Geothermal Resources of the Western Arm of the Black Rock Desert, Northwestern Nevada

PART I, Geology and Geophysics

By Donald H. Schaefer, Alan H. Welch,
and Douglas K. Maurer

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CONVERSION FACTORS AND ABBREVIATIONS

Only the metric system is used in this report. Abbreviations and conversion factors from metric to inch-pound units are listed below.

Multiply	*By*	*To obtain*
Centimeters (cm)	0.3937	Inches (in.)
Meters (m)	3.281	Feet (ft)
Kilometers (km)	0.6214	Miles (mi)
Square kilometers (km^2)	0.3861	Square miles (mi^2)

ALTITUDE DATUM

The term "National Geodetic Vertical Datum of 1929" (abbreviation, NGVD of 1929) replaces the formerly used term "mean sea level" to describe the datum for altitude measurements. The NGVD of 1929 is derived from a general adjustment of the first-order leveling networks of both the United States and Canada. For convenience in this report, the datum also is referred to as "sea level."

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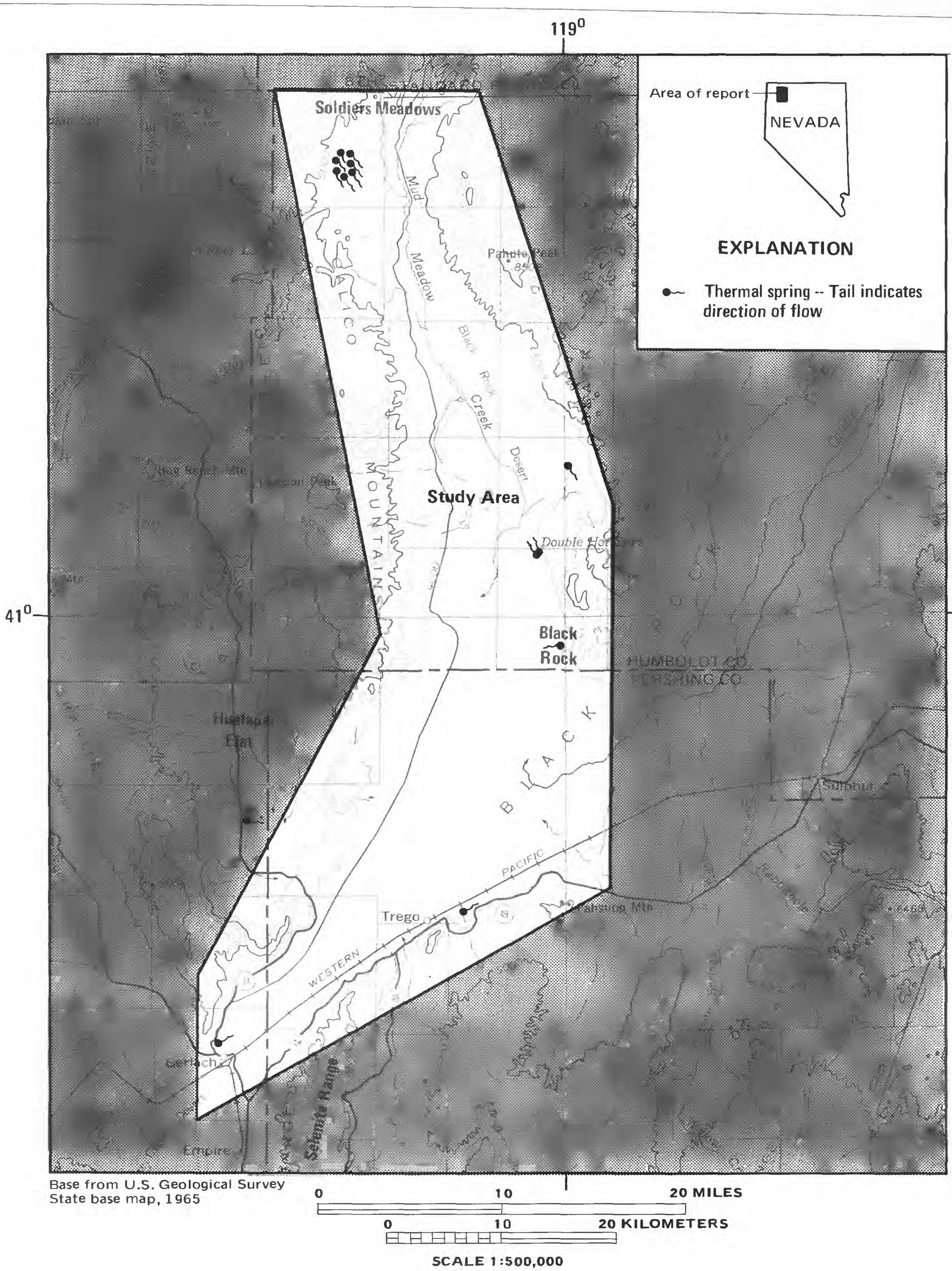
ABSTRACT

Studies of the geothermal potential of the western arm of the Black Rock Desert in northwestern Nevada included a compilation of existing geologic data on a detailed map, a temperature survey at 1-meter depth, a thermal-scanner survey, and gravity and seismic surveys to determine basin geometry.

The temperature survey showed the effects of heating at shallow depths due to rising geothermal fluids near the known hot spring areas. Lower temperatures were noted in areas of probable near-surface ground-water movement.

The thermal-scanner survey verified the known geothermal areas and showed relatively high-temperature areas of standing water and ground-water discharge. The upland areas of the desert were found to be distinctly warmer than the playa area, probably due to the low thermal diffusivity of upland areas caused by low moisture content.

Surface geophysical surveys indicated that the maximum thickness of valley-fill deposits in the desert is about 3,200 meters. Gravity data further showed that changes in the trend of the desert axis occurred near thermal areas.



Base from U.S. Geological Survey State base map, 1965

Figure 1.--Study area and thermal springs.

INTRODUCTION

Geographic Setting

The western arm of the Black Rock Desert covers an area of about 2,000 square kilometers in parts of Humboldt, Pershing, and Washoe Counties, Nev. (figure 1). The major population center is the town of Gerlach, which lies 177 kilometers north of Reno.

The desert consists of a large, flat lakebed (playa) at an altitude of 1,190 meters above sea level. Except for the gap near Gerlach, the playa is completely surrounded by mountains. The Granite Range southwest of the desert attains a maximum altitude of 2,760 meters, the Calico Mountains on the west and the Black Rock Range on the east reach altitudes of about 2,600 meters, and the Selenite Range, extending to the south from Gerlach, has an average altitude of 2,150 meters.

The western arm of the Black Rock Desert contains 5 of the 30 currently listed Known Geothermal Resource Areas (KGRA's) in Nevada, indicating definite potential for geothermal development. Numerous hot springs are found in the area (figure 1), and some private companies have undertaken test drilling in the area to determine geothermal resources.

Previous Investigations

Previous geologic mapping in the western area of the Black Rock Desert consists of the various county maps and more recent detailed mapping, as discussed under "Geology."

A ground-water reconnaissance of the entire Black Rock Desert area was done by Sinclair (1963). That study included water-quality sampling of wells, locating wells in the area, and computing the ground-water budget. Basic hydrologic data for the study area are available in that report. Geophysical investigations were made by Crewdson (1976) and summarized by Keller and Grose (1978a and 1978b). Geothermal investigations were made by Olmsted and others (1973 and 1975), Sass and others (1979a and 1979b), and Mace and Sass (1980).

Purpose and Scope

The purpose of this report, prepared in conjunction with the U.S. Bureau of Land Management, is to provide the Bureau with the information necessary to determine the geothermal potential of the western arm of the Black Rock Desert. The information required by the Bureau includes: (1) A geologic map of the Black Rock area, showing lithologic units and known and inferred faults, (2) definition of possible geothermal anomalies from the examination of thermal infrared imagery, (3) delineation of the surface thermal gradient, and (4) delineation of the depth to bedrock beneath the study area. These objectives were accomplished by a multidiscipline approach of hydrological, geochemical, geophysical, and remote-sensing techniques. The work was done between February 1979 and May 1980.

This report contains the results of the geologic and geophysical studies. The geologic map was compiled by using previous geologic mapping, aided by examination of aerial photographs and field verification. Near-surface temperatures were determined by a series of measurements at a depth of 1 meter below land surface. Both newly obtained and previously published data (Sass and others, 1979b) were used in the analysis of heat flow.

Acknowledgments

The authors wish to thank personnel of the U.S. Bureau of Land Management for their assistance in this project. Their help in providing personnel and equipment is greatly appreciated. Thanks are also extended to Frank Olmsted, U.S. Geological Survey, Water Resources Division, for providing manpower and technical assistance.

GEOLOGY

Plate 1 shows the geology of the area as compiled from the three county geologic maps (Bonham, 1969; Willden, 1964; and Johnson, 1977); the State geologic map at a scale of 1:500,000 (Stewart and Carlson, 1978); and detailed studies in the Hualapai Flat area (Grose and Sperandio, 1978), the Soldier Meadow area (Korringa, 1973), and along the Black Rock Fault (Grose and Sperandio, 1978). The map units used were taken primarily from the State geologic map, and the additional references were used to add detail wherever possible. Low-sun-angle aerial photographs at 1:24,000 scale, supplied by R. L. Dodge of the Colorado School of Mines, and U.S. Geological Survey photographs at 1:30,000 and 1:12,000 scale were used to delineate the Black Rock fault and other lineaments, and the distribution of eolian dunes.

Rock units surrounding the western arm of the Black Rock Desert range in age from Permian to Holocene. Consolidated rocks have been divided into three groups based in part on their lithologic properties: (1) Metasedimentary, metavolcanic, and minor sedimentary rocks of Permian, Triassic, and Jurassic age, which usually occur as roof pendants; (2) Cretaceous granodiorite and quartz-monzonite intrusive rocks; and (3) Tertiary sedimentary and volcanic rocks. Quaternary sediments are divided into alluvial, eolian-dune, landslide, and playa deposits.

Complete descriptions of pre-Cenozoic rocks are given by Sperandio (1978), and Grose and Sperandio (1978, pages 2-4). Details of Cretaceous intrusive rocks are given by Sperandio (1978, pages 51-68), Grose and Sperandio (1978, page 4), and Smith and others (1971). The Tertiary volcanic rocks have been described by Grose and Sperandio (1978, page 4), Noble and others (1970, 1973), Korringa (1973), and Bonham (1969, pages 9-22).

Pre-Cretaceous Rocks

The oldest rocks in the area are Permian and Triassic metavolcanic and metasedimentary rocks exposed mainly in the southern end of the map area. Isolated exposures also occur at the famous Black Rock and in the extreme northeastern end of the Black Rock Range. Fine-grained sedimentary units of Jurassic and Triassic age have been metamorphosed to phyllite, slate, and quartzite, and are exposed in the extreme northeast and southeast corners of the map area. Both units are thought to have undergone regional metamorphism (Smith and others, 1971, page 2936, and Willden, 1964, page 50) before the intrusion of granodiorite thermally metamorphosed them to at least the level of the lower greenschist facies (Johnson, 1977, page 9).

