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SHALLOW SUBSURFACE TEMPERATURE SURVEYS IN THE BASIN AND RANGE PROVINCE, U.S.A.—I. REVIEW AND EVALUATION

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Abstract—Temperature surveys at depths of 1 – 2 m have had varying success in geothermal exploration in the Basin and Range province. The most successful surveys have identified patterns of near-surface thermal-fluid flow within areas of less than 2 km^2. Results have been less consistent in larger areas where zones of hydrothermal upflow are less well known, nongeothermal perturbing factors are significant and lateral variations in shallow subsurface temperature are small. Nongeothermal perturbations can be minimized by use of mean annual temperatures instead of synoptic temperatures, by physically based simulation of ground temperatures or by statistical modeling.

INTRODUCTION

Temperature surveys at shallow depths are widely used as an economical geothermal exploration method in the Basin and Range province. The common goal of such surveys is to delineate heat-flow anomalies, but their effectiveness varies and depends upon the intensity of the heat-flow anomaly, local geologic and hydrologic factors and the methods used. This paper presents new data and interpretations from several localities in northern and central Nevada, summarizes the results of earlier surveys in the same region and evaluates the utility of various survey techniques under a range of conditions.

Theoretical basis of technique

A shallow subsurface temperature survey may be defined as a set of areally distributed temperature measurements at any depth where temperature fluctuates measurably in response to periodic and aperiodic variations in solar energy input at the land surface. Temperature measurements near the land surface are easier to obtain than those at greater depths, but a tradeoff is involved because the effects of solar energy fluctuations and other factors unrelated to geothermal heat flow, such as topography, albedo and vegetation, become increasingly important as the depth decreases. Most earlier surveys have been made at depths of 1 – 3 m; all the surveys described herein were made at depths of 1 – 2 m.

The perturbing effects of factors unrelated to geothermal heat flow on shallow subsurface temperatures have been discussed in detail by Lovering and Goode (1963), Poley and Van Steveninck (1970), Kappelmeyer and Haenel (1974) and Olmsted (1977). No attempt is made to review these effects systematically, but some of them are referred to in the discussion of previous studies.

REVIEW OF PREVIOUS STUDIES

For convenience of discussion, previous shallow subsurface temperature surveys in the Basin and Range province are grouped into three categories: (1) detailed surveys of small areas (about 0.2 – 2 km^2); (2) surveys of moderate-sized areas (about 2 – 200 km^2); and (3) surveys of large areas (about 200 – 2000 km^2). The objectives of the surveys tend to differ with size of the area surveyed, as discussed below.

Detailed surveys of small areas

Detailed surveys of small areas have been described at the following localities (see Fig. 1 for locations).

(1) Soda Lakes steam-well area, Nevada (Olmsted *et al.*, 1975; Olmsted, 1977)—see discussion below;
(2) Allen Springs—Lee Hot Springs area, Nevada (Miller, 1978);
(3) Caliente area, Nevada (Trexler *et al.*, 1980a);
(4) Eastern Eagle Valley, Nevada (Trexler *et al.*, 1980b);
(5) Saratoga Hot Springs, Nevada (Trexler *et al.*, 1980b);
(6) Spencer's Hot Springs, Nevada (Trexler *et al.*, 1980b);
(7) McLeod Ranch Hot Springs, Nevada (Trexler *et al.*, 1980b);
(8) Darrough's Hot Springs, Nevada (Trexler *et al.*, 1980b); and
(9) Crump Geyser, Oregon (Sammel and Craig, 1981).

The small areas range in size from 0.19 to 2.0 km^2; average spacing between measurement sites ranges from 0.059 to 0.34 km. In general, the purpose of these surveys was to identify patterns of near-surface vertical and lateral flow of thermal fluids associated with known hot springs, fumaroles or other sites of hydrothermal discharge. At most places, areal differences in synoptic* temperatures were large and uncorrected temperatures clearly indicated the location of ascending thermal fluids. Because of the large areal variations in temperature and correspondingly large near-surface heat flows, perturbing effects of nongeothermal factors were relatively unimportant and did not significantly affect the configuration of the thermal anomalies at depths of 1 – 2 m.

The thermal maxima commonly coincide with the location of hot springs or other surface-discharge features, but at McLeod Ranch Hot Spring, neither of two identified thermal maxima coincides with the hot spring (Trexler *et al.*, 1980b). At Caliente, Nevada, the near-surface thermal maximum is displaced from the deeper thermal maximum identified in wells because of the effects of shallow ground-water flow (Trexler *et al.*, 1980a).

No significant shallow subsurface temperature anomaly was observed in eastern Eagle Valley, Nevada; instead, a small temperature anomaly (only 2°C) in the southern part of the area was attributed by Texler *et al.* (1980b) to localized increased warming of the ground surface by solar radiation.

Surveys of moderate-sized areas

Shallow subsurface temperature surveys at depths of 1 – 2 m in eight moderate-sized areas are listed below (see Fig. 1 for locations).

(1) Soda Lakes geothermal area, Nevada (Olmsted *et al.*, 1975; Olmsted, 1977; Olmsted *et al.*, 1981);
(2) Upsal Hogback geothermal area, Nevada (Olmsted, 1977; Olmsted *et al.*, 1981; LeSchack *et al.*, 1979; LeSchack and Lewis, 1983);
(3) Hualapai Flat, Nevada (Crewdson, 1976, 1978);
(4) Stillwater geothermal area, Nevada (Morgan, 1982);
(5) Paradise Valley, Nevada (Trexler *et al.*, 1981);
(6) Hawthorne area, Nevada (Trexler *et al.*, 1981);
(7) Long Valley, California (LeSchack *et al.*, 1977, 1979, 1980; Sorey *et al.*, 1978); and
(8) Coso Hot Springs, California (LeSchack *et al.*, 1977, 1979, 1980, LeSchack and Lewis, 1983).

