboat Springs (MB-1) fluids suggest an age of 39.85 to 43.3 Ka (± 24.0 Ka for two standard deviation units). The unusually large two standard deviation units indicate that the sample activity is at the minimum detection limits and approaches background activity. Nehring (1980) reported four samples from Steamboat Hot Springs, Nevada, with ages that ranged from recent to less than 5 Ka. These values were not corrected with respect to carbon-13 and represent a maximum age. Craig (1963) noted that the ^{14}C activity of thermal fluids at Steamboat was less than 0.5% of modern carbon and suggested that Steamboat fluids spend a minimum of 30 Ka, and possibly longer, underground.

The carbon-13 value indicates that 62-75% of the carbon in the water is dissolved limestone. This is a reasonable conclusion since carbonate deposits are mapped in the Steamboat area. Sample MB-1 has <5 T.U., indicating little or no mixing with recent waters. Although given modern precipitation of 30 T.U. (Szecsody, 1982), there could be less than 15% modern water in the Steamboat sample (mixed with old water) which would make the total tritium activity 5 T.U. To ascertain more accurately if any water from Steamboat Springs has any modern water in it, a tritium analysis with detection and accuracy of ±0.2 T.U. is necessary. Nehring (1980) analyzed nine samples from various seeps at Steamboat Springs and reported: seven were <0.7 T.U., one was 4.8 ± 0.4 T.U., and one was 12.0 ± 0.6 T.U. These data suggest that the two tritium-rich samples could have resulted from contamination by modern atmospheric tritium. The

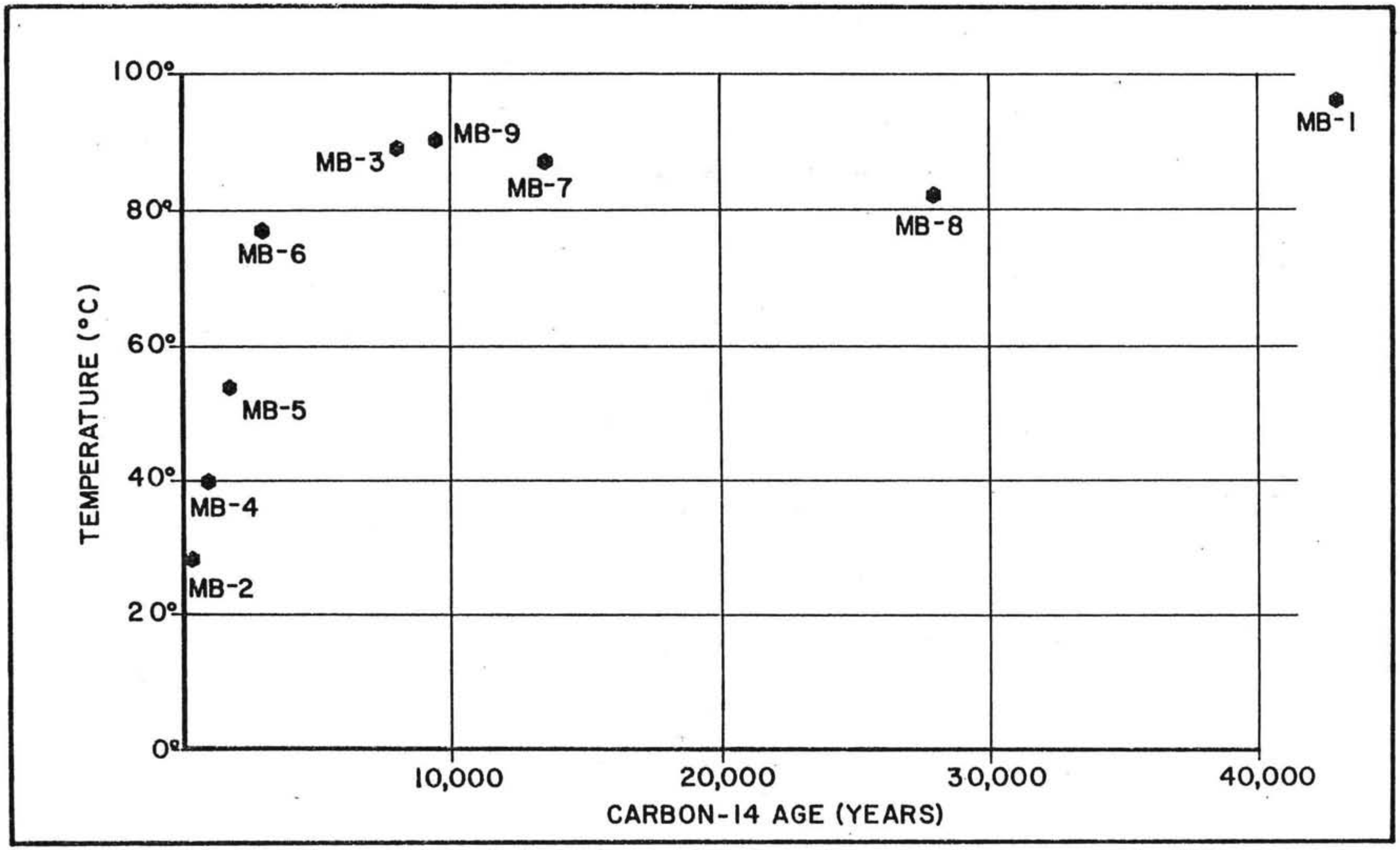


Figure 24. Corrected carbon-14 age vs. fluid temperature for samples 1 through 10.

other seeps and springs which contain <0.7 T.U. indicate essentially no mixing with recent (<.05 Ka) water.

Major ion chemistry indicates this sample is predominantly Cl-rich water, typical of the group of oldest waters in the Nevada basin and range (group C), based on analyses of 1040 samples (Bohm, 1982).

Sample MB-2 is a thermal spring located several kilometers north of Steamboat which has an uncorrected carbon-14 activity of 105% PMC, and contains modern tritium 24 ± 4 T.U. This sample contains over 100% PMC because some of the carbon-14 was introduced within the past 30 years, as seen in the modern tritium values, when atmospheric thermonuclear testing increased C-14 activity to approximately 180% PMC. This water is either a mixture of very old and recent (30 year old) water, or it is water <10 years old, when tritium levels in the atmosphere in Nevada would now have decayed to 20-40 T.U. Sample MB-2 affords another unique calculation; the carbon-13 value of -17.1% indicates a mixture of ^{13}C sources. This mixture could be: 59% (-25%) + 41% (-6.4%) = -17.1%. This means about 60% of the water has equilibrated within a soil zone in the high-altitude recharge areas, and about 40% is from infiltration of water with an atmospheric CO_2 - $\delta^{13}C$. This appears most likely since two recharge sources of -25% and -12% have not been identified or reported (Payne, 1972). In addition, the use of a value of -17.1% for calculating corrections or carbon-14 activity has been successfully used in other studies in the area.

Sample MB-3, collected from a thermal well, has a corrected age of 4.88 to 8.02 Ka (±.45 Ka). The sample also contained <5 T.U., indicating that it consists of 15% or less modern water (>30 years). This sample age is probably correct, since modern water apparently has not altered the C-14 activity. The tritium content of MB-3 is significantly different from other Moana samples (MB-4, 5, 6, 7, 7, and 9). Sample MB-3 $\delta^{13}C$ indicates that about 41-60% of the

carbonate in the water is from dead carbonate (dissolved flow path carbonate).

Sample MB-4 contains 21 ± 3 T.U. and has a corrected carbon-14 age of recent to .91 Ka (±.03 Ka). This indicates that most of the water was recently recharged, and the apparent age is probably the result of dead carbon dilution (estimated at 9-38% of the sample carbonate).

Sample MB-5 contains 14 ± 4 T.U. The corrected age is recent to 1.68 Ka (±.038 Ka). The tritium activity indicates that the flow cycle is <30 years suggesting that this sample contains considerable dilution from modern water. It is impossible to correct the C-14 activity for modern water dilution along with dead carbon dilution correction. Therefore, the apparent age of any samples containing tritium and measurable ^{14}C have questionable C-14 ages. The apparent corrected C-14 age may be derived entirely from modern water diluted with dead carbon (<.5 Ka water with a C-14 activity of 100-180% PMC plus >50.0 Ka water with 0% PMC yields recent water with an apparent ^{14}C age). For example, sample MB-4 could be a mixture of 68% modern water (activity 120% PMC) and 32% water with an activity of 0% PMC which would equal its reported C-14 activity of 81%. A dead carbon dilution of 32% is within the range of 9-38% approximate dead carbon based on carbon-13 analysis.

Sample MB-6 contains 12 ± 4 T.U. and has a corrected carbon-14 age of recent to 3.14 Ka (±.1 Ka). Again, due to the presence of tritium, which was also noted in the Fallon area (Glancy, 1980), the sample could be of recent age with dilution of dead carbon. This can be approximated by 38% modern water (120% PMC) plus 62% dead carbon (0% PMC) equaling the reported C-14 activity of 45% PMC. The carbon-13 analysis suggests that dead carbon dilution is in the range of 3-55%. It is also possible that the water is a mixture of 2 recharge sources, dead carbon and modern water; in this case, an estimation of the percentages of each component is very difficult.

Sample MB-7 contains 8 T.U. and has a corrected carbon-14 age of 10.55 to 13.68 Ka (±1.73 Ka). The sample is partially diluted by recent water (<.03 Ka). It is not possible for this sample to be composed entirely of modern water and dead carbon. Ten percent modern water (120% PMC activity) plus 90% dilution from dead carbon (0% PMC) is needed to equal the sample activity of 11.5% PMC. The carbon-13 analysis suggests that dead carbon dilution is in the range of 40-60%, so 90% carbon derived from limestone is unrealistic. Sample MB-7 probably represents a mixture of old water (>500 years), modern water (<30 years), with some dead carbon dilution. Note that samples MB-6, MB-7, and MB-9 have virtually identical chemistry. Sample MB-6 shows a more recent C-14 age, which is in agreement with its higher tritium activity (12 T.U. versus 8 T.U. for the other samples). Samples MB-6, MB-7, and MB-9 probably are the same water.

Sample MB-8 has a tritium activity of 9 ± 4 T.U. and a corrected carbon-14 age of 24.89 to 28.03 ± 7.38 Ka. The sample is partially diluted by modern water, but as with MB-7, the C-14 activity of 1.3% suggests that the water cannot be realistically composed of modern water plus dead carbon. Dead carbon dilution ranges from 61 to 74%. This sample could be composed of 29% old water (1% PMC), 1% modern water (120% PMC) and 70% dead carbon (0% MPC), producing a C-14 activity of 1.5% PMC. The modern water must be about 20 years old with a decayed tritium activity of 500 T.U., which is possible, since tritium in precipitation in southern Nevada reached 1500 T.U. This solution is unlikely because for a 9 T.U. tritium activity, the carbon-14 activity should be considerably higher.

Sample MB-9 contains 8 ± 3 T.U. and has a corrected carbon-14 age of 6.39 to 9.53 Ka (±.18 Ka). This sample is chemically identical to MB-7, so the same conclusions apply; MB-9 probably represents a mixture of 7.5 Ka water, modern water (<.03 Ka) and dead carbon.

Sample MB-10 is surface water with a carbon-14 activity of 120% PMC and a tritium activity of 21 ± 3 T.U. This represents modern precipitation values for these isotopes. The C-14 activity had increased to 180% during the 1960's; exact numbers in the basin and range are unknown. Dilution of this sample (^{13}C = -6.4% for atmospheric CO_2) by dead carbon (0%) may also be the result of atmospheric isotopic variation.

In conclusion, the carbon isotope age data were shown to be somewhat ambiguous when compared with tritium data. This demonstrates that conclusions regarding the age of fluids should not be based strictly on the carbon-14 method.

In general, a number of samples (MB-4, MB-5, MB-6, MB-7, MB-8, and MB-9) probably represent a mixture of old water (>.5 Ka), modern water (<.03 Ka), and dead carbon. The carbon-13 analysis establishes a range of dilution by dead carbon. The presence of tritium in these samples means that the C-14 ages are invalid, since the percentage of modern water dilution is unknown. In addition, samples MB-4, MB-5, and MB-6 could represent a mixture of entirely modern water and dead carbon. Modern water could account for 40-70% of the volume for these samples.

Samples MB-1 and MB-3 were not shown to be diluted by modern water (<5 T.U.). Sample MB-1, Steamboat Springs, which has a corrected age of 39.85 to 43.30 Ka (±24.0 Ka) may be questionable since at least one worker at Steamboat Springs (Nehring, 1980) did not report C-14 ages greater than 5.0 Ka. However, it can still be concluded that the Steamboat recharge cycle is on the order of several thousand to 40,000 years, with little modern water dilution. Sample MB-3 contains less than 15% modern (<30 years) water, based on tritium data (<5 T.U.), and the age is approximately 8.02 Ka (±.45 Ka). Even with some (<15%) modern water dilution, the average age would still be on the order of several thousand years. All waters containing measurable tritium indicate that some recharge during the past 30 years has occurred.

OBSERVATION/MONITOR WELLS

SITE SELECTION AND DRILLING SPECIFICATIONS

In order to accurately determine the effects of thermal fluid withdrawal during the heating season (October through March), five observation/monitor wells were drilled in strategic locations throughout the Moana geothermal area (fig. 25). Four wells (1, 2, 3, 4) were drilled to a total depth of 400 feet. The remaining well (5) was drilled to a depth of 800 feet.

Drill site selection consisted of consideration of areas of heavy resource use, geophysical anomalies, and available open space. Since virtually all open space is owned by the City of Reno or Washoe County, 4 of the 5 wells were drilled on public land. Wells 1 and 4 are located on City of Reno land and wells 2 and 3 are located on land owned by Washoe County. Well 5 is located on Warren Estates property approximately 125 feet east of the Warren Estates production well.

After drill sites were selected it became necessary to obtain a permit to drill. Usually temperature gradient holes must be backfilled and abandoned after measurements have been made. This requirement was waived and a permit (W116) was issued on March 21, 1983.

Well design included casing the six to seven inch diameter hole with 2 1/2 inch diameter T/C steel pipe to total depth. The bottom 20 feet of the casing has torch-cut perforations and is gravel-packed. The remaining annulus is back filled with cuttings to within 50 feet of the surface where the annulus is filled with cement (fig. 26).

Well drilling was performed by Fred Anderson & Sons Exploration Drilling, Inc., of Woods Cross, Utah. Drilling began on May 14, 1983, and proceeded smoothly until well 5 was completed on May 28, 1983.

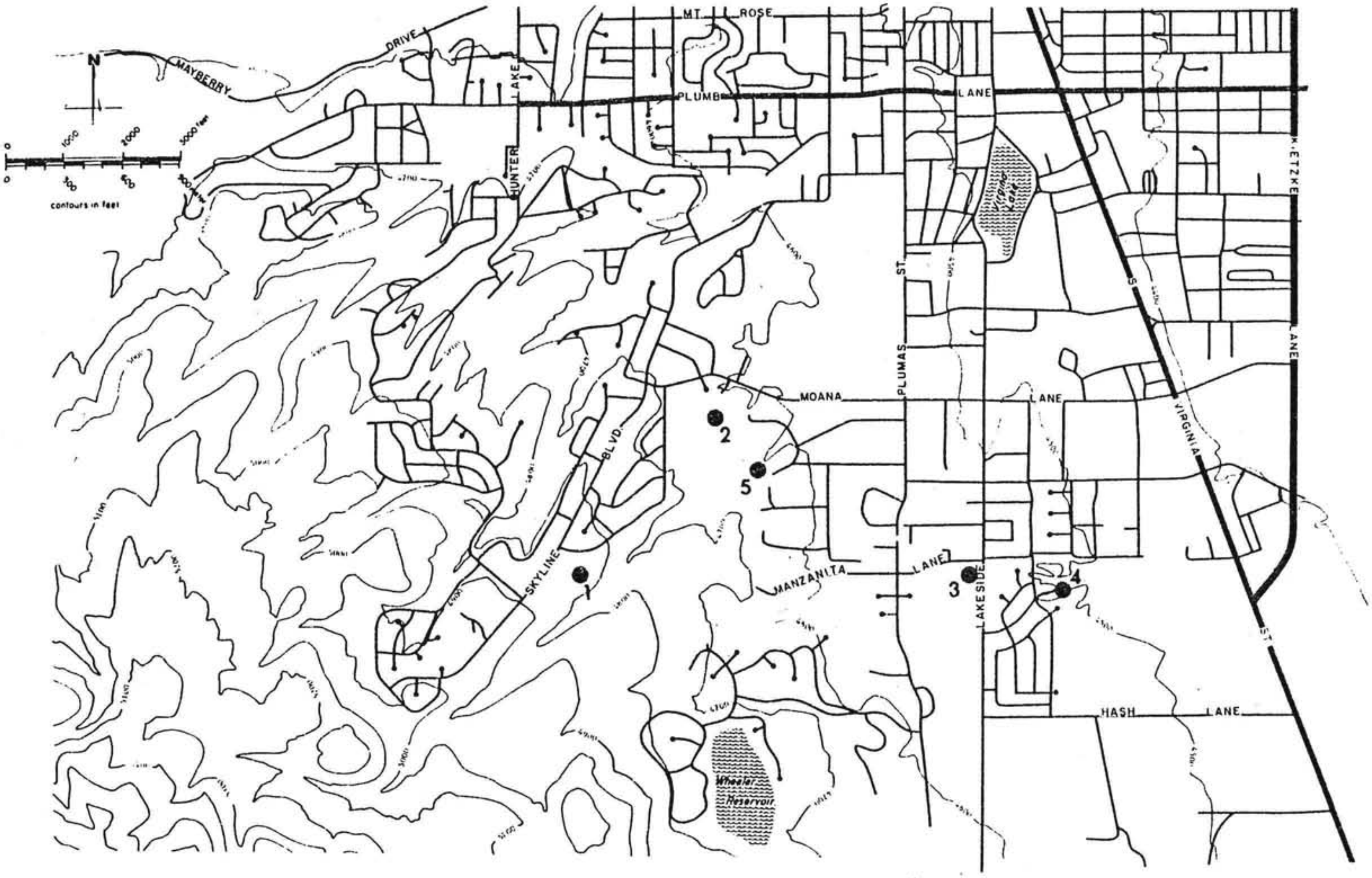


Figure 25. Location map of five observation/monitor wells in Moana.

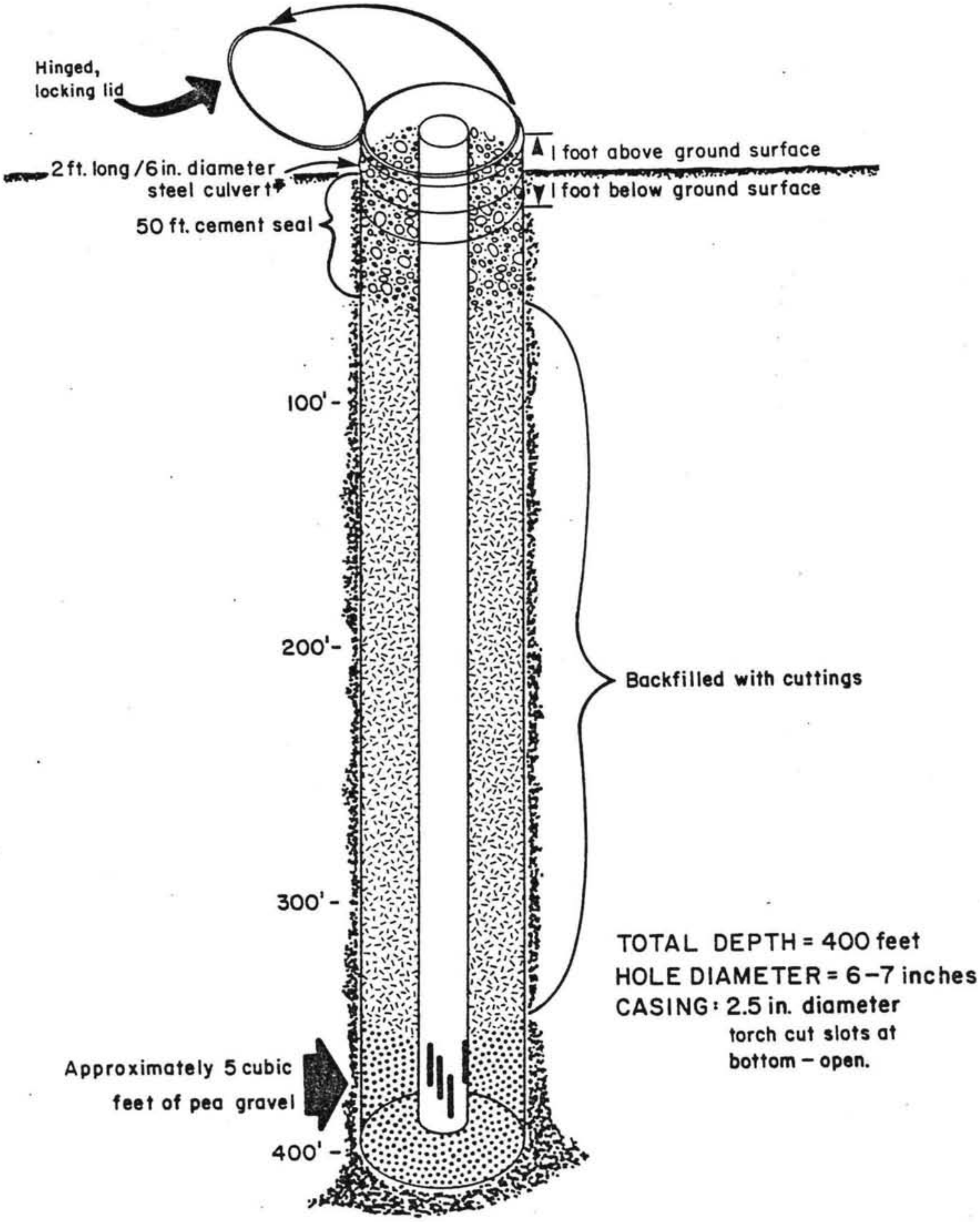


Figure 26. Completion diagram of observation/monitor well.

Well #5 was completed to 800 feet of which 400 feet was part of this study and the remainder was paid for by the Warren Estates in order to monitor the same aquifer level as the existing production well. Unfortunately, well #5 was vandalized rending the zone from 660 to 800 feet inaccessible. Efforts to remove the obstruction by DES personnel and Aqua Drilling of Reno failed. Since the perforations are below the obstruction, the well will not yield reliable data and monitoring of well #5 was discontinued.

WATER LEVEL MONITORING

Using static water level data for 100 sites throughout the Moana area, a piezometric surface elevation map was created (fig. 27). This map reveals a general southwest to northeast flow approaching the surface elevation near Manzanita Lane and Lakeside Drive.

Figure 28 is an isometric projection for three cross sections through the center of the Moana area. Note that the piezometric surface is <u>not</u> the water table; it represents the pressure of the thermal water resource at a given location.

Static water levels in Monitor Wells 1 through 4 were monitored from July through December, 1983, using an electric sounding device. The results are presented in figure 29. The data show a reduction of 2 to 3 feet in water levels in wells #3 and #4, the closest to the heavy use area. Wells #1 and #2 show an increase in water level which may represent a pressure transient moving southeast due to an increase in thermal fluid withdrawal. Further monitoring will reveal long term effects of pumping. It should be noted that these water level changes, while not large, are enough to reduce artesian flow if the artesian head is small (i.e., one to two feet above ground level).

