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SHALLOW SUBSURFACE TEMPERATURE SURVEYS IN THE BASIN AND RANGE PROVINCE—II. GROUND TEMPERATURES IN THE UPSAL HOGBACK GEOTHERMAL AREA, WEST-CENTRAL NEVADA, U.S.A.

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Abstract—Numerous temperature surveys at a depth of 1 m were made in 1973–1985 in the Upsal Hogback and Soda Lakes geothermal areas in west-central Nevada. Whereas the surveys effectively delineated temperature at depth and heat flow within the relatively intense Soda Lakes thermal anomaly, they were not effective at the diffuse Upsal Hogback anomaly, where several perturbing factors that affect shallow subsurface temperatures are exceedingly variable. Albedo is the most important factor in the Upsal Hogback area, even at a depth of 30 m. All possible perturbing factors should be considered when designing a shallow temperature-based prospecting scheme.

INTRODUCTION

The Upsal Hogback geothermal area is in the western Carson Desert, approximately 100 km east of Reno, Nevada and 20 km north of Fallon (Fig. 1). The geothermal area is generally north and east of the Upsal Hogback, which is a series of overlapping cones of basaltic tuff of late Pleistocene and Holocene age (Morrison, 1964). The Hogback is probably aligned along a concealed fault or fault zone with Soda Lakes (Olmsted *et al.*, 1984), another locus of late Quaternary basaltic eruptions that lies about 15 km to the southwest. Soda Lakes geothermal area lies between Soda Lakes and Upsal Hogback.

The Upsal Hogback thermal anomaly is caused by convective hydrothermal upflow that rises to a depth of 245 m and then flows laterally in an aquifer within Tertiary rocks. The Soda Lakes anomaly is related to a similar convective upflow that rises to within a few tons of meters of the land surface before flowing laterally (Olmsted *et al.*, 1984). Because of the shallower lateral flow of hot water, the Soda Lakes heat-flow anomaly is much more intense than the Upsal Hogback anomaly.

In 1973–1985, numerous temperature surveys at a depth of 1 m were made in the Upsal Hogback and Soda Lakes geothermal areas. Abundant thermal data from depths of 15–45 m were available from U.S. Geological Survey test wells in these areas, providing a straightforward means of checking the correlation between temperature at 1-m depth and temperature at greater depths, or temperature at 1 m and heat flow.

Results of the early temperature surveys made it apparent that, whereas synoptic 1-m surveys effectively delineated temperatures at depth and heat flow within the relatively intense Soda Lakes anomaly, where the maximum near-surface heat flow is > 300 hfu,* they were not as effective at Upsal Hogback (Olmsted, 1977). The maximum near-surface heat flow in the Upsal Hogback area is about 12 hfu, and most values are less than 7 hfu. The Upsal Hogback area is also characterized by relatively great variability in several perturbing factors that affect temperatures at 1 m but are unrelated to geothermal heat flow. These factors include thermal

*1 heat-flow unit (hfu) = 41.84 mW/m^2.