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*The term "synoptic" refers to observations at various places made at or near the same time.

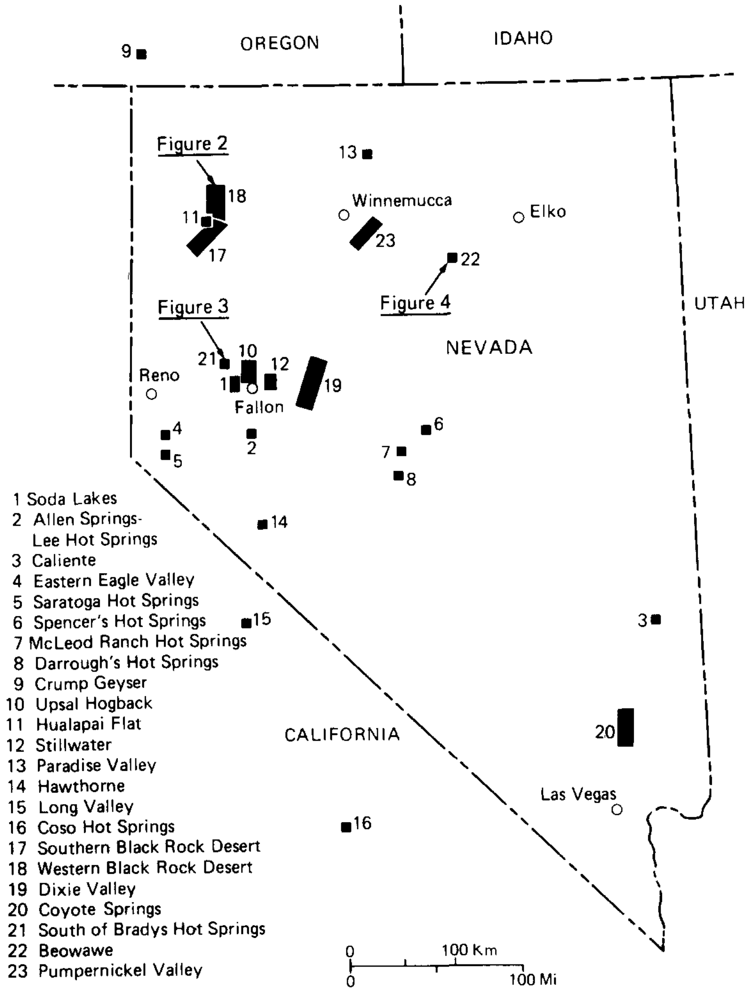

Fig. 1. Location of shallow subsurface temperature surveys in the Basin and Range province.

These areas range in size from about 2 to 200 km^2 but most are larger than 15 km^2; average spacing between measurement sites range from 0.14 to 1.9 km. In both density of coverage and purpose these surveys overlap the detailed surveys described earlier. In general, however, the location and even the existence of zones of hydrothermal upflow are less well known in the moderate-sized areas than in the small areas and surface discharge of thermal fluid may not occur at some of the thermal anomalies.

Earlier temperature surveys at Soda Lakes and Upsal Hogback in the western Carson Desert, Nevada are described in a later section. At the Stillwater geothermal area in the eastern Carson Desert, Morgan (1982) used temperatures at a depth of 1 m to identify zones of hydrothermal upflow and to refine estimates of near-surface conductive heat flow which were made on the basis of data obtained from shallow test drilling. The survey, made in April and May of 1979 in order to minimize areal variations in temperature caused by areal variations in thermal diffusivity (see Olmsted, 1977, Fig. 2), delineated two separate thermal maxima at 1 m that were not shown by the sparser temperature-gradient data from test wells.

In Paradise Valley in north-central Nevada Trexler *et al.* (1981), in a series of synoptic surveys in September, October and November 1980, measured temperatures at 2 m ranging from 12 to 71°C and inferred that thermal fluids are not transported to the land surface along recent faults but, instead, rise in narrow pipes whose location is indicated by tufa mounds. Interpretation of results doubtless benefitted from the large range in temperature, the 2-m depth of measurement, and the timing of the surveys, which spanned one of the optimal times of year (October) for synoptic measurements.

At Hualapai Flat, a 30-km^2 area adjacent to the Black Rock Desert in northwestern Nevada, Crewdson (1976, 1978) observed an areal variation in temperature of 10°C at a depth of 1 m in a January 1975 survey. Unlike the Stillwater and Paradise Valley surveys described above, interpretation was complicated by the timing of measurements, which emphasized areal temperature variation caused by areal variation in thermal diffusivity.

One of the earliest shallow subsurface temperature surveys in the Basin and Range province was made in the fall of 1972 in east-central Long Valley, California, by Robert E. Lewis (Sorey *et al.*, 1978). The data were used to modify a map of temperatures at a depth of 10 m constructed on the basis of sparser data from temperature-gradient holes by Lachenbruch *et al.* (1976).

A shallow subsurface temperature survey was made in July 1977 in a 62-km^2 area that is part of the larger area described above in order to test the efficacy of a survey method developed by LeSchack *et al.* (1977, 1979, 1980). The temperatures observed at a depth of 2 m were corrected for the effects of surface roughness, albedo, soil thermal diffusivity, topography and elevation. Corrected temperatures reportedly showed the same areal pattern as those measured at 10 m in shallow test wells by Lachenbruch *et al.* (1976), although the pattern differs in some details from that inferred by Sorey *et al.* (1978).

