ABSTRACT

Shallow (2-m) soil temperature data have been collected at 27 sites at Long Valley, California and at 102 sites at Coso, California. These geothermal areas are locations where traditional deep reconnaissance geothermal survey bore holes have been emplaced, allowing us to compare directly our shallow temperature results with standard geothermal exploration techniques. We have considered the effects of surface roughness, albedo, soil thermal diffusivity, topography and elevation in making the necessary corrections to our 2-m temperature data. The corrected data for both locations have been plotted up by computer to avoid any personal bias, and have been compared with the published 10-m contour data at Long Valley and the 30-m contour data for Coso. Close geometrical similarity has been observed. Additionally, we have identified previously located faults with our shallow temperature survey technique. Due to the relative inexpensiveness of our technique, we conclude that shallow temperature exploration should be one of the first geophysical surveys initiated at a geothermal prospect to help guide the development and expenditure of financial resources when embarking on a detailed exploration program.

CONTENTS

RAPID RECONNAISSANCE OF GEOTHERMAL PROSPECTS USING SHALLOW TEMPERATURE SURVEYS

L.A. LeSchack, J.E. Lewis and D.C. Chang

1. Introduction

1.1 Background

Shallow temperature measurements (2-5 m) have been made by a number of investigators in the geological sciences for the past several decades, but the potential of shallow reconnaissance surveys for geophysical exploration has not been extensively developed. This appears to be due to the lack of experience that most geophysicists have with shallow thermal surveys, and, until now, the limited number of case history studies incorporating this method.

This report will document two case histories where the shallow temperature survey method was used in eastern California and the results can be compared with existing relatively deep reconnaissance temperature gradient and heat flow measurements. The comparison suggests that at least in this terrain the shallow temperature survey can generate the same valuable reconnaissance data available from deeper surveys, but at substantial cost savings.

An early example of shallow temperature surveying at a geothermal area was presented by Kintzinger (1956) in his survey of hot ground near Lordsburg, New Mexico. Using thermistors emplaced at a depth of 1 m, he observed a temperature anomaly of some 10°C surrounding a hydrothermal area. Cartwright (1968) showed that thermistors emplaced at a depth of 50 cm could closely approximate theoretical temperature anomalies at the surface owing to shallow lying aquifers. Birman (1969), emplacing thermistors at a depth of 3 m, measured temperature variations due to groundwater flow in southern California and began actively using shallow temperature geothermal surveying as one of a combination of geophysical and geological techniques for locating ground water on a commercial basis. O'Brien (1970) also conducted studies of a groundwater flow using shallow temperature survey techniques.

A detailed study of the application of this technique to locating salt domes and shallow faults in the Netherlands was provided by Poley and Van Steveninck (1970). Their technique was used most satisfactorily in southern California by Sabins (1976). Noble and Ojiambo (1975), emplacing thermistors at 1-m depth, helped delineate a geothermal area in Kenya. Lee (1977), using data obtained at depths greater than we consider shallow (up to 15 m) has shown the potential of extrapolating near-surface temperature gradients to much greater depths in known geothermal areas. Despite the previous research cited, little attempt has been made to use the shallow temperature survey technique as an operational geophysical exploration tool, especially for geothermal reconnaissance surveys. This, we suspect, is because adequate case histories of known geothermal areas where this technique has been used have not been presented in the literature, and potential perturbing effects on the shallow temperature data--real or imagined--have not been subjected to adequate scrutiny. In summary, Birman (1969) says:

> "..........shallow geothermal survey appears to be a valuable exploration tool long overlooked or deliberately avoided because of expected interference from a multitude of surface and subsurface variables. The latter seem much more formidable in theory than in practice, if reasonable precautions are used. Temperature, like pressure, composition, and time, is one of the basic physical parameters, and its use as a geological tool has only begun to be explored."

1.2 Two KGRA Case Histories Studied

In the past few years data from relatively deep reconnaissance heat flow holes and complementary geological and geophysical data have become available for the Long Valley and Coso Geothermal areas of eastern California. As a result, it was possible to examine the efficacy of shallow temperature measurement as a reconnaissance mapping tool at these two areas. Direct comparisons with deeper temperature and heat flow measurements could be made. Lachenbruch, et al. (1976) provided a temperature map of the Long Valley area at a depth of 10 m. They concluded:

> "As long as synoptic observations are used at these sites, essentially the same (temperature) pattern emerges for contours at the 6-m depth, and much of it persists at 3 m."