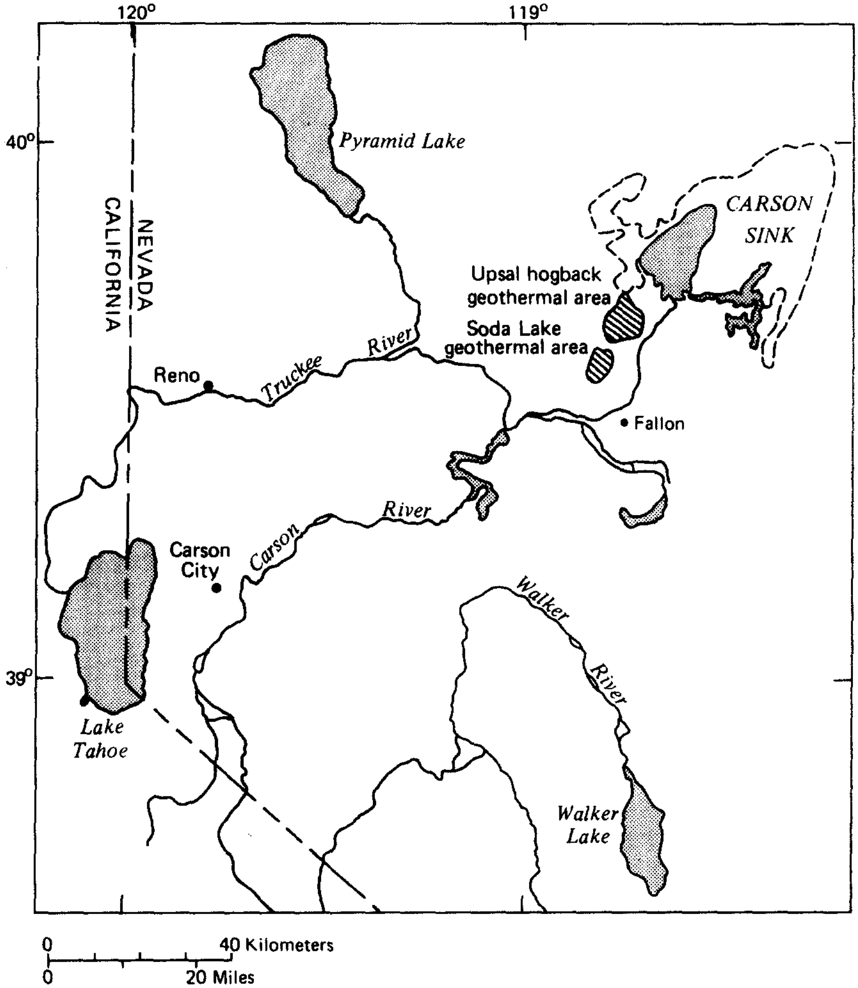

Fig. 1. Map of west-central Nevada showing the location of Soda Lakes and Upsal Hogback geothermal areas.

diffusivity, albedo, slope and topographic relief, and depth to the water table. In midsummer and midwinter, areal variations in thermal diffusivity alone could lead to differences in temperature at 1 m of more than 4°C (Olmsted, 1977). By comparison, the maximum amplitude of the Upsal Hogback thermal anomaly at 1 m is only about 7°C. In order to eliminate the effects of areal variations in thermal diffusivity, mean annual temperatures were defined by a series of synoptic measurements. Other perturbing factors were also studied in some detail.

METHODOLOGY

Olmsted *et al.* (1981) used the Pallmann method to obtain integrated-average temperatures (Pallmann *et al.*, 1940), and obtained a stronger correlation of shallow-subsurface temperatures (at 1 and 2 m) with temperatures at 15 m than were obtained in earlier synoptic measurements. Periodic temperature measurements at approximately monthly intervals were begun during the time of the Pallmann-method study (December 1976 – December 1977) at five sites in the Upsal Hogback area. These measurements were made at a depth of 1 m using the methods described in Part I. They were continued and expanded and became the basis for the studies described below.

Temperatures were measured at intervals of 1 – 2 months at four of the five sites and, beginning in the summer of 1978, at many additional sites selected to provide more complete areal coverage of the thermal anomaly. By mid May 1979, a total of 49 sites were being measured and, from May 1979 to May 1980, temperatures were measured at approximately 1-month intervals in order to define mean annual temperature at all 49 sites in the Upsal Hogback area.

After May 1980, temperatures were measured sporadically until November 1982, when systematic monthly measurements were resumed at nine index sites. These measurements, which continued until late February 1985, were supplemented by surveys of all or most sites in April and July 1983, January, April, May, July and August 1984, and late January – early February 1985. From these data, mean annual temperature for several periods was calculated by correlation methods for all sites.