Probably the most intensively studied area mapped by shallow subsurface temperature surveys in the Basin and Range province is Coso Hot Springs in east-central California (LeSchack *et al.*, 1977, 1979, 1980; LeSchack and Lewis, 1983). Temperatures were measured at a depth of 2 m by LeSchack and his coworkers in September 1977, February, May and August 1978 at 102 sites within an area of about 170 km^2. Unlike most of the other areas described above, which are lowlands underlain by unconsolidated deposits, the Coso Hot Springs area is an upland of moderately strong local relief (nearly 500 m within the surveyed area) underlain at shallow depth by consolidated volcanic rocks. Observed temperatures were corrected for the effects of surface roughness (Lettau, 1969), albedo, soil thermal diffusivity and, because of the relief, for topography and elevation as well. Mean annual temperatures were derived for all the sites. In addition to confirming the subsurface-termperature and heat-flow patterns established by much more costly drilling, the shallow subsurface temperature surveys confirmed the location of mapped faults, probably owing to the anomalous thermal properties of the materials in the fault zones (LeSchack *et al.*, 1979).

Surveys of large areas

Shallow subsurface temperature surveys of large areas (hundreds of km^2) have been oriented toward the search for so-called "hidden" hydrothermal systems or defining the boundaries of several known systems rather than detailed characterization of single known systems. Five large areas in the Basin and Range province are described in the literature (see Fig. 1 for locations).

(1) Southern Black Rock Desert, Nevada (Crewdson, 1976, 1978);
(2) Western Black Rock Desert, Nevada (Schaefer *et al.*, 1981)—see discussion below;
(3) Dixie Valley, Nevada (Campana *et al.*, 1980);
(4) Coyote Spring Valley, Nevada (Trexler *et al.*, 1982); and
(5) Pumpernickel Valley, Nevada (Trexler *et al.*, 1982; Flynn *et al.*, 1982).

The areas range in size from 230 to 1500 km^2 and average spacing between measurement sites ranges from 0.95 to 2.7 km. The first two areas overlap.

The surveys in the Black Rock Desert, made at a depth of 1 m in June 1975, were affected greatly by areal variation in thermal diffusivity, which, in turn, is affected by differences in both lithology and water content of the deposits from 0 to 1 m depth (Crewdson, 1976; Schaefer *et al.*, 1981).

At Dixie Valley, Campana *et al.* (1980) found several thermal anomalies inferred to be associated with zones of hydrothermal upflow and discharge in a series of surveys at 1-m depth made at monthly intervals from April to September 1979. Temperatures also were inferred to be affected greatly by ground-water flow (Campana *et al.*, 1980).

At Coyote Spring Valley in southeastern Nevada, temperatures measured at a depth of 2 m during a 6-month period from June to November 1981 were adjusted for seasonal variation to a common time in August using detailed records obtained at four sites; one thermal anomaly was associated with zones of Holocene faulting, but another probably was caused by radiant and conductive heating of the ground by an adjacent asphalt-paved highway (Trexler *et al.*, 1982).

At Pumpernickel Valley, several thermal anomalies were identified using temperatures measured at a depth of 2 m in October and November 1981 (Flynn *et al.*, 1982; Trexler *et al.*, 1982). The observed temperatures were corrected for the effects of the annual temperature wave and altitude; the corrected temperatures ranged from 17.5 to 26°C (Flynn *et al.*, 1982). Not all the thermal anomalies, which were explored by later test drilling to depths as much as 150 m, are associated with surface discharge; the Kemp anomaly in northern Pumpernickel Valley has no nearby thermal springs.

PRESENT STUDIES

Present studies include temperature surveys at a depth of 1 m in: (1) the western Black Rock Desert area, (2) the southern Bradys Hot Springs area, (3) the Beowawe thermal area, (4) the Soda Lakes thermal area and (5) the Upsal Hogback thermal area. Locations of these areas as well as those of previous surveys are shown in Fig. 1.

Equipment and methodology

The equipment and methodology used in the present studies are similar to those described by Olmsted (1977). Temperatures were measured with thermistors mounted at the lower end of anodized aluminum probes 1 m in length, connected by three-conductor cables to solid-state Wheatstone bridges that indicate temperature directly, to the nearest 0.01°C. The probes and Wheatstone bridges were calibrated before and after the surveys using quartz or platinum thermometers, and individual measurements are believed to have an accuracy of ± 0.2°C.

Access holes were made with soil augers in sandy deposits or with steel drivers in silty or clayey deposits. Lithology and moisture content of the materials were recorded at most sites. Some of the holes in the Beowawe thermal area were bored with a truck-mounted power auger, as described in a later section.

Temperatures were measured at each site at regular intervals of 2 – 6 minutes and equilibrium temperature was calculated by extrapolation to infinite time using a least-squares exponential curve fit to the temperature – time data, as described by Parasnis (1971). Repeat measurements were made at monthly or irregular intervals at many sites, by either boring or redriving to remove the material accumulated in the hole since the previous measurement.

Field measurements of albedo were made at 49 sites in the Upsal Hogback geothermal area and at 14 sites in the Soda Lakes geothermal area using an Exotech model 100 radiometer*. This instrument has four spectral filters which match the Landsat multispectral scanners (MSS) bands. The mean reflectance of the land surface across these four bands was used as a measure of albedo in the 0.5 – 1.1 μm wavelength region.

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*The use of a brand name is for identification purposes only and does not constitute an endorsement of this product by the U.S. Geological Survey.

Western Black Rock Desert area

The area surveyed is the western part of the Black Rock Desert in northwestern Nevada (Fig. 1), which forms a part of the bed of pluvial Lake Lahontan and consists of a central playa and adjacent alluvial slopes at the foot of the surrounding mountains. The water table is within about 1 m of the land surface on the playa but is deeper beneath the alluvial slopes. The playa is flooded during most winters but dries up by spring, owing primarily to evaporation.

The temperature survey, which was done during April and May 1979 in an attempt to minimize temperature variations caused by areal variations in thermal diffusivity, consisted of measurements at a depth of 1 m at 215 sites within an area of about 1500 km^2; average spacing between sites was 2.6 km. Because temperature was changing during the survey, measurements were repeated at two sites selected to represent the range of thermal diffusivity likely to be encountered within the area: one site on the playa to represent low thermal diffusivity, the other in a sand dune to represent high diffusivity. All temperatures were adjusted to an arbitrary time, using the rates of change observed at the two sites (Schaefer *et al.*, 1981).