The Permian and Triassic rocks (shown on geologic map as TrPvs) consist of metaandesite, metadacite, and minor limey shale and chert in the northwest Selenite Range (Johnson, 1977, page 9). There, they have been locally metamorphosed to an amphibolite facies, grading to a hornblende-hornfels facies near the granodiorite contact, where the unit has been partly assimilated into the pluton (Grose and Sperandio, 1978, page 3). In the northern Granite Range, the Permian and Triassic rocks are metabasalt and metaandesite flows, breccia, tuff, and metamorphosed silty limestone containing thin beds of pebble conglomerate (Bonham, 1969, page 5). Permian and Triassic rocks at the southwest tip of the Calico Mountains consist of metamorphosed mafic volcanic flows interbedded with chert, limestone, sandstone, shale, and mudstone (Grose and Sperandio, 1978, page 3). A similar metamorphosed volcanic and sedimentary sequence of Permian age at the Black Rock (Gianella and Larson, 1960) is assigned by Willden (1964, page 34) to the Happy Creek Volcanics. However, Sperandio (1978, page 48) believes that the metavolcanic-metasedimentary sequence in the Hualapai Flat area is younger than, and not part of, the Happy Creek Group. Grose and Sperandio (1978, page 2) recognize three assemblages of the sequence, consisting of amphibolite near the north end of the Selenite Range, metavolcanic rocks forming a middle zone in the north Granite Range, and a northern zone of interbedded metavolcanic and metasedimentary rocks.

Grose and Sperandio (1978, page 7) reported that the bedding planes throughout the isolated exposures of Permian and Triassic rocks to the east-northeast consistently dip almost vertically and strike mostly to the west-southwest. Estimated thickness for the unit ranges from 7,500 to 30,000 meters (Grose and Sperandio, 1978, page 2). Faults paralleling bedding planes in the unit suggest tectonic thickening of the sequence by isoclinal folding or thrust faulting along a north-northwest axis (Grose and Sperandio, 1978, pages 7,8). These features are cut by Cretaceous intrusive rocks, suggesting deformation at some period ranging from Triassic to middle Cretaceous time (Sperandio, 1978, page 110; Grose and Sperandio, 1978, page 8).

The metamorphosed sequence of phyllite, slate, and quartzite (JTrs) in the northeast Black Rock Range was mapped by Willden (1964, page 49), who assigned a tentative Triassic to Jurassic age. All pre-Cretaceous rocks in the area have undergone dynamic metamorphism, and the rocks are thermally metamorphosed to hornfels, schist, and gneiss near Cretaceous instrusive contacts. A similar sequence occurs in the southeast corner of the map area, with argillite and interbedded sandstone and limestone metamorphosed to slate, phyllite, hornfels, and quartzite. Johnson (1977, page 21) assigns these rocks to the Auld Lang Syne Group, undivided, which she considered to be of Late Triassic to Early Jurassic age.

Consistent strike of the Permian and Triassic unit throughout Hualapai Flat area suggests that it is continuous beneath the alluvial fill. Core samples obtained during this study indicate a metamorphosed silicious limestone below the playa near the north end of the Selenite Range. Also, core samples taken near Double Hot Spring show quartzite 700 feet below the playa possibly correlative to the Triassic-Jurassic unit seen farther to the north. Thus, metavolcanic and metasedimentary units are possibly present as basement rocks throughout much of the area.

Cretaceous Intrusive Rocks

Granitic plutons in northwest Nevada were emplaced during a well-defined time span from 105 to 85 million years ago, which Smith and others (1971, page 2934) have called the Lovelock intrusive epoch. Smith and his coworkers also suggest that these rocks form a link between the Sierra Nevada and Idaho batholiths. Potassium-argon dates obtained from intrusive granite in the study area fall within a narrow age range of 89 to 91 million years in the Granite Range (Bonham, 1969, page 9) and are about 92 million years in the Selenite Range (Smith and others, 1971, page 2936).

Intrusive rocks in the study area lie mainly in the south, with isolated exposures in the central and northeast parts. The rocks in the Granite Range are mostly granodiorite (Anderson, 1977), grading over hundreds of meters to a quartz monzonite and, near intrusive borders, to a quartz diorite or a diorite (Bonham, 1969, page 9; Grose and Sperandio, 1978, page 4), implying cooling of a single pluton. Sperandio (1978, page 61) points out that assimilation of the surrounding Permian and Triassic wall rock is evidenced by the gradation to a dioritic rock type near wall-rock contacts and by xenoliths of wall rock within the dioritic zone. Grose and Sperandio (1978, page 4) proposed a depth of emplacement at 4.8 to 9.6 kilometers (upper mesozone to lower epizone). This concept is supported by the discordant contacts of the plutons, the lack of a chilled border, the assimilation of wall rock, and the metamorphic aureole surrounding the plutons.

Tertiary Volcanic and Related Rocks

Tertiary rocks form a highly diverse and complex sequence of volcanic rocks interfingering with sedimentary and tuffaceous sedimentary rocks. The volcanic rocks include basalt, andesite, and rhyolite flows; andesite breccia; and welded and nonwelded ash-flow tuffs. The oldest of these rocks include units Tts, Tob, and Ta2, 23-31 million years old, mapped in the Hualapai Flat area by Grose and Sperandio (1978), and units associated with the Ashdown Tuff--Tt2, Tob, Tal, and Tr2--in the Black Rock Range (Noble and others, 1970).

Rocks in Hualapai Flat were named and assigned to the South Willow Formation by Bonham (1969, page 10), who dated the rocks at 31 million years. He described the formation as volcanic flows and breccia ranging from olivine basalt to dacite. Grose and Sperandio (1978, page 5) mapped a section of the area consisting of a basal unit of andesite flows and flow breccias more than 610 meters thick, overlain by a silicic unit comprising mainly tuff and tuffaceous sedimentary rocks, which is more than 1,200 meters thick, and capped by basalt flows as much as 300 meters thick. Bonham (1969, page 10), however, stated that basalt cropping out northwest of Hualapai Flat lies near the base of the South Willow Formation. Sperandio (1978, page 92) gave a potassium-argon date of 23-28 million years for basalt in the area, regardless of position.

The silicic tuffaceous unit mapped in Hualapai Flat may correlate with the Ashdown Tuff (Tt2) in the Black Rock Range (Grose and Sperandio, 1978, page 6), a rock unit that was thought by Noble and others (1970, page 24) to underlie the north end of the Black Rock Desert and extend beneath the north Calico Mountains. Thus, the Ashdown Tuff (Tt2) may correlate with the older tuffaceous part of the Tts unit mapped in Hulapai Flat and the north Calicos. The silicic tuff overlies an olivine basalt (Tob) (Noble, 1972, page 144) that possibly correlates with olivine basalts of Bonham's (1969) South Willow Formation. The Ashdown Tuff is in turn overlain by extensive rhyolite flows (Tr2) in the Black Rock Range dated at 25-26 million years by Noble and others (1973, page 1396).

A decrease in volcanism from about 23 to 16 million years ago is shown by the lack of middle Miocene volcanic rocks in the northwest Great Basin (Grose and Sperandio, 1978, page 6; Noble and others, 1973, page 1395; McKee and others, 1970; and McKee, 1971, page 3497). This hiatus was followed by eruption of volcanic rocks, mainly rhyolitic flows and welded and nonwelded tuffs. These rocks in turn are overlain by intermediate to mafic lavas younger than 15 million years (Bonham, 1969, page 10; Korringa, 1973, page 3852; and Noble and others, 1970, page 30).

Rhyolite flows (Tr3) of large aerial extent along the west edge of the map area were assigned to Merriam's (1910) Canon (Canyon) Rhyolite by Bonham (1969, page 13), who gave an approximate age of 14 million years to the unit. This unit forms the bedrock on which rocks of the High Rock sequence (Tts) (Bonham, 1969, page 15) were deposited. The High Rock sequence also covers a large area in the northwest corner of the map area and consists of ash-flow tuffs and tuffaceous fluviolacustrine sedimentary rocks dated by potassium-argon at 15 million years (Bonham, 1969, page 18).

In the vicinity of Soldier Meadow, several distinguishable tuffs have been mapped (Noble and others, 1973). The Soldier Meadow Tuff, tuff of Trough Mountain, and the Summit Lake Tuff are the most widespread in the map area (Tt3). They have been potassium-argon dated by Noble and others (1973, page 1400) at about 15 million years and consist of densely welded to nonwelded ash-flow and air-fall tuffs. These tuffaceous sequences compose the main rock exposures in the Soldier Meadow area and form cap rocks in the southern Black Rock Range (Noble and others, 1973). The lava related to the Soldier Meadow Tuff is rhyolitic and occurs along a linear vent area due north of Soldier

Meadow (Korringa, 1973). Noble and others (1970 and 1973) suggested that these tuffs may be the crystal fractionation product of basalts mapped near the area by Bonham (1969) and Gunn and Watkins (1970), and units mapped as Tb and Tba in the north part of the map area. The end of widespread deposition of tuffs occurred 6 million years ago throughout northern Nevada and Utah (Stewart and others, 1977).

The youngest Tertiary volcanic unit cropping out in much of the map area is undifferentiated basalt and andesite of upper Miocene to lower Pliocene age (Tba). According to Bonham (1969, pages 21-22), these rocks can be correlated in part with the Mesa Basalt of Merriam (1910), the Warner Basalt of Russell (1928), and with the Steens Basalt (Fuller, 1931) in southeast Oregon. Basalt in the northwest Granite Range (Bonham, 1969), the middle Calico Range, north Black Rock Range, north and west of Soldier Meadow (Stewart and Carlson, 1978), and in the southern Black Rock Range (Dean Willis, Colorado School of Mines, oral commun., 1980), has been assigned a late Miocene to early Pliocene age. However, a wide age range is probable, as the Mesa Basalt of Merriam (1910) has been dated by Walker and Swanson (1969, page 581) at 1.2 million years. Noble and others (1973, page 1397) stated that mafic volcanism has continued from middle Pliocene to the Holocene.

Johnson (1977, page 6) mapped a sedimentary unit (Ts3) of late Miocene age in the southeast corner of the map area. The rocks consist of a lacustrine sequence of siltstone, shale, and sandstone, which has been faulted and tilted. This unit is more extensively exposed in the Elko area to the east.

Quaternary Units

Unconsolidated Quaternary deposits have been mapped as alluvium (Qal), eolian dune deposits (Qd), landslide deposits (Qls), and playa deposits (Qp). Alluvial materials include fan and streambed deposits of poorly to well-sorted silt, sand, gravel, and boulders eroded from upgradient consolidated rocks.