The wide range of albedo observed in the Upsal Hogback area suggested that albedo might have an important influence on mean annual temperature at 1 m depth. Between January 1983 and June 1984, five sets of albedo measurements were made at the 1-m sites using an Exotech model 100 radiometer.* This instrument has four spectral filters which match the Landsat multispectral scanner (MSS) bands. The Landsat MSS bands cover the 0.5 – 1.1-μm region, which includes approximately 52% of solar irradiance. The mean bidirectional reflectance of the land surface across these four bands was used to estimate albedo. The method used to measure bidirectional reflectance in the field is shown in Fig. 2. During each albedo survey, six readings were made within a 2-m radius around each measured temperature site to account for local variability in albedo.

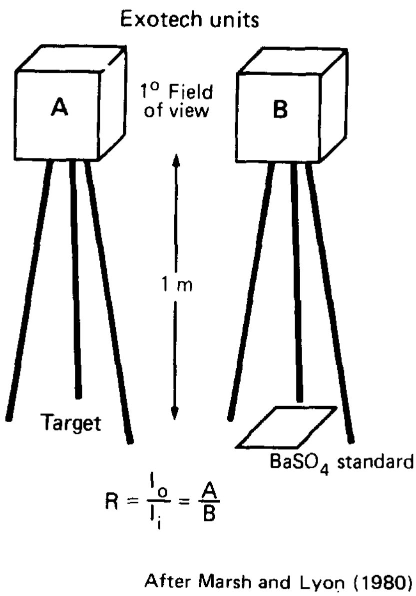

Fig. 2. Field measurement of reflectance with an Exotech radiometer. I_0 is reflected radiation and I_i is incident radiation, measured using a barium sulfate reflectance standard.

*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.

ALBEDO

Albedo in the Upsal Hogback area varies greatly in space and over time. A lag surface of basalt cinders north and east of Upsal Hogback has a reflectance of 8 – 10% in the 0.5 – 1.1-µm region, whereas the reflectance in areas of bare-soil evaporation characterized by seasonal accumulation of salts approaches a maximum of 60% (see Fig. 3). The greatest temporal variation in albedo measured at any one site is 19% (June 1984) to 57% (April 1983) on a playa surface. Albedo also varies in response to changes in soil moisture outside the areas of bare-soil evaporation, but less dramatically.

Initial estimates of albedo at 51 1-m in the Upsal Hogback area were made from a Landsat image, using the method of Robinove *et al.* (1981). This analysis suggested a strong correlation between 1-m temperatures and albedo. However, the "Landsat albedo" values represent an average over an area of approximately 0.62 ha, and, of course, do not account for the temporal variations in albedo. Field measurements of reflectance at the 1-m sites were designed to determine local albedo values more accurately and to quantify the time-variance. Figure 4 shows the relation between the mean annual temperature at 1 m and the weighted-average albedo of the land surface for the period from November 1982 to November 1983. Albedo values measured in January, February, April and July of 1983 were weighted by relative insolation (U.S. Department of Energy, 1982) to obtain an estimate of the average albedo for the annual period (measurements taken at times of the year when insolation is higher were weighted more heavily). The strength of the linear least-squares correlation ($r^2 = 0.75$ with $n = 51$) suggests that albedo is the dominant factor controlling long-term average ground temperatures in the Upsal Hogback area.

Sites 223A, 223B and 223C (Figs 3 and 5a) were chosen as index sites because they exhibit a wide range of albedo (approximately 20, 32 and 37%, respectively), but are similar in terms of altitude, slope and slope orientation, soil-moisture content and depth to the saturated zone. The effect of topography on near-surface heat flow was determined by numerical modeling, assuming a constant temperature boundary at 245-m depth (see Introduction). The resulting heat-flow values and estimated thermal conductivities at these index sites were used to compute mean land-surface temperatures, on the basis of mean annual temperature at 1-m depth. The relation between land-surface temperature and albedo defines a regression slope similar to that obtained for temperature at 1 m versus albedo at all 51 sites (Fig. 5b).