This observation provided strong motivation for us to pursue our shallow temperature studies. At the Coso Geothermal area, 150 miles south of Long Valley, Combs (1975) and Combs (1976) showed the temperature anomaly pattern he observed at 30-m depth persisted at depths of 20 m as well as at 10 m. With the encouragement provided by these independently conducted studies, we felt it was worthwhile drilling a series of 2-m deep holes at these two sites to determine just how much of the anomalies identified by these previous studies could be detected at a depth of 2 m.

1.3 The Advantages and Disadvantages of Shallow Temperature Surveys

The obvious advantage of a shallow temperature survey is that it is rapid and inexpensive. Whelan (1977) determined that an overall average cost in 1975 for drilling relatively deep thermal gradient or heat flow holes was approximately \$60/m. This was based on use of a Mayhew 1000 drill and included mobilization, materials and incidental costs. Several days were required to complete each hole and make measurements. On the other hand, we drilled our shallow holes at Long Valley with a 2-man hand-held, 3-hp hole digger, and at Coso with a truck-mounted post hole digger. At both locations 1-2 holes an hour could be drilled and instrumented, the speed depending largely on the nature of the terrain and the distance between consecutive holes. We estimate an approximate cost of \$25-\$50 per hole for such drilling when 100 or more holes are to be emplaced at a given survey site.

The economic advantages of shallow temperature surveying are clear. The overall disadvantages are clear also, and have long been known. The major purpose of our study has been therefore to evaluate the various perturbing effects which impinge on shallow temperature measurements, and in the context of our case study comparisons, evaluate (a) the severity of these effects and (b) if they can be adequately compensated for to permit cost-effective use of shallow temperature reconnaissance surveys for geothermal exploration.

Lovering and Goode (1963), Poley and Van Steveninck (1970), and Kappelmeyer and Haenel (1974), have very adequately covered the perturbing effects which are of concern to us, and which have in fact encouraged deep reconnaissance drilling almost to the exclusion of shallow measurements. These effects are due to:

(1) Diurnal solar heating variation.

(2) Annual solar heating variations.

(3) Aperiodic solar heating variations.

(4) Variations in surface albedo, which affects amount of energy absorbed.

(5) Variations in surface roughness, which affects amount of heat convected away due to turbulent flow of the wind.

(6) Variations of soil thermal diffusivity.

(7) Slope and exposure of the terrain.

(8) Variations in elevation.

(9) Variations in level of ground water and ground-water movement.

Temperature variations owing to these effects are generally negligible below a depth of 20-30 m, with the exception of ground-water movement. Hence, the great majority of reconnaissance surveying has been conducted below this level to avoid these effects, and to obtain a relatively long vertical section along which temperature gradients can be measured. In the interests of developing a rapid, cost-effective thermal reconnaissance surveying technique, however, we have developed along the lines shown by Birman (1969) and Poley and Van Steveninck (1970) a methodology for evaluating the perturbing effects (with the exception of ground-water movement) and correcting for them at a depth of 2 m. As a result, we believe that at least for certain areas the many perturbing effects often held up as disadvantages to shallow temperature surveying can be eliminated or shown to have little effect, leaving for the shallow temperature surveying technique the advantages of speed and low cost.

2. Field Procedures

At the outset of our field work, our basic procedures were those outlined by Poley and Van Steveninck (1970) which had been modified as a result of discussions with Birman (1977) and Sabins (1976). These procedures were then modified again and augmented, especially during the conduct of the September 1977 Coso survey, as a result of the experience gained during the Long Valley field work. The basic procedure involves augering a 2-m deep hole for each measurement location, inserting a thermistor probe in the hole, backfilling the hole, waiting until the thermistor equilibrates, and finally making a measurement of the temperature at that site. This is done at a sufficient number of locations at a given survey area so that a contour map of temperatures at the 2-m depth can be constructed.

Drilling was accomplished at the Long Valley site by use of a two-man General Hole Digger (Model 21) powered by a 3-hp Tecumseh 2-cycle gasoline engine. A 5-cm (2-in) auger was used with the hole digger (Figure 1). This was generally satisfactory in the sandy and silty soils of the high desert area in the Long Valley caldera. The soil generally had sufficient cohesiveness so that a 2-m hole could be augered without the use of drilling water. Where there were stones or gravel too large for the auger to handle, the procedure was simply to move to another location nearby and try again.