The adjusted temperatures (Fig. 2A) are distinctly higher in the alluvial-fan deposits than in the playa deposits, probably because of several factors, including areal variations in thermal diffusivity and surface albedo, and the cooling effect of winter flooding and spring evaporation of the playa.

Surface albedo was estimated using digital Landsat MSS data (Gerald Moore, U.S. Geological Survey, written commun., 1984). Radiance for each pixel in MSS bands 4, 5, 6 and 7 (0.5 – 1.1 µm) was determined and albedo was calculated as a weighted average of the radiance values, using the method of Robinove *et al.* (1981). "Landsat-albedo" values at all the temperature-measurement sites were used to generate a map showing lines of equal albedo (Fig. 2B), using the same algorithm that was used to create the map showing lines of equal temperature.

No previously unrecognized thermal anomalies related to high geothermal gradients or heat flow were identified. All the observed anomalies are associated with hydrothermal upflow that discharges at the land surface. If additional thermal anomalies are present at depth, the temperature perturbations caused by nongeothermal factors apparently prevent their detection. The poor correlation of albedo and temperature at 1-m depth (the coefficient of determination r^2, is only 0.16 for a linear least-squares fit) suggests that other factors, such as playa flooding and ground-water flow, may be of equal or greater importance. Although an attempt was made to minimize the effect of thermal-diffusivity differences, they may still be an important factor. The poor correlation of albedo and temperature may also result in part from comparing a point value (the temperature measurement) with a value that represents an average for an area of 0.62 ha (the nominal MSS pixel size).

Southern Bradys Hot Springs area

Bradys Hot Springs, about 27 km northeast of Fernley, Nevada (Fig. 1), is near the center of an elongate thermal anomaly produced by hydrothermal upflow along a north-trending normal fault. Data from temperature-gradient holes drilled during a geothermal reconnaissance in 1972 – 1975 were insufficient to determine the southward extent of the anomaly (Olmsted *et al.*, 1975), and, in November 1975, a temperature survey at a depth of 1 m was made south of the mapped part of the anomaly. During and after the 1-m survey, several shallow (10 – 40 m) temperature-gradient holes were drilled in the same area to define the near-surface heat-flow pattern (Fig. 3).

The surveyed area, known locally as Eagle Marsh (Benoit *et al.*, 1982), is nearly flat and level, and near-surface materials are largely playa deposits of silt, clay and salts left by evaporation from a shallow water table. Major ground-water discharge is believed to occur from a thermal

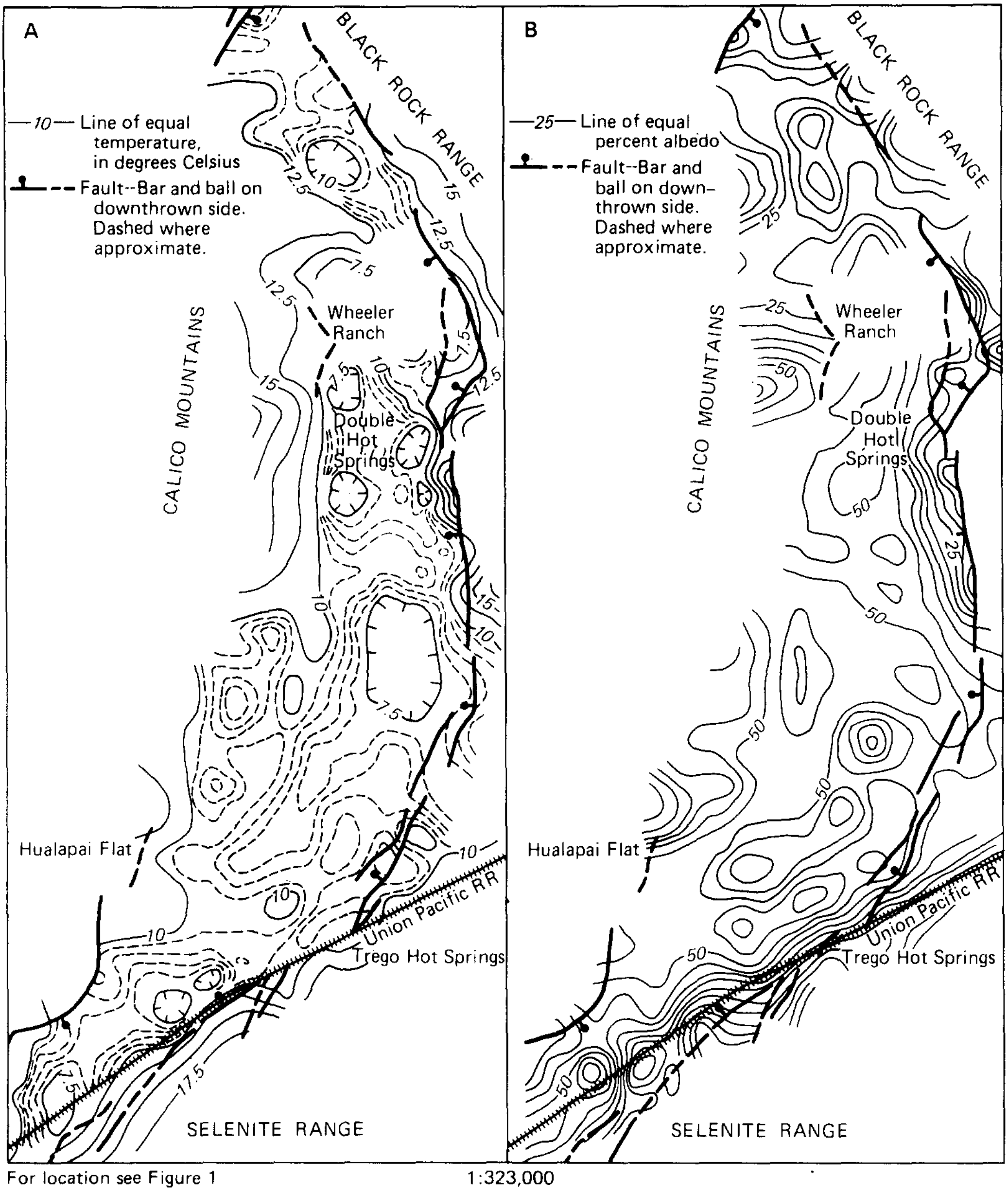

Fig. 2. (A) Lines of equal temperature at a depth of 1 m in the western Black Rock Desert, April – May 1979. (B) Lines of equal albedo in the western Black Rock Desert.