The strong correlation between albedo and temperature extends to at least 30-m depth (Fig. 6). Temperatures at 30 m at 19 test-well sites in the Upsal Hogback area are nearly as highly correlated with albedo ($r^2 = 0.70$ for a linear least-squares correlation) as with heat flow ($r^2 = 0.85$). In the past, it has been assumed that temperature variations due to surface conditions are negligible below a depth of 20 – 30 m, and much reconnaissance surveying has been based on this premise (LeSchack and Lewis, 1983).

OTHER FACTORS

Other factors that affect mean annual ground temperatures include altitude, land-surface slope and orientation, vegetation, land use, topography, lithology and water content of material, ground-water flow, depth to the saturated zone and heat flow. All these factors except heat flow may be regarded as perturbations, because they tend to mask areal variations in subsurface heat flow. They may be divided into two groups: (1) those that affect mean annual temperature at the land surface and (2) those that affect the temperature gradient between the land surface and the depth of the temperature measurements (1 m at Upsal Hogback). Albedo would be included in the first group. Other important factors in this category are altitude, land-surface slope and orientation, vegetation and land use. The second group includes topography, lithology and water content, ground-water flow, depth to the saturated zone and heat flow.

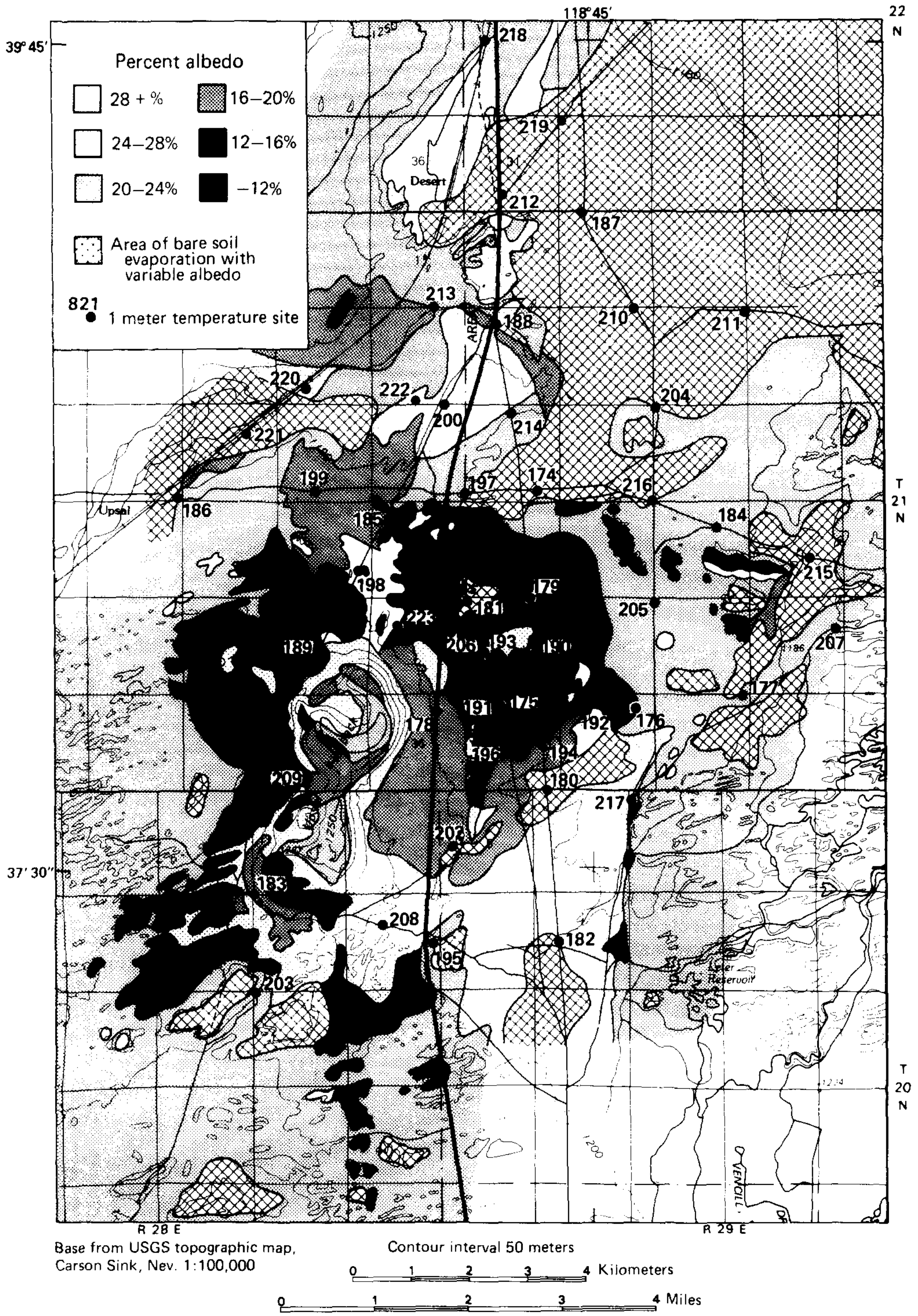

Fig. 3. Albedo map of the Upsal Hogback geothermal area showing the 1-m temperature sites. Several panchromatic aerial photos were used in conjunction with an albedo image from a Landsat scene to develop this map. Boundaries were drawn directly on aerial photos on the basis of tonal differences. The tonal categories were assigned albedo values by calibration with the Landsat image and field measurements of reflectance at the 1-m sites. Areas of bare soil evaporation were identified by P. A. Glancey (written communication, 1979).

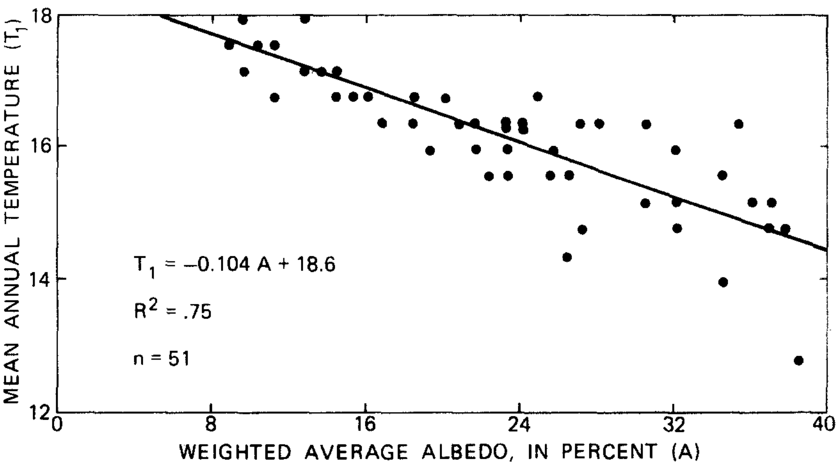

Fig. 4. Relationship between mean annual temperature and weighted-average albedo for the annual period from November 1982 to November 1983.