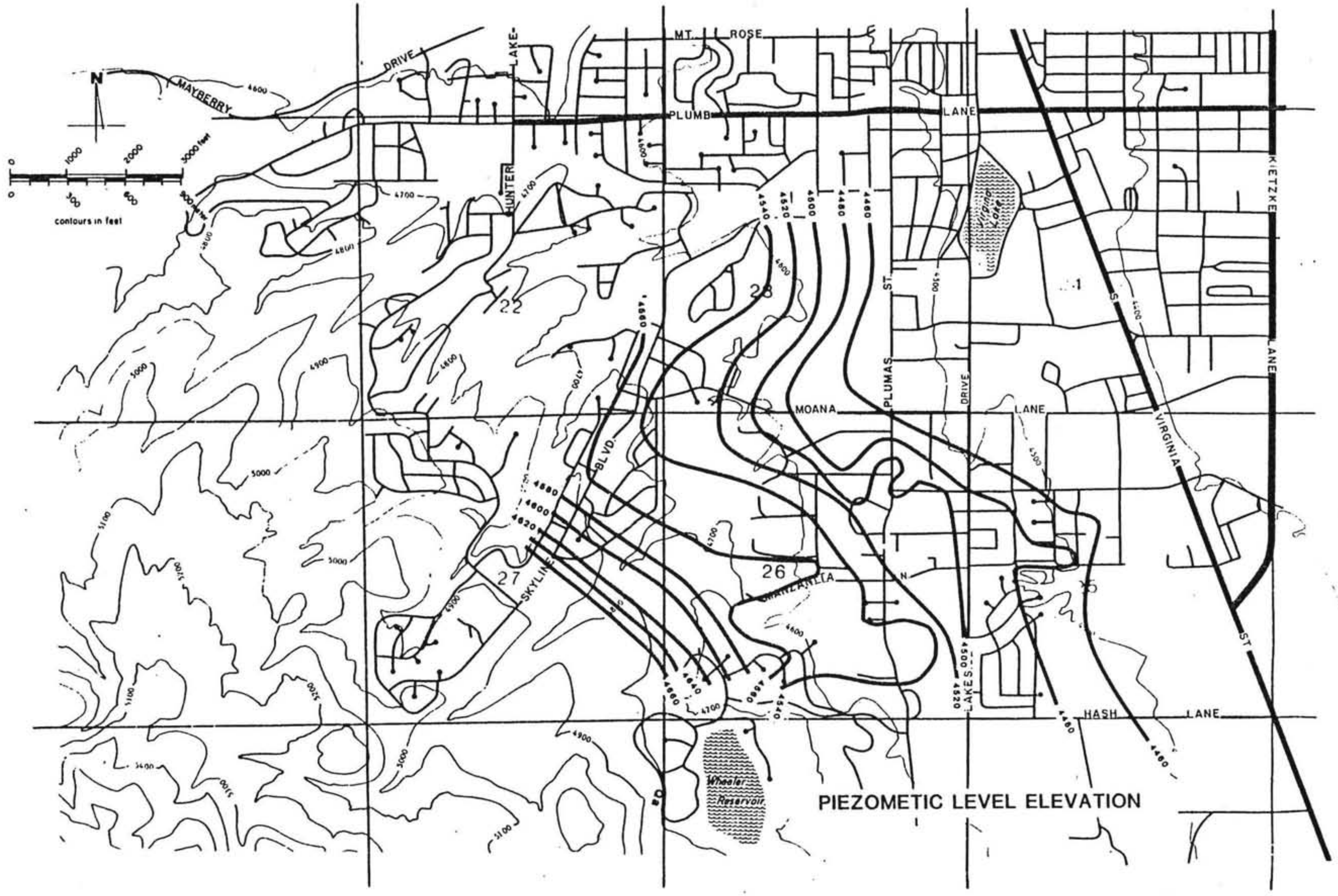


Figure 27. Piezometric surface elevations of thermal fluids in Moana.

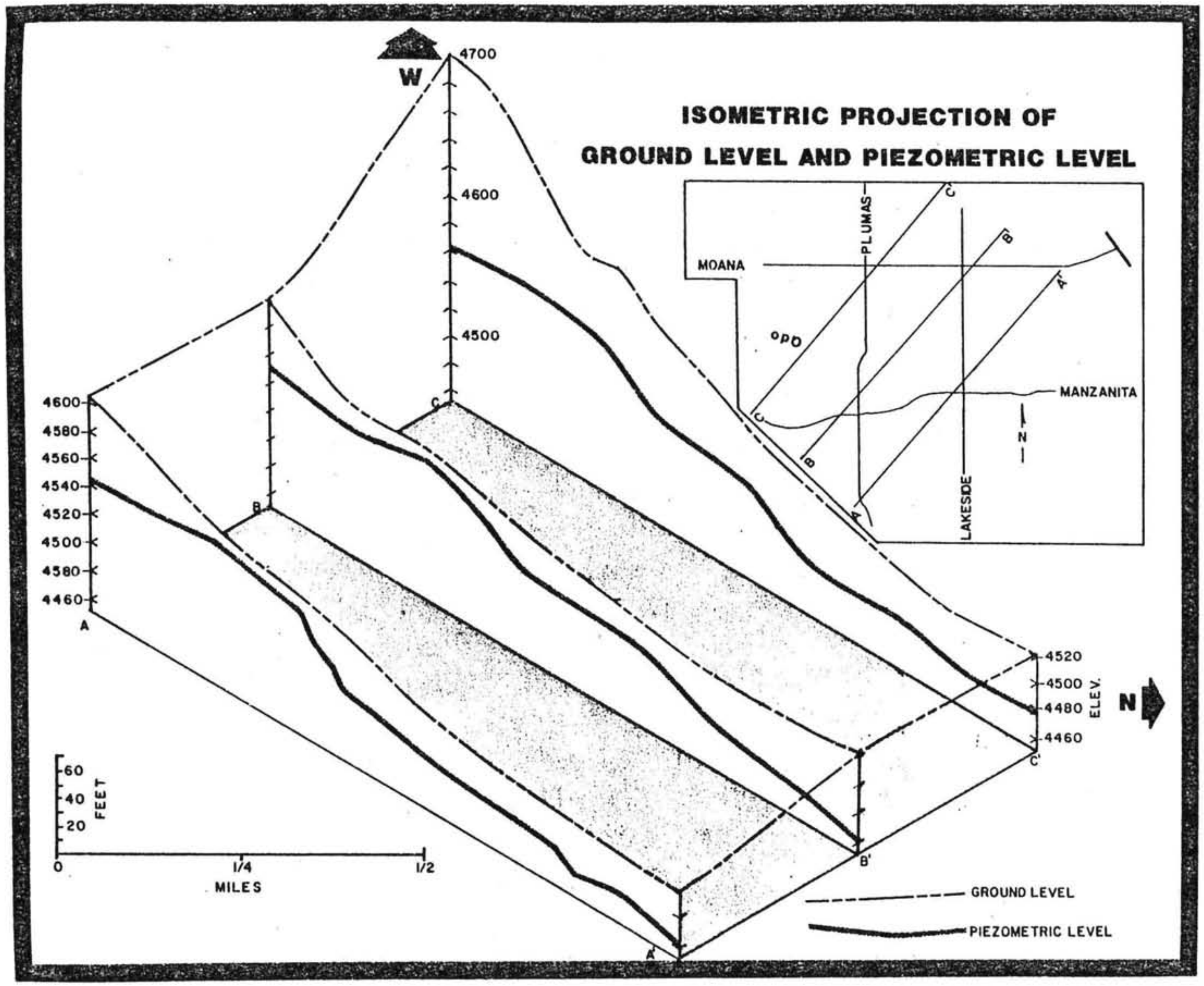


Figure 28. Isometric projection of ground level and piezometric surface of thermal fluids in Moana.

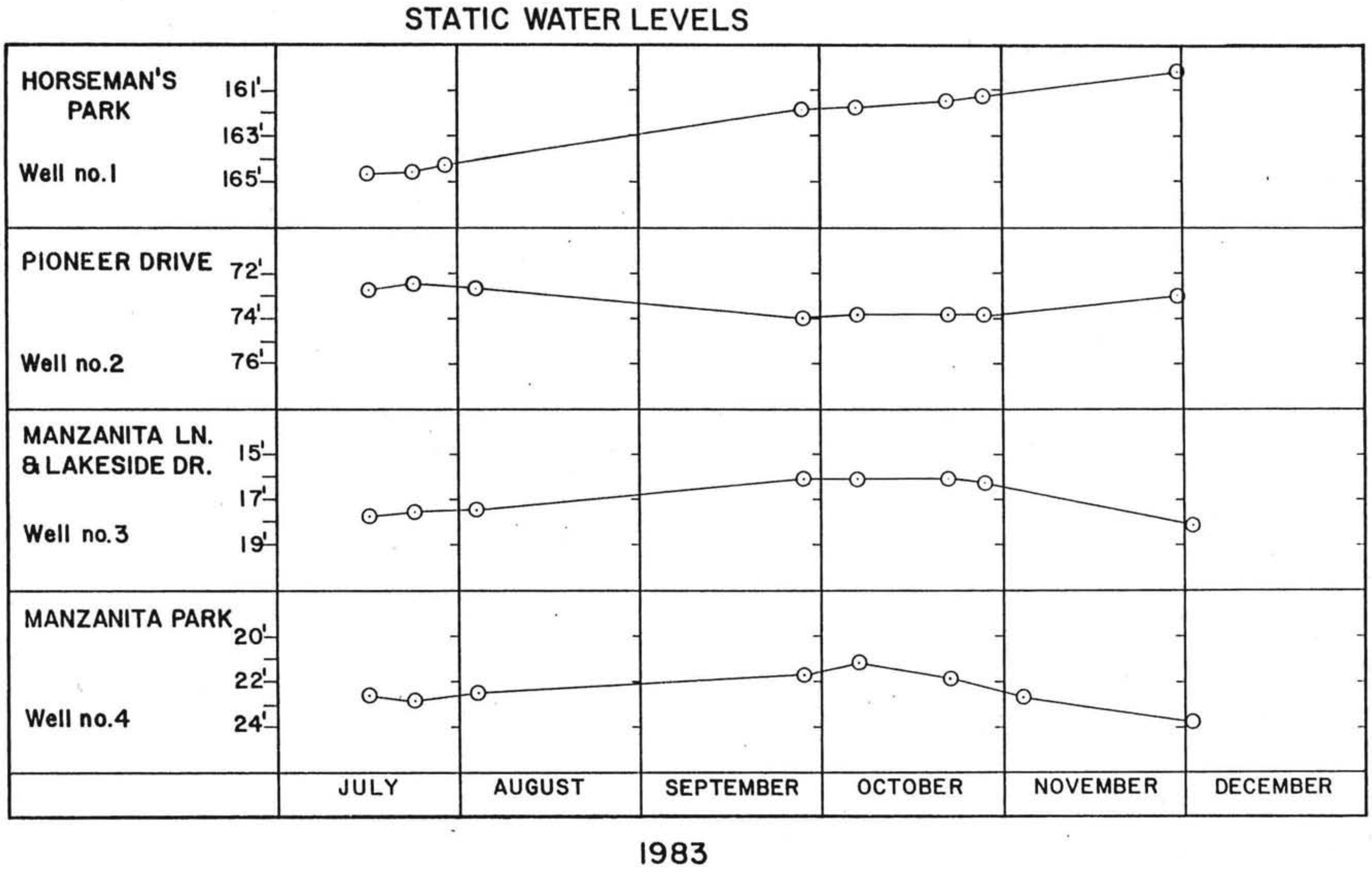


Figure 29. Static water levels for observation/monitor wells 1, 2, 3, and 4 in Moana, July to December, 1983.

TEMPERATURE DEPTH MEASUREMENTS AND LITHOLOGIC LOGS

Temperature measurements were made shortly after well completion and routinely thereafter from June through December, 1983. Measurements were obtained with an Envirolab Cable-reel Digital Thermometer with a range of 0° to 150°C and a precision of .1°C. Temperatures were measured in 20 foot intervals.

Lithologic logs were constructed from drill chips, collected at 20 foot intervals during drilling. For alluvial material, little or no distinction could be made between the various Quaternary units. Two distinctive and important units encountered are the Sandstone of Hunter Creek and Kate Peak andesite.

The combined temperature and lithologic logs for drill sites 1 and 2 are shown in Figures 30 and 31. Both holes, completed to 400 feet, penetrate similar lithologic units and have similar positive gradients. The nearly linear gradient in both wells from approximately 180 to 400 feet is indicative of heat transfer in a conductive environment. Diment (in Kestin, 1980) suggested that conductive heat transfer could be differentiated from convective heat transfer if the heat flow in the well is constant at any interval. The heat flow equation is: $q = K (\delta T/\delta Z)$ where q is heat flow, K is thermal conductivity and $\delta T/\delta Z$ is temperature gradient. For wells 1 and 2, the gradient is constant and the thermal conductivity of the diatomite may also be considered constant. Therefore, the heat flow in the well is constant, indicating an environment of heat transfer. This analysis is consistant with reports of very high temperature water associated with the contact between the diatomaceous siltstone and the Kate Peak andesite below.

Well number 3 (fig. 32) was completed near the center of the Moana area and is representative of many wells now in use. The upper 150 feet of the lithologic log indicates alternating layers of alluvial material. In this

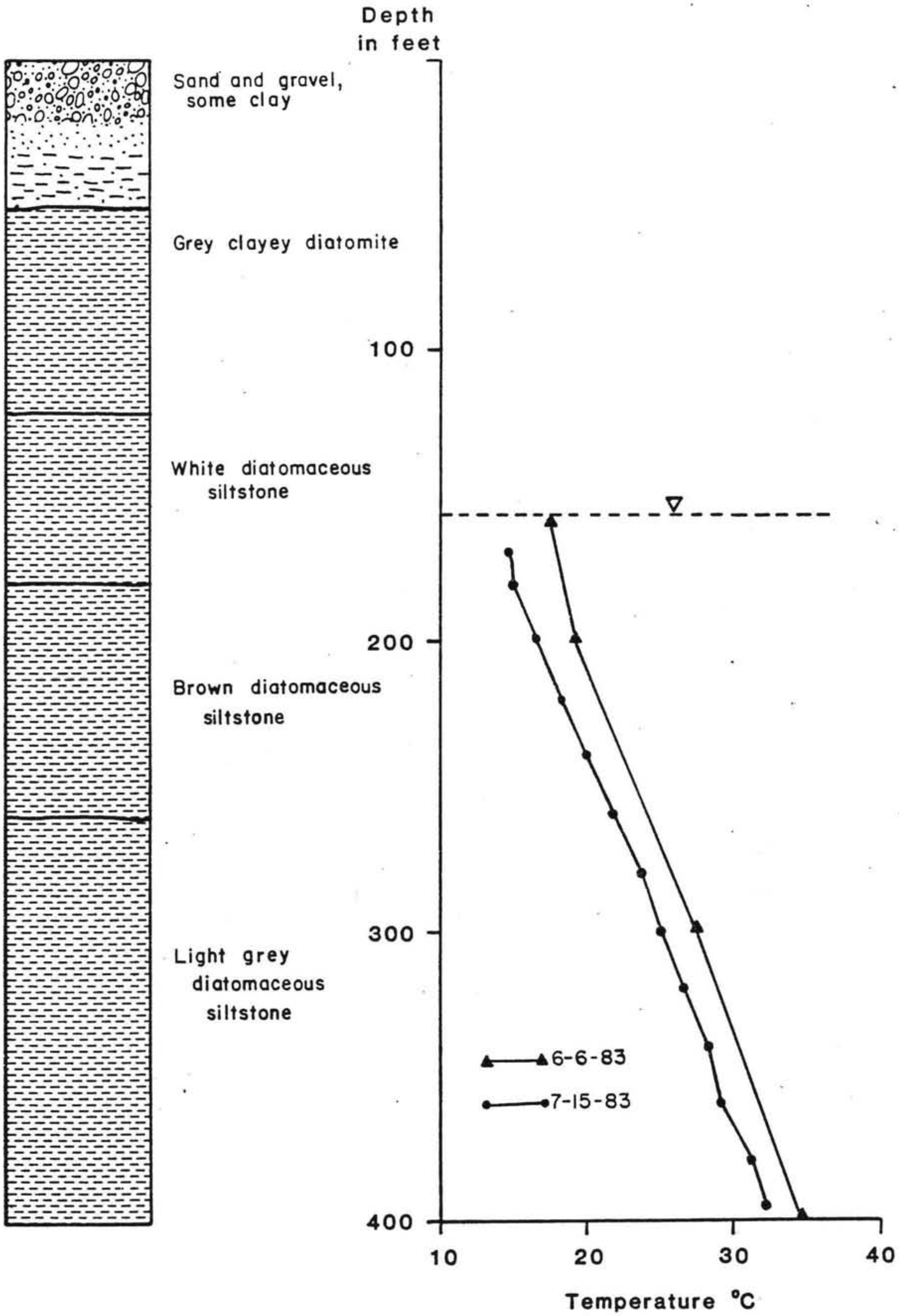


Figure 30. Lithologic log and temperature-depth profile, well 1.

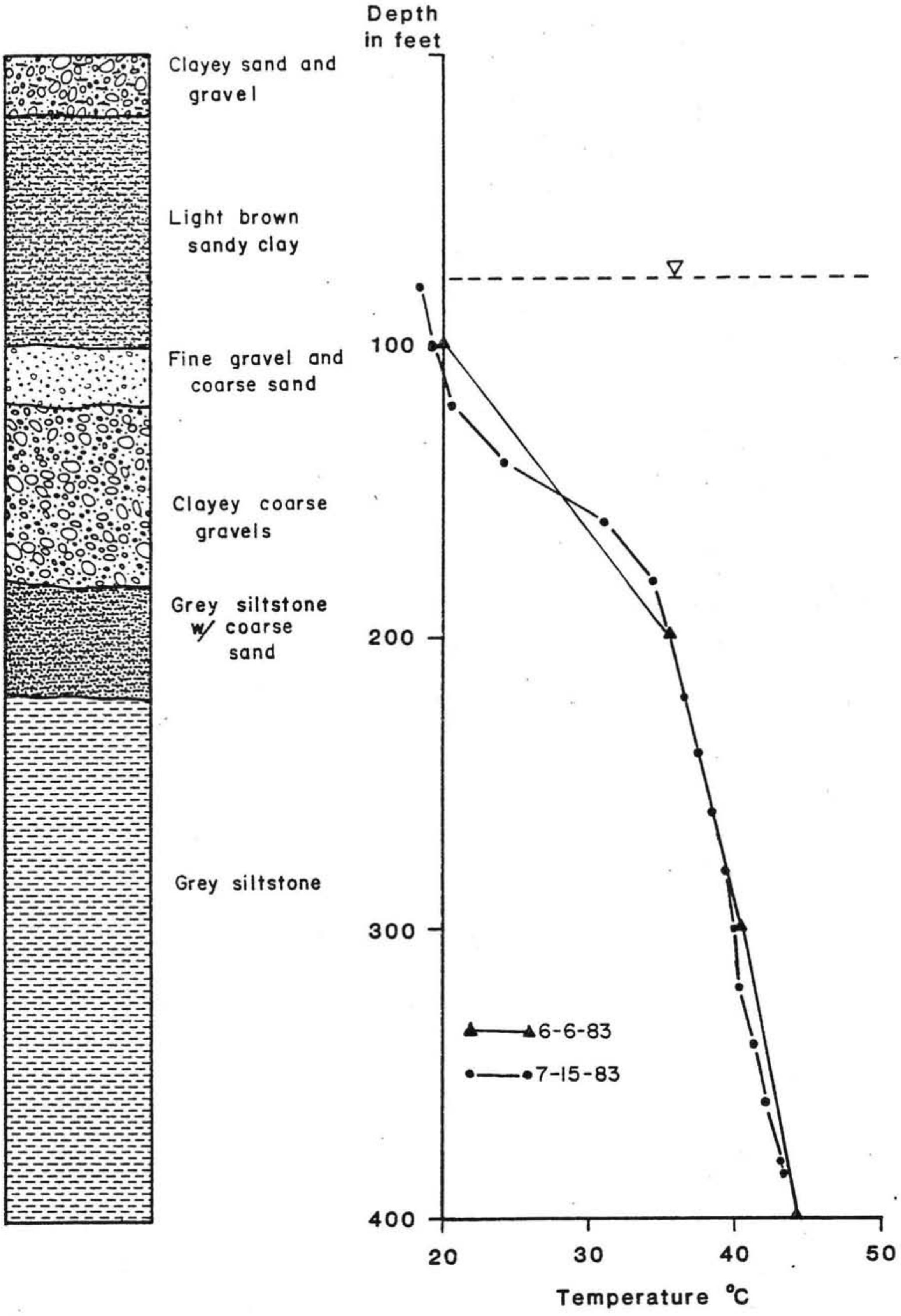


Figure 31. Lithologic log and temperature-depth profile, well 2.

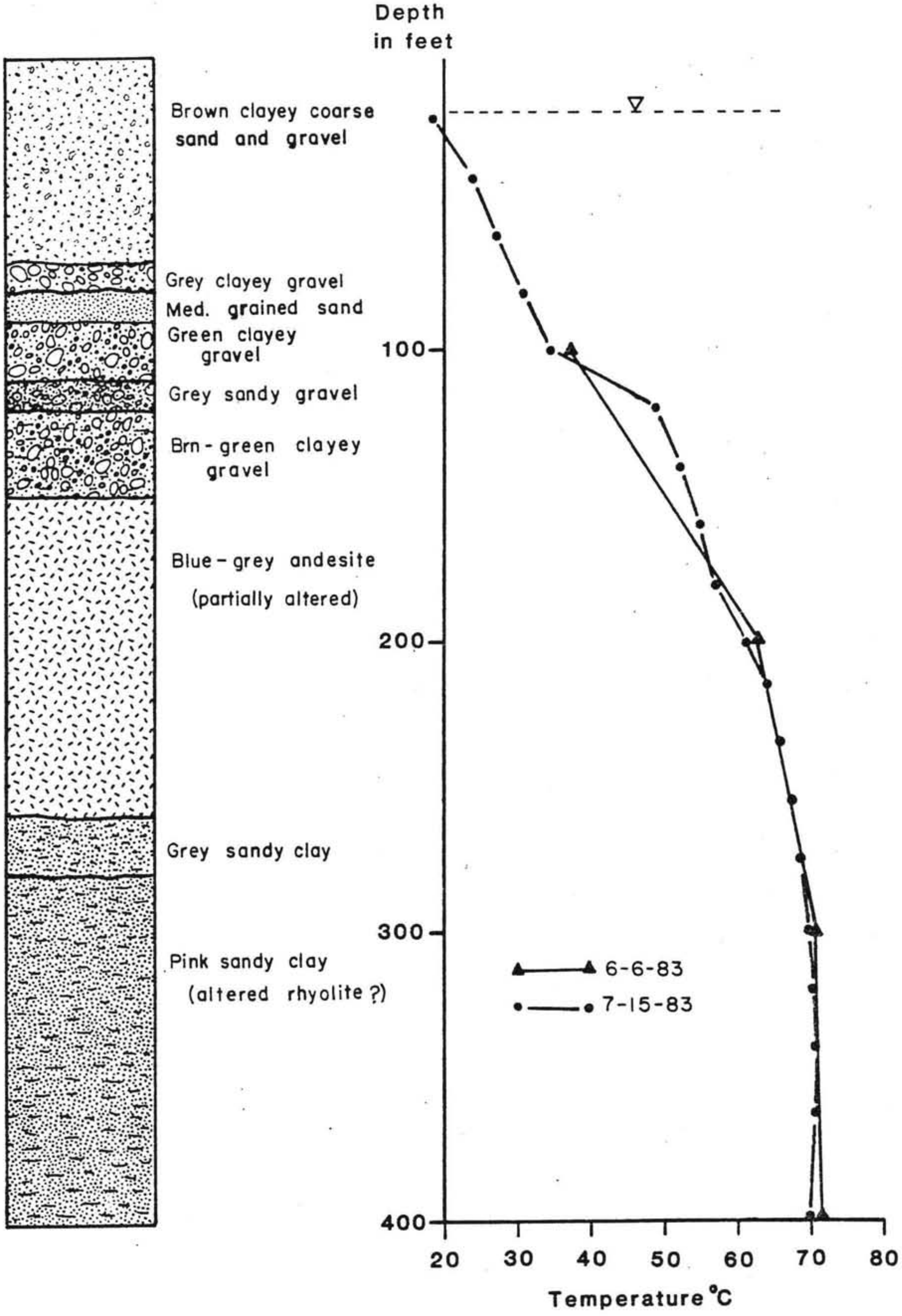


Figure 32. Lithologic log and temperature-depth profile, well 3.

well, the diatomaceous siltstone is missing and the alluvium is underlain by altered Kate Peak andesite. Drill chips from well 3 were lithologically similar to material encountered in 3 other nearby wells (fig. 33, 34 & 35). The blue-grey andesite is actually a hydrothermally altered vitrophyre that consists largely of smectite. This has been identified as the famous "blue clay" of Moana. The temperature profile for well 3 (fig. 32) shows that the highest temperatures are achieved and maintained within the "clay." In this area, the altered andesite is the principal geothermal reservoir rock.