aquifer in the Desert Peak geothermal systems to the northeast (Benoit *et al.*, 1982).

Temperature was measured at a depth of 1 m at 14 sites on 4 November 1975 (Fig. 3). The area surveyed was about 5.2 km^2; average spacing between sites was 0.61 km. Measured temperatures ranged from 16.1 to 18.5°C. Three separate temperature highs were identified along the road in the northern part of the area, but no control was available to indicate the northward extent of the highs. The lowest temperatures were in the southern part of the area, near some abandoned salt evaporators (Fig. 3).

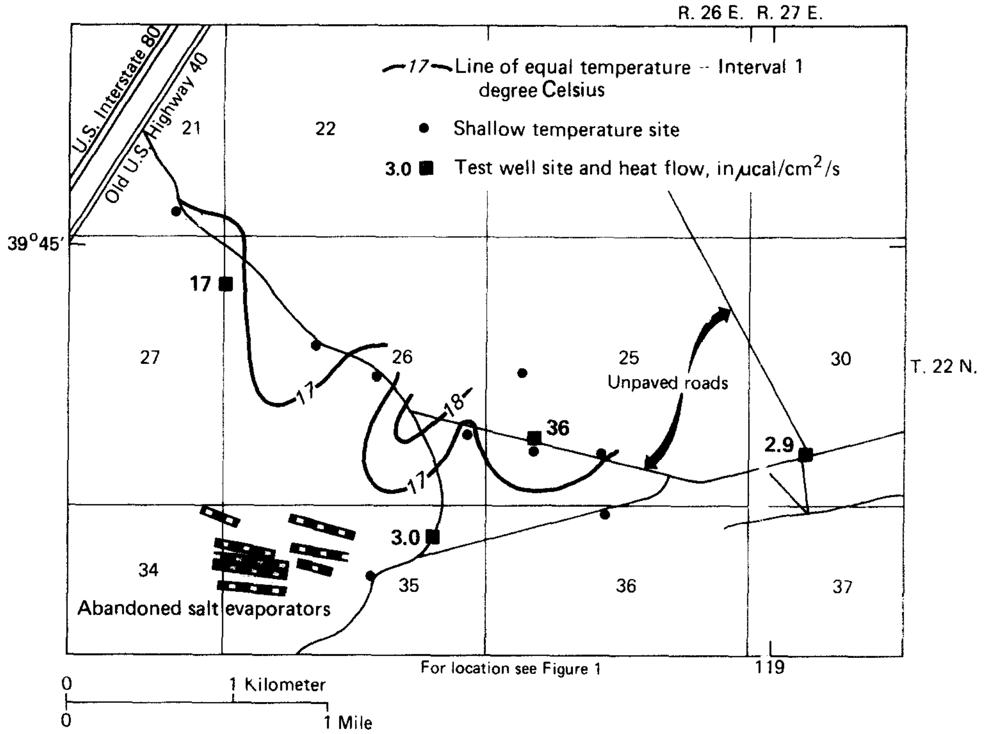

Fig. 3. Temperature at a depth of 1 m, November 1975, and heat flow at test-well sites in the southern Bradys Hot Springs area.

Results of the 1-m temperature survey were inconclusive in terms of defining the southern extent and configuration of the thermal anomaly mapped by Olmsted *et al.* (1975). Part of the difficulty may be due to the time of year of the survey: theoretically, the effects of areal differences in thermal diffusivity would have been less had the survey been made in October instead of November (see Olmsted, 1977, Fig. 2). These effects might account, in part at least, for the lower temperatures in the southern part of the surveyed area, where the saturated and nearly saturated sands at depths of 0 – 1 m presumably have higher thermal diffusivity than the drier clay, silt and fine sand at the more northerly sites. A survey 6 months later, in the spring, would have indicated higher temperatures in the south if thermal-diffusivity differences were the chief cause of the temperature differences observed in November 1975. Whether thermal diffusivity differences account for the three thermal maxima observed along the northern road is moot, however; no obvious relation exists between temperature and materials penetrated at those sites.

Beowawe thermal area

Before initial geothermal drilling and testing in the early 1960s, the Beowawe thermal area, which is in Whirlwind Valley about 75 km southwest of Elko, Nevada (Fig. 1), was characterized by hot springs, geysers and fumaroles along a set of normal faults near the foot of a north – northwest-facing escarpment. Many of the hot springs continue to flow, but geyser activity largely ceased soon after the original drilling (Hose and Taylor, 1974). Rocks and deposits exposed in the area include Quaternary alluvium, basalt and andesite of Tertiary age, and sedimentary rocks of Paleozoic age (Roberts *et al.*, 1967; Stewart and McKee, 1970; Smith, 1983; Zoback, 1979).