Dune deposits occur along the southeast margin of the Black Rock Desert, between Hualapai Flat and the main part of the Black Rock Desert, and in the north end of the Black Rock Desert. Dune fields in the south end of the desert are generally small and widespread; dunes are several tens of meters long and have a relief of about 3 meters. The northern dunes are more isolated and of a larger scale, some stretching for hundreds of meters with a relief of 6 to 9 meters. Both contain fine, well-sorted sand and most are stabilized by vegetation.

Playa deposits are flat-lying, fine-grained lacustrine silt and clay. During winter, they are usually water saturated, but during summer they are desiccated and mosaicked by polygonal mud cracks. Willden and Mabey (1961) reported giant polygonal mud cracks forming blocks up to 76 meters wide on the northwest margin of the playa. These cracks apparently developed some time between 1957 and 1960, but were not present during the field work for this study. A high salt content prevents any significant vegetation from growing on the playa surface except in areas where artesian flows allow a buildup of soil and vegetal material.

Several landslide deposits occur in the northern Black Rock Range, near High Rock Lake, and in the northwest Granite Range. In the Granite Range, the slide involves blocks of granodiorite, limestone, and basalt, whereas slides in the north involve Tertiary tuff and basalt. The common cause of sliding is the collapse of the resistant basalt overlying soft tuff on over-steepened slopes (Bonham, 1969, page 41). One large, impressive slide occurred on the southeast side of Soldier Meadow and appears to be related to the bounding fault on the west side of the Black Rock Range.

Geologic Structure

Normal faulting of the basin-and-range type (late Cenozoic) controls the present structural and physiographic setting in the study area (Grose and Sperandio, 1978, page 8). These faults offset earlier structure in Permian and Triassic and lower to middle Tertiary units. The Permian and Triassic rocks have a consistent east-northeast strike, and internal faults parallel the bedding (Grose and Sperandio, 1978, page 7). This faulting plus an unusually large estimated depositional thickness for the unit suggest isoclinal folding and imbricate thrusting along a north-northwest axis sometime betweeen Triassic and middle Cretaceous time (Grose and Sperandio, 1978, page 8).

Moderate southwest regional dips are seen in the lower Tertiary andesite in the Calico Mountains north of Hualapai Flat, causing exposure of the basal andesitic unit (Grose and Sperandio, 1978, page 5). A capping basalt unit overlies the Tertiary volcanic rocks in the Hualapai Flat area in an angular unconformity, suggesting tilting and erosion prior to volcanism in the early Miocene (Sperandio, 1978, page 93; Grose and Sperandio, 1978, page 8). A similar angular unconformity exists between rhyolite (Tr3) and andesite in the northwest Calico Mountains (Bonham, 1969, page 15). In the Black Rock Range, Tertiary volcanic rocks generally have conformable contacts and low dips. There, Willden (1964, pages 75 and 86) noted gentle fold-like structures and a gentle easterly dip of the rocks.

Stratigraphic relations show that the onset of normal faulting was contemporaneous with the volcanic pulse beginning in middle Miocene time, 14-16 million years ago (Noble and others, 1973, page 1397; Noble, 1972, page 145). Faulting has been active to the present, as evidenced by lack of fault-block erosion, undissected landslides, and tectonic control of drainage (Noble and others, 1970, page 31).

Dodge and Grose (1980, page 2) noted a pediment along the west margin of the Black Rock Range and suggested that it represents a hiatus of a few million years in tectonic uplift along the bounding fault. A detailed study of the fault, called the Black Rock Fault, was done by Dodge and Grose (1980). The modern scarp shows 3 to 7 meters of displacement and was formed during an earthquake about 1,000 years ago. They estimated a recurrence interval of 5,000 to 6,000 years for movement along the fault. The earthquake which formed the scarp was estimated to have had a magnitude of about 7 on the Richter scale; however, the magnitude of previous faulting is not known. Slemmons and others (1965, page 526) listed a 4.1-magnitude earthquake in 1936 at 41° N. 119° W., just north of the Black Rock along the Black Rock Fault.

The northwest-trending fault zone that defines the southwest scarp of the Granite Range is formed by several en echelon faults, suggesting a right lateral component of offset (Grose and Sperandio, 1978, page 8). Other major faults in the area are reported to have dip-slip movement only (Dodge and Grose, 1980, page 1; Grose and Sperandio, 1978, page 8; Bonham, 1969, page 48). The largest minimum vertical displacements, associated with bounding faults on the Granite Range, are estimated to be at least 1,500 meters (Grose and Sperandio, 1978, page 8; Bonham, 1969, page 48).

The normal faulting produces a system of horsts and grabens, the downthrown blocks comprising the Black Rock, Smoke Creek, and San Emidio Deserts and northern Hualapai Flat. The Granite Range consists of four uplifted blocks stepping down toward the Black Rock Desert (Grose and Sperandio, 1978). Sperandio (1978, pages 119-122) showed that the southern part of Hualapai Flat is a graben tilted to the west, its east edge forming the topographic high of Steamboat Ridge. He further pointed out that the south end of the Calico Mountains forms a symmetrical horst and graben with the north end of Hualapai Flat. The northern two-thirds of the Calico Mountains has been tilted to the east, according to Willden (1964, page 93). He also noted a gentle eastward tilt of volcanic rocks in the Black Rock Range, which is probably caused by uplift along the Black Rock Fault.

Three major structural trends are shown by the northeast trend of the Black Rock Desert and ranges to the southeast of Trego, the northwest trend of the Granite Range, and the north trend of the Black Rock, Selenite, and southern Calico Ranges, Hualapai Flat, and faults through the center of the Granite Range. These trends intersect near Gerlach at the southern tip of the Granite Range. These structural trends are defined by normal faults which bound the major relief features in the area. The various orientations of structural trends imply quasi-radial crustal extension in the map area (Grose and Spernadio, 1978, page 8). A conspicuous northeast-trending lineament is also present, extending through High Rock Lake, Soldier Meadow Hot Springs, Summit Lake, and into Oregon. Hose and Taylor (1974, page 12) described the lineament in relation to hot-spring activity and suggested that it represents a fault which was active in the early Tertiary, with only minor displacement after deposition of Miocene volcanic rocks. This lineament intersects the north-south trend of the southern Calicos near Soldier Meadows Hot Springs.

SHALLOW-TEMPERATURE SURVEY

Purpose and Previous Work

Shallow-temperature data have been used as a geothermal exploration technique in the Basin and Range province by Olmsted (1977) and Crewdson (1976, page 53; 1978a, page 23). The advantage of this method is that many measurements can be made with a relatively small investment of both time and money, in comparison to the drilling of heat-flow or temperature holes. The purposes of this effort were to: (1) Produce a map of shallow (1-meter) temperature distribution, (2) compare the results of this method with those from the thermal scanning effort and heat-flow drilling, and (3) guide the siting of future heat-flow holes.

Previous shallow-temperature surveys in the Hualapai Flat and Gerlach areas were made during January and June 1975 (Crewdson, 1976, page 56, and 1978a, page 23). Comparison of results from the two surveys showed striking seasonal effects on temperatures at the 1-meter depth. The alluvial areas had a much greater increase in temperature at 1 meter than the playa areas, and were distinctly warmer during both surveys. The differences and changes in temperature were attributed to the effect of decreasing water content, and therefore a greater thermal diffusivity, in the areas away from the playa (Crewdson, 1978a, page 24). Effect of differing albedos is discussed later.

Data-Collection Techniques

Temperature measurements were made using a two-head thermistor mounted on the end of a 1-meter probe. The probe was connected to a solid-state Wheatstone bridge by a three-conductor cable. The digital temperature reading was recorded to the nearest 0.01°C, although the accuracy is substantially less, probably not better than about ±0.3°C.

The majority of the holes were in the playa sediments, which are damp to wet silt and clay. In these and other soft, coherent deposits, the holes were excavated using a hand-operated steel driver. In coarser deposits, a hand auger was used, and in extremely coarse areas on alluvial fans, the holes were excavated to nearly the total depth using a shovel. The final section of the holes in the very coarse deposits was formed using the driver or auger. At each location, the lithology, moisture content, and general vegetation density were recorded. An attempt was made to locate the holes away from any abrupt, local topographic features to minimize their effect on the temperature. The holes were also located away from vegetation as much as practicable, in an attempt to minimize the effects of transpiration and shading.

Temperature readings were made at regular intervals after insertion of the probe into the hole. The readings were then extrapolated to an equilibrium value using the graphical method described by Parasnis (1971) for solving the following equation:

$$T_f = T_\tau + \frac{(\Delta T/\Delta t)_\tau}{K} ,$$

where T_f = the equilibrium temperature, in degrees Celsius,
T_τ = the temperature at some arbitrary time τ,
$(\Delta T/\Delta t)_\tau$ = the rate of change of the temperature with time at time τ, and
K = a constant.

The probes and Wheatstone bridges were calibrated against a mercury-glass thermometer, and the extrapolated temperature was adjusted to a final value using the calibration data.

Measurement-site selection was based on a grid in much of the area, and additional sites were selected along the Black Rock Fault and along existing roads (plate 2). The grid utilized the stations established for the gravity survey and was supplemented by sites near the centers of the squares of the original grid. In an attempt to locate thermal anomalies associated with upwelling along the Black Rock Fault, measurements were made on either side of the fault. Additional sites, primarily along existing roads, were established in the north part of the area. Two areas were not examined because of access problems: One, approximately 7 kilometers southwest of the Black Rock, was wet during the survey; and the other, northwest of Double Hot Springs, has a dense pattern of vertically incised drainages that made the area inaccessible.

Data Analysis

The effects of temperature changes at land surface on the temperature at 1 meter have been discussed by Olmsted (1977). Although the temperature changes due to diurnal and weather effects are not generally a problem, the annual temperature wave should be considered. In an attempt to minimize the effect of the annual temperature wave, the temperature survey was made during a time period when the annual effect should have been minimized. At two times each year, the effects on the temperature at 1 meter in soils with differing thermal diffusivities are approximately equal (figure 2). If this idealization is a reasonable approximation of the physical system, then a synoptic survey conducted at or near these two times should not be affected appreciably by the differing diffusivities. Two problems associated with this phenomenon are as follows: (1) A sizable survey cannot realistically be made during a very short time period without a large commitment of equipment and personnel, and (2) the rate of change of the temperature with time is near its maximum, which makes the need for a synoptic survey more critical.