Well 4 was completed near the geographic edge of the Moana resource. The lithologic log (fig. 36) suggests that only alluvial material was encountered. In heavily altered sections, the Kate Peak andesite is difficult to distinguish from alluvial material.

The temperature gradient shows the effects of mixing thermal and nonthermal fluids and gives an indication, near the bottom, of lateral flow. The thermal water appears to be largely confined to the interval between 200 and 300 feet. Above this zone, a thick layer of sand and clay form an aquiclude, preventing large-scale mixing. The temperature gradient between 20 and 150 feet is zero, indicating that all of the convecting or conducting heat from below has been dissipated.

Well 5 was vandalized shortly after completion and attempts to clear the obstruction were only partially successful. Well 5 is significant because it is the only well that penetrates the contact between the Sandstone of Hunter Creek (diatomaceous siltstone) and the Kate Peak andesite (fig. 37). In addition, a previously unknown member of the diatomaceous siltstone was encountered at a depth of approximately 500 feet. This unit consisted of a reddish-brown, organic rich clay. This clay layer had a strong hydrogen sulfide odor which may account for some of the sulfate in Moana fluids. This well was drilled

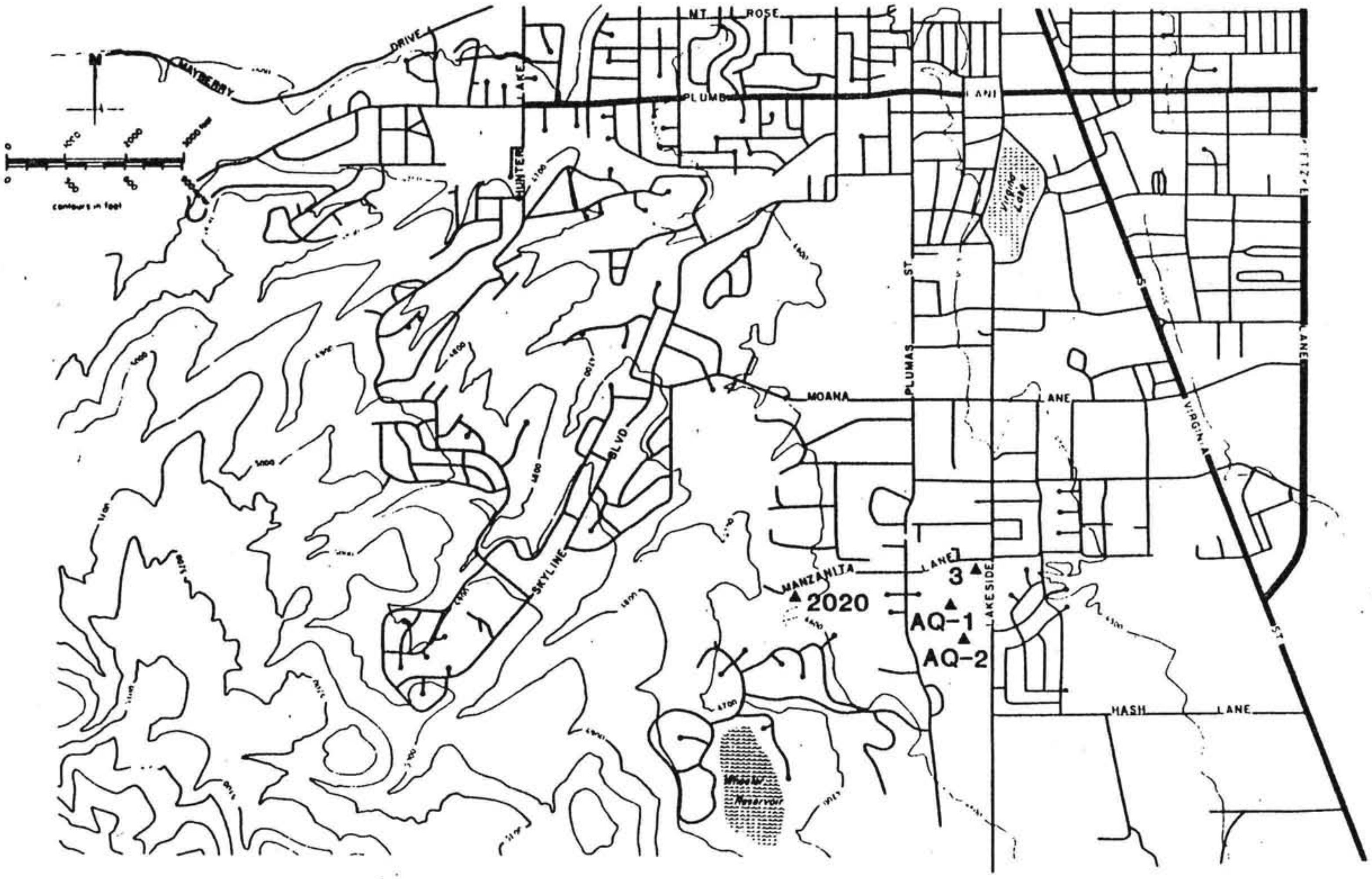


Figure 33. Location of three geothermal wells in Moana in relation to observation well 3.

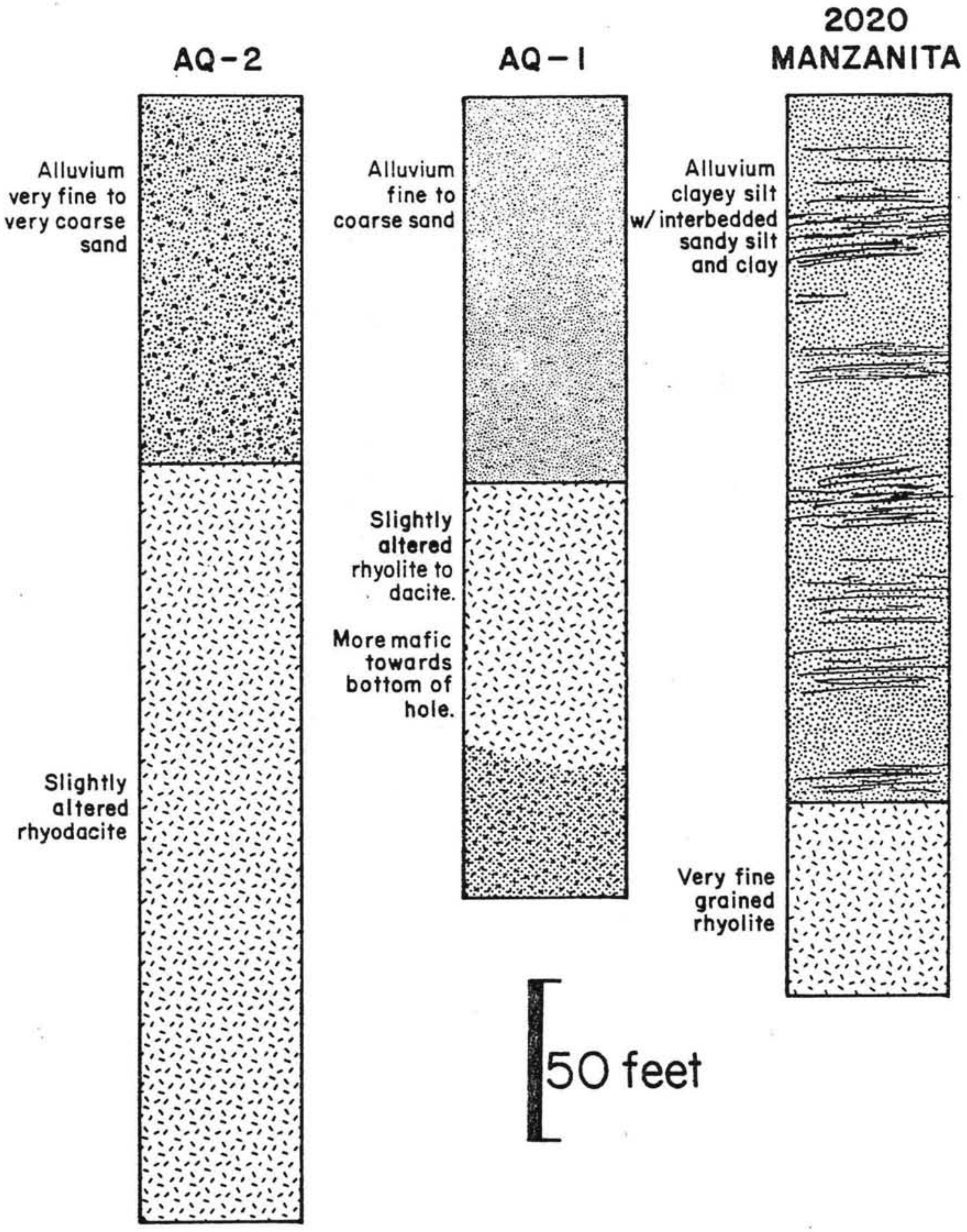


Figure 34. Lithologic logs of three geothermal wells in Moana. (Drill chips courtesy of Aqua Drilling and McKay Drilling.)

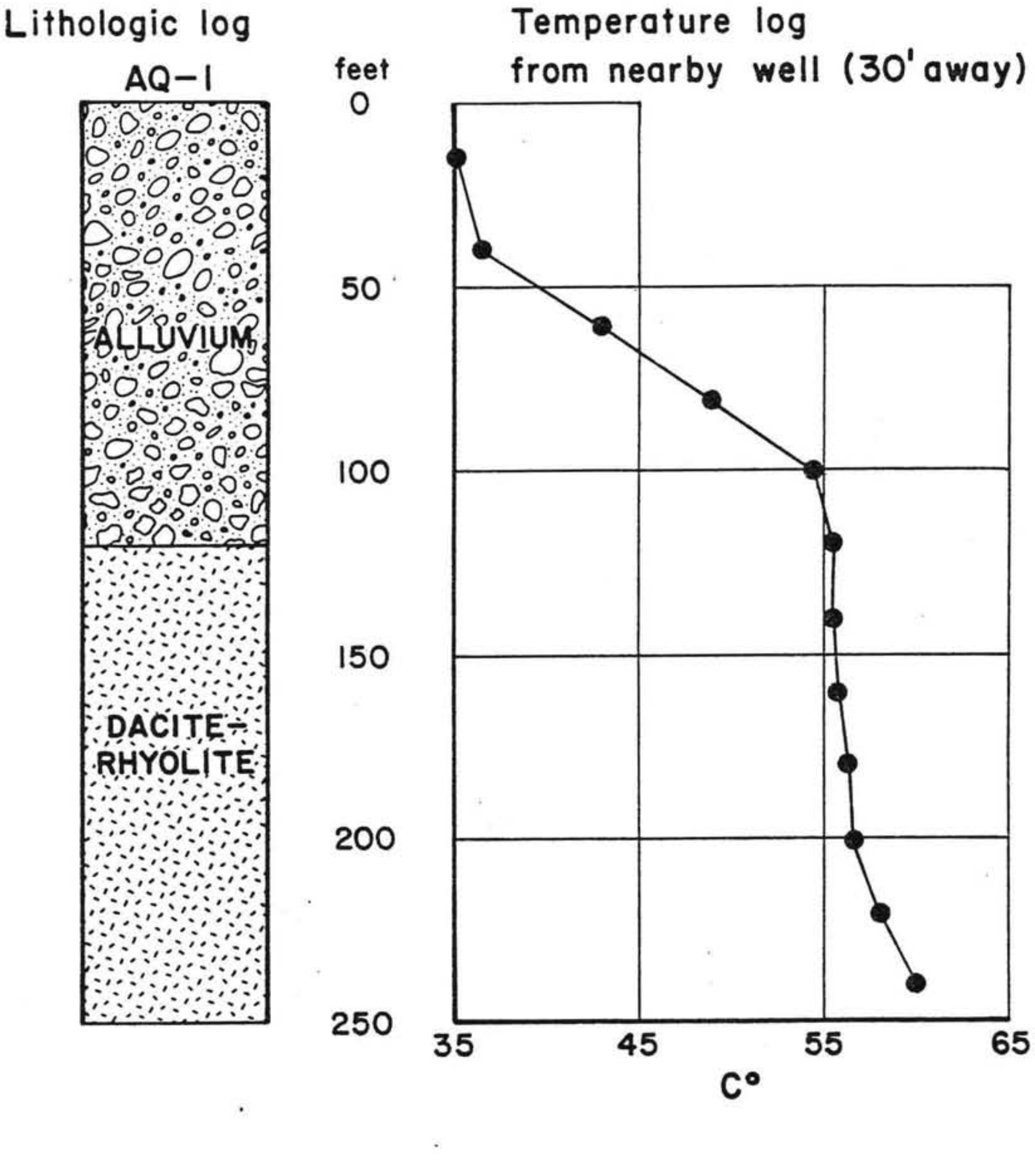


Figure 35. Lithologic log and temperature-depth profile from two adjacent wells in Moana.

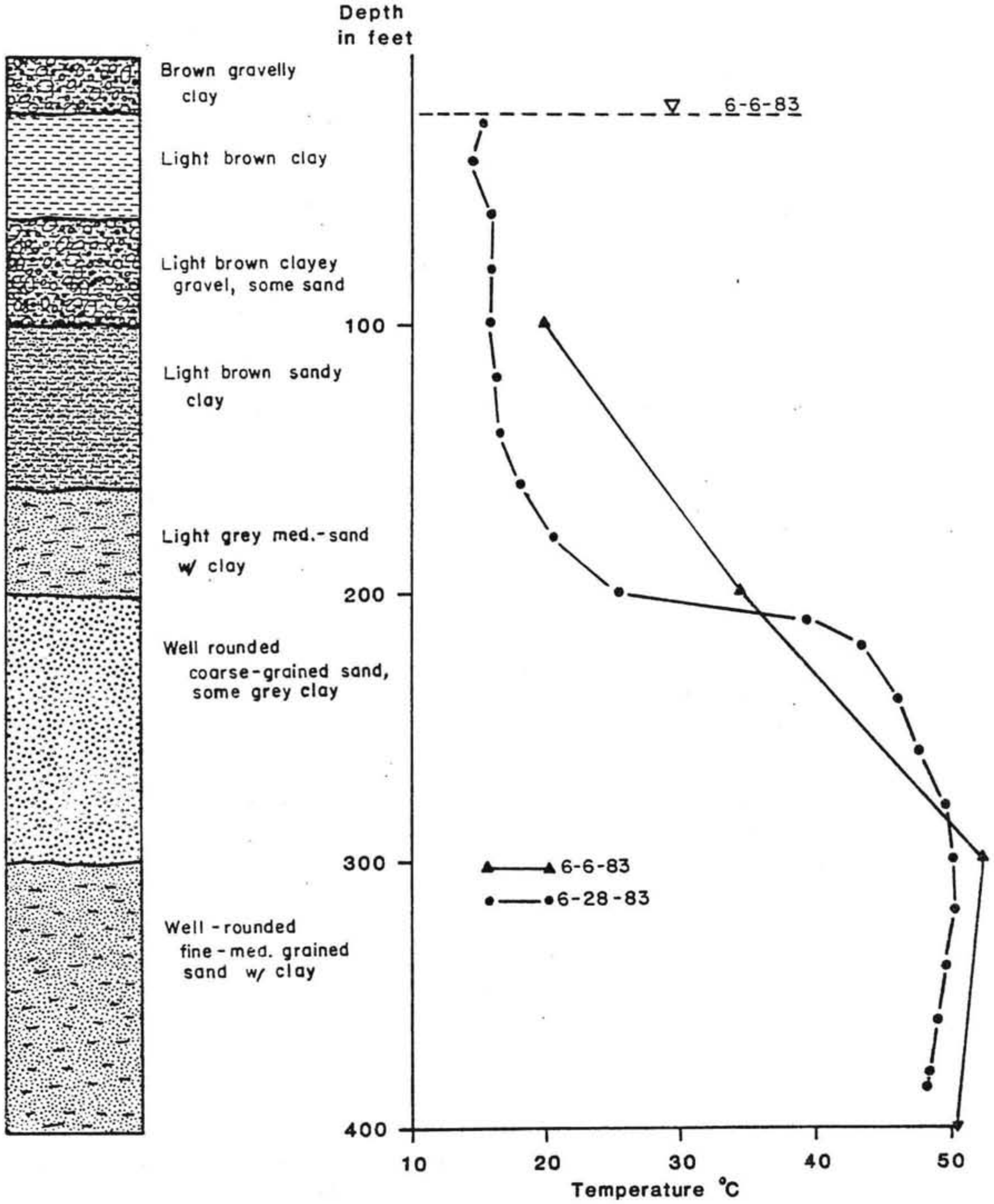


Figure 36. Lithologic log and temperature-depth profile, well 4.

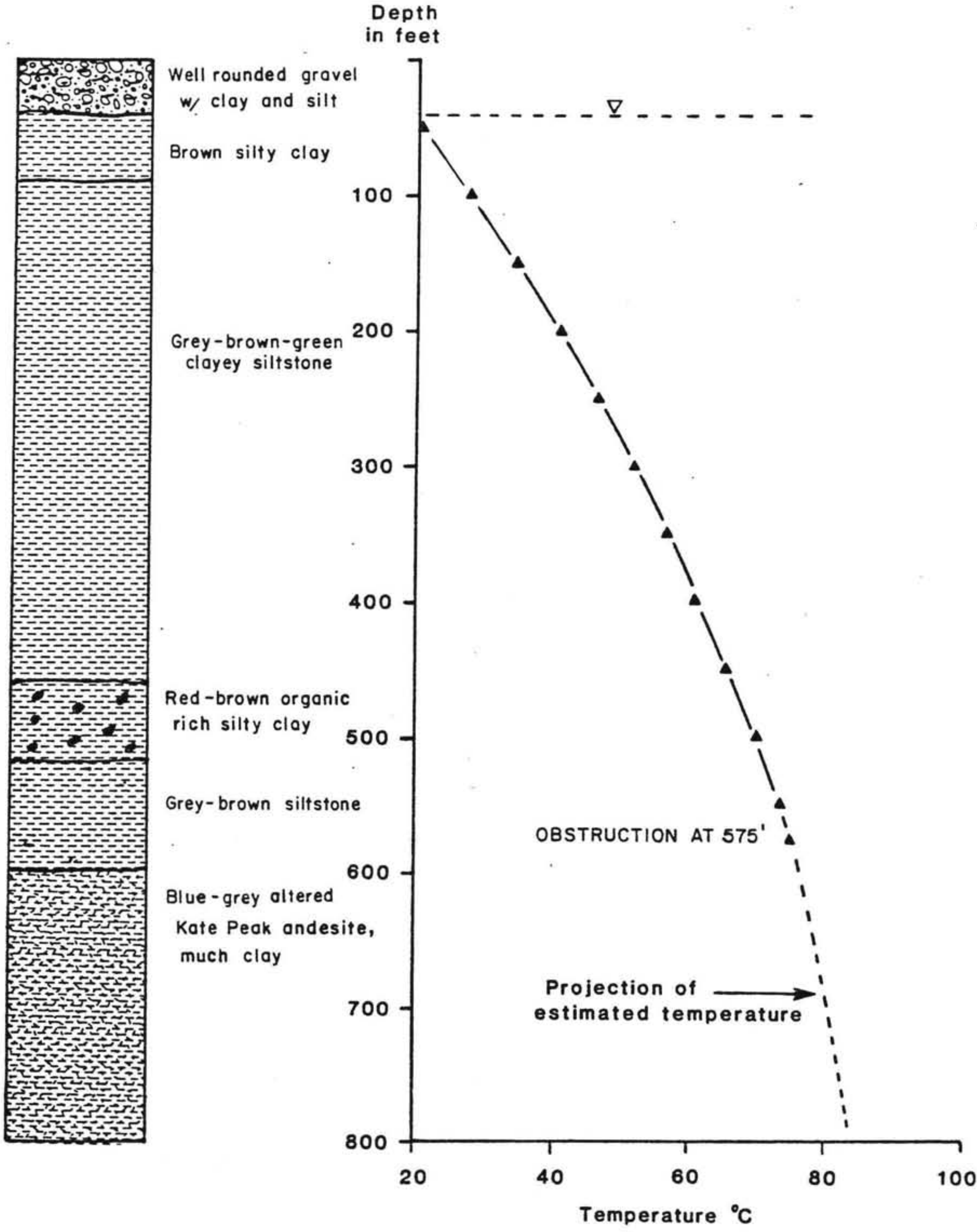


Figure 37. Lithologic log and temperature-depth profile, well 5.

near the Warren Estates geothermal well which produces 95°C fluids. The minimum estimated temperature at 800 feet for well 5 is 85°C.

Temperature measurements in these wells from June through December, 1983, did not reveal any significant drop in temperature within the andesite reservoir rock. Minor temperature variations (1 to 2°C) near the top of some wells is probably the result of seasonal variations and instrument error. A temperature drop of 6.5°C at a depth of 120 feet in well 3 occurred between November and December, 1983. However, temperatures immediately above and below this interval were not as significantly affected. Temperatures were unchanged from 200 to 400 feet. From a single reading, it is difficult to establish a trend. For this reason, continued monitoring of the wells is certainly warranted.

DIRECT USE

The Moana geothermal resource supplies heat to approximately 140 homes and 3 commercial establishments for space heating, domestic hot water, and often swimming pool and/or spa heating. At one residence, the hot water is even used for clothes drying. Most users have natural gas-fired, forced air heating systems which are kept as back-up heaters to take over in case of a failure of the geothermal system or to assist during peak loads. Some users have hot-water baseboard heaters which require higher operating temperatures than forced-air and/or more baseboard heater units.

Three commercial establishments, the Peppermill Motel, the Mark Twain Motel and the Virginia Lake Townhouses, use hot water for space heating, pool heating, and domestic hot water. Due to the large heating loads, these wells are pumped; the water flows through surface heat exchangers and is discharged into storm drains. The Warren Estates subdivision uses a district heating system scheme employing a downhole heat exchanger with intermittent pumping of the well. The fluids are reinjected into another well 1500 feet away. The system currently supports 5 homes.