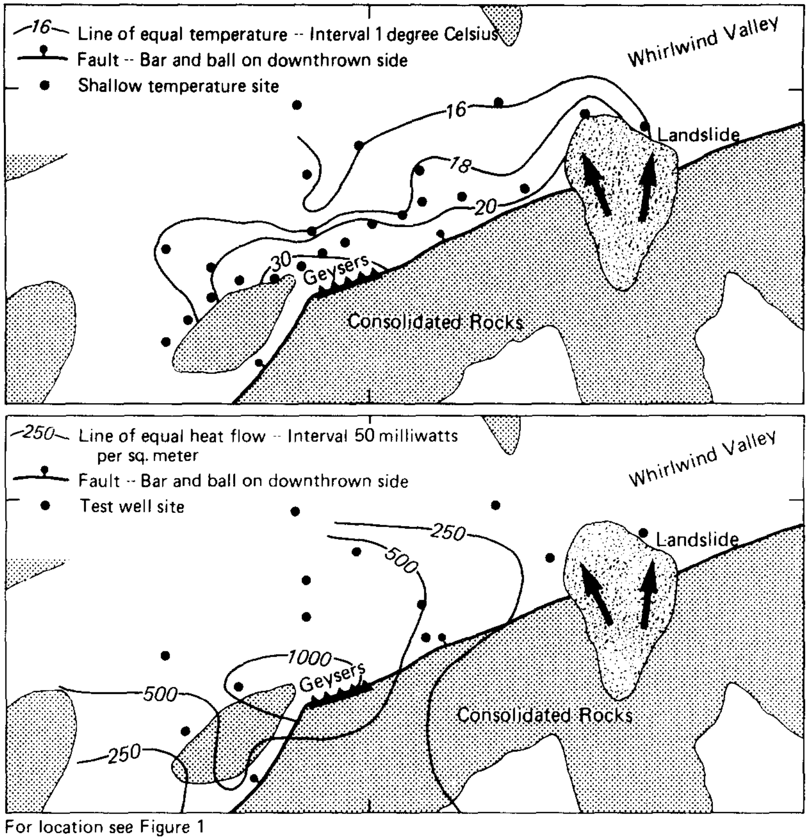

Fig. 4. Temperature at a depth of 1 m, October 1974, and near-surface heat flow in the Beowawe geothermal area. Contours in mW/m^2.

Surface drainage in Whirlwind Valley is eastward to the Humboldt River, and the ground-water gradient likewise indicates subsurface flow in that direction (Smith, 1983). Thermal water apparently moves upward along faults of the escarpment mentioned above and some of it moves laterally in the direction of shallow ground-water flow. The area of the shallow (1 m) temperature survey includes the northern part of the area of hydrothermal discharge adjacent to the fault scarp (Fig. 4).

The shallow subsurface temperature surveys were done as part of a reconnaissance hydrological appraisal of the Beowawe Geysers hydrothermal system (U.S. Geological Survey open-file basic-data release, August 1977). In addition to mapping geologic and hydrologic features, the field studies included the drilling of 34 shallow multipurpose test holes used to obtain geologic, hydraulic-head, hydrochemical and temperature data.

Five sets of synoptic temperature measurements at a depth of 1 m were made at irregular intervals from late September 1974 to early May 1975. A total of 24 sites were occupied within an area of about 13 km^2; average spacing between sites was 0.74 km. Some of the access holes were augered by hand; others, in soft silty or clayey sediments, were driven with a steel rod; and those along roads were bored with a truck-mounted power auger and cased with 2-in. (51-mm) polyvinyl chloride pipe. The last group required 2 – 3 days to reach temperature equilibrium after they were bored on 25 and 26 September 1974. Except for the first set of measurements on 25 – 29 September 1974, each of the five sets of temperature measurements was done within a span of two days. Average hourly rates of temperature change were calculated from preceding and following sets of measurements, and temperatures were adjusted to noon on 28 September, 8 October and 6 December 1974, and 18 March and 7 May 1975. Hourly rates of change at the 24 sites varied by a factor of more than two for some periods, which indicates a substantial areal variation in thermal diffusivity. Because the data were insufficient to define mean annual temperatures, the 8 October 1974 set of measurements was selected to represent the areal variation in temperature (Fig. 4) in order to minimize the effect of areal differences in thermal diffusivity.

Temperatures at 1-m depth in early October 1974 ranged from less than 16 to more than 34°C; the highest temperatures correspond to the area of highest heat flow, as delineated by Smith (1983). The patterns of heat flow and shallow temperature are generally similar, and the temperature survey may be regarded as successful in identifying the principal zone of hydrothermal upflow and lateral flow at shallow depths (see Fig. 4).

Soda Lakes geothermal area

The Soda Lakes geothermal area, about 12 km northwest of Fallon, Nevada (Fig. 1), was one of seven areas included in a reconnaissance appraisal of selected hydrothermal systems in northern and central Nevada by Olmsted *et al.* (1975). Temperature surveys at a depth of 1 m were an integral part of the early studies at Soda Lakes, which included the drilling of 21 test wells to depths of about 10 – 45 m in order to obtain thermal, hydraulic and hydrochemical data. Additional test wells were drilled after those reported by Olmsted *et al.* (1975), and the 1-m temperature surveys also were continued and expanded (see Olmsted, 1977; Olmsted *et al.*, 1981, 1984).

Several temperature surveys were made from 1973 to 1978. The first synoptic survey, in November 1973 at 97 sites within an area of about 1.8 km^2, identified two elongate *en echelon* thermal maxima believed to be caused by hydrothermal upflow in two steeply inclined fault-controlled conduits, whereas more sparse control using data from temperature-gradient holes had identified only one thermal maximum (Olmsted *et al.*, 1975). The thermal anomaly is strongly asymmetrical and elongated toward the northeast, in the direction of lateral groundwater flow in aquifers within a few tens of meters of the land surface (Olmsted *et al.*, 1975, 1984). A part of the November 1973 survey consisted of much more detailed coverage of a 0.20-km^2 area surrounding an abandoned steam well (Olmsted, 1977). This detailed survey successfully delineated linear conduits for steam rising from a boiling water table at depths of 5 – 7 m. The zones of highest temperature were associated with the most intense hydrothermal alteration.