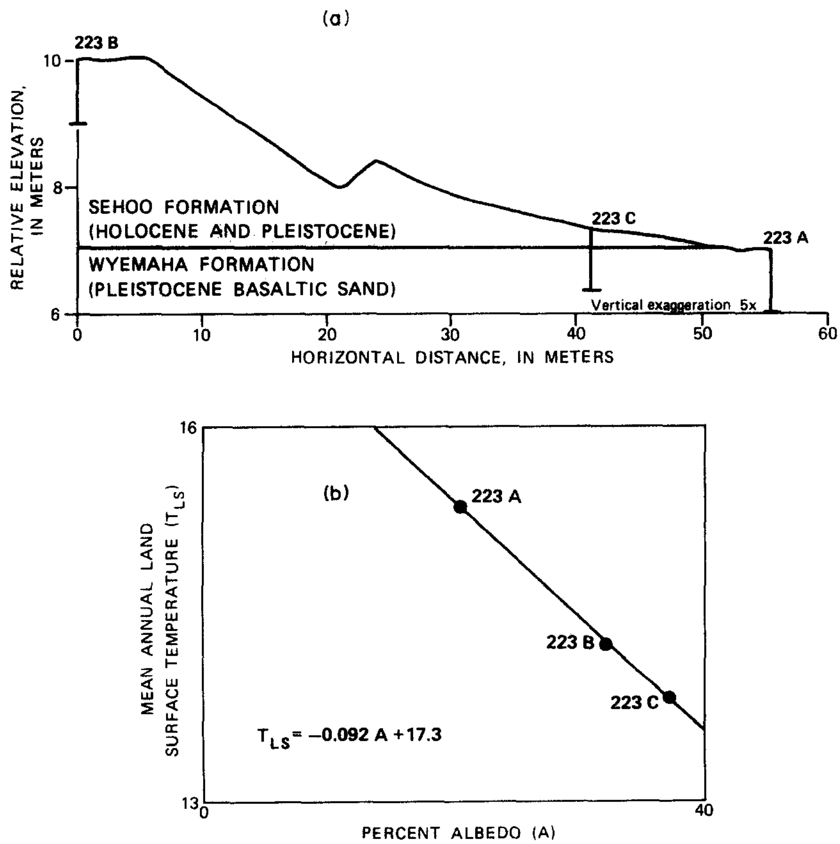

Fig. 5. Cross-section through index sites 223A, 223B and 223C and relationship between mean annual land-surface temperature and albedo at these sites.

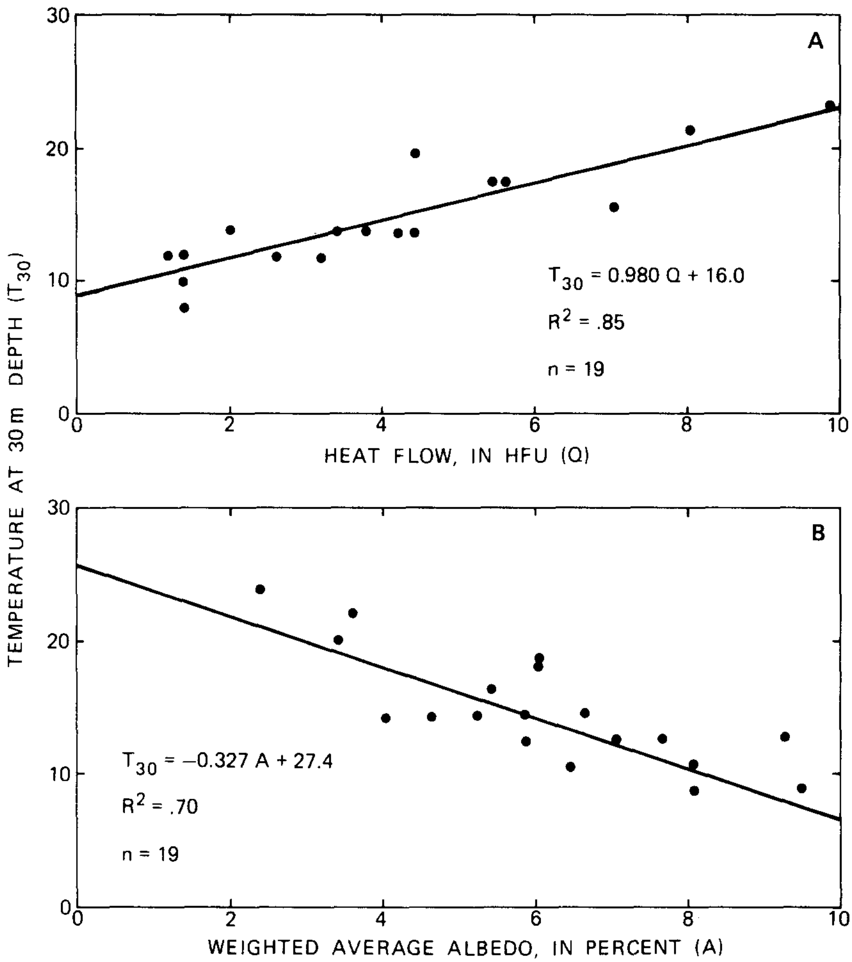

Fig. 6. Relationship between weighted-average albedo and temperature at 30-m depth and relationship between heat flow and temperature at 30 m at 19 test-well sites in the Upsal Hogback area.