Geothermal wells in the Moana area are drilled with either cable-tool or rotary drill rigs to depths ranging from 200 to 1500 feet. Most single residence wells are completed as ordinary water wells using 6 to 8 inch diameter casing for the entire depth and cementing the upper 50 feet of casing in place as a sanitary seal. Perforations are usually at the bottom of the well where the maximum temperatures are generally found. Figure 38 shows that the high-temperature isothermal zones vary considerably even over small lateral distances. The upper, typically cooler, sections of the Moana wells are completed

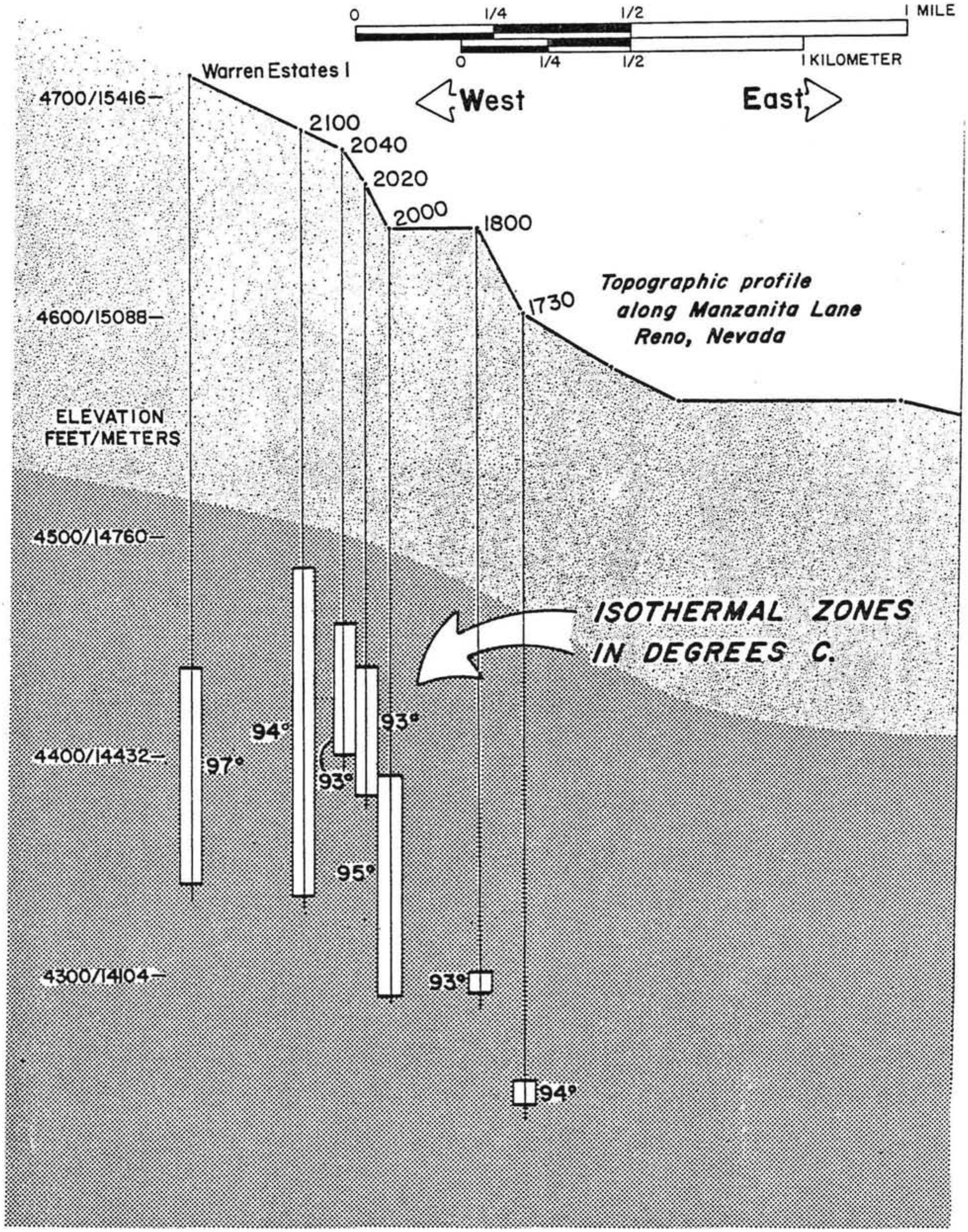


Figure 38. West to east cross-section through Moana showing high-temperature isothermal zones in selected geothermal wells.

with unperforated casing and may even be cemented to prevent mixing of hot and cold fluids.

With few exceptions, the Moana geothermal resource is tapped exclusively by downhole heat exchangers. The state-of-the-art design for heat exchangers in the Moana area is a simple-loop downhole heat exchanger, known as a trombone for its resemblance to a trombone slide. Fiberglass reinforced plastic (FRP) pipe is used for the heat exchanger. Around one leg of the loop is another pipe of ABS or polybutadiene plastic which is open at the top and bottom. This "convection tube" sets up one large convection cell within the well. The result is a redistribution of temperatures within the well bore along the length of the convection tube, enhancing heat transfer. Figure 39 shows this effect of a convection tube on the Warren Estates production well. Figure 40 is a diagram of the heat exchanger system at the Warren Estates well.

Experience and experimental work (Allis, 1981) show convection tubes enhance heat output but are not a substitute for pumping in most wells. This has been attributed to slow natural flow (low permeability) in the reservoir in many places.

The use of FRP for the heat exchanger is the solution to a number of problems with copper and galvanized iron pipe. The use of copper pipe produces electrolytic corrosion of both the iron casing and the solder joints. Galvanized iron pipe corrodes above the static water level and couplings and brazes frequently leak. Both metal pipes exhibited scaling, probably sulfides, and oxides, usually less than 2mm (1/16") thick both inside and outside. Contractors found FRP did not corrode or scale and had fewer mechanical problems. In many cases, the new FRP-convection tube systems outperformed galvanized iron and copper systems without convection tubes. This is probably the result of both heat loss and scaling. Heat loss is high in the upper portions of a well

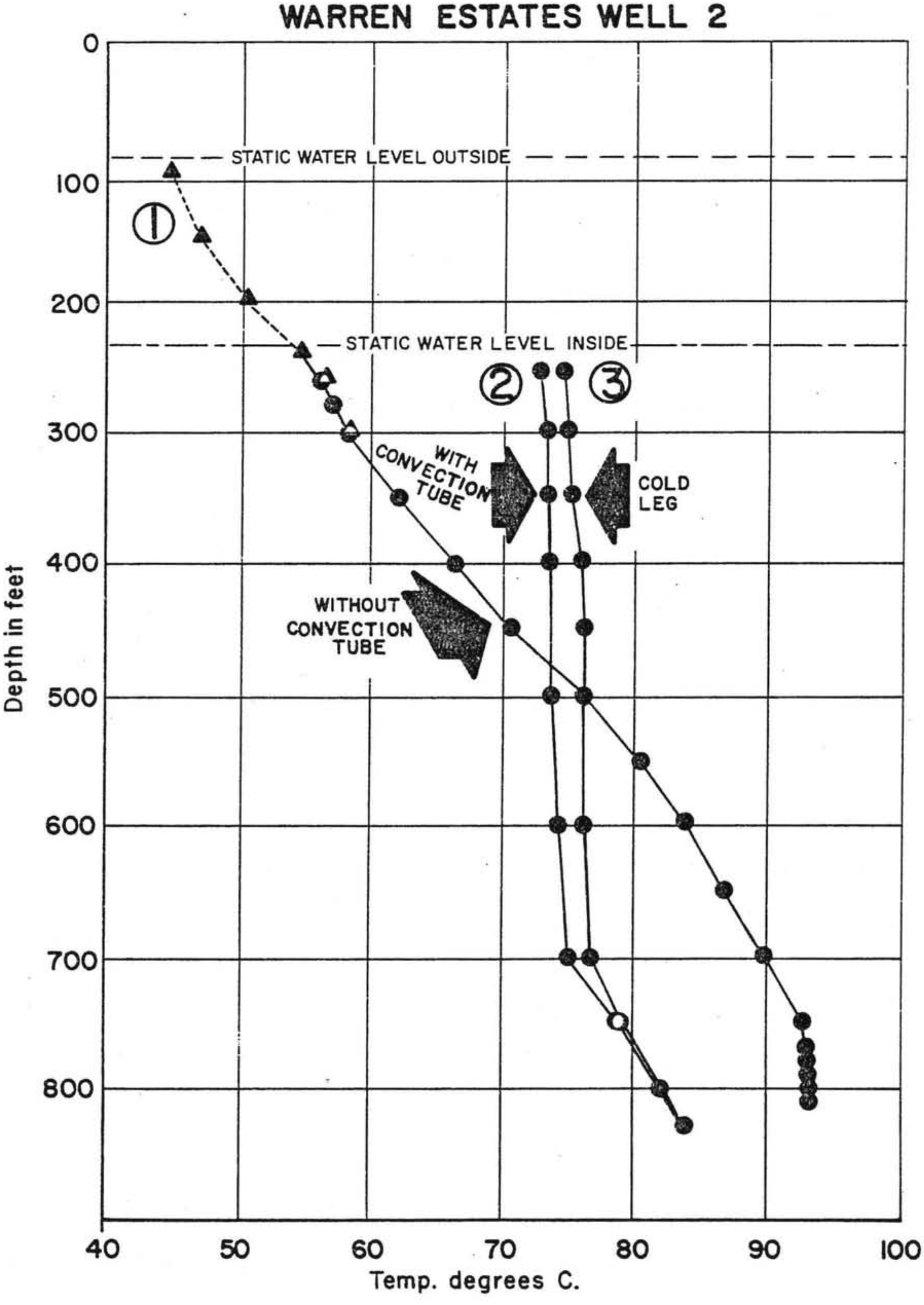


Figure 39. Temperature-depth profiles of Warren Estates geothermal production well: 1) before installation of convection tube, 2 & 3) after installation of convection tube.

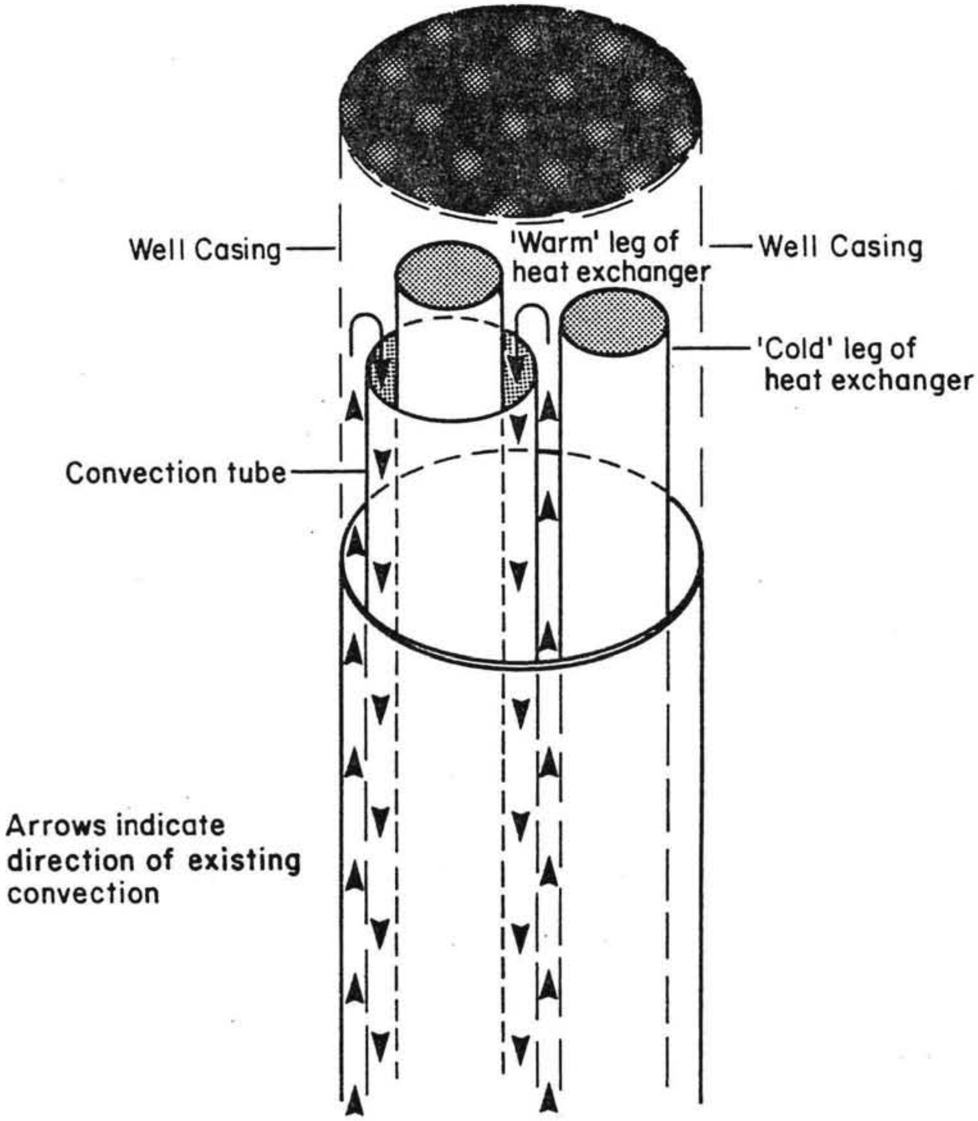


Figure 40. Illustration of down-hole heat exchanger and convection tube in Warren Estates geothermal production well.

not equipped with a convection tube. Scale-buildup on metal pipes reduces the thermal conductivity. Although FRP is 1000 times less efficient than copper for conducting heat, overall system efficiency for copper and iron pipes exceeds FRP by a maximum factor of 4.

A computer program called HEATM, presented in Appendix V, will run on almost any home computer and will give an approximation of heat output, based on certain parameters, for a geothermal well and heat exchanger. It is important to note that this is an approximation based on theoretical equations and some simplified assumptions. One important assumption is that the well will maintain nearly constant temperature either naturally or with intermittant pumping. Except for wells along Manzanita Lane, west of Lakeside, and a few deep wells (>800 ft.) to the northwest on Monterey Circle, Dant Blvd., and Skyline Blvd., Moana geothermal wells require intermittent pumping to maintain high temperatures.

The typical Moana geothermal well increases in temperature with depth until a maximum temperature is attained. Many wells then become isothermal, exhibiting no significant temperature increase with increasing depth. In fact, the temperature will often decrease (known as a temperature reversal) with increasing depth beyond a limit that changes with each well. Deeper is not always hotter in Moana.

Figure 41 is an areal distribution map of resource depth and temperature based on data from more than 130 wells collected from this and other studies (Bateman and Schiebach, 1975; Ghusn, 1982). This map divides the Moana resource into zones of expected depth to maximum temperature. Zones A and B represent the low-temperature portion of the Moana area. All wells in these zones must be pumped in order to provide sufficient heat energy. Many single-family homes and all of the commercial establishments are within these zones.

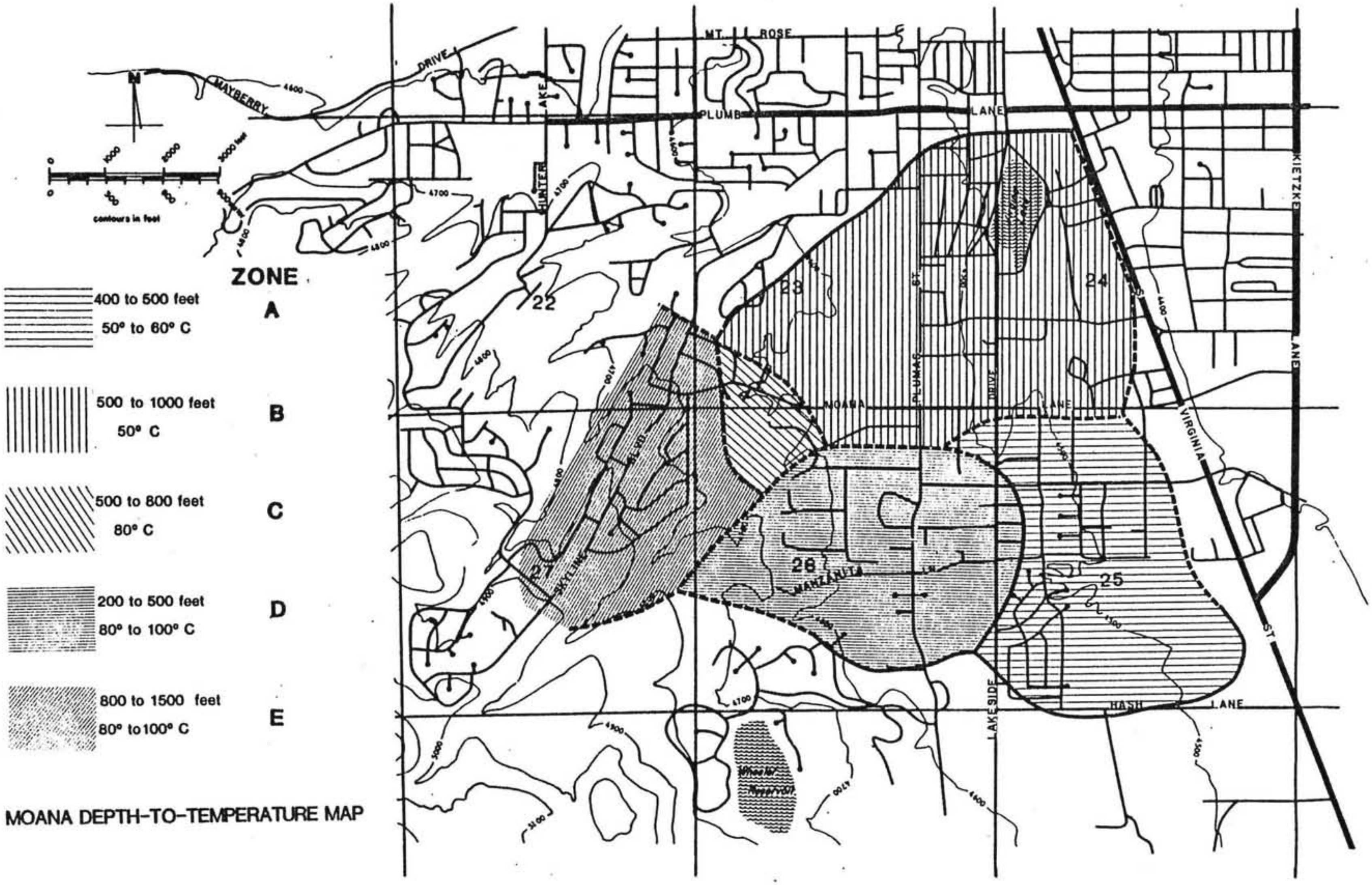


Figure 41. Moana area depth-to-temperature of geothermal resource map.

Spent geothermal fluid disposal is via storm drains, sewers, or in a few cases, reinjection wells.

Zones C, D, and E cover the high-temperature region of the Moana area. Wells in this area need to be pumped only occasionally, if at all, to maintain temperature. Downhole heat exchangers are used for single family homes as well as a small district heating system. Fluids pumped from the wells are drained into the storm drains or sewers.

The boundaries of each zone are approximate and reflect the data base as of November, 1983. Future wells will no doubt refine and change the boundaries.

The distribution map and the well location map (Figure 42) can be used to determine the approximate depth necessary to obtain the maximum temperature in a zone. Depth and temperature information, for each well shown on the well location map, is included in Appendix III. Temperature gradients for selected wells are shown in Appendix IV. Because of large scale lateral variations in resource temperature, depth, and permeability in different locations, any interpretations from these maps and data must be viewed cautiously.

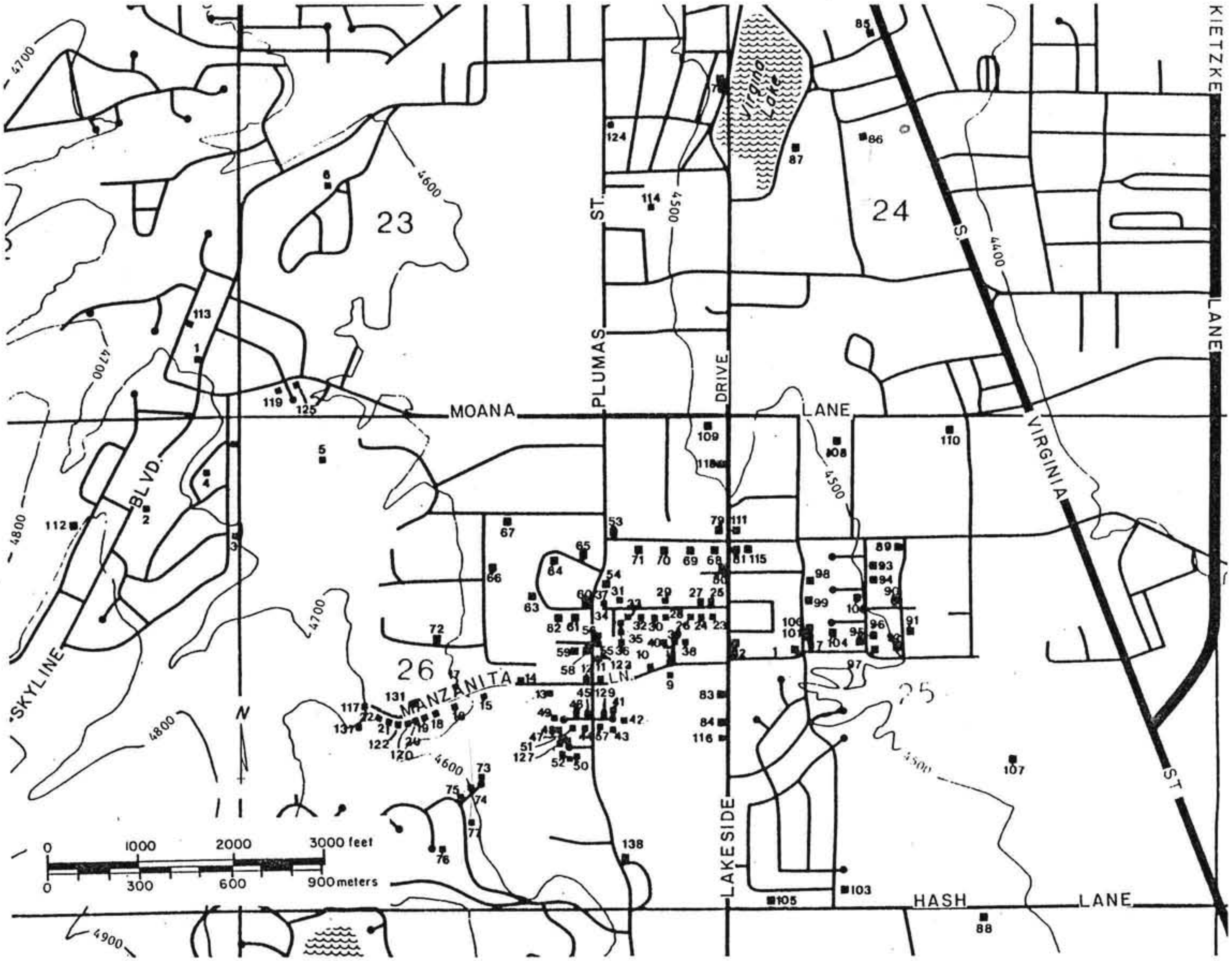


Figure 42. Location map of known geothermal wells in Moana, 1983.