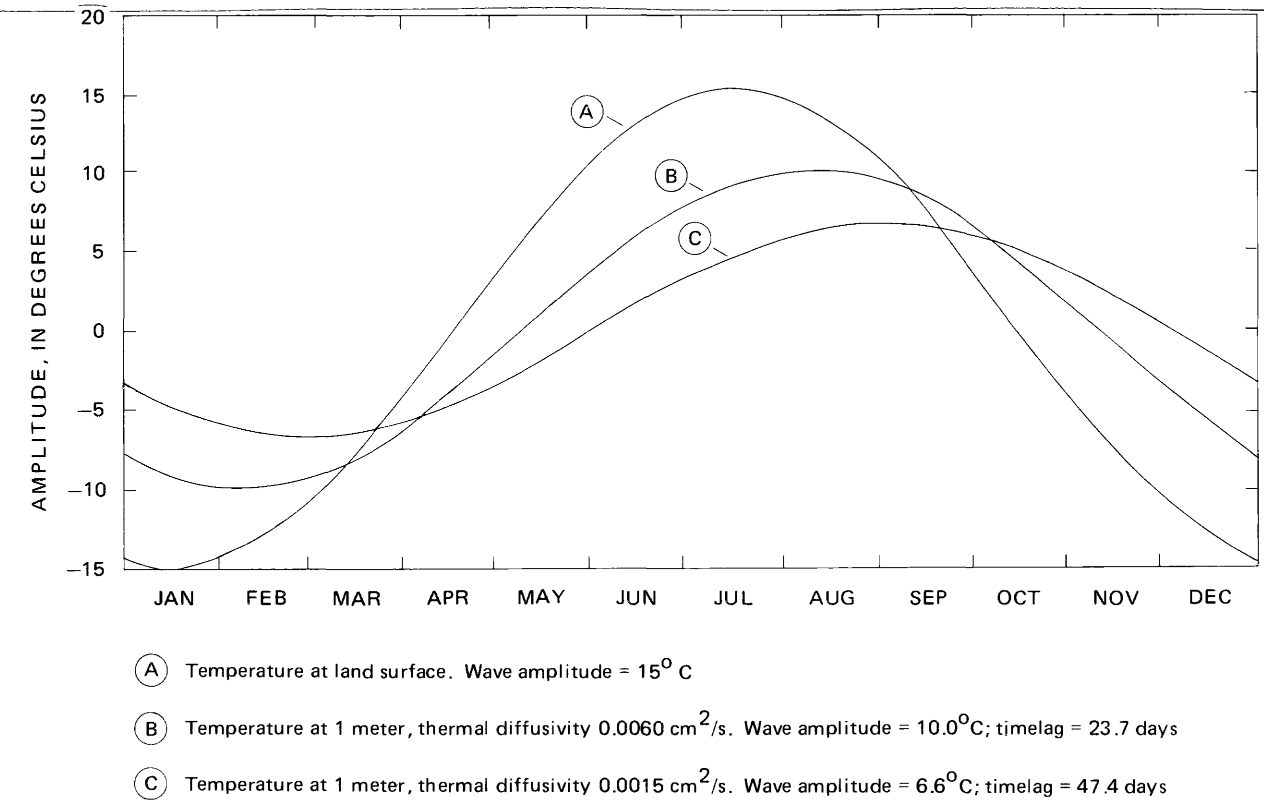


Figure 2.--Idealized annual temperature fluctuations at land surface and at depth of 1 meter (Olmsted, 1977, figure 2).

To evaluate the effect of the temperature changes with time at a 1-meter depth, two control stations were established at sites with different lithologies. These sites were in the playa and in a dune area; they were thought to represent more or less typical hydrologic settings that could be used to evaluate the effects due to an overall warming of the area. Mean annual air temperature at the closest weather station, near Winnemucca (about 120 kilometers to the east), indicates a distinct air-temperature increase during the survey. An increase at a 1-meter depth in the study area (figure 3) was also noted. At each site, the temperature was adjusted using one of the two control sites--the choice of which control to use was based upon the lithology at the site. The slope of a regression-line fit for each of the control data sets was then used to adjust the temperature data to an arbitrarily selected date (Julian date 108, 1979). Lines of equal temperature (plate 2) were drawn using the Calcomp GPCP[1] software package.

To evaluate the accuracy of the temperature data, repeat measurements were made at control site No. 1 and at three other sites (plate 2). The data at the control site were collected in the grid shown on plate 2. To detect changes over small distances, two separate measurements about 30 to 60 centimeters apart were taken at each grid point. The data were then adjusted in the same manner as described above for the other temperature measurements. The adjusted temperature values have a distinctly smaller standard deviation than the unadjusted data, which probably indicates that a better estimate of the parameter is being achieved (table 1).

Repeat measurements were made at sites F11E, K3W, and N2E, as a further check on the variability of the measured values (table 2). A one-way analysis of variance was applied where replicate values were available. Use of the F-test, which is a method of evaluating the means of different samples (see Till, 1974), indicates that, except for a comparison of the temperature data at F11E and N2E, the mean temperatures can be considered to be from separate populations at the 95-percent confidence level. The F-test indicated that the values at F11E and K3W could be considered separate populations at the 85-percent confidence level but not at a 90-percent confidence level. The results indicate that a moderately large number of repeat measurements allows a fairly high degree of precision (a standard deviation of less than 0.1°C may not be unreasonable to expect), but that a much greater uncertainty, perhaps on the order of 0.3°C, should probably be expected if only one or two measurements are made.

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[1] Use of brand names in this report is for descriptive purposes only, and in no way constitutes endorsement by the U.S. Geological Survey.

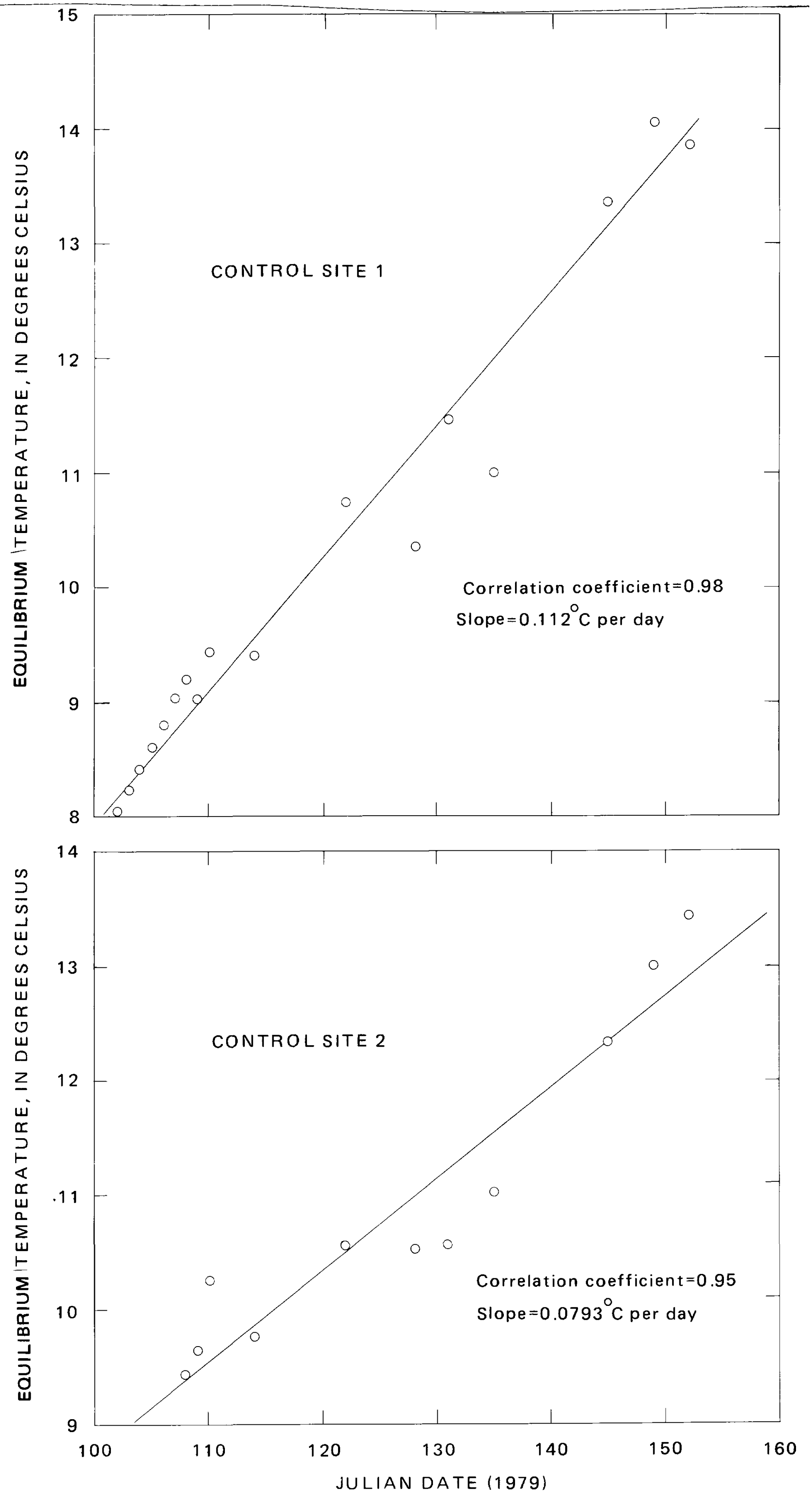


Figure 3.--Changes in temperature at 1-meter control sites between Julian dates 102 and 152, 1979.

TABLE 1.--*Measured and adjusted 1-meter temperatures at control site No. 1*

Measurement point[1]	Measured temperature (°C)	Date measured (Julian date, 1979)	Adjusted temperature (°C)
1	8.06	101	8.06
1	8.18	102	7.98
2	8.30	102	8.10
2	8.24	102	8.04
3	8.35	103	7.95
3	8.37	103	7.98
4	8.70	104	8.11
4	8.30	102	8.10
5	8.45	103	8.06
5	8.52	104	7.93
6	8.58	104	7.99
6	8.64	104	8.05
7	8.58	104	8.00
7	8.76	105	7.98
8	9.01	106	8.03
8	8.75	105	7.97
9	8.60	104	8.01
9	8.31	103	7.92
10	8.17	102	7.97
10	8.05	101	8.05
11	7.98	101	7.98
11	8.50	103	8.11
12	8.84	105	8.06
12	8.39	103	8.00
13	8.49	103	8.10
13	8.74	105	7.96
14	8.74	105	7.96
14	8.85	105	8.07
15	8.89	105	8.11
15	9.04	106	8.06
16	9.01	106	8.03
16	9.10	106	8.12
17	8.64	104	8.05
17	9.20	107	8.02
18	8.83	105	8.05
18	8.77	105	7.99
Mean	8.85	--	8.03
Standard deviation	0.31	--	0.056

[1] See diagram of measurement grid on plate 2.