Later surveys using the Pallmann technique of temperature integration (Pallmann *et al.*, 1940) extended the area of coverage to include most of the deeper thermal anomaly defined by temperature-gradient-hole data—about 36 km^2—and gave integrated-average temperatures at 1 and 2 m for December 1976 – December 1977 and December 1977 – March 1978 (Olmsted *et al.*, 1981). The results indicated a strong correlation of temperatures at 2 m with temperatures at 15 m (r^2 = 0.93) (Olmsted *et al.*, 1981).

After 1978, temperature measurements were continued at six of the sites used in the earlier studies. The purpose of the later measurements was to define mean annual temperatures at places believed to be representative of the range of conditions found in the Soda Lakes area. Mean annual temperature at a depth of 1 m for the period November 1982 – November 1983 was derived from monthly measurements at the six sites and, by correlation methods, for eight other sites.

As in the earlier studies of the Soda Lakes geothermal area (Olmsted, 1977; Olmsted *et al.*, 1981), temperature at a depth of 1 m is strongly correlated with temperature at greater depths. The coefficient of determination, r^2, for the linear least-squares correlation of temperature at a depth of 20 m with mean annual temperature at 1 m is 0.96—slightly better than the r^2 of 0.95 for a correlation of temperature at 20-m depth with synoptic temperature at 1 m for September 1974 at 12 of the 14 sites used in the present comparison (see Olmsted, 1977).

Correlation of mean annual temperature at 1 m with near-surface heat flow is equally strong. The least-squares linear-regression equation for the correlation of mean annual temperature at 1-m depth with heat flow at the same 14 sites used in the correlation above is

$$T = 0.098q + 15.1$$

where T is mean annual temperature at 1 m for November 1982 – November 1983, in °C and q is near-surface heat flow, in heat-flow units;* r^2 for this correlation is 0.96. Ranges in T and q used in this correlation are, respectively, 14.8 – 27.3°C and 1.8 – 130 hfu.

Upsal Hogback geothermal area

The Upsal Hogback geothermal area, which lies about 12 km northeast of the Soda Lakes geothermal area and about 20 km north of Fallon, Nevada (Fig. 1), is caused by convective hydrothermal upflow similar to that in the Soda Lakes area, but, instead of rising to within a few tens of meters of the land surface, as at Soda Lakes, the thermal water rises only to a depth of 245 m before flowing laterally in an aquifer within Tertiary volcanic (basaltic) and sedimentary rocks (Olmsted *et al.*, 1984). As a result, the near-surface heat-flow anomaly at Upsal Hogback is much less intense (maximum about 12 hfu) than that at Soda Lakes (maximum > 300 hfu) (Olmsted *et al.*, 1984). Regional ground-water flow is generally toward the north to northeast and the heat-flow anomaly is elongated toward the north. Depth to the water table ranges from more than 20 m beneath Upsal Hogback to less than 1 m beneath the low-lying parts of the area. At most places, a strong upward component of the hydraulic gradient reflects the discharge of ground water by evapotranspiration (Olmsted *et al.*, 1984).

Shallow subsurface temperature surveys in the Upsal Hogback area began in the summer of 1975, at the same time as a program of test drilling designed to identify a possible thermal anomaly, the existence of which was suggested by earlier drilling (Olmsted *et al.*, 1975). The shallow subsurface temperature surveys, at a depth of 1 m, were intended to assist in selecting drilling sites and to provide additional detail regarding the configuration of the suspected thermal anomaly.

The early studies showed that the thermal anomaly, mostly east and northeast of Upsal Hogback, was much less intense (about 12°C range in temperature at a depth of 30 m) than the Soda Lakes anomaly (more than 100°C range in temperature at 30 m), and that the perturbing effects of nongeothermal factors on shallow subsurface temperatures in the Upsal Hogback area are large. Thus, synoptic surveys covering areas of 26 – 90 km² showed a poor correlation of temperatures at 1-m depth with those at a depth of 30 m (Olmsted, 1977). However, by eliminating from the comparison the sites in Olmsted's (1977) data set having obviously anomalous thermal diffusivity, LeSchack *et al.* (1979) and LeSchack and Lewis (1983) obtained a much stronger correlation.

Between May 1979 and May 1980, temperatures at a depth of 1 m were measured at intervals of 1 – 2 months at 49 sites in the Upsal Hogback area. Monthly measurements were begun at nine index sites in November 1982 and continued until June 1984. Relatively complete surveys of all or most of the 49 sites were made in April and July 1983, January, April, May, June and August 1984, and January – February 1985. These data allowed mean annual temperatures for several periods to be computed for all 49 sites by correlation methods.

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*1 heat-flow unit (hfu) = 1 μcal/cm² s = 41.84 m W/m².

Comparison of mean annual temperatures at 1-m depth with surface albedo determined from Landsat imagery suggested a strong correlation, and, in January, February, April and July 1983, and June 1984, field albedo measurements were made at the temperature sites, using the method described earlier. Because surface albedo and temperature at 1 m appeared to be so strongly correlated, the November 1982 – November 1983 period, which spans most of the five albedo measurements, was selected to represent average temperature conditions in the Upsal Hogback area.

Heat flow within the depth interval 0 – 45 m is estimated for all the sites in the Upsal Hogback geothermal area on the basis of measured temperature gradients and estimated thermal conductivities for 19 test wells. The least-squares linear regression equation for the correlation of mean annual temperature at a depth of 1 m with heat flow at 19 test-well sites in the Upsal Hogback geothermal area is

$$T = 0.204q + 15.4$$

where T is mean annual temperature at 1 m for November 1982 – November 1983, in °C and q is near-surface heat flow, in heat-flow units. The r^2 value for this correlation is only 0.51, which indicates a much weaker relationship than that in the Soda Lakes geothermal area. Range in T and q used in this correlation are, respectively, 14.8 – 17.7°C and $-2.1 - 9.8$ hfu.