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REFERENCES

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APPENDIX I

PRINCIPAL FACTS FOR GRAVITY STATIONS

Station Number	Elevation	Simple Bouguer	Area Coordinates	Complete Bouguer	Theoretical Gravity	Observed Gravity
1	4428.9000	-182.1100	9390 10020	-181.4086	980136.1347	979688.7204
2	4433.7000	-182.0907	9560 10020	-181.3893	980136.1347	979688.4472
3	4438.5000	-181.9958	9660 10020	-181.2944	980136.1347	979688.2546
4	4445.3000	-181.7682	9750 10020	-181.0668	980136.1347	979688.0748
5	4448.6000	-181.9361	9860 10030	-181.2340	980136.1347	979687.7092
6	4451.3000	-181.9965	10000 10000	-181.2965	980136.1347	979687.4871
7	4471.8000	-182.5347	10300 10020	-181.8333	980136.1347	979685.7208
8	4483.4000	-183.3402	10500 10030	-182.6381	980136.1347	979684.2205
9	4521.0000	-185.0838	10800 10010	-184.3831	980136.1347	979680.2245
10	4516.3000	-185.7613	11000 10000	-185.0613	980136.1347	979679.8285
11	4530.3000	-185.7600	11150 10020	-185.0586	980136.1347	979678.9911
12	4554.0000	-185.5026	11340 10020	-184.8012	980136.1347	979677.8288
13	4559.4000	-185.3615	11460 10020	-184.6601	980136.1347	979677.6464
14	4569.3000	-185.3394	11600 10020	-184.6380	980136.1347	979677.0755
15	4577.7000	-185.4043	11640 10020	-184.7029	980136.1347	979676.5074
16	4589.2000	-185.5275	11840 10020	-184.8261	980136.1347	979675.6953
17	4595.5000	-185.8023	12000 10030	-185.1002	980136.1347	979675.0431
18	4599.9000	-185.9568	12110 10010	-185.2561	980136.1347	979674.6250
19	4604.6000	-186.1624	12200 10020	-185.4610	980136.1347	979674.1378
20	4617.8000	-186.3829	12300 10020	-185.6815	980136.1347	979673.1266
21	4626.0000	-186.6018	12440 10050	-185.8983	980136.1347	979672.4165
22	4608.0000	-186.5632	12510 10030	-185.8611	980136.1347	979673.5334
23	4604.2000	-186.5548	12600 10060	-185.8505	980136.1347	979673.7694
24	4604.4000	-186.6130	12690 10060	-185.9087	980136.1347	979673.6993
25	4618.9000	-186.9291	12780 10060	-186.2248	980136.1347	979672.5145
26	4626.4000	-187.1085	12880 10060	-186.4042	980136.1347	979671.8859
27	4626.0000	-187.0469	12950 10060	-186.3426	980136.1347	979671.9714
28	4623.3000	-187.6981	13050 10050	-186.9946	980136.1347	979671.4820
29	4639.3000	-188.1949	13210 10050	-187.4914	980136.1347	979670.0267
30	4643.7000	-188.6545	13310 10040	-187.9517	980136.1347	979669.3035
31	4648.8000	-188.8347	13380 10040	-188.1319	980136.1347	979668.8178
32	4650.8000	-189.3163	13500 10040	-188.6135	980136.1347	979668.2164
33	4649.9000	-186.8315	12780 10280	-186.1116	980136.1347	979670.7551
34	4710.5000	-185.8326	12940 10850	-185.0723	980136.1347	979668.1238
35	4938.8000	-180.4708	13530 11680	-179.6515	980136.1347	979659.8095
36	4982.1000	-189.1745	13490 11930	-188.3375	980136.1347	979648.5119
37	4942.8000	-188.3305	13350 11970	-187.4906	980136.1347	979651.7102
38	4885.5000	-184.8817	13100 12000	-184.0397	980136.1347	979658.5915
39	4856.4000	-184.8404	12950 12050	-183.9714	980136.1347	979660.3760
40	4853.1000	-183.4816	13020 12380	-182.5707	980136.1347	979661.9325
41	4997.3000	-184.3357	13210 12970	-183.4383	980136.1347	979652.4402
42	4941.5000	-183.6186	12980 12780	-182.7553	980136.1347	979656.5000
43	4836.9000	-185.9909	12600 12300	-185.1986	980136.1347	979660.3936
44	4665.5000	-186.9639	12100 11300	-186.1801	980136.1347	979669.6882
45	4645.9000	-187.1494	12040 11180	-186.3699	980136.1347	979670.6768
46	4631.7000	-187.1418	12020 11120	-186.3815	980136.1347	979671.5351
47	4617.0000	-186.8342	12000 10850	-186.1200	980136.1347	979672.7232
49	4629.8000	-190.0756	11600 10790	-189.3195	980136.1347	979668.7151
50	4646.1000	-189.5992	11780 10900	-188.8353	980136.1347	979668.2151
51	4662.3000	-189.5012	11750 11040	-188.7274	980136.1347	979667.3426

Station Number	Elevation	Simple Bouguer	Area Coordinates	Complete Bouguer	Theoretical Gravity	Observed Gravity
52	4535.3000	-185.9525	10800 10600	-185.2099	980136.1347	979678.4991
53	4535.3000	-186.2627	10800 10800	-185.5059	980136.1347	979678.1890
54	4533.1000	-186.2322	10810 10980	-185.4626	980136.1347	979678.3513
55	4529.5000	-186.3060	10810 11150	-185.5244	980136.1347	979678.4931
56	4523.3000	-186.1368	10820 11310	-185.3438	980136.1347	979679.0336
57	4513.6000	-185.0626	10810 11580	-184.2504	980136.1347	979680.6890
58	4592.4000	-187.7474	11550 11550	-186.9374	980136.1347	979673.2837
59	4587.3000	-187.8391	11680 11490	-187.0333	980136.1347	979673.4975
60	4610.1000	-187.5683	11810 11420	-186.7675	980136.1347	979672.4025
61	4613.6000	-187.1445	11880 11440	-186.3423	980136.1347	979672.6167
62	4672.2000	-186.9791	12050 11500	-186.1726	980136.1347	979669.2717
63	4503.7000	-183.4131	10200 11600	-182.5995	980136.1347	979682.9315
64	4465.3000	-184.2520	9640 12000	-183.4100	980136.1347	979684.3929
65	4479.8000	-183.6092	9850 12000	-182.7672	980136.1347	979684.1671
66	4487.9000	-184.0663	9990 12000	-183.2243	980136.1347	979683.2248
67	4514.5000	-182.8519	10190 11990	-182.0106	980136.1347	979682.8457
68	4510.2000	-183.2810	10190 11850	-182.4497	980136.1347	979682.6742
69	4505.0000	-183.4095	10190 12100	-182.5604	980136.1347	979682.8572
70	4509.7000	-182.9865	10180 12370	-182.1182	980136.1347	979682.9987
71	4492.2000	-183.3920	10170 12520	-182.5131	980136.1347	979683.6415
72	4491.0000	-183.5369	10150 12590	-182.6530	980136.1347	979683.5685
73	4493.8000	-183.6970	10110 12690	-182.8060	980136.1347	979683.2406
74	4513.5000	-183.7037	10110 13090	-182.7843	980136.1347	979682.0538
75	4523.0000	-183.7385	10100 13140	-182.8156	980136.1347	979681.4500
76	4544.2000	-181.9177	10540 13150	-180.9941	980136.1347	979682.0008
77	4548.2000	-181.8627	10600 13150	-180.9391	980136.1347	979681.8162
78	4578.1000	-181.1663	10750 13200	-180.2391	980136.1347	979680.7215
79	4580.6000	-181.0196	10750 13280	-180.0867	980136.1347	979680.7183
80	4598.7000	-180.2664	11050 13150	-179.3428	980136.1347	979680.3873
81	4604.8000	-179.9845	11260 13100	-179.0644	980136.1347	979680.3038
82	4673.0000	-180.0721	11700 13100	-179.1520	980136.1347	979676.1307
83	4572.3000	-180.8661	10750 13120	-179.9446	980136.1347	979681.3691
84	4654.1000	-175.0857	10800 13040	-174.1699	980136.1347	979682.2493
85	4654.1000	-175.0389	10800 12970	-174.1280	980136.1347	979682.2961
86	4549.5000	-180.5883	10880 12660	-179.6994	980136.1347	979683.0127
87	4553.0000	-180.8586	10880 12580	-179.9754	980136.1347	979682.5328
88	4548.8000	-181.1807	10880 12470	-180.3053	980136.1347	979682.4622
89	4551.0000	-181.7329	10880 12330	-180.8675	980136.1347	979681.7782
90	4547.9000	-182.2962	10880 12200	-181.4400	980136.1347	979681.4006
91	4560.4000	-178.5100	11020 12200	-177.6538	980136.1347	979684.4381
92	4552.9000	-182.1381	10850 12100	-181.2890	980136.1347	979681.2592
93	4550.9000	-182.7780	10830 12000	-181.9360	980136.1347	979680.7391
94	4536.9000	-182.9298	10830 11900	-182.0949	980136.1347	979681.4260
95	4516.9000	-185.0833	10820 11690	-184.2633	980136.1347	979680.4706
96	4537.8000	-182.6023	10800 12210	-181.7454	980136.1347	979681.6995
97	4461.0000	-185.4934	9250 12400	-184.6230	980136.1347	979683.4091
98	4466.6000	-184.8911	9390 12400	-184.0207	980136.1347	979683.6759
99	4469.4000	-184.3641	9640 12380	-183.4951	980136.1347	979684.0352
100	4466.6000	-184.1418	9650 12220	-183.2842	980136.1347	979684.4252
101	4465.2000	-184.2042	9640 12040	-183.3594	980136.1347	979684.4467

Station Number	Elevation	Simple Bouguer	Area Coordinates	Complete Bouguer	Theoretical Gravity	Observed Gravity
102	4486.8000	-183.6660	9870 12210	-182.8091	980136.1347	979683.6909
103	4495.2000	-183.3466	9980 12210	-182.4897	980136.1347	979683.5072
104	4500.6000	-183.3295	9980 12370	-182.4612	980136.1347	979683.2008
105	4494.9000	-183.7828	9870 12380	-182.9138	980136.1347	979683.0889
106	4514.5000	-182.7308	10290 12200	-181.8746	980136.1347	979682.9669
107	4511.2000	-182.6957	10290 12300	-181.8324	980136.1347	979683.1996
108	4487.8000	-183.5285	10410 11320	-182.7348	980136.1347	979683.7685
109	4483.5000	-183.6760	10410 11120	-182.8965	980136.1347	979683.8786
110	4474.5000	-183.6161	10400 10800	-182.8593	980136.1347	979684.4777
111	4471.4000	-179.4068	10380 10400	-178.6784	980136.1347	979688.8727
112	4472.4000	-182.7813	10340 10200	-182.0671	980136.1347	979685.4383
113	4542.8000	-184.7051	11220 12330	-183.8397	980136.1347	979679.2973
114	4572.0000	-184.3579	11220 12110	-183.5081	980136.1347	979677.8953
115	4565.4000	-185.3582	11220 11900	-184.5233	980136.1347	979677.2904
116	4601.3000	-185.7518	11400 11900	-184.9169	980136.1347	979674.7461
117	4644.1000	-185.4170	11490 12110	-184.5672	980136.1347	979672.5171
118	4607.5000	-183.6932	11550 12240	-182.8342	980136.1347	979676.4333
119	4590.2000	-186.2373	11370 11810	-185.4088	980136.1347	979674.9256
120	4550.3000	-186.2163	11100 11700	-185.3956	980136.1347	979677.3368
121	4559.9000	-183.6920	11050 12050	-182.8465	980136.1347	979679.2859
122	4701.3000	-180.9937	11600 12510	-180.1155	980136.1347	979673.5138
123	4675.8000	-186.1043	12050 11800	-185.2765	980136.1347	979669.9308
124	4710.4000	-185.0060	12050 12090	-184.1576	980136.1347	979668.9564
125	4718.4000	-179.8508	11950 12930	-178.9428	980136.1347	979673.6324
126	4574.5000	-180.6262	9450 12790	-179.7281	980136.1347	979681.4771
128	4509.1000	-182.7079	10350 12880	-181.8034	980136.1347	979683.3132
129	4497.1000	-183.2824	10200 12760	-182.3864	980136.1347	979683.4575
130	4507.3000	-183.1363	10200 12900	-182.2304	980136.1347	979682.9926
131	4515.9000	-183.3208	10220 13090	-182.4014	980136.1347	979682.2929
132	4507.6000	-183.6478	10110 12920	-182.7405	980136.1347	979682.4631
133	4548.9000	-186.6185	11010 11580	-185.8063	980136.1347	979677.0185
134	4576.8000	-186.2787	11280 11580	-185.4665	980136.1347	979675.6869
135	4555.9000	-187.4666	11000 11310	-186.6736	980136.1347	979675.7510
136	4574.5000	-188.4807	11480 11280	-187.6898	980136.1347	979673.6227
137	4635.9000	-187.0029	11640 11760	-186.1779	980136.1347	979671.4224
139	4641.2000	-187.7287	11900 11800	-186.9009	980136.1347	979670.3791
140	4670.3000	-185.3107	11800 11700	-184.4900	980136.1347	979671.0539
141	4463.1000	-183.3572	10000 10880	-182.5947	980136.1347	979685.4195
142	4467.4000	-183.6625	10000 11150	-182.8809	980136.1347	979684.8566
143	4470.7000	-183.6083	10140 11120	-182.8288	980136.1347	979684.7132
144	4501.5000	-184.1770	10620 11600	-183.3634	980136.1347	979682.2994
145	4507.8000	-183.6237	10620 11770	-182.6980	980136.1347	979682.5753
146	4500.2000	-182.8852	10300 12600	-182.0006	980136.1347	979683.6691
147	4529.8000	-181.5825	10590 12820	-180.6823	980136.1347	979683.1986
148	4556.7000	-182.6914	10450 13320	-181.7557	980136.1347	979680.4783
149	4572.5000	-182.7779	10450 13500	-181.8294	980136.1347	979679.4453
150	4592.9000	-182.7524	10450 13700	-181.7897	980136.1347	979678.2487
151	4623.2000	-181.6534	10450 14120	-180.6609	980136.1347	979677.5327
152	4707.4000	-180.3320	11600 13170	-179.4069	980136.1347	979673.8102
153	4538.2000	-183.7396	9850 13450	-182.7947	980136.1347	979680.5383

Station Number	Elevation	Simple Bouguer	Area Coordinates	Complete Bouguer	Theoretical Gravity	Observed Gravity
157	4623.9000	-181.5416	10650 13750	-180.5754	980136.1347	979677.6025
158	4623.8000	-181.9364	10500 13800	-180.9666	980136.1347	979677.2137
159	4683.9000	-181.5065	10800 13800	-180.5367	980136.1347	979674.0433
160	4720.4000	-181.1849	11720 13240	-180.2549	980136.1347	979672.1785
161	4966.1000	-191.2792	13780 11750	-190.4550	980136.1347	979647.3657
162	5054.4000	-193.4182	14000 12000	-192.5762	980136.1347	979639.9372
163	5093.8000	-192.4432	14100 12120	-191.5927	980136.1347	979638.5520
164	5205.2000	-177.0212	14480 12630	-176.1345	980136.1347	979647.3006
165	5223.0000	-177.4030	14550 12750	-176.5078	980136.1347	979645.8526
166	5283.3000	-186.8221	14580 13000	-185.9091	980136.1347	979632.8213
167	4781.5000	-176.9981	11360 13360	-176.0595	980132.4461	979669.0165
168	4797.2000	-176.7935	11530 14000	-175.8095	980132.4461	979668.2807
169	4812.3000	-175.6739	12090 13820	-174.7027	980132.4461	979668.4957
170	4828.1000	-175.4053	12200 13300	-174.4710	980132.4461	979667.8178
171	4682.4000	-178.1182	10450 14000	-177.1342	980132.4461	979673.8329
171	4514.6000	-183.7297	7850 16900	-182.5398	980132.4461	979678.2733
172	4684.5000	-178.0950	8900 16900	-176.9051	980132.4461	979673.7303
172	4552.3000	-182.0140	10940 14240	-181.0130	980132.4461	979677.7307
173	4600.3000	-183.1582	8890 17600	-181.9186	980132.4461	979673.7110
174	4678.6000	-186.4548	8550 18600	-185.1442	980132.4461	979665.7240
175	4648.7000	-187.1013	8120 18450	-185.8014	980132.4461	979666.8686
176	4581.1000	-184.2941	7590 18000	-183.0261	980128.7585	979670.0378
177	4512.5000	-183.4460	7330 17590	-182.2071	980128.7585	979674.9952
178	4533.5000	-191.1775	6100 19700	-189.7888	980128.7585	979666.0058
179	4561.0000	-191.0747	6500 19700	-189.6860	980128.7585	979664.4612
180	4518.9000	-191.3647	6700 19830	-189.9668	980128.7585	979666.6932
181	4507.9000	-190.8391	6880 19150	-189.4895	980128.7585	979667.8778
182	4627.1000	-189.7344	7050 19650	-188.3493	980128.7585	979661.8418
183	4697.5000	-187.7881	7600 19650	-186.4030	980128.7585	979659.5709
184	4650.6000	-188.3701	7500 19650	-186.9850	980128.7585	979661.7984
185	4800.7000	-186.1180	8300 19650	-184.7329	980128.7585	979655.0589
186	4886.7000	-185.7845	8900 19650	-184.4249	980128.7585	979650.2406
187	4821.6000	-191.0316	8900 19290	-190.0689	980134.6591	979654.7939
188	4456.0000	-185.8538	10000 13700	-184.8506	980132.4461	979679.6596
189	4494.0000	-181.2253	8850 14270	-180.2094	980132.4461	979682.0117
190	4540.9000	-180.2400	9850 14450	-179.1836	980132.4461	979680.1875
191	4569.9000	-178.6020	9820 15020	-177.5186	980132.4461	979680.0883
192	4564.9000	-179.2713	9650 15400	-178.2731	980132.4461	979679.7185
193	4693.4000	-179.9723	10280 14200	-178.7576	980132.4461	979671.3199
194	4578.6000	-177.5364	9260 17250	-176.3493	980128.7585	979676.9452
195	4584.8000	-175.3720	9900 16860	-174.1608	980128.7585	979678.7381
196	4609.2000	-175.4923	9920 17200	-174.2534	980128.7585	979677.1562
197	4679.5000	-176.1162	9980 17590	-174.8695	980128.7585	979672.3210
198	4755.9000	-176.5381	10320 17700	-175.2843	980128.7585	979667.3225
199	4807.2000	-177.6552	10500 17800	-176.3837	980128.7585	979663.1323
200	4851.7000	-179.5575	10500 18050	-178.3002	980128.7585	979658.5643
201	4679.3000	-177.7343	9850 17850	-176.4457	980128.7585	979670.7150
202	4670.3000	-185.6739	10020 18290	-184.3832	980128.7585	979663.3145
203	4730.2000	-180.7839	9720 18320	-179.5983	980128.7585	979664.6163
204	4650.1000	-178.5884	10500 16840	-177.3829	980132.4461	979675.2976

Station Number	Elevation	Simple Bouguer	Area Coordinates	Complete Bouguer	Theoretical Gravity	Observed Gravity
205	4689.9000	-177.6700	10500 17120	-176.5099	980132.4461	979673.8357
206	4669.0000	-177.7839	10500 16480	-176.6700	980132.4461	979674.9699
207	4626.7000	-180.1348	10800 15830	-179.0060	980132.4461	979675.1530
208	4653.1000	-182.8373	10920 16040	-181.7603	980132.4461	979670.8690
209	4635.4000	-179.0925	10490 15310	-178.0446	980132.4461	979675.6741
210	4605.2000	-182.3130	10440 14900	-180.6971	980132.4461	979674.2627
211	5461.4000	-193.7899	10600 22900	-192.9408	980132.4461	979611.4959
211	5040.5000	-192.0655	13800 12100	-191.0219	980136.1347	979642.1226
212	4951.9000	-178.6704	12000 14840	-177.0510	980132.4461	979614.2474
212	5433.6000	-192.7037	10320 22950	-191.6892	980132.4461	979657.1366
213	4878.9000	-177.8442	12000 14430	-176.2489	980132.4461	979662.3606
213	5241.8000	-191.1449	9370 22610	-189.5468	980132.4461	979662.3357
214	5139.8000	-190.6182	8810 22650	-189.0179	980132.4461	979633.9327
215	4951.1000	-188.3048	8340 22680	-186.7067	980128.7585	979643.8625
216	4883.0000	-188.5085	7200 22650	-186.9295	980128.7585	979647.7383
217	4800.0000	-187.6474	6670 22380	-186.0919	980128.7585	979653.5715
218	4750.5000	-187.1662	6250 22050	-185.6178	980128.7585	979657.0179
219	4685.3000	-187.4822	6000 21950	-185.9600	980128.7585	979660.6076
220	4629.4000	-188.7649	5380 21580	-187.6616	980128.7585	979662.6736
221	4588.1000	-174.7228	10050 15680	-173.6224	980128.7585	979679.1897
222	4559.2000	-175.2058	9650 15640	-174.1061	980128.7585	979680.4379
223	4522.4000	-175.0069	9120 15630	-173.9058	980128.7585	979682.8413
224	4497.5000	-175.7006	8560 15650	-174.6158	980128.7585	979683.6393
225	4508.3000	-175.3089	9000 15420	-174.2340	980128.7585	979683.3839
226	4512.3000	-175.2429	8990 15280	-174.1851	980128.7585	979683.2104
227	4509.2000	-175.2237	8950 15040	-174.1687	980128.7585	979683.4152
228	4480.6000	-175.7403	8560 15000	-174.6889	980128.7585	979684.6119
229	4473.6000	-176.3230	8260 14950	-175.2481	980128.7585	979684.4485
230	4479.2000	-176.1815	8180 15280	-175.4488	980128.7585	979684.2546
400	4448.4000	-182.9193	9880 10460	-182.1774	980136.1347	979686.7380
401	4446.4000	-183.0499	9810 10590	-182.2860	980136.1347	979686.7272
402	4442.9000	-183.3530	9700 10900	-182.5827	980136.1347	979686.6338
403	4444.4000	-183.6424	9660 10990	-182.8622	980136.1347	979686.2545
404	4443.8000	-183.6995	9620 11130	-182.9129	980136.1347	979686.2334
405	4442.2000	-183.8358	9580 11220	-183.0371	980136.1347	979686.1929
406	4442.8000	-184.1687	9520 11390	-183.3310	980136.1347	979685.8241
408	4448.8000	-185.2124	9330 11940	-184.3399	980136.1347	979684.4210
410	4456.7000	-185.7631	9100 12430	-184.8806	980136.1347	979683.3970
411	4463.8000	-186.1565	9020 12570	-185.3820	980136.1347	979682.5782
412	4497.4000	-178.2151	9640 11050	-177.3767	980136.1347	979688.5069
479	4439.2000	-186.4867	8820 11950	-185.6816	980136.1347	979683.7217
480	4432.4000	-186.1484	8840 11480	-185.3490	980136.1347	979684.4673
481	4430.1000	-185.8368	8830 11400	-184.9373	980136.1347	979684.9168
485	4467.3000	-186.0936	9000 12810	-185.1920	980136.1347	979682.4315
486	4469.9000	-186.3472	8980 12840	-185.4413	980136.1347	979682.0221
487	4470.4000	-186.2051	8970 12900	-185.2942	980136.1347	979682.1343
488	4472.0000	-185.9256	8930 12970	-185.1958	980136.1347	979682.3180
692	4608.1000	-185.8166	11980 10420	-185.0818	980136.1347	979674.2740
693	4600.4000	-186.2887	11860 10490	-185.5426	980136.1347	979674.2632
694	4594.0000	-186.4071	11920 10650	-185.6524	980136.1347	979674.5281