TABLE 2.--*Paired 1-meter temperature measurements*

Location (plate 2)	Date measured (Julian date, 1979)	Temperature (°C)		
		Measured	Mean	Deviation
F11E	122 122	10.44 9.94	10.19	0.35
K3W	123 123	11.78 12.20	11.99	.26
N2E	121 121	10.81 10.86	10.83	.04

Interpretation

The most striking features shown on plate 2 are the distinctly higher temperatures found in the areas underlain by unconsolidated alluvium as opposed to playa sediments. This relationship was noted by Crewdson (1978a, page 23) in the southern part of the area from a survey made in June 1975. A generally lower thermal diffusivity of the upland materials due to a lower soil moisture and a greater depth to the water table results in a greater response to the annual temperature changes. The earlier survey of Crewdson (1978a, page 23) showed a lower temperature in the upland areas during January 1975, indicating that the annual temperature change is a major control on the 1-meter depth in materials with a low thermal diffusivity. The results of the current, larger survey agree with the observations of Crewdson to the extent that the low temperatures were dominant in the generally saturated playa sediments. Relatively low temperatures were also noted between Steamboat Rock and the southern end of the Calico Mountains. Although soil moisture may be partially responsible for this situation, the eastward movement of ground water from Hualapai Flat into the Black Rock Desert may be depressing the temperatures by advection of geothermal heat. This possibility is being explored further using geochemical and hydrologic techniques, and will be considered in a future report.

The effects of heating at shallow depth due to rising geothermal fluids are evident in the vicinity of Great Boiling Springs (approximately 1 kilometer northwest of Gerlach) and Double Hot Springs. Another high value was found in the vicinity of a hot spring at the base of the Black Rock and probably is also affected by thermal fluids. A lower amplitude thermal anomaly north of Wheeler Ranch may be due to slightly thermal water being used for irrigation in this area. Two additional, albeit minor, anomalies were identified; one is approximately 3 kilometers northeast of Trego Hot Springs and the other, an even less pronounced anomaly, is about 6 kilometers northeast of the same hot springs. These features are mentioned because a thermal scanning survey confirmed their presence, as discussed in a subsequent section.

The higher temperatures in the upland alluvial materials during both the winter (January) and spring (June) surveys imply that the average annual soil temperature is higher than on the topographically lower playa sediments. Differing albedos for the two areas may account, at least in part, for this relationship. (The movement of ground water may also cause some of the differing temperatures, as previously discussed.) In general, the playa deposits have a much lighter (lower albedo) color than the upland deposits, which would cause correspondingly less heating by solar radiation. This appears to be the case in the Carson Desert, approximately 130 kilometers to the south-southeast (F. A. Olmsted, U.S. Geological Survey, written commun., 1980). The possible effect of albedo on the 1-meter temperatures is being examined further, and will be discussed in a future report.

THERMAL SCANNER SURVEY

On April 28, 1979, an aerial survey consisting of panchromatic photography and thermal infrared (IR) imagery was flown at an altitude of 4.1 kilometers over the playa surface and surrounding alluvial fans of the Black Rock Desert (Becker, 1979). The infrared radiation received from an object is directly proportional to its temperature. This survey was an attempt to delineate areas with geothermal heat anomalies, and therefore was flown in the predawn hours to minimize solar-heating effects. The thermal scanner recorded far infrared radiation from 8 to 14 micrometers in wavelength. However, no ground temperatures were taken during the survey and count levels therefore record only relative temperatures. This results in a qualitative rather than quantitative evaluation of the area.

The thermal data were digitally processed, the count levels above an arbitrary threshold assigned colors, and the resulting image was reproduced on color film. Figure 4 shows the representation of the resulting image and relative count levels. The highest count levels represent the warmest temperatures.

The western flank of the Black Rock Range, the southwest corner of the playa, and the sink of the Quinn River are the warmest areas shown by the imagery. Isolated, high-count areas on the playa occur north of Trego, east of Hualapai Flat, and near the Humboldt County line along the western edge of the playa.

The source of heat for several of these warm areas is difficult to determine. Bodies of standing water, such as reservoirs and the channel of the Quinn River, have the highest count levels. These bodies of water are known to be nonthermal and probably are warm relative to their surroundings due to solar heat remaining from the previous day. Also, high count levels are seen in the southwest corner of the playa and along the Quinn River sink

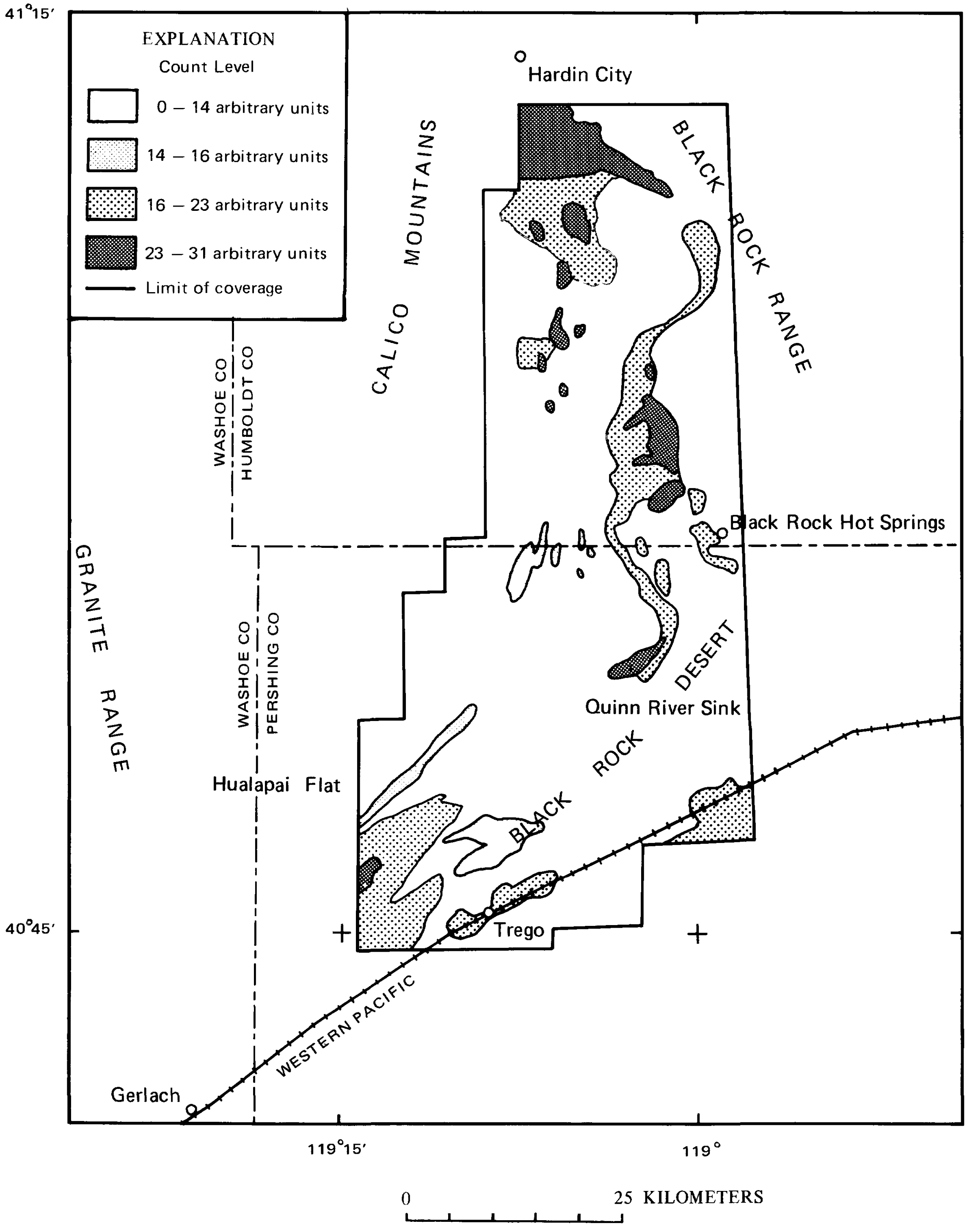


Figure 4.--Thermal infrared coverage and count-level distribution.

where moist soils are known to exist. The 1-meter temperature survey shows these areas to be relatively cool. Huntley (1978, page 1082) used a computer model to show that high soil moisture results in high soil temperatures relative to dry soil during the predawn hours because of slower radiant-heat loss during night hours. Thus, some areas that appear warm could be related to solar heating and the relative moisture of the soil, rather than heating from geothermal sources.

Warm spots along the western flank of the Black Rock Range are more difficult to assess. The warmest areas were between Black Rock and Double Hot Spring and at Hardin City, and coincide with known locations of springs and large areas of moist to saturated soil. However, these springs are known to be thermal, and the relative contribution of solar heat to the observed geothermal heat is not discernible.

Albedo is another factor along the western scarp of the Black Rock Range that could affect soil temperature. Moderately warm spots coincide with dark areas seen on aerial photography taken a few hours after the thermal imagery. Huntley (1978, page 1082) modeled the reflectance of soils and found that in predawn hours, highly reflecting soils are only slightly cooler than those with little reflection; during the day, however, a major difference in heating rate produces a large temperature difference. If nonreflecting soils are moist, much more heat may be added during the day and retained by the soil during the night. Thus, along the western margin of the Black Rock Range, varying soil moisture and reflectance greatly affect solar heating; and geothermal heating is effectively masked to the thermal scanner.

Geothermal heating may occur where isolated low-count areas previously described on the playa surface seem to coincide with warm areas seen in the 1-meter temperature survey. Lithologic logs taken during the 1-meter temperature survey indicate that soils in these areas are dry relative to the surrounding soils, which were saturated. Huntley (1978, page 1082) stated that evaporation should lower the temperature of moist soils. Air temperatures during April generally are a maximum of 10° to 16°C--fairly cool compared to those in July and August. In the spring, however, the entire playa dries from a shallow body of muddy water to a hard, mud-cracked surface. Humidity at Winnemucca drops by half over the period from March to May, evaporation during April is probably high. Thus, the thermal anomalies on the playa could be the result of evaporative cooling of the surrounding moist soils or geothermal heating of the dry soils, or both. Robertson and Dawson (1964, page 142) describe a surficial dryness in soils which have been conductively heated by a geothermal source. Because the warm areas are not anomalous in terms of altitude, relief, or lithology, the scanner and 1-meter data suggest geothermal heating. However, a test hole drilled in the warm area north of Trego indicated low heat flow.

Watson (1974) discussed the limits of detectability of thermal anomalies by thermal IR scanners. From his conclusions, only the areas directly adjacent to flowing hot springs have sufficient geothermal heat flux to be detected by such scans. Away from these areas of high heat flow, the effects of solar heat flux create background "noise" (Watson, 1974) that masks variations in geothermal heat flow to the Earth's surface.