Each of these factors is discussed below; several are highly intercorrelated.

Sites at greater altitudes tend to be cooler than sites at lower altitudes, owing to the normal lapse rate of about −0.6°C per 100 m. The range in altitude for the Upsal Hogback area sites is less than 20 m, however, so the theoretical range in temperature produced by this effect would be only about 0.1°C. It would be difficult to identify the altitude effect in the data because some of the other factors are related to altitude. For example, greater altitudes tend to be associated with greater depths to the water table and also with lower albedo because of the dark basaltic detritus surrounding the Hogback; lower altitudes may be correlated weakly with higher albedo because of the seasonal abundance of salt crust in Carson Sink and adjacent playas. The relation between altitude and mean annual temperature is shown in Fig. 7(a); the correlation is insignificant. The effect of land-surface slope and orientation is believed to be small at Upsal Hogback, as most sites are on level or nearly level ground.

Vegetation affects surface temperature because it affects aerodynamic surface roughness (Lettau, 1969), shading and albedo. However, vegetation is sparse to absent in most of the area and measurement sites were located as far as possible from large shrubs. Land use is also an insignificant factor in the Upsal Hogback area, as virtually all the land is either unused or used only for grazing.

Local topography affects the temperature gradient near the land surface; this factor is important near steep slopes such as the slip faces of sand dunes and erosional escarpments. Most sites were selected so as to minimize topographic effects, but this factor is important at a few sites, particularly 207 (Fig. 3) and 223A, 223B and 223C (Fig. 5a). Mean annual temperatures at 223A, 223B and 223C were corrected for topographic effects, as discussed above.

The lithology and water content of material between the land surface and 1-m depth is important because it affects the thermal conductivity and other thermal properties and, therefore, determines the temperature gradient over this interval. For synoptic measurements, it also determines the amplitude and phase lag of thermal response at 1 m. Thermal conductivity at the 1-m temperature sites was estimated on the basis of the lithology and water content described at the times the access holes were made; direct correlation of mean annual temperatures with these estimates is significant at the 0.005 level (Fig. 7b).

Ground-water flow is locally important, especially near zones of ground-water recharge and near boundaries of contrasting albedo because of the heat advected by lateral ground-water flow. Temperatures downgradient from zones of ground-water recharge usually are lower than elsewhere. Temperatures downgradient from areas of high albedo are likely to be lower than would be otherwise and the converse is true downgradient from areas of low albedo.

Water-table depth is an important factor in determining the temperature gradient from the land surface to a depth of 1 m, probably because it determines, in part, the moisture content of the materials and, therefore, their thermal conductivity and other thermal properties. The relation between water-table depth and ground temperature is apparently nonlinear (Birman, 1969); it is significant at the 0.01 level at Upsal Hogback (Fig. 7c).

Heat flow is the chief factor of interest in a geothermal study, and it is, of course, a major determinant of the mean gradient between the land surface and a depth of 1 m. Near-surface conductive heat flow at Upsal Hogback is strongly correlated with temperature below the zone