Station Number	Elevation	Simple Bouguer	Area Coordinates	Complete Bouguer	Theoretical Gravity	Observed Gravity
695	4601.8000	-187.7092	11850 10770	-186.9986	980136.1347	979672.7588
696	4633.2000	-186.7183	12780 10150	-185.9927	980136.1347	979671.8687
697	4670.7000	-186.8243	12780 10360	-186.0817	980136.1347	979669.5164
699	4740.5000	-186.6886	12800 10600	-185.9354	980136.1347	979665.4707
700	4704.8000	-186.2937	12850 10750	-185.5277	980136.1347	979668.0041
701	4731.3000	-185.7367	12900 10930	-184.9373	980136.1347	979666.9737
702	4782.1000	-186.1919	13350 11400	-185.3868	980136.1347	979663.4754
703	4842.3000	-186.7530	13480 11480	-185.9493	980136.1347	979659.3081
704	4874.8000	-188.1656	13580 11460	-187.3598	980136.1347	979655.9486
708	4703.1000	-187.2308	12150 11490	-186.4165	980136.1347	979667.1689
709	4730.3000	-187.2946	12200 11610	-186.4739	980136.1347	979665.4758
710	4739.5000	-187.0965	12280 11700	-186.2630	980136.1347	979665.1227
711	4770.9000	-187.0509	12390 11880	-186.2075	980136.1347	979663.2873
712	4783.0000	-186.7814	12450 12020	-185.9273	980136.1347	979662.8320
713	4817.4000	-186.3253	12530 12170	-185.4492	980136.1347	979661.2274
714	4845.2000	-185.4308	12720 12480	-184.5490	980136.1347	979660.4565
715	4887.3000	-183.9373	12810 12560	-183.1273	980136.1347	979659.4280
716	4875.3000	-186.5027	13450 11550	-185.6919	980136.1347	979657.5815
717	4885.4000	-185.5851	13240 11560	-184.7566	980136.1347	979657.8941
718	4908.0000	-185.6391	13250 11810	-184.8092	980136.1347	979656.4862
719	4891.2000	-184.7865	13100 11830	-184.0567	980136.1347	979658.3452
724	4562.8000	-188.6013	11180 10420	-187.8623	980136.1347	979674.2030
726	4578.6000	-189.4459	11330 10560	-188.7061	980136.1347	979672.4119
727	4595.1000	-184.2660	11480 10560	-183.5262	980136.1347	979676.6034
728	4603.5000	-189.0547	11700 10700	-188.3050	980136.1347	979671.3114
729	4587.5000	-185.5039	11990 10160	-184.7925	980136.1347	979675.8207
761	4452.2000	-185.3416	9280 12070	-184.4946	980136.1347	979684.0880
762	4454.9000	-185.4695	9250 12150	-184.6169	980136.1347	979683.7984
767	4473.0000	-186.2689	8920 13200	-185.3417	980136.1347	979681.9147
771	4489.8000	-185.7540	9200 13200	-184.8268	980136.1347	979681.4232
775	4502.3000	-185.1451	9500 13200	-184.2179	980136.1347	979681.2834
779	4509.6000	-183.7966	9740 13200	-182.8694	980136.1347	979682.1945
784	4531.6000	-183.2152	10100 13200	-182.2880	980136.1347	979681.4581
787	4543.3000	-182.8115	10310 13200	-181.8843	980136.1347	979681.1609
795	4507.0000	-182.5781	10440 12000	-181.7361	980136.1347	979683.5688
796	4511.1000	-182.6754	10440 12100	-181.8263	980136.1347	979683.2259
797	4513.5000	-182.6385	10440 12200	-181.7823	980136.1347	979683.1191
798	4514.9000	-182.3781	10440 12300	-181.5148	980136.1347	979683.2955
799	4512.8000	-181.9990	10440 12400	-181.1286	980136.1347	979683.8005
800	4516.6000	-181.6599	10440 12580	-180.7767	980136.1347	979683.9119
801	4522.2000	-181.5549	10440 12750	-180.6597	980136.1347	979683.6815
803	4534.3000	-181.7975	10440 13100	-180.8774	980136.1347	979682.7140
808	4456.8000	-184.1543	9400 11990	-183.3130	980136.1347	979684.9998
810	4466.0000	-183.8825	9500 12000	-183.0405	980136.1347	979684.7204
813	4480.4000	-183.4242	9760 11610	-182.6099	980136.1347	979684.3161
818	4489.3000	-183.3341	10000 11610	-182.5198	980136.1347	979683.8731
837	4456.5000	-183.8941	9700 11420	-183.0933	980136.1347	979685.2779
840	4467.7000	-183.5646	9920 11500	-182.7581	980136.1347	979684.9366
841	4473.8000	-183.5102	9900 11600	-182.6966	980136.1347	979684.6255
917	4524.1000	-186.1863	10820 10430	-185.4558	980136.1347	979678.9362

Station Number	Elevation	Simple Bouguer	Area Coordinates	Complete Bouguer	Theoretical Gravity	Observed Gravity
956	4449.1000	-182.9672	9850 10570	-182.2267	980136.1347	979686.6482
958	4458.1000	-183.4785	10040 10630	-182.7338	980136.1347	979685.5977
983	4530.2000	-186.0490	10800 10340	-185.3249	980136.1347	979678.7082
984	4528.9000	-185.6981	10800 10250	-184.9804	980136.1347	979679.1369
985	4522.1000	-185.3187	10800 10100	-184.6116	980136.1347	979679.9237

APPENDIX II

RADIOCARBON DATING OF GROUNDWATER

THEORY

RADIOCARBON DATING OF GROUNDWATER, THEORY

Carbon-14, like tritium, is a radioactive isotope which is produced in the upper atmosphere by cosmic ray bombardment at the rate of 2.5 $atoms/cm^2/sec$ (Payne, 1972). The carbon-14 content in the atmosphere has been shown, by tree ring analysis, to have varied naturally during the last 7000 years, but the variation is small. Due to atmospheric thermonuclear testing in the 1950's and 1960's, the carbon-14 concentration in the atmosphere had increased in 1963 to 184% of the natural level in the northern hemisphere (Geyh, 1972).

Carbon-14 decays at a log-linear rate to nitrogen-14, emitting a beta particle and an antineutrino. The decay can be described by:

$$A = A_o 2^{-t/T} \text{ or } t = -8267 \ln A/A_o$$

A_o = initial activity
A = activity at time t
T = 1/2 life = 5730 years
$8267 = 5730/\ln 2$

Geochemists use the accepted half-life for carbon-14 of 5730 years, although Paleontologists commmonly use the Libby half-life of 5570 years.

Because of the long half-life of carbon-14 compared to tritium, radiocarbon dating can be used to determine the age of water which is 1,000 to 50,000 years old (Campana, 1976). The zero age date is A.D. 1950 (Faure, 1977).

The original carbon-14 activity is now defined as 95% of the activity of NBS oxalic acid in 1950; and equal to 13.56 decays per minute per gram (dpm/g) of carbon (A_o= 13.56 dpm/g). An older standard used was wood grown in 1890 in a fossil CO_2-free environment (Fritz and Fontes, 1980). Activity of a sample is frequently reported as deviation in parts per thousand (°/oo) from the standard with negative deviation meaning less activity than the standard. Carbon-14 activity used in this study is reported as activity (A), percent modern carbon (A(PMC) or $\delta^{14}C$ defined by:

Where A_o= 13.56 dpm/g

$$A = \frac{\delta^{14}C\% \; A_\circ}{1000} + A_\circ = \text{Activity of sample in decays per minute per gram of carbon (dpm/g)}$$

$$A(\text{PMC}) = \left[\frac{A}{A_\circ}\right] \text{ as a fraction: } = \left[\frac{A}{A_\circ}\right] 100\% \text{ expressed as a percent}$$

$$\delta^{14}C\% = \left[\frac{A}{A_\circ} - 1\right] 1000$$

An activity of 100% is close to steady state activity of CO_2 in plants (Fritz and Fontes, 1980).

CASE 1: A single recharge area.

To calculate the actual age of the groundwater sampled at a point, one must know what percent of carbon is from the soil zone in the recharge area and what percent is from dissolved carbonate along the flow path, as described by:

$$\underset{\text{(soil)}}{CO_2} + H_2O + \underset{\text{(dissolved)}}{CaCO_2} <> Ca^{2+} + \underset{\text{(sampled)}}{2HCO_3} \quad \text{(Mook, 1972)}$$

This is compounded by cation exchange with clays:

$$2Na - clay + Ca^{2+} <> Ca - clay + 2Na^{+} \quad \text{(Pearson and White, 1967)}$$

which is thought to produce $NaCO_3$ waters. There seems to be no theoretical methods by which one can correct for both the proportion of plant carbon in diluted carbonate and cation exchange. This type of dilution is approximated by use of a stable isotope, carbon-13. Carbon-13 values used are reported in parts per thousand (°/oo) deviation from the Cretaceous Pee Dee formation belemnites (Belemnitella Americana) in South Carolina (Faure, 1977), commonly abbreviated PDB. For confined flow from a single area, the soil zone in the recharge area is assumed to be a single value (based on root respiration), and dissolving carbonate along the flow path is assumed to have a different value.

Carbon-13 analysis of the collected sample is used to calculate the percentage of each of these two components. One then divides the sample C-14 activity by the fraction of water from the recharge area to presumably get the "actual" C-14 activity of a sample, corrected for dilution by "dead" carbon.

CASE 2: Multiiple recharge areas

Unconfined aquifers or confined aquifers with several source areas present more difficulties in the calculation of the percentage of water from different sources. A simple case has two recharge sources; water from the root zone in recharge areas and direct infiltration of precipitation along stream channels. These sources have considerably different carbon-13 values since precipitation infiltrating the recharge area exchanges CO_2 from root respiration. The third source of carbon-13 is from dissolving carbonate along the flow path. In the case of two recharge sources and one dilution source, one must assume or estimate proportions of recharge sources to be able to correct the carbon-14 for flow path carbonate dilution. Actual aquifer recharge in an unconfined aquifer is probably more complicated than this three source solution.

Recharge sources have the following carbon-13 values:

1. Root respiration by Calvin photosynthetic plants (C3), primarily in cold regions: $\delta^{13}C = -25 \pm 3°/oo$ (Fritz & Fontes, 1980)

2. Root respiration by Hatch-Slack photosynthetic plants (C4) common in arid regions: $\delta^{13}C = -12°/oo$ (Osmond, 1981; Payne, 1972) applicable to eastern Sierras.

3. Atmospheric CO_2 (in precipitation): $\delta^{13}C = -6.4°/oo$ worldwide for uncontaminated air (Craig, 1953; Craig and Keeling, 1962)

Carbon is not an ideal tracer since some carbonate from limestone and carbonate cement will mix with the groundwater as it flows through the aquifer. Since most limestone beds are greater than 50,000 years old, they will have essentially no carbon-14 activity ("dead" carbon), and as such will effectively lessen the carbon-14 activity of groundwater, making samples appear to be older than they actually are.

Dilution from "dead" carbon along the flow path has the following values:

a. Marine limestone (most common) $\delta^{13}C = 0.0 \pm 2.5‰$ (Smith and Others, 1976; Fritz and Fontes, 1980)

b. Fresh water limestones: $\delta^{13}C = +5$ to $-16°/oo$ (Edmunds and Wright, 1979)

The case of a single recharge source from the soil zone in cold region recharge areas and marine limestone dilution produces the following carbon-14 correction equations:

$$\text{A corrected} = A_C = \text{A measured}/p \quad \text{where } p = \frac{\delta^{13}C \text{ sample}}{-25}$$

A variation on this correction method (Pearson and White, 1967) does not produce significantly different results. An example of this cycle and correction is presented in Figure A10.

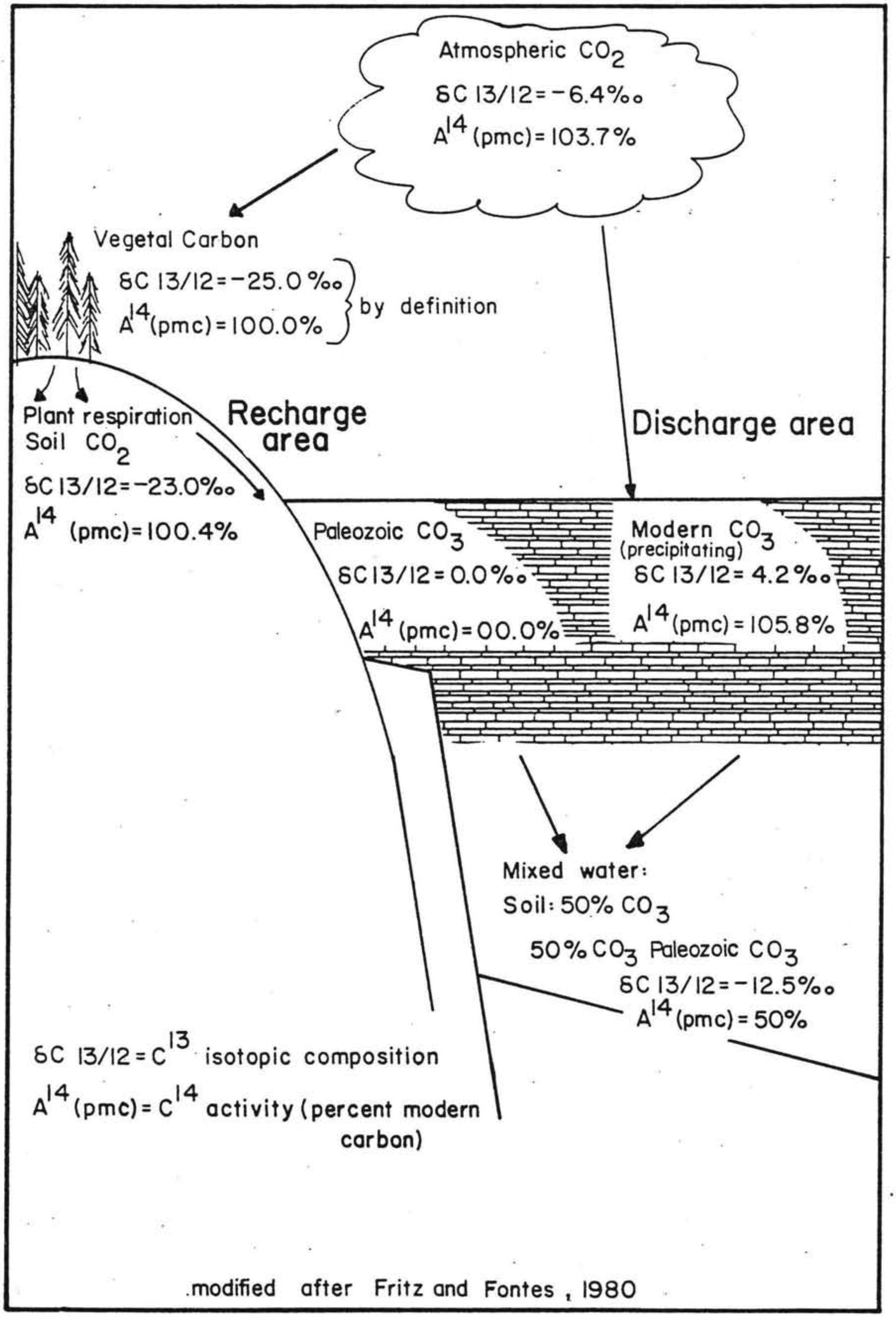
The case of two recharge sources (soil zone and direct infiltration) in cold regions produces the following equations for correction:

$$\text{A corrected} = A'_C = \text{A measured}/p' \quad \text{where } p' = \frac{\delta^{13}C \text{ sample}}{-25x - 6.4y}$$

x = fraction recharge from soil zone

y = fraction recharge from direct infiltration

This assumes soil zone recharge has a $\delta^{13}C = -25°/oo$, and infiltrating precipitation has a $\delta^{13}C = -6.4°/oo$.



.modified after Fritz and Fontes, 1980

Figure A1. The carbon isotope cycle for a single recharge source and a single dilution source.

A second possibility of two recharge sources is one high altitude C3 recharge source (-25.°/oo) and a second low altitude C4 recharge source (-12.°/oo). This may approximate low altitude infiltration along stream channels thought to be the major recharge mechanism in the basin and range providence. It is unknown whether this recharge water would retain its carbon-13 content (-6.4°/oo) or equilibrate with the soil zone (-12°/oo). Payne (1972) suggests that wherever recharge occurs via infiltration from riverbeds or fissured rocks, the processes in the unsaturated zone are short circuited and some water would retain the $\delta^{13}C = -6.4°/oo$ from atmospheric CO_2.

The mixture of two recharge sources can be estimated by collecting a modern sample which has no dead carbon (derived from dissolving carbonate). One can then estimate the fractions of the two other sources by assuming A + B = 1 which gives:

$$x = \text{fraction recharge from soil zone} = \frac{\delta^{13}C\ \text{sample} - \delta^{13}C\ \text{Precip.}}{\delta^{13}C\ \text{soil zone} - \delta^{13}C\ \text{Precip.}} = \frac{\delta^{13}C\ \text{sample} + 6.4}{-25 + 6.4}$$

$$y = \text{fraction recharge from direct infiltration} = 1 - \text{fraction recharge from soil zone}$$

In Szecsody (1982), a sample with modern carbon-14 activity had a $\delta^{13}C$ value of -17.3 which means 59% soil zone recharge and 41% direct infiltration recharge. Assuming soil zone equilibration (-12.°/oo), there would be 40% high altitude recharge, and 60% low altitude recharge. Either way, the equation for correcting dilution then read:

$$A'_c = A\ \text{measured}/p' \text{ where } p' = \delta^{13}C\ \text{sample}/-17.3$$

Glancy (1981) used a value of -15.°/oo for this factor based on other work done by the U.S. Geological Survey. Wigley (1975) recommends using -15.

°/oo to -16.°/oo for initial carbon-13 in open systems, where atmospheric CO_2 + SO_2 CO_2 is input continuously. One notes that the first approach of a single recharge source produces corrected carbon-14 values well over 100% PMC indicating fault in the equations, whereas the second approach produces more reasonable values.

This "two recharge source" solution is a very simple approximation of recharge to an aquifer. In the Sierra Nevada, while most precipitation is in the high mountain regions, aquifer recharge occurs via deep percolation, mountain front recharge and lower elevation stream channel infiltration where some of this stream flow is from soil zone interflow. At best, the fraction recharge from the soil zone (x) represents the water which on the average equilibrated with soil zone CO_2 ($\delta^{13}C$ = -25.°/oo), and the fraction from direct infiltration (y) represents the average of the water which equilibrated with atmospheric CO_2 ($\delta^{13}C$ = -6.4°/oo). Actual infiltration is from water whose $\delta^{13}C$ probably ranges from -25 to -6.4°/oo.

The best method for using any carbon-14 correction method would be to measure the $\delta^{13}C$ values of all sources. The $\delta^{13}C$ of surface runoff was measured in this study, a more accurate representation of direct infiltration source $\delta^{13}C$ than the worldwide $\delta^{13}C$ of atmospheric CO_2.

APPENDIX III

DATA ON GEOTHERMAL WELLS

RECORD NUMBER	ADDRESS	MAXIMUM TEMP °C	DEPTH (m)
1	1701 Skyline Blvd.	75.6	203.0
2	2270 Skyline Blvd.	75.0	259.1
3	2190 Dant Blvd.	76.7	175.3
4	2135 Richter Dr.	97.2	198.0
5	A. Warren Estates Test Well	95.0	211.9
	B. Warren Estates Production Well	97.0	254.0
6	166 Greenridge Dr.	26.3	155.0
7	795 Manzanita Lane	48.9	74.4
8	1195 Manzanita Lane	91.7	54.6
9	1200 Manzanita Lane	80.0	60.4
10	1301 Manzanita Lane	65.8+	30.0
11	1385 Manzanita Lane	85.0	61.0
12	1425 Manzanita Lane	82.21	56.4
13	1460 Manzanita Lane	82.2	45.7
14	1495 Manzanita Lane	58.4	30.5
15	1560 Manzanita Lane	93.3	67.1
16	1680 Manzanita Lane	75.0	76.2
17	1730 Manzanita Lane	94.5	121.9
18	1800 Manzanita Lane	91.0	99.1
19	1840 Manzanita Lane	85.0	228.6
20	1960 Manzanita Lane	93.3	94.5
21	2000 Manzanita Lane	97.2	99.1
22	2190 Manzanita Lane	87.8	103.0
23	1140 Sweetwater Dr.	71.1	80.8
24	1150 Sweetwater Dr.	77.8	94.5
25	1155 Sweetwater Dr.	85.9	96.9
26	1160 Sweetwater Dr.	85.0	60.0
27	1165 Sweetwater Dr.	88.9	76.2
28	1170 Sweetwater Dr.	77.2	54.9
29	1175 Sweetwater Dr.	90.0	50.3
30	1184 Sweetwater Dr.	82.0	39.6
31	1185 Sweetwater Dr.	85.0	61.0
32	1188 Sweetwater Dr.	86.1	61.0

RECORD NUMBER	ADDRESS	MAXIMUM TEMP °C	DEPTH (m)
33	1192 Sweetwater Dr.	85.0	62.2
34	1196 Sweetwater Dr.	80.0	68.6
35	1198 Sweetwater Dr.	85.0	64.0
36	1204 Sweetwater Dr.	90.0	70.1
37	1275 Sweetwater Dr.	85.0	109.7
38	A. 1165 Yates Lane	52.0	59.5
	B. 1165 Yates Lane	85.0	76.0
39	1175 Yates Lane	88.0	?
40	1185 Yates Lane	86.7	45.7
41	1350 Doral Cr.	81.1	76.2
42	1355 Doral Cr.	75.6	68.6
43	1370 Doral Cr.	87.8	39.0
44	1400 Huntington Cr.	82.2	51.8
45	1405 Huntington Cr.	90.6	52.7
46	1435 Huntington Cr.	82.2	53.4
47	1440 Huntington Cr.	86.7	70.4
48	1465 Huntington Cr.	91.7	54.3
49	1495 Huntington Cr.	73.9	88.7
50	1440 Bermuda Cr.	85.0	36.6
51	1465 Bermuda Cr.	82.2	55.8
52	1490 Bermuda Cr.	88.9	56.4
53	3850 Plumas St.	71.3	138.7
54	4000 Plumas St.	85.0	91.4
55	4280 Plumas St.	82.7	55.0
56	4270 Plumas St.	91.0	52.0
57	4400 Plumas St.	92.2	30.0
58	1410 Ayershire Cr.	93.3	70.0
59	1440 Ayershire Cr.	60.0	68.6
60	1625 Wendy Way	58.0	115.9
61	1640 Wendy Way	60.0	76.2
62	1660 Wendy Way	82.2	201.0
63	1770 Wendy Way	82.2	193.6
64	1840 Wendy Way	68.3	80.8

RECORD NUMBER	ADDRESS	MAXIMUM TEMP °C	DEPTH (m)
65	1855 Wendy Way	73.9	82.3
66	4042 Swanson Lane	81.2	195.1
67	1880 Meadowview Lane	70.0	247.0
68	1120 W. Peckham Lane	85.0	75.3
69	1160 W. Peckham Lane	85.0	74.7
70	1170 W. Peckham Lane	80.0	80.8
71	1180 W. Peckham Lane	89.9	123.5
72	2020 Willow Tree Lane	82.2	183.0
73	1735 Sand Point Cr.	76.7	76.2
74	1775 Sand Point Cr.	90.6	76.2
75	1785 Sand Point Cr.	88.3	76.2
76	5000 Lakeridge Dr.	26.7	125.0
77	4850 Rio Pinar Dr.	75.6	94.0
78	2075 Lakeside Dr.	51.7	189.9
79	3835 Lakeside Dr.	70.0	122.0
80	3905 Lakeside Dr.	82.2	141.4
81	Lakeside and Peckham	60.0	82.3
82	4100 Lakeside Dr.	77.8	135.7
83	4235 Lakeside Dr.	70.0	61.0
84	4595 Lakeside Dr.	54.4	48.0
85	2201 S. Virginia St.	42.2	274.3
86	2707 S. Virginia St.	53.0	227.9
87	2600 Eastshore Dr.	58.8	306.6
88	760 Hash Lane	27.8	33.5
89	3905 Garlan Lane	51.5	92.7
90	4095 Garlan Lane	48.3	67.4
91	4200 Garlan Lane	43.3	54.9
92	4255 Garlan Lane	50.6	91.2
93	4000 Jasper Lane	48.9	75.3
94	4030 Jasper Lane	46.1	79.3
95	4155 Jasper Lane	48.9	89.9
96	4200 Jasper Lane	43.3	75.3
97	4290 Jasper Lane	43.3	61.6