The least-squares linear regression of temperature at 1-m depth versus temperature at 30-m depth for November 1982 – November 1983 is

$$T = 0.236T_{30} + 11.5$$

and r^2 is 0.77, which indicates a much stronger correlation than that of temperature at 1 m with heat flow. The correlation is also much stronger than those obtained with synoptic measurements—for example, that of temperature at 30-m depth for December 1975, where r^2 is only 0.23 (see Olmsted, 1977). Thus, it appears that the mean annual temperature at 1-m depth is a fairly reliable indicator of temperatures at greater depths but is not as successful in defining the heat-flow anomaly under the conditions encountered in the Upsal Hogback geothermal area.

As mentioned earlier, albedo of the land surface was believed to have a significant effect on temperature at 1-m depth. The range of albedo values in the Upsal Hogback area is unusually large: from less than 10% on exposures of dark basaltic detritus surrounding the Hogback to about 50% on areas of salt crust on Carson Sink and other low-lying playas. The least-squares linear regression of mean annual temperatures at 1-m depth for November 1982 – November 1983 versus albedo for the 19 test-well sites is

$$T = -0.097a + 18.49$$

where a is albedo, in %; r^2 is 0.85 for this correlation. For 51 1-m sites in the area, the regression equation is

$$T = -0.104a + 18.60$$

and r^2 is 0.75.

It is notable that the temperature at 30-m depth at the 19 test-well sites is predicted nearly as well by the mean annual temperature at 1-m depth ($r^2 = 0.77$ for a linear least-squares correlation) as by heat flow ($r^2 = 0.81$). As the 1-m temperatures are controlled largely by albedo, this implies that the effects of albedo have a strong influence on the temperature distribution at 30 m, and, in fact, an r^2 of 0.70 is obtained for linear regression of temperature at 30-m depth on albedo.

The various factors influencing shallow subsurface temperatures in the Upsal Hogback geothermal area are discussed in some detail in a companion paper in this volume.

SUMMARY AND CONCLUSIONS

Shallow subsurface temperature surveys have been widely used in the Basin and Range province as an economical geothermal exploration method. At the depths of 1 – 2 m used in the surveys, periodic and aperiodic variations in solar energy input cause temperature fluctuations that can mask suspected geothermal anomalies. Other factors unrelated to geothermal heat flow that cause perturbations in near-surface temperatures include topography, albedo and vegetation.

In general, the most successful surveys reported in the literature are those of small areas ranging in size from about 0.2 to 2 km^2, where near-surface vertical and lateral flow of thermal fluids associated with known hot springs, fumaroles or other sites of hydrothermal discharge produce large lateral variations in shallow subsurface temperature. Uncorrected synoptic temperatures clearly indicate the location of the ascending fluids and their subsequent lateral flow (if not all the fluid discharges at the surface), and the perturbing effects of nongeothermal factors are relatively unimportant.

Surveys of moderate-sized (2 – 200 km^2) and large (200 – 2000 km^2) areas have not been as uniformly successful as surveys of small areas. In part, the difference arises from the fact that the zones of hydrothermal upflow are less well known. In addition, the perturbing effects of nongeothermal factors are locally significant, owing to the greater heterogeneity of the larger areas and, in many cases, lateral variations in shallow subsurface temperature are relatively small. In some surveys, notably those at Coso Hot Springs and Long Valley in California, these perturbing effects have been minimized by acquisition of additional data so that corrections to observed temperatures could be made for the effects of surface roughness, albedo, soil thermal diffusivity, topography and elevation. In addition, perturbations have been minimized by measuring temperature at 2 m instead of 1 m, or by making several synoptic surveys and correcting for areal differences in thermal diffusivity.

Two principal methods have been used to minimize or eliminate the effects of areal variations in thermal diffusivity, which cause shallow subsurface temperatures to respond differently to variations in solar energy input at the land surface. The first method uses mean annual temperatures rather than synoptic temperatures. Mean annual temperature can be defined by the Pallmann technique of temperature integration, by periodic measurements during the annual temperature cycle or by the average of measurements in midwinter and midsummer. The second method involves making one or two synoptic measurements in April or October, when areal differences in temperature caused by differences in thermal diffusivity are the least.

The effects of other perturbing factors are more difficult to mask or eliminate. Two approaches are physically based simulation of ground temperatures (like those used at Coso Hot Springs and Long Valley) and statistical modeling. With the first approach, climatological, surface and soil parameters are input to a numerical code that solves a one-dimensional heat-transfer equation and simulates the annual temperature wave (LeSchack and Lewis, 1983). The second approach involves developing a regression model of heat flow or temperature at depth that includes temperature and several near-surface parameters as predictor variables.

Both methods have requirements that in part vitiate the shallow subsurface temperature survey as a rapid and uncomplicated exploration tool. The first method requires accurate estimation or measurement of several parameters at each site in order to achieve the desired sensitivity. Some of the parameters, such as thermal diffusivity, thermal conductivity and, commonly, albedo, vary significantly in time as well as space. Drawbacks to the second method include the lack of generality of regression models, the requirement of prior information about conditions at depth in order to develop a model and, again, the problem of measuring ancillary parameters that are commonly time-variant as well as space-variant.

The results documented in this paper suggest that an effective shallow subsurface temperature survey should be timed to minimize the effect of areal variations in thermal diffusivity, or designed to obtain an estimate of mean annual temperature; that measurement sites should be chosen so as to minimize the variability in other perturbing factors; and that ancillary data about near-surface conditions would be acquired, where feasible. Experience at Upsal Hogback shows that the perturbing effects of near-surface conditions can influence temperatures at depths of 30 m or more. It is less important to consider the effects of perturbing factors in areas of high near-surface heat flow near thermal-discharge features.

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