SURFACE GEOPHYSICAL SURVEYS

Two types of surface geophysical techniques were employed to determine and verify depths to bedrock in the Black Rock Desert. A gravity survey was the primary method used to determine the depth to bedrock, and gravity stations were located throughout the study area. Subsequent seismic soundings at several sites served to check depths computed from the gravity data.

Gravity Survey

Purpose and Previous Work

A gravity survey of the western arm of the Black Rock Desert from Gerlach to Soldier Meadow was made to determine depths to bedrock. When the configuration of the bedrock surface beneath the desert is known, faulting and bedrock structures that are associated with geothermal potential may become evident.

Crewdson (1976, page 60, and 1978b, page 73) completed a gravity survey of the southern part of the Black Rock Desert and Hualapai Flat, which included 707 gravity stations--primarily on nine roughly east-west traverses with stations spaced at 400-meter intervals. From these gravity data, bedrock depths were computed. These data are discussed in more detail in a later section.

Other gravity work in the area was done at Double Hot Springs (Peterson and Kaufmann, 1978a) and Gerlach (Peterson and Kaufmann, 1978b). Another survey was made west of the study area at the Fly Ranch KGRA in Hualapai Flat (Peterson and Kaufmann, 1978c). No bedrock depths were calculated from these data and no attempt was made to incorporate the data with gravity values obtained during this study because of incompatibility.

Discussion of Method

Gravimetry is a geophysical technique that measures the vertical acceleration of gravity at discrete points on the Earth's surface. In gravity studies, the gravitational variations are measured in milliGals, where 1.0 Gal is equal to an acceleration of 1.0 centimeter per second, per second.

A more complete description of the theory used in gravimetric surveys can be found in most geophysics textbooks, such as that of Dobrin (1976, pages 357-403). Basically, the method involves measurements of very small variations in the gravitational acceleration on the Earth's surface that can be attributed to density variations in the material beneath the surface. For example, a structural basin filled with low-density alluvial and lacustrine deposits and underlain by a relatively high-density crystalline bedrock shows lower gravity values across the basin then if bedrock were exposed at land surface throughout the basin. The difference between (1) what the gravity profile would be if sedimentary deposits were absent and (2) what it actually is in the presence of low-density deposits is referred to as a residual-gravity anomaly. The thickness of the low-density material overlying the higher-density material is approximately proportional to the magnitude of the residual anomaly, and as such, it can be determine quantitatively.

Field Techniques

Gravity measurements were made at 469 sites in the western arm of the Black Rock Desert (plate 3). Measurements were made again at 23 of the sites, and a third time at one station, to determine the repeatability of the gravity values. The results of the repeat measurements are discussed in a later section. A Worden Master-model gravimeter with a dial constant of 0.0965 milliGal per scale division was used for the gravity survey.

Stations on the playa were positioned on 16 east-west profiles spaced at 3.2-kilometer intervals starting just south of Gerlach (line A, plate 3) and extending to just north of Double Hot Springs (line R). Stations along each profile were spaced at intervals of 610 meters. Stations north of line R to Soldier Meadow were spaced randomly, depending on terrain and availability of roads.

Horizontal Control

Horizontal control for individual stations on the profiles was accomplished using a Radar Positioning System (RPS), which allowed the gravity-meter operator to receive continuously updated information on his location. The location is referenced to two fixed transmitter locations whose positions are known to a high degree of accuracy. The RPS measures the travel time of a high-frequency microwave signal from the transmitter to the vehicle-mounted receiver. The receiver then computes the distances of the vehicle to the two transmitters. From this triangulation, the position was converted to latitude and longitude. The RPS has a nominal positional range of 37 kilometers and a position accuracy of 3 meters.

A few of the gravity stations in the northern Black Rock Desert (line R to Soldier Meadow) were located using the RPS, but the majority were located on recoverable landmarks such as bench marks, section corners, and road intersections. Some station locations, however, were surveyed with an electronic transit that used an infrared light source. The transit was also capable of computing altitude of the surveyed site. End points of the playa profile were located on bedrock outcrops using this technique.

Vertical Control

The altitude of the individual gravity stations is a critical parameter in a gravimetric survey. Errors of as little as 1.5 meters yield errors in the Bouguer gravity of 0.3 milliGal.

The ideal method to determine station altitudes is to survey each individual site. Because of the short time available and the great extent of the study area, most altitudes were interpreted from large-scale (1:24,000) topographic maps. Because the position of the stations was known accurately, altitudes taken from these maps were assumed to be accurate to within 1.5 meters. Gravity stations actually surveyed have an altitude accuracy better than 0.3 meter. Stations located at recoverable landmarks, as well as the majority of stations on the nearby level playa, are probably accurate within at least 0.3 meter.

Corrections and Observed Gravity

All gravity measurements were referenced to four project base stations in the study area. During the course of a day, one of these base stations was reoccupied at least three times to determine tidal and instrument drift. The reoccupation of a base station of known location also served to check the repeatability of the radar positioning system.

The project base stations in turn were tied to the primary base station in Gerlach (Peterson and Kaufman, 1978a, page 5). The primary station has an adopted observed gravity value of 979,829.16 milliGals, and from this value the observed gravity values for all stations were computed.

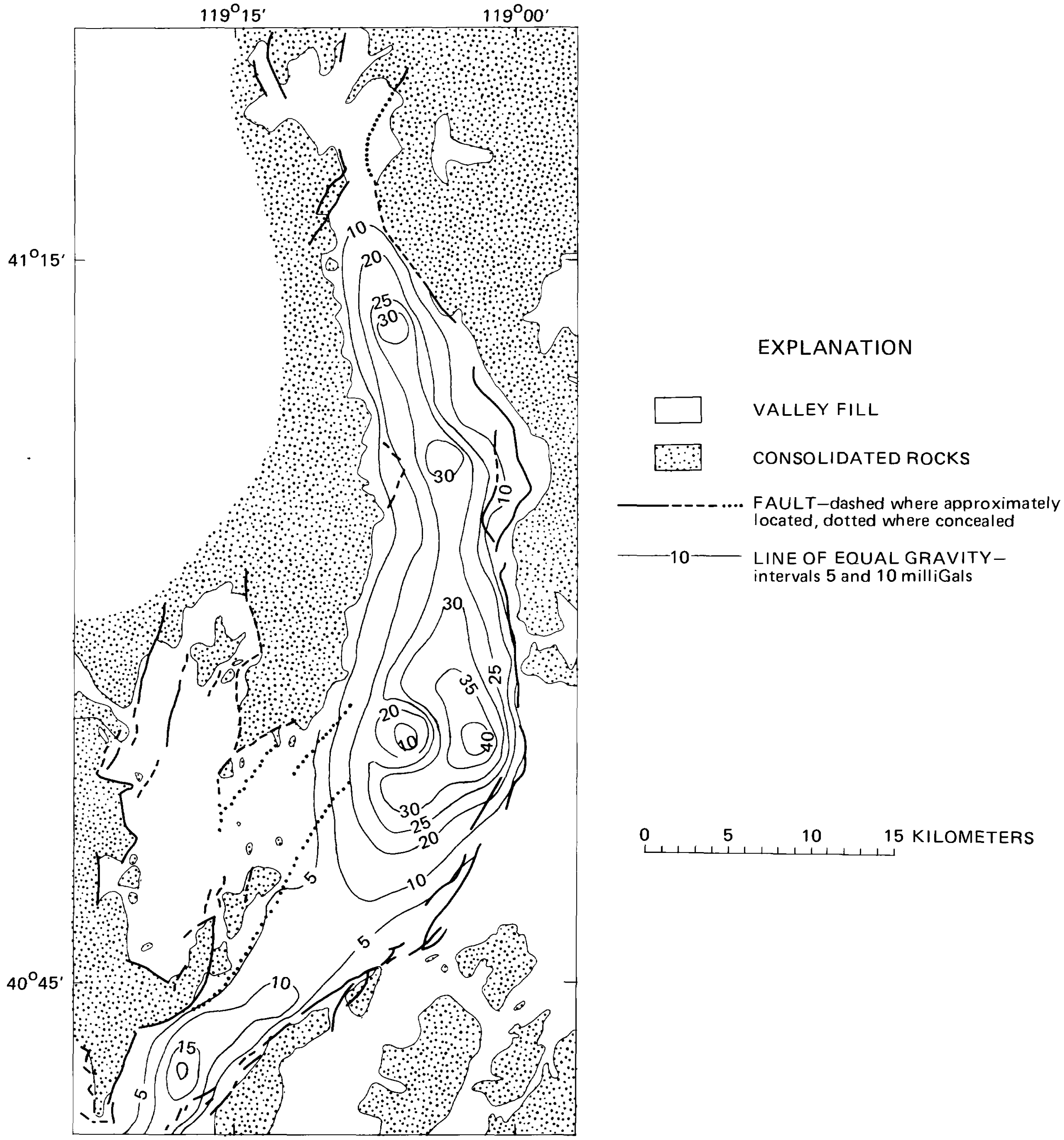
Data Reduction

Gravity data were reduced using a computer program developed by Plouff (1977), which utilizes values of latitude, longitude, altitude, and observed gravity as input, and yields theoretical gravity, free-air anomaly, and Bouguer anomalies as output. The program also computes the terrain correction radially outward from the station for a distance of 166.7 kilometers. Bouguer corrections were made using a density value of 2.67 g/cm^3. Final gravity data for the stations occupied during this study were listed by Schaefer and Maurer (1980).

Bouguer Anomalies

Plate 3 shows lines of equal Bouguer gravity superimposed on a generalized geological map. Bouguer gravity values range from -125 to -180 milliGals in the Black Rock Desert. The less negative values are associated with mountainous, more dense lithology, and the more negative values indicate less dense accumulations of valley-fill deposits.

Magnitude of the negative Bouguer gravity increases from the mountains to the desert floor, and rather large anomalies occur northeast of Gerlach (-175 milliGals), southwest of the Black Rock (-180 milliGals) and southwest of Pahute Peak (-180 milliGals). Bouguer gravity contours near the Black Rock Fault (plate 3) become very closely spaced, indicating a steeply dipping interface possibly associated with faulting. Closely spaced contours near Gerlach also may reflect faulting in that area.



Generalized geology by D.K. Maurer, 1979
Geophysics by D.H. Schaefer and D.K. Maurer, 1980

Figure 5.--Residual gravity values.

The lines of equal Bouguer gravity indicate three distinct linear trends in the desert. The first trend begins near Gerlach and terminates as a saddle in the contours northwest of Trego Hot Springs. This trend strikes approximately N. 45° E. The second structural trend strikes almost due north from Trego Hot Springs to Double Hot Springs (plate 3). The third trend strikes approximately N. 10° W. and terminates in Soldier Meadow. Thus, these structural trends seem to change direction or terminate in the vicinity of known thermal areas or hot springs.