RECORD NUMBER	ADDRESS	MAXIMUM TEMP °C	DEPTH (m)
98	4000 Warren Way	43.9	67.1
99	4100 Warren Way	48.9	67.4
100	4210 Warren Way	48.9	68.0
101	4260 Warren Way	48.9	69.5
102	4295 Warren Way	47.8	63.7
103	4860 Warren Way	36.1	105.5
104	690 Starlight Cr.	54.4	69.5
105	970 Pinebrook Rd.	20.6	121.9
106	600 Sapphire Cr.	49.4	93.6
107	.5 miles W. of Big 5	36.9	?
108	3575 Grant Dr.	80.0	99.1
109	1100 Moana Lane	43.3	50.3
110	Moana Pool #1 Well	51.7	152.4
111	955 W. Peckham	81.7	114.3
112	2300 Solari	82.0	290.0
113	1450 Granite	82.0	399.0
114	2700 Plumas	64.0	286.0
115	960 W. Peckham	78.0	112.8
116	Lakewood Court	61.0	74.1
117	2100 Manzanita Lane	93.8	106.7
118	3705 Lakeside Dr.	73.0	103.9
119	2690 Monterey	62.0	170.1
120	2020 Manzanita Lane	94.8	86.3
121	Mt. Rose Highway	33.3	88.8
122	2040 Manzanita Lane	93.1	89.3
123	4250 Plumas	84.2	58.5
124	2400 Plumas (at Country Club)	51.0	228.7
125	2695 Monterey Cr.	64.4	253.4
126	A. 1275 Sweetwater Dr.	71.9	72.9
	B. 1275 Sweetwater Dr.	65.6	118.9
127	Bermuda Circle North	88.3	62.8
128	Bermuda Circle South	81.5	85.4
129	1375 Doral	72.2	87.5

RECORD NUMBER	ADDRESS	MAXIMUM TEMP °C	DEPTH (m)
130	2000 Dant	94.8	243.9
131	1885 Manzanita Lane	89.3	127.4
132	Horseman's Park	33.0	122.0
133	Pioneer Dr.	45.2	122.0
134	Manzanita/Lakeside	73.0	122.0
135	Manzanita Park	51.7	122.0
136	Warren Estates	86.2	243.9
137	2160 Manzanita Lane	87.9	97.6
138	4960 Plumas	25.2	91.5
139	300 ft. west of Lakeside 300 ft. north of Meadowridge intersection	15.3	56.4
140	Kivett Lane, Steamboat Area	32.0	60.4
141	Sagehill Road, Steamboat Area	123.0	56.4
142	Trailer park on West Fourth St., next to Truckee River, near Chalk Bluff	39.5	436.6
143	1845 Manzanita Circle	94.0	190.5