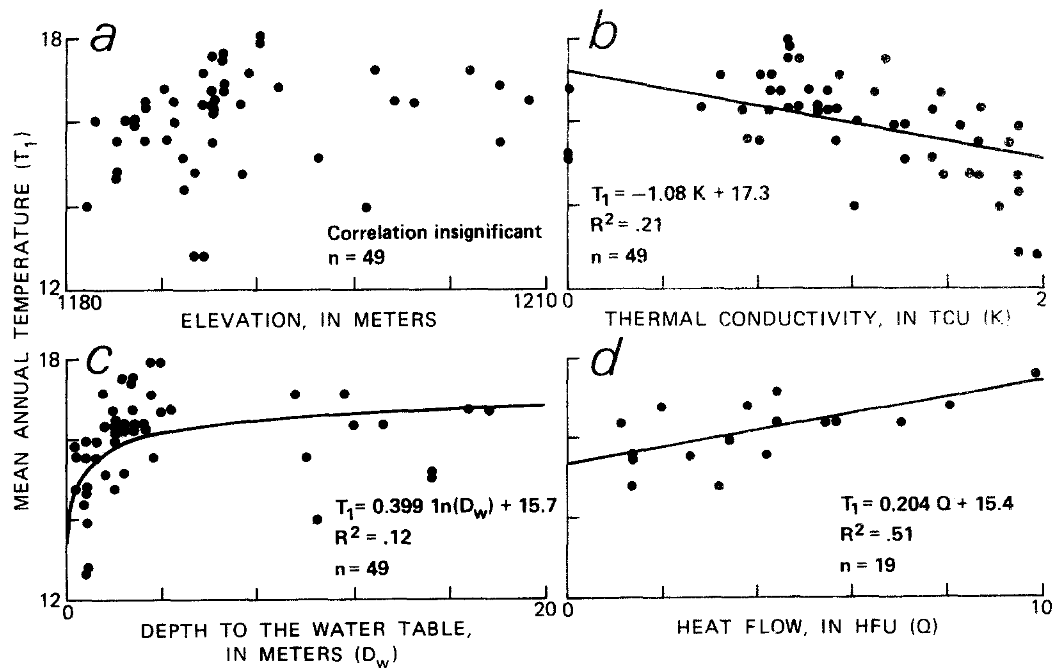

Fig. 7. Mean annual temperature at 1 m for the period from November 1982 to November 1983 versus altitude, thermal conductivity, depth to the water-table and heat flow.

of significant seasonal temperature fluctuation, such as the depth of 30 m used by Olmsted (1977) or 15 m used by Olmsted *et al.* (1981). The correlation between heat flow and mean annual temperature at 1 m at 19 test-well sites (Fig. 7d) is much weaker than that between albedo and mean annual temperature (Fig. 4), but stronger than the correlation of mean annual temperature with other measured parameters (Fig. 7). Inspection of Fig. 7(d) suggests that the data can be broken into two groups. Where heat-flow values $\geqslant$ 5 hfu, mean annual temperature at 1 m is highly correlated with heat flow ($r^2 = 0.89$ with $n = 5$), whereas in areas where heat flow is $\leqslant$ 5 hfu, mean annual temperature is only weakly correlated with heat flow ($r^2 = 0.29$ with $n = 14$).

CONCLUSIONS

On a single date, thermal diffusivity can be the primary parameter controlling areal variations in temperature at 1-m depth in the Upsal Hogback area. Albedo is the most important factor controlling long-term mean temperature. In the nearby Soda Lakes geothermal area, where the heat-flow anomaly is relatively intense and albedo is relatively uniform, there is not a significant correlation between albedo and mean annual temperature. Ground temperature is also only weakly correlated with albedo in the western Black Rock Desert (see Part I) and at Coso Hot Springs (LeSchack and Lewis, 1983).

In fairly diverse environments, ground temperatures have been shown to be highly correlated with ground-water movement (Cartwright, 1968, 1974), depth to the saturated zone (Birman, 1969), heat flow (Olmsted, 1977), thermal diffusivity (LeSchack and Lewis, 1983) and albedo (this study). This illustrates the importance of considering all possible influences when designing a shallow temperature-based prospecting scheme. The results of the Upsal Hogback study also show that the effects of surface boundary conditions can be important even at depths of 30 m.

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