Regional and Residual Gravity

The regional gravity trend of an area approximates the gravity configuration that would be observed if the low-density sediments of the basin were replaced by typical bedrock. The regional trend was constructed from 63 gravity measurements taken on bedrock outcrops and in the mountain blocks. A fourth-order trend surface was fitted to the data, using the technique described by Davis (1973, pages 322-337).

The generalized regional surface is then subtracted from the Bouguer gravity surface (plate 3); the resultant values are termed residual Bouguer gravity, and they primarily reflect the changes in depth to bedrock beneath the basin sediments. Figure 5 shows the residual gravity superimposed on a generalized geologic map. The negative residuals indicate that the complete Bouguer values were less (larger negative values) than the regional trend. The 0-milliGal line shows where the Bouguer gravity value was equal to the regional gravity. This situation occurs where bedrock is at or near land surface.

The residual-gravity map shows the general topographic configuration of the buried bedrock surface. The largest residual value found in the area is about -40 milliGals, in the large depression southwest of Black Rock. Most of the remaining values average between -20 and -25 milliGals. North of Double Hot Springs, the residual values do not show much deflection, but instead have a nearly regular gradient. This reflects shallow, flat bedrock surfaces. The exception here is a depression southwest of Pahute Peak (figure 5).

The lines of equal residual gravity closely follow fault traces in the Black Rock Desert. Displacement across the Black Rock Fault (figure 5) caused a considerable increase in the residual gradient. Many of the other faults can be seen bending and offsetting the 150-milliGal line, indicating a considerable amount of deformation of the bedrock surface by faulting. The area north of Double Hot Springs is a good example of this feature.

Depth to Bedrock

The resultant residual values were gridded to form a regularly spaced grid network for input into a three-dimensional gravity anomaly model. The program (Cordell, 1970) computes the approximate solution of depth to bedrock for an area of homogenous density and a fixed model boundary. The program uses the technique described by Cordell and Henderson (1968); the basis and limitations of that technique were also discussed by them.

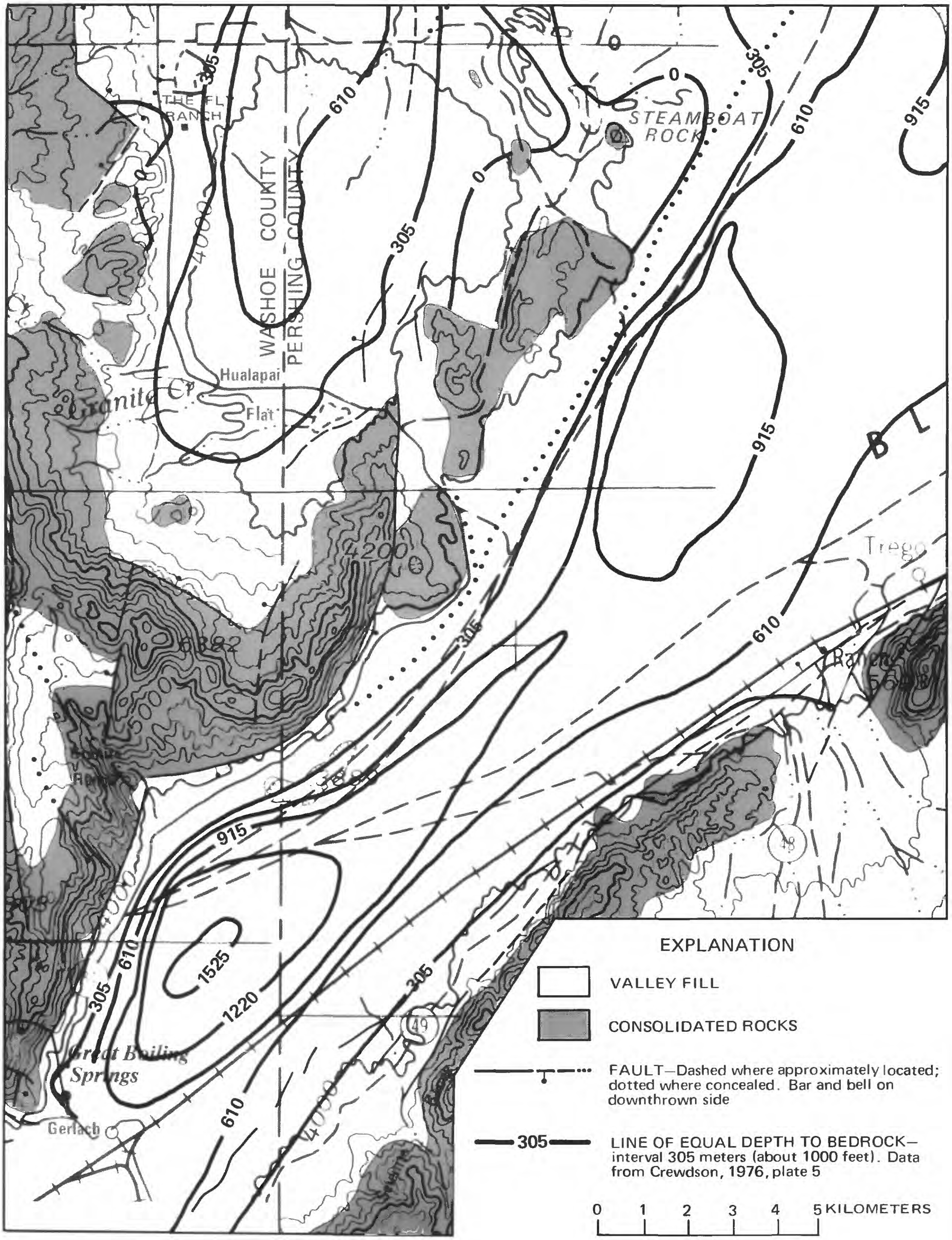


Figure 6.--Depth to bedrock in and adjacent to the southern part of the study area, from Crewdson (1976, plate 5).

Plate 4 shows the calculated depth to bedrock below land surface in the desert, using a density contrast of 0.50 g/cm^3 (2.76 g/cm^3 for bedrock and 2.17 g/cm^3 for the valley-fill deposits). The actual density contrast is far too variable to produce a single value for the entire area; however, 2.17 g/cm^3 is a fairly representative average value for the valley-fill deposits in the desert. During his gravity work in the southern part, Crewdson (1976, page 131) used a contrast of 0.67 g/cm^3 (2.00 g/cm^3 for the valley fill and 2.67 g/cm^3 for bedrock).

The grid spacing for the data input to the model was rather large (a land-surface spacing of 3 kilometers was equivalent to 2.54 centimeters in the model grid) but was necessitated by the data-handling limitations of the model with regard to the large areal extent of the desert. The effect of the large grid spacing is to smooth, to some extent, localized features such as steep gradients or gravity-line inflections associated with faulting. The advantage of a three-dimensional model is a more realistic representation of the depth to bedrock. A two-dimensional model produces a less accurate interpreted cross section because adjacent gravity anomalies are not included in the calculations.

The maximum depth calculated from the model is about 3,200 meters below land surface. This maximum depression is 6.4 kilometers southwest of Black Rock (plate 4) and along the Black Rock Fault. A somewhat shallower depression to the southwest (2,500 meters below land surface) seems to be related to a bedrock high just to the north of this depression. Two shallower depressions in the bedrock surface, near Gerlach (plate 4), reach maximum depths of about 900 and 1,200 meters below land surface.

Soldier and Mud Meadows in the north are shallow basins, characteristically less than 300 meters deep. A small depression deeper than 300 meters is centered on a fault that extends through the eastern margin of Soldier Meadows.

Virtually all the depressions on the depth-to-bedrock map are fault-controlled. By extending some of the more prominent faults through the depressions, the effect of faulting on the basement surface becomes evident. Some of the extensions of faults based on gravity data are shown on plate 4.

Figure 6 is a map of depth to bedrock calculated by Crewdson (1976, plate 5). In general, depths obtained from the current gravity survey (plate 4) compare reasonably well with depths that Crewdson calculated in the southern desert (figure 6). This result, to some extent, is expected because similar density contrasts were used. The major difference was the geometry of the gravity station locations. The general rise and shape of the depression is fairly similar, but Crewdson's maximum depth was 1,500 meters below land surface and the maximum depth obtained from the present study was 1,250 meters, for a depression slightly to the east.

Depths computed from seismic data in this study and those calculated by other investigators are compared to the gravity depths in a later section.

Errors in Measurements and Interpretations

As with any geophysical technique, errors in measurements and assumptions may make the final interpretation somewhat less exact than desired. Inaccuracies in equipment and techniques are sometimes unavoidable but still enter into the overall error of the interpretation.

Twenty-three of the gravity stations were reoccupied for a second reading (and one station was occupied three times) to obtain a measurement of repeatability for the gravity values. Of the repeat stations, about 30 percent were exactly repeatable from the original reading, about 60 percent were within 0.1 milliGal, about 80 percent were within 0.2 milliGal, and 100 percent were within 0.3 milliGal. Figure 7 is a histogram showing the distribution of errors for the repeat stations.

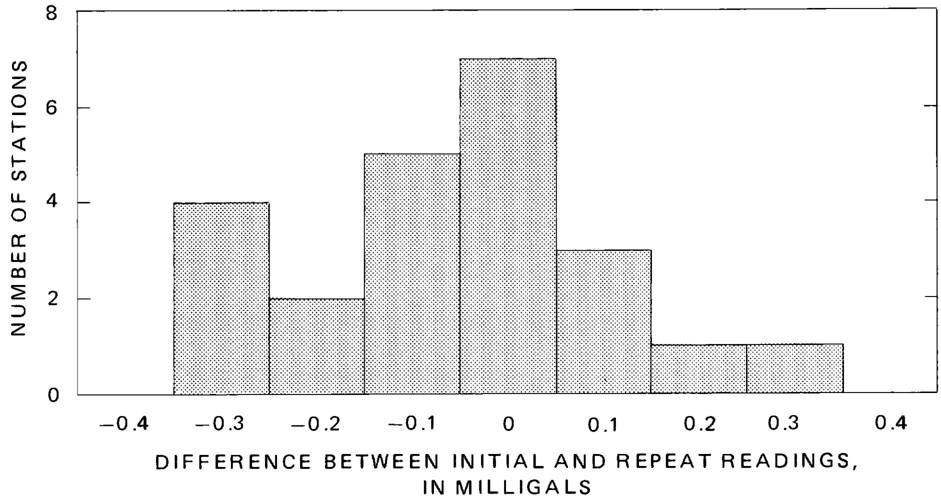


Figure 7.--Distribution of errors in gravity measurements.

The locations of all the stations are assumed to be accurate laterally within a 15-meter margin of error. This corresponds to a maximum error of 0.015 milliGal. As indicated earlier, the altitudes of the gravity stations are believed to be accurate to at least 1.5 meters, which gives an error of 0.3 milliGal.