APPENDIX IV

TEMPERATURE GRADIENTS OF GEOTHERMAL WELLS

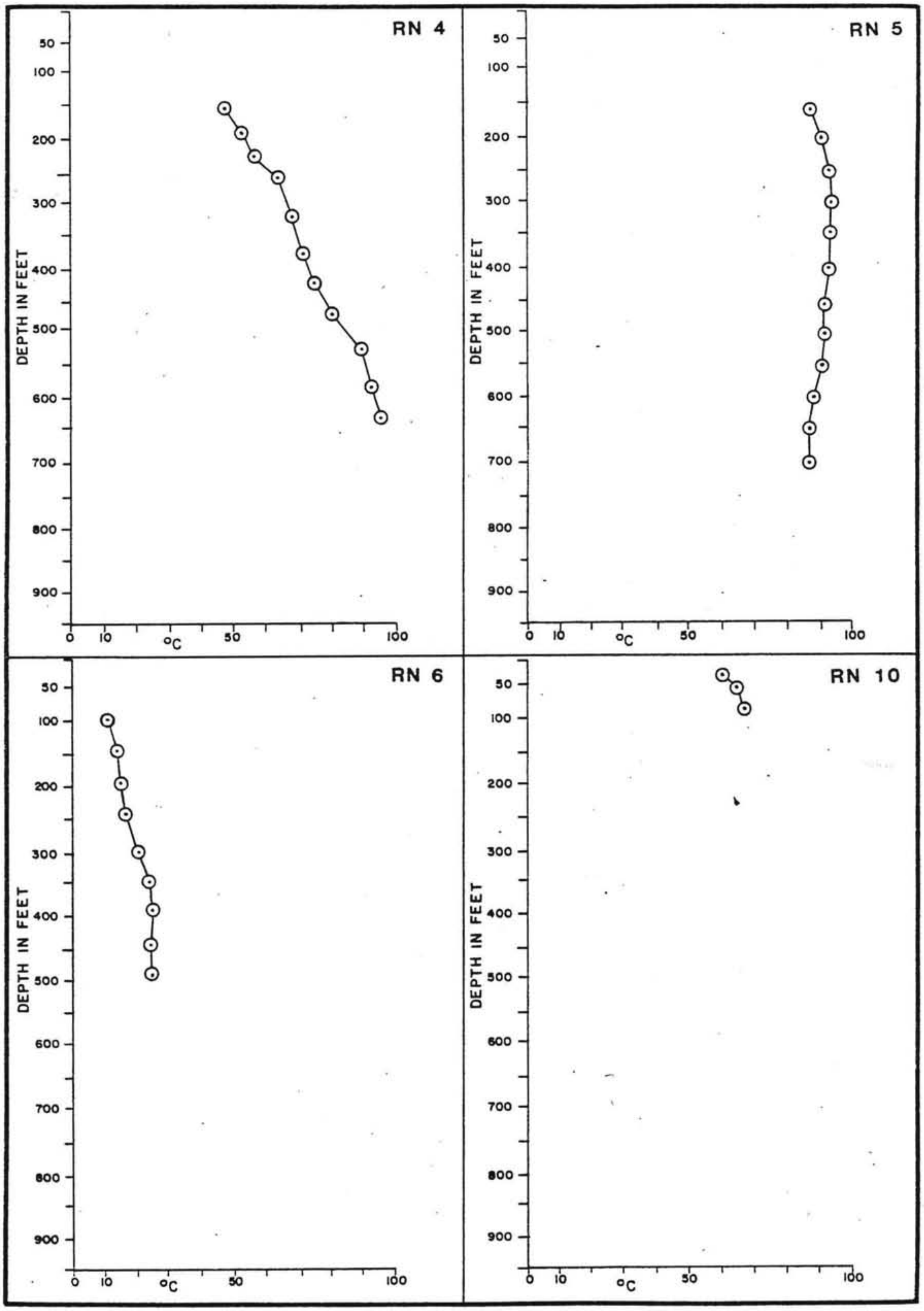


Figure A2. Temperature-depth profiles, wells RN 4, 5, 6, 10

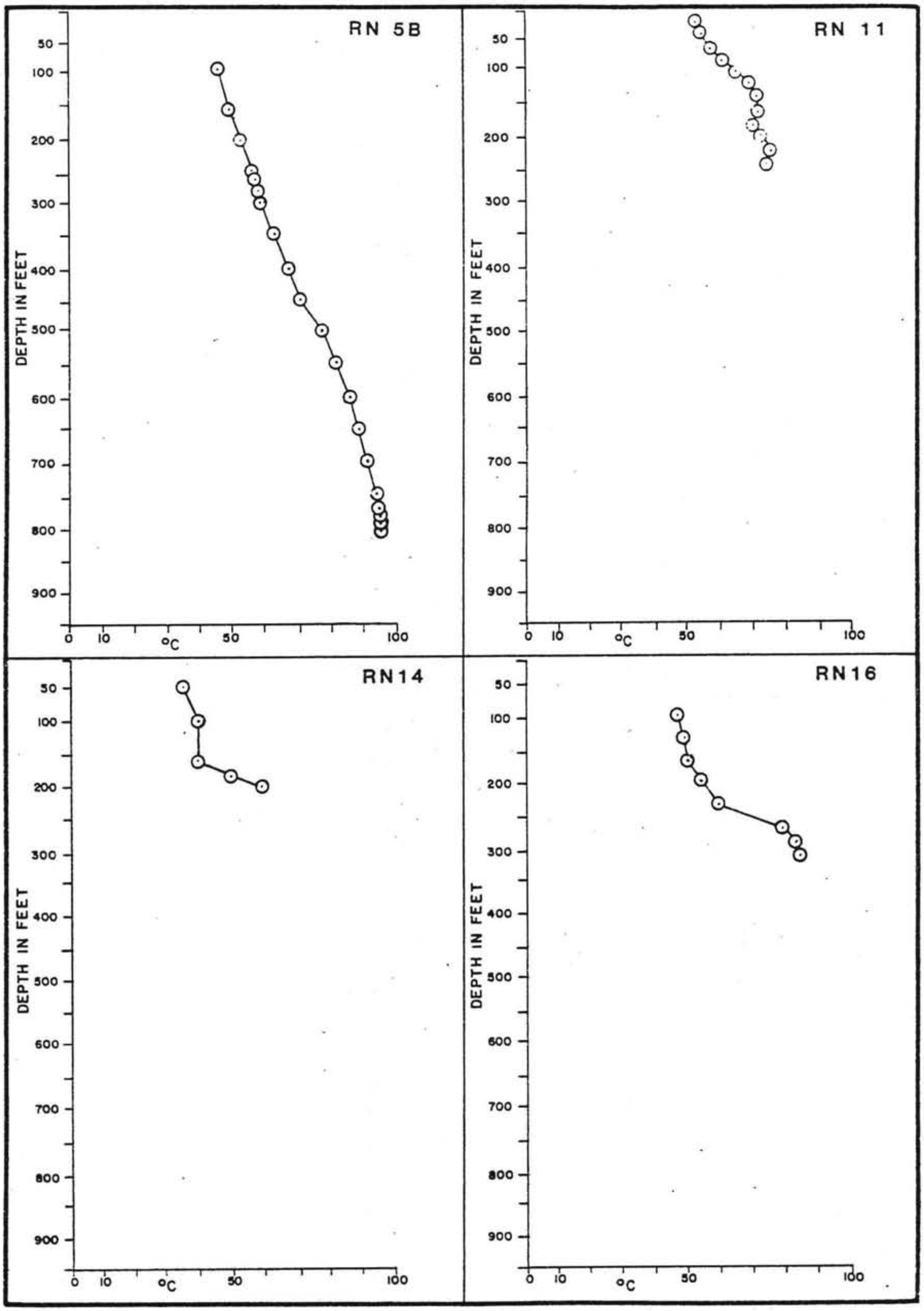


Figure A3. Temperature-depth profiles, wells RN 5B, 11, 14, 16

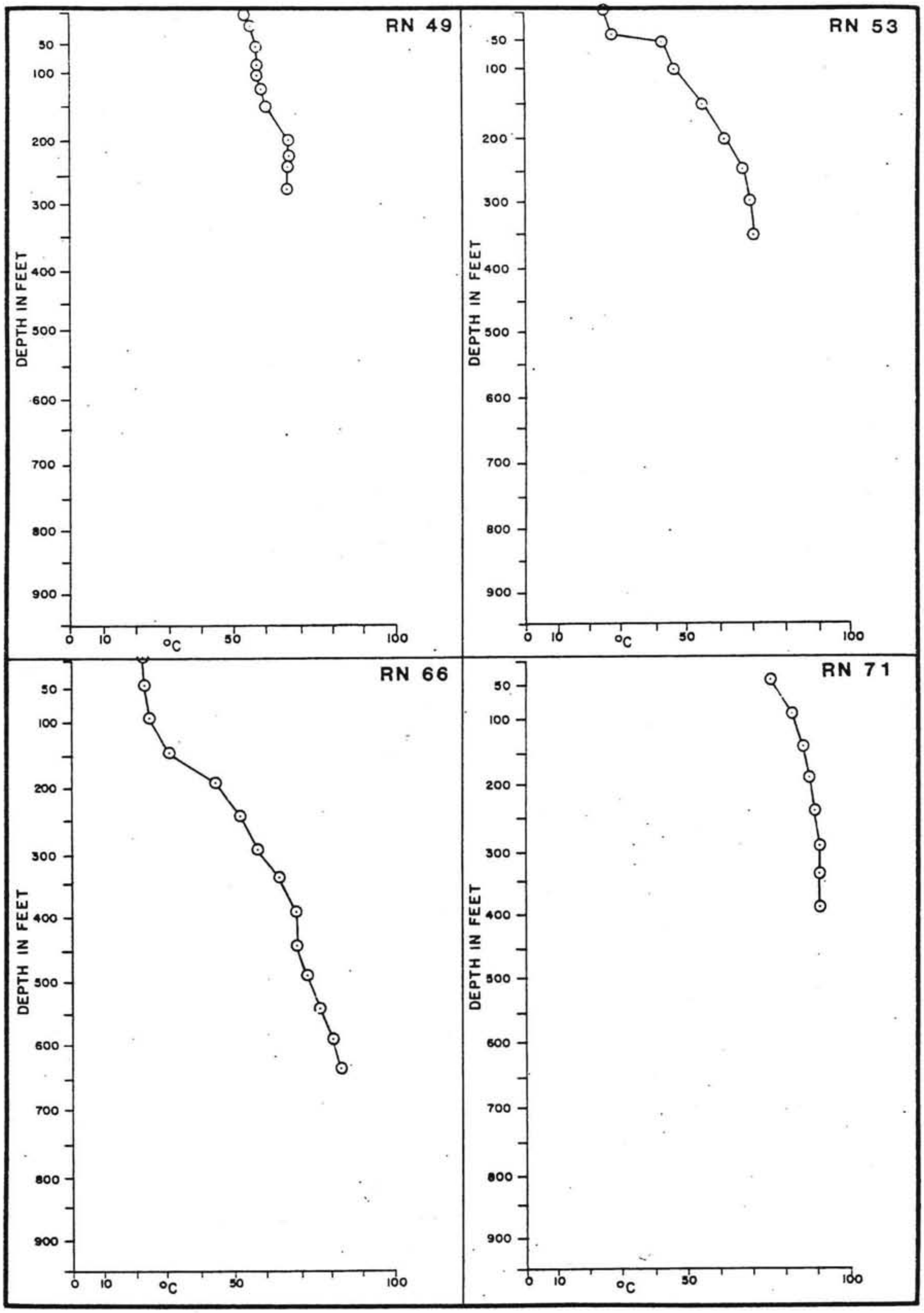


Figure A4. Temperature-depth profiles, wells RN 49, 53, 66, 71

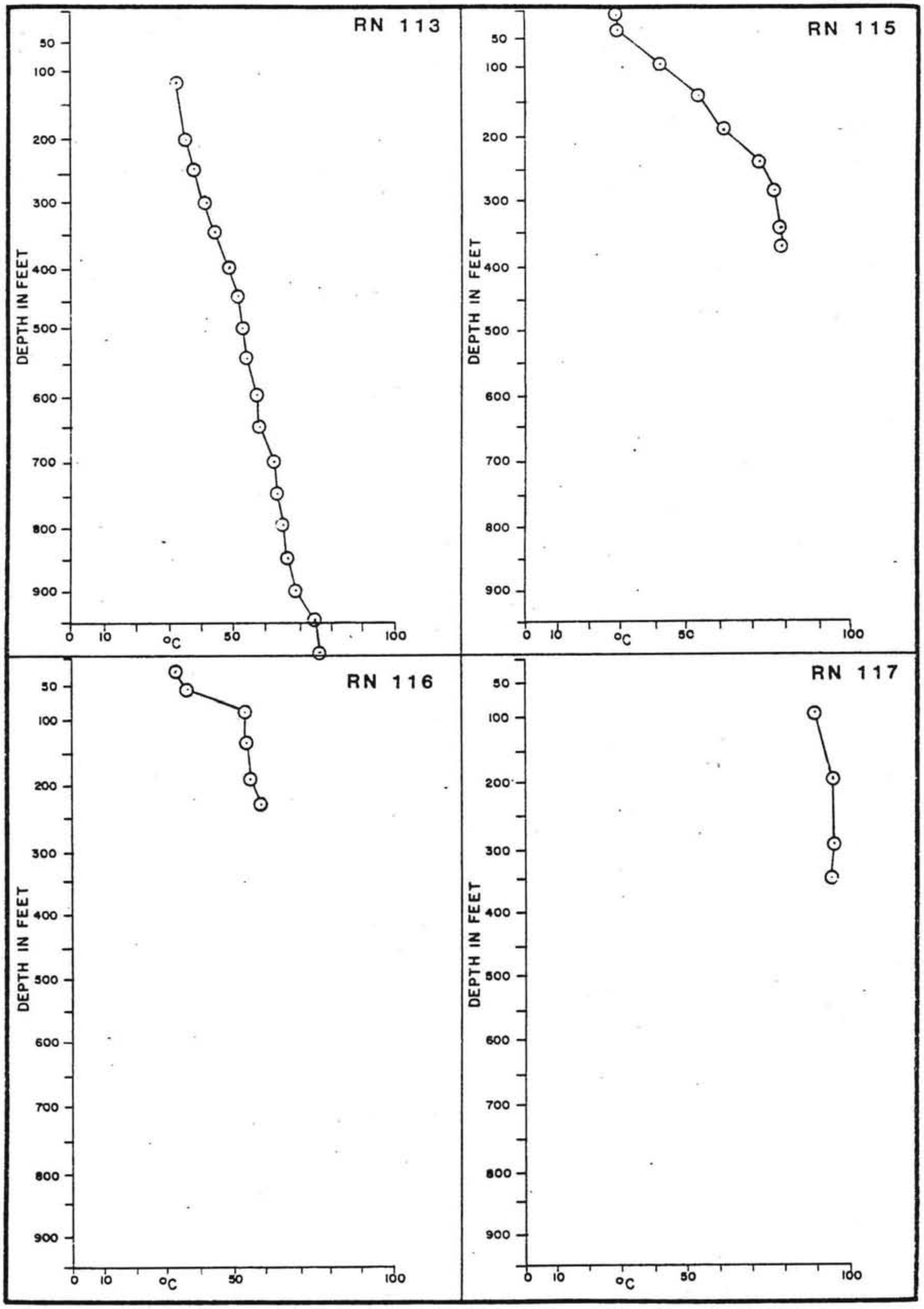


Figure A5. Temperature-depth profiles, wells RN 113, 115, 116, 117

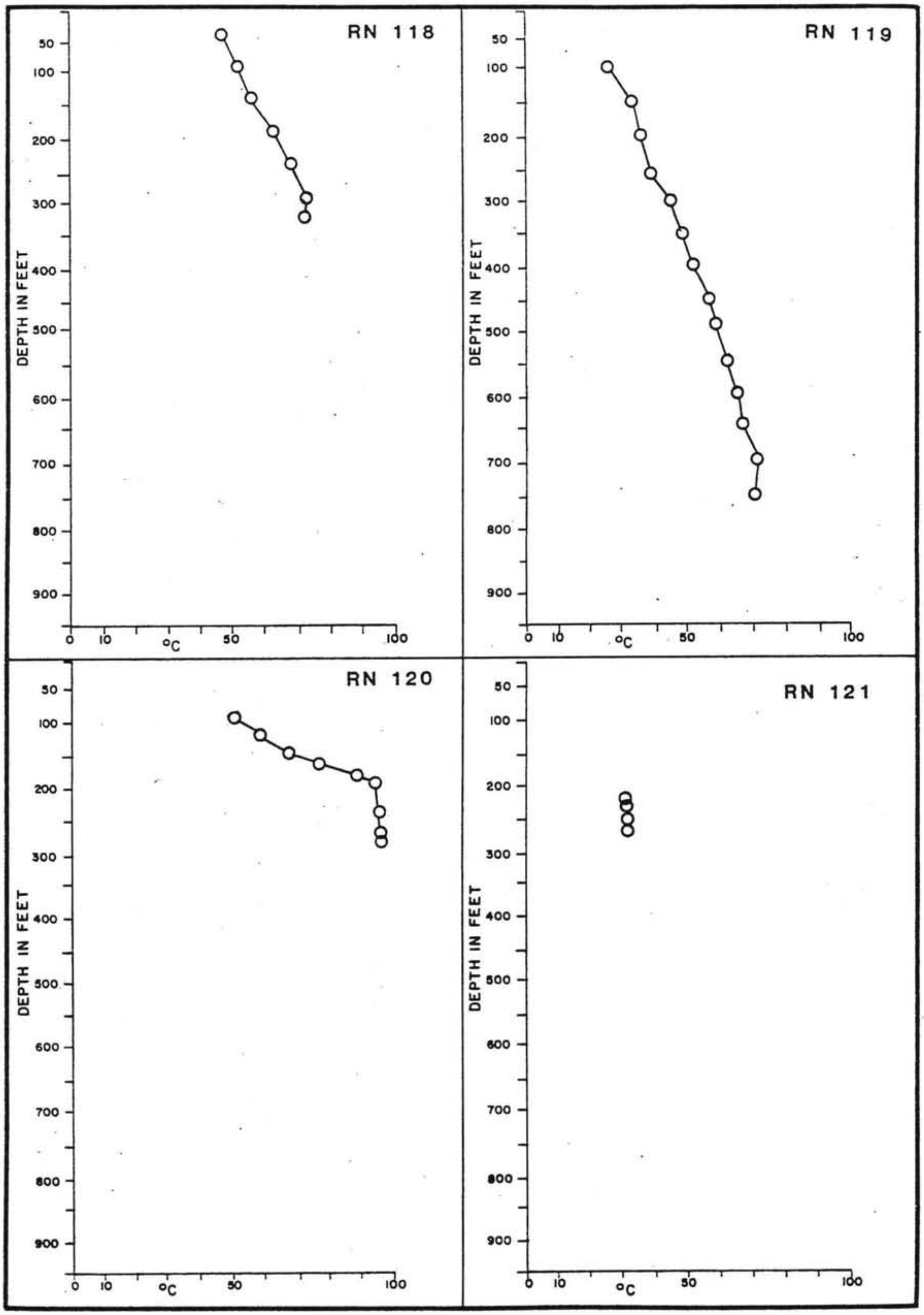


Figure A6. Temperature-depth profiles, wells RN 118, 119, 120, 121

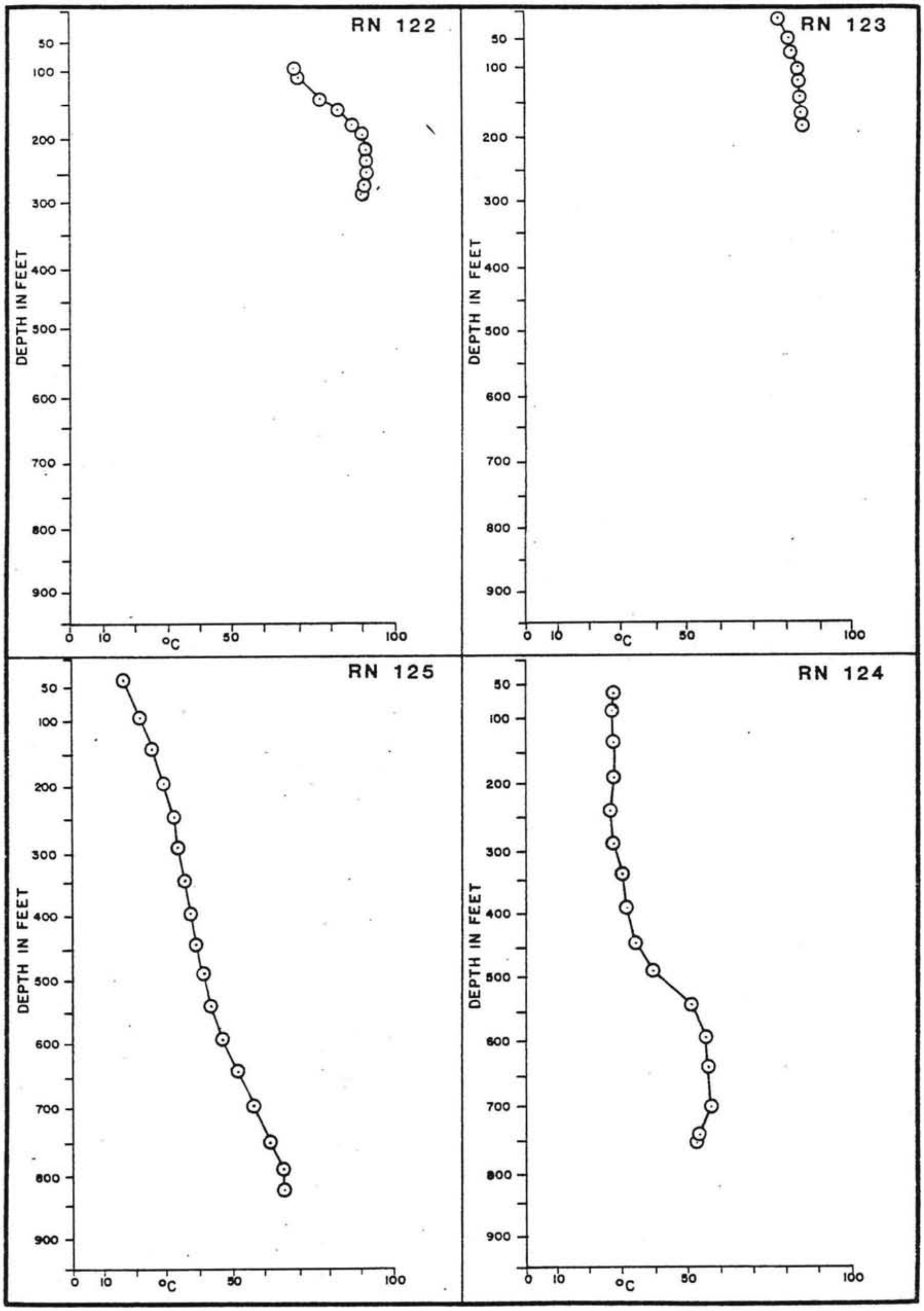


Figure A7. Temperature-depth profiles, wells RN 122, 123, 124, 125

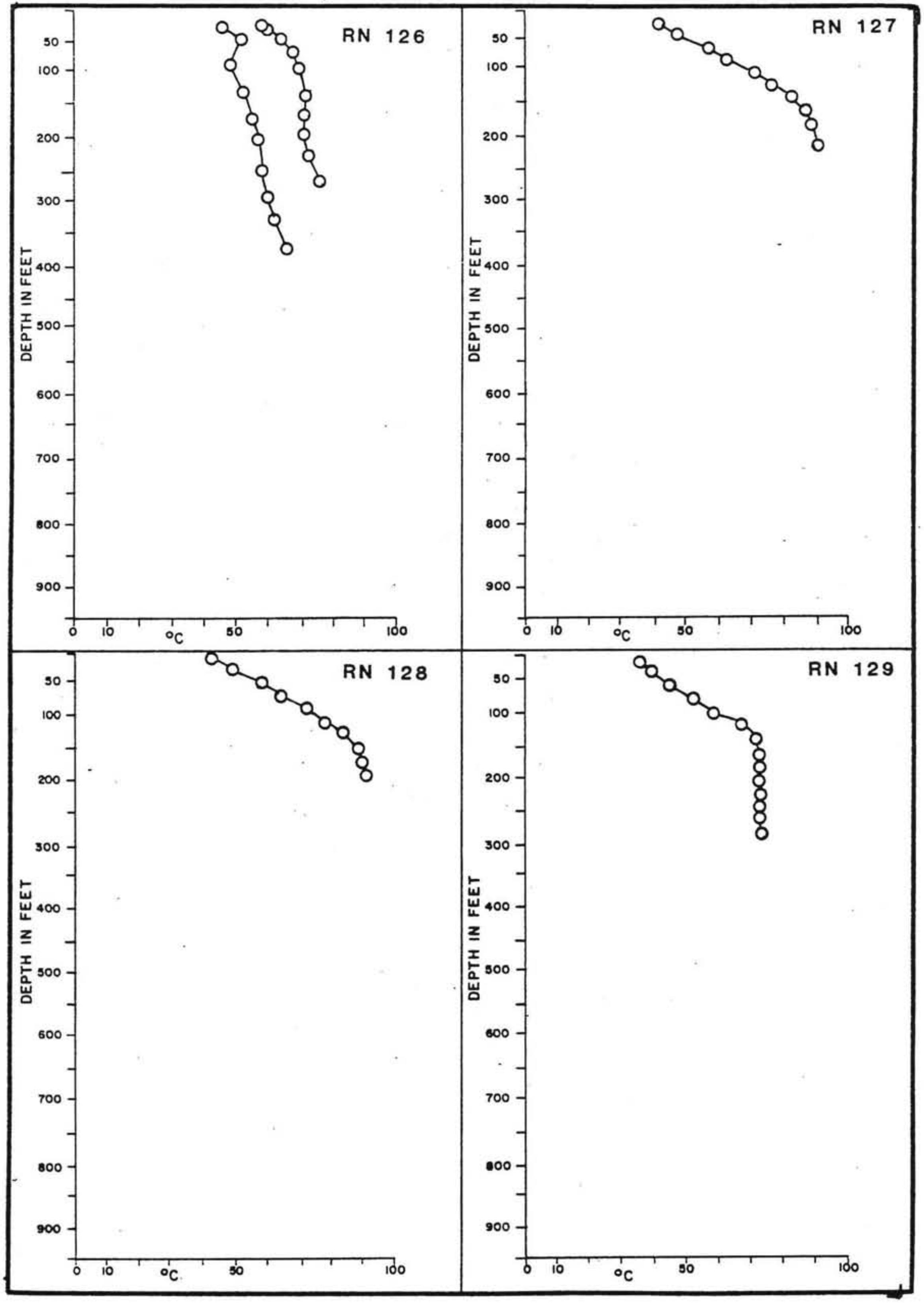


Figure A8. Temperature-depth profiles, wells RN 126, 127, 128, 129

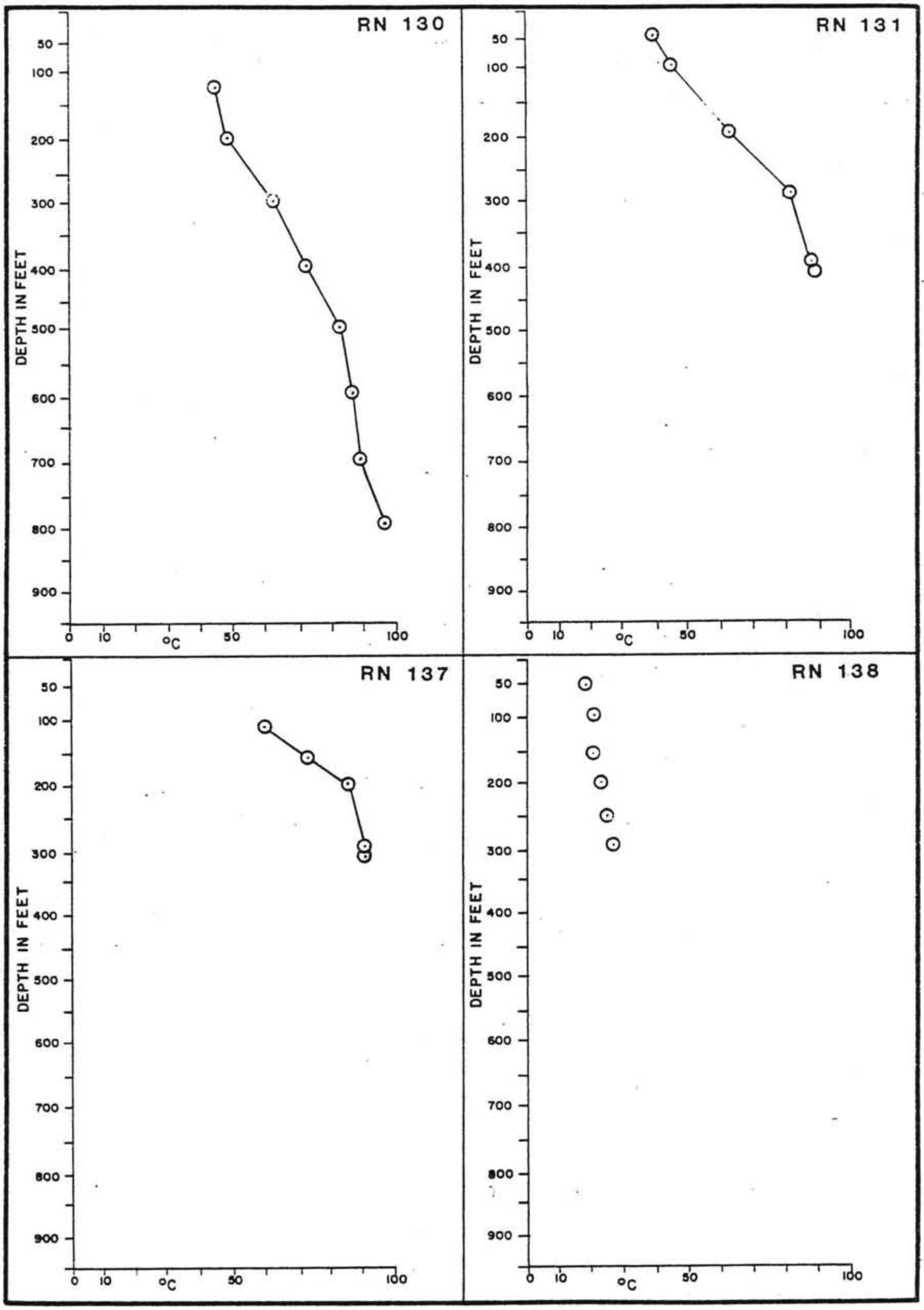


Figure A9. Temperature-depth profiles, wells RN 130, 131, 137, 138

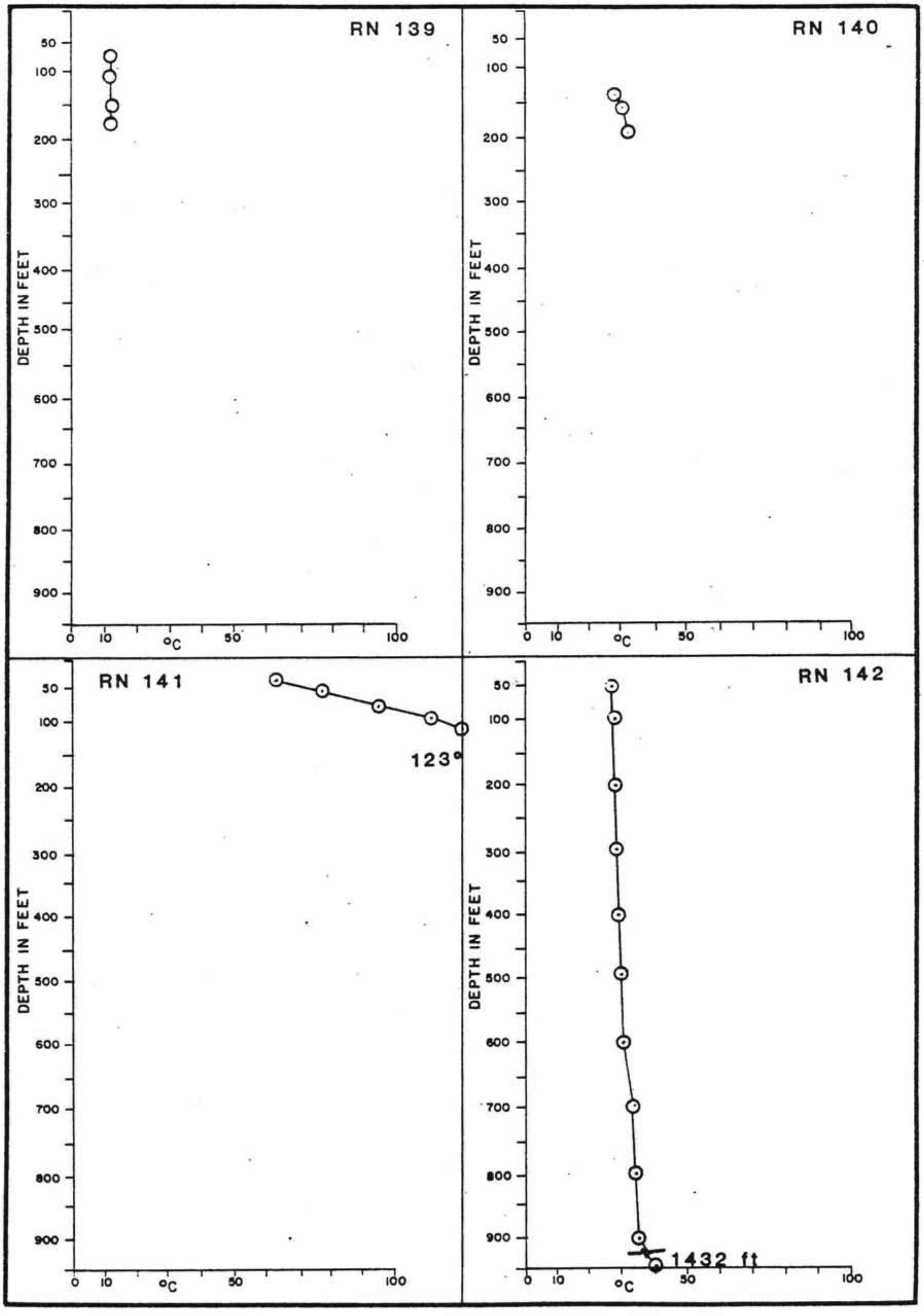


Figure A10. Temperature-depth profiles, wells RN 139, 140, 141, 142

APPENDIX V

HEAT EXCHANGER, THEORY

HEATM, COMPUTER PROGRAM

HEAT EXCHANGER THEORETICAL DISCUSSION

Nomenclature:

A = Area (ft^2)

Cp = Specific heat capacity. For water in the temperature range considered in this paper: Cp (water) = 1.0 BTU/(lb_m x °F)

D = Diameter of heat exchanger tubing (ft.)

h_i = Heat transfer coefficient for water inside heat exchanger tube in BTU/(hr x °F x ft^2)

h_o = Heat transfer coefficient for water in the well in BTU/(hr x °F x ft^2)

K = Thermal conductivity in BTU/(hr x °F x ft) for water assumed constant, K = .390

t = Thickness of pipe wall or scale in feet

U = Overall heat transfer coefficient in BTU/(hr x °F x ft^2)

V = Velocity of water in pipe (ft/hr)

Greek Symbols

BETA = Thermal expansion coefficient for water (1/°F)

MU = Dynamic viscosity in lb_m/(ft x hr)

PI = 3.14159

RHO = Density of water at a temperature (lb_m/ft^3)

DELTA T = Temperature difference between inside and outside of heat exchanger

In the Direct Use section, it is stated that in many cases a fiberglass reinforced pipe (FRP) heat exchanger performed as well as or better than systems of galvanized iron or copper pipe.

To explain how this is possible requires a basic understanding of heat transfer principles. Heat transfer across a solid boundary (such as a pipe wall) is given by the equation:

Heat Transferred = (U) (A) (DELTA T)

Examination of the equation reveals that an increase in any one or combination of factors will produce an increase in heat transfer and heat output of a heat exchanger. The temperature difference is limited by the upper temperature in the well and the minimum useful temperature required to heat the house. The area of the heat exchanger is limited by the size of the well and the expense of buying more pipe. The "U" term can prove to be the controlling factor in the recovery of heat from geothermal wells in Moana.

The overall heat transfer coefficient is a function of the heat transfer coefficients of each material the heat must pass through. These individual coefficients are based on the physical characteristics of the material such as velocity, thermal conductivity, viscosity, thickness, temperature, and other properties. For the case of a heat exchanger in a well:

$$1/U = 1/h_i + 1/h_o + t_1/k_1 + \ldots t_n/k_n$$

For maximum output, all of the components of this equation other than thickness should be large. If one component fraction (i.e., $1/h_i$) is large, then U will be small regardless of how large the others are. The value for the pipe wall is very easy to estimate. The values for the water inside and outside the pipe are more difficult to estimate.

For the pipe wall, typical values:

MATERIAL	K (BTU/(hr x °F x ft)
FRP	.2
COPPER	200.0
IRON	34.0
SCALE	Assumed .4*

(*Average for sulfides and oxides)

Since pipe walls for FRP are approximately 1/4", the part of U attributed to FRP is: K/t = 9.6 BTU/(hr x °F x ft^2) Assuming a similar thickness for copper and galvanized iron:

Copper: K/t = 9600 BTU/(hr x °F x ft^2)

Iron: K/t = 1632 BTU/(hr x °F x ft^2)

But since iron and copper will scale 1/16" (typically) inside and outside (t = 1/8") and assuming the scale has a K value of .4,

Scale: K/t = 76.8 BTU/(hr x °F x ft^2)

which is the controlling portion of the pipe wall for copper and iron pipe.

For the case of water flowing in a pipe, the following equation is suggested (Bateman and Schiebach, 1975):

$$\frac{h_1 D}{k} = .026 \left(\frac{VD(rho)}{mu}\right)^{.8} \left(\frac{Cp(mu)}{k}\right)^{.333} \left(\frac{mu_b}{mu_w}\right)^{.14}$$

The last term $(mu_b/mu_w)^{.14}$ is considered to be equal to 1 since bulk (b) and wall (w) temperatures are close in value. This equation is not strictly accurate for flow in long vertical pipes since convection changes the velocity profile across the pipe. An analysis by Petukhov (1976) showed the heat transfer is enhanced for water flowing upward but is reduced for water flowing downward. Since the water in the downhole exchanger is flowing both up and down the net effect on heat transfer is similar to horizontal pipes. Hence the equation given above is considered a fair approximation.

For the heat transfer from the water in the well to the exchanger, the analysis is much more complex. The heat transfer coefficient depends on the velocity of the water in the well, the natural recharge to the well, and the shape of the space through which the water flows. Without a pump in the well, the velocity in the well is dependent on natural convection. The rate of free (or natural) convection is a function of the density differences in the well caused by temperature differences from top to bottom in the well. Since the temperatures in a well are rarely constant, the rate of flow of water and therefore heat changes. A convection tube averages the temperature between its top and bottom; the well will be nearly isothermal along the convection tube's length. This feature simplifies the analysis of velocities inside and outside the tube by equating frictional loss to the bouyant driving force. This will yield velocities for a given temperature difference. However, when the resulting values were used in equations for heat transfer in annular spaces, h_o was unreasonably low. An alternative approach, proposed by Bateman and Scheibach (1975) is to approximate h_o by using the expression for h_o from natural convection in an infinite space outside vertical cylinders (McAdams, 1954):

$$\frac{h_o L}{k} = 0.13 \left[\frac{L^3 \text{ (rho)}^2 \text{ (beta)(delta T) Cp (mu)}}{\text{(mu)}^2 \ k}\right]^{.3333}$$

where: L = depth of the well, ft.

This equation can be simplified to:

$$h_o = \frac{.13}{k} \left[\frac{\text{(rho)}^2 \text{ (beta) (delta T)}}{\text{(mu)} \quad k}\right]^{.3333}$$

The equation for h_i can also be reduced to:

$$h_i = \frac{.026k}{D} \left(\frac{\text{DV (rho)}}{\text{mu}}\right)^{.8} \left(\frac{\text{mu}}{k}\right)^{.3333}$$

Using the equations above, a short computer program written in BASIC uses the flow rate in the exchanger, the average temperature, the length of heat exchanged, and the temperature difference between the well and the heat exchanger to calculate the amount of heat expected from a trombone heat exchanger. HEATM should run on almost any home computer. It must be noted that the well temperature is considered to be kept constant by either natural flow or pumping.

Using the Warren Estates production well as a test case, HEATM calculates a heat output of 234,179 BTU/hr based on the following input:

Diameter of exchanger = 4 inches
Average temp. of well = 170°F
Flow rate = 100 GPM
Average temp. diff. = 15°F
Length of exchanger = 1600 ft.
Type of pipe = FRP
Wall thickness = .25 inches

The actual measured output for the system was 244,671 BTU/hr using input and output temperatures for the trombone of 152 and 157, respectively. Since the flow rate through the loop is 100 GPM, the heat output is simply the volume of water times the temperature drop. The Warren Estates can boost the heat output simply by pumping the well more often raising the temperature difference and improving h_o. The program's results are within 5% of the actual results which is fairly good since many assumptions are made and the equations are approximate. A listing of HEATM and documentation are on the following pages.

HEATM

```
10 ' Downhole heat exchanger
20 ' 11/16/83
30 PRINT"Downhole heat exchanger approx."
40 'v1.0 by George Ghusn Jr.
50 'this program assumes the well has
60 'good cross flow or is pumped to
70 'maintain its temperature and has
80 'a convection tube installed
90 DEFSNG A-Z:PI=3.14159:K=.390
100 INPUT"Diameter of exchanger(inches)";D
110 INPUT"avg. temp(F),flow(gpm)";T,F
130 INPUT"Length of heat exchanger in water";L
140 INPUT"Temp. difference(F)";TD
150 D=D/12:V=(F/448.831)/(D^2*PI/4)
160 B=((1-((250-T)/150))*2.8+2)*10000
169 K=0.390:T1=(T-32)*.5556:TC=TD*.5556
170 T3=T1:GOSUB 400:GOSUB 500
180 H2=(D*V*P/MU)^.8*(MO/K)^.3333*.026*K/D
190 T3=T1-TC:GOSUB 400:GOSUB 500
200 H1=(P^2*B*TD/(MO*K))^.3333*.13/K
210 INPUT"Type of pipe,wall thickness(in.)";P$,TH:TH=TH/12
220 IF P$="IRON" THEN K1=30
230 IF P$="COPPER" THEN K1=200
240 IF P$="FRP" THEN K1=.2
250 IF K1>1 THEN K3=1 ELSE K3=0
260 IF K1=0 THEN 210
270 U=1/(1/H1+1/H2+TH/K1+.0104/.4*K3)
280 Q=U*D*L*PI*TD
290 PRINT "max output=";
300 PRINT USING"######,";Q;
310 PRINT" BTU/hr"
320 PRINT"where:"
330 PRINT"u=";U;"ho=";H1;"hi=";H2
340 PRINT"in BTU/hr*F*ft"
350 GOTO 1000
400 P=(999.83952+16.945176*T3-.007987*T3*T3)/(1+.016880*T3)*.062427961
410 RETURN
500 MU=1.3272*(20-T3)-0.001053*(T3-20)^2
510 MU=EXP(MU/(T3+105)*2.3)*0.000672:MO=MU*3600
520 RETURN
1000 END
```

Variables: (in order of appearance in program)

PI = 3.14159 - constant

K = .390 - constant

D = Diameter of exchanger tube

T = Average temperature in the well

F = Flow in exchanger

L = Length of heat exchanger in water

TD = Temperature difference between water in well and in exchanger - arithmetic average of temperature in exchanger subtracted from the average temperature in well

V = Velocity of water in exchanger

B = Beta, the thermal expansion coefficient for water; depends on temperature

T1 = Conversion of T to °C

TC = Conversion of TD to °C

T3 = Working temperature in subroutines

H2 = Heat transfer coefficient inside exchanger

H1 = Heat transfer coefficient outside exchanger

P$ = Iron, copper, or FRP - pipe material

TH = Pipe wall thickness

K1 = Thermal conductivity of pipe wall

K3 = Allows for scale if copper or iron pipe