If the worst possible case is assumed, in which altitude, location, and meter errors are maximized, the Bouguer gravity could be in error by as much as 0.62 milliGal. The depth model was tested using this maximum error, and the depth results were compared to the depths used in this report. The test case showed that depths differed by as much as 58 meters, but averaged about a 25-meter difference.

Another potential major source of error is the assumed density contrast between bedrock and valley fill. To test the density assumptions, an analysis was done with the depth program over a range of density values for the valley-fill deposits of 1.97 to 2.37 g/cm^3 (a common range of densities for valley-fill sedimentary materials) along a representative profile. This analysis was to determine the range of error possible with different densities. The errors and maximum depths computed for various density contrasts are listed below.

Density of valley fill (grams per cubic centimeter)	Density contrast (grams per cubic centimeter)	Maximum depth (kilometers)	Error
1.97	0.70	1.8	0.325
2.07	.60	2.3	.424
2.17	.50	3.2	.581
2.27	.40	4.3	.832
2.37	.30	7.1	1.25

The error listed above is calculated by (1) squaring the difference between measured and calculated gravities at each station along the profile, (2) summing the squares for the profile, and (3) taking the square root of the sum. A density of 1.97 g/cm^3 yields the smallest error, but depths calculated using this figure seem to be too shallow when compared to inferred geologic structure.

The density assumed for the unconsolidated deposits may not be valid for the entire study area or throughout the entire vertical section of the deposits. Some compaction and a resultant increase of density with depth could be expected. There may be basalt layers at depth that also contribute to density errors. Such density changes, however, cannot be dealt with in the model in its present form. The density used here is an assumed average value, areally and vertically.

One final source of error is in the regional gravity surface used to derive the residual map. As the regional surface is based on a very limited number of data points, the resultant map may be in error by as much as 5 milliGals, with a local error of as much as 10 milliGals (Andrew Griscom, U.S. Geological Survey, written commun., 1981). The use of a trend surface with the regional data, however, should help to minimize the errors.

Seismic Survey

Purpose and Previous Work

The seismic-reflection and refraction survey in the Black Rock Desert was done to determine independently the depths to bedrock obtained by the gravity-survey method. Seven seismic-reflection measurements were made, mostly south of Double Hot Springs. In addition, three seismic-refraction soundings were made at various locations to determine seismic velocities and thicknesses of the valley-fill deposits where the depth to bedrock is less than 300 meters.

Previous seismic work in the desert was described in Crewdson (1976, page 40). It consisted of a 30-kilometer seismic-reflection traverse across Hualapai Flat and the Black Rock Desert (figure 8). Depths to bedrock obtained by Crewdson agree reasonably with data from his gravity traverse at the same locations. Maximum depth to bedrock determined from Crewdson's seismic survey was about 800 meters, compared with about 500 meters from the present gravity survey.

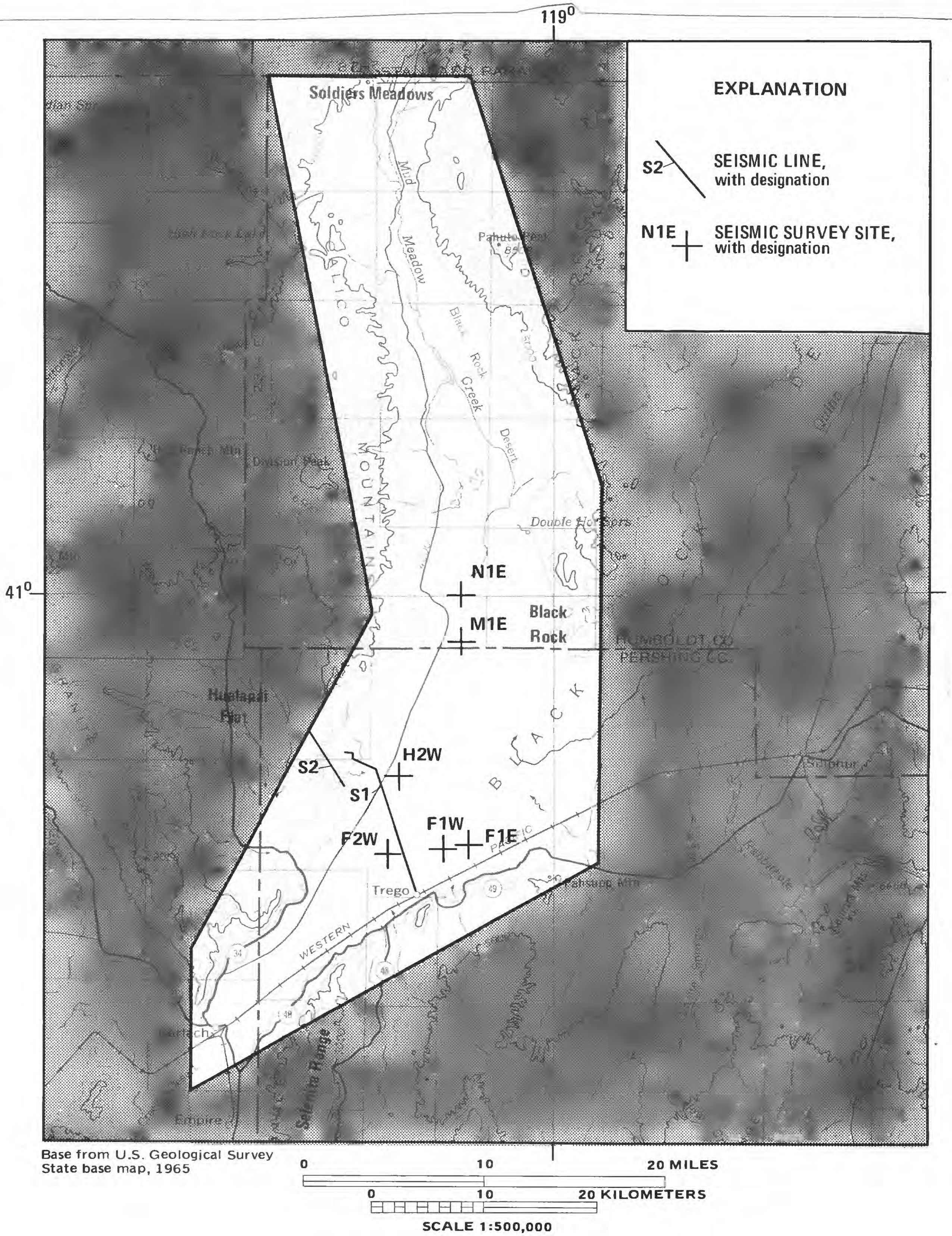
Previous work in the Black Rock Desert also included a microseismicity study (Crewdson, 1976, page 30) and a seismic-refraction line between Hualapai Flat and the Black Rock Desert (McGinnis and Dudley, 1964, page 31), as shown in figure 8.

Method and Field Techniques

Seismic-exploration principles and techniques are described in detail in most geophysics textbooks, such as that of Dobrin (1976, pages 25-57), and the following discussion is a brief summary. Two seismic techniques were used to delineate depths in the Black Rock Desert, refraction and reflection. Both involve detonating an explosive charge and measuring the time for the compressional wave to reach a series of receivers (geophones) at known distances from the detonation. From the time of travel of the waves, either the seismic velocity of the material or the thickness of the material can be calculated. In the case of refraction, both parameters can often be calculated.

Seismic refraction was used along the western front of the Black Rock Range (figure 8). The refraction method is complicated by the fact that a large spacing between the energy source and detector is needed for even a relatively thin accumulation of valley-fill deposits. This sometimes causes field logistic problems, and for this reason the refraction technique was used primarily for determination of seismic velocities. However, depths to bedrock were determined at a few locations.

Seismic reflection, having a somewhat less complicated field setup, was used successfully at three locations on the playa. Interference from near-surface waves produced from detonation of the explosives caused somewhat anomalous results at the remaining locations. Where possible, the seismic stations were located at existing gravity stations.



Base from U.S. Geological Survey
State base map, 1965

Figure 8.--Seismic survey sites and lines.

Results

Analysis of data from the seismic-refraction soundings made in this study and earlier seismic work by Crewdson (1976, page 40) and McGinnis and Dudley (1964, page 31) indicate an average seismic velocity of the valley-fill deposits in the Black Rock Desert of 1.8 kilometers per second. Using this velocity, seven seismic-reflection stations were located on the playa to determine the depths to bedrock. Table 3 compares the depths obtained from the seismic and gravity surveys. Agreement is reasonable at most of the sites. Table 3 includes some depths determined from the seismic work of the other investigators and compares them to the gravity work done for this study. The depth to bedrock at site S2 indicated by gravity data obtained in this study differs by 300 meters from the depth indicated by the seismic results of Crewdson (1976, page 41). There is no explanation for this discrepancy.

TABLE 3.--*Depths to bedrock calculated from seismic and gravity surveys*

[Data from U.S. Geological Survey, except as indicated]

Location (figure 8)	Depth (meters)	
	Seismic survey	Gravity survey
F1W	480	520
F1E	340	370
F2W	520	490
H2W	470	520
M1E	2,600	2,600
N1E	1,300	1,200
V1E	210	240
S1	[a]800	500
S2	[b]53	<150

[a] Maximum depth for common-depth-point seismic-reflection line, from Crewdson (1976, page 41, figures 10, 15).

[b] Maximum depth for seismic-refraction profile B-B', from McGinnis and Dudley (1964, page 31, figures 5, 6).

CONCLUSIONS

The results of the 1-meter temperature survey show the effects of heating at shallow depths due to rising geothermal fluids near Great Boiling Springs, Double Hot Springs, and the base of the Black Rock (plate 2). Other, lower temperature anomalies were noted approximately 3 and 6 kilometers northeast of Trego Hot Springs. Relatively low temperatures at 1 meter were noted between Steamboat Rock and the southern end of the Calico Mountains (plate 2). This may be due to the movement of ground water from Hualapai Flat into the Black Rock Desert.

The thermal-scanner survey tends to indicate known hot-spring locations, standing water, and discharge areas in the desert (figure 4). These bodies of standing or near-surface water probably are warm due to their relatively high thermal diffusivities.

The upland areas are distinctly warmer than the playa; this probably is due to a low thermal diffusivity caused by the low moisture content of upland surface materials, or their lower albedo, or both.

The gravity and seismic data show that the Black Rock Desert contains a fairly thick accumulation of valley-fill deposits. Analysis of gravity data indicates that these deposits attain a maximum thickness of about 3,200 meters near the Black Rock (plate 4). In most areas, seismic work substantiates the depths computed from gravity data.

The geophysical surveys also show that most of the structure of the bedrock surface is fault controlled. The survey further shows that thermal activity increases where the geographic trend of the desert changes direction (plate 4).

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