At the Coso site, a truck-mounted hydraulic posthole digger was used (Figure 2). The auger was approximately 18 cm (7 in) in diameter, and the soil, largely volcanic ash, was so friable that drilling water was essential. The 5-cm hand-held power hole digger would not work here because of the soil's friability; the hole would collapse as soon as the auger was removed.

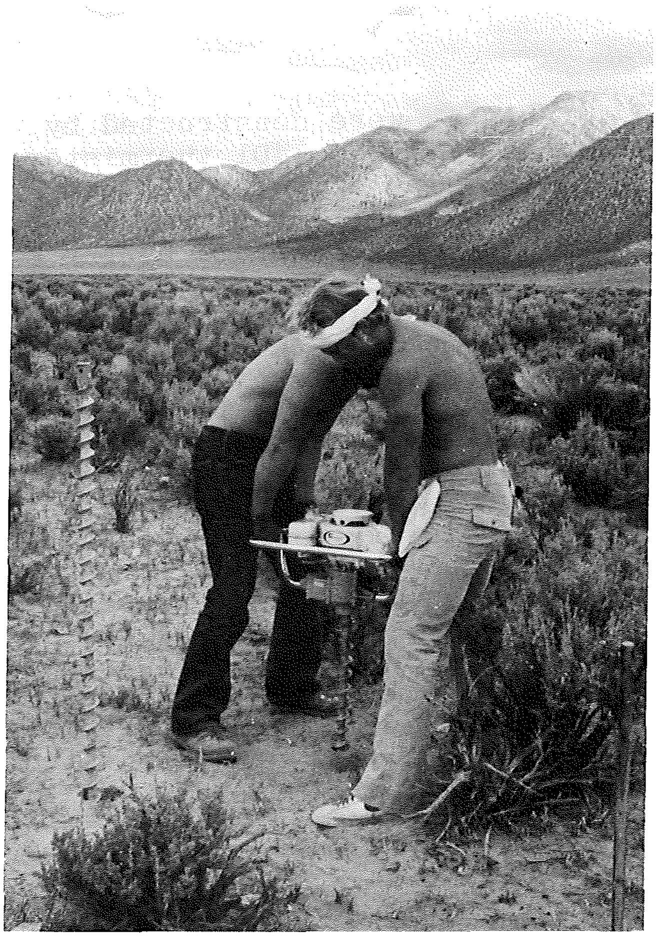


FIGURE 1: A 2-man, 3-hp hole-digger was used at Long Valley.

FIGURE 2: A truck-mounted hydraulic posthole-digger was used at Coso.

The thermistor probes were constructed by taping a Yellow Springs Instrument Company (YSI) No. 401 thermistor to the end of a 2.1-m long, 1.3-cm (0.5-in) diameter PVC pipe (Figure 3). Both single and multi-element thermistor probes were used at the two sites. The thermistors are guaranteed by the manufacturer to be interchangeable to a tolerance of ± 0.1°C within the temperature range of 0°-80°C, the range in which we worked. They were read with a YSI Model 46 TUC Tele-thermometer, a Wheatstone bridge that has an accuracy of ± 0.15°C. The thermistor probes were inserted in each hole as soon as it was drilled and the hole was backfilled with the auger cuttings. Fill was dropped into the hollow PVC pipe. At both the Long Valley and the Coso sites a random probe was read at frequent intervals after insertion to determine the time delay required for the thermistor to come to equilibrium with its surroundings. Figures 4 and 5 show the decay curves for Station 25 at Long Valley and Station 13 at Coso, respectively.

Since the major portion of the disturbance of the 2-m soil temperature is due to the friction-generated heat of the auger, it is appropriate to plot the decay curves on semi-log paper because the decay is exponential. This type of presentation shows clearly the point at which the thermistor comes into equilibrium. The 5-cm diameter Long Valley holes reached equilibrium in approximately 300 minutes; in practice, we read them the following day. The Coso holes, because of the larger diameter (18 cm) auger, took between 700 and 1000 minutes to equilibrate; in practice, we waited four or five days before we read them.

3. Data Collection

3.1 Long Valley

Figure 6 shows that area of Long Valley where we conducted our survey. It is the same area mapped by Lachenbruch *et al*. (1976) at a depth of 10 m. We used their study to provide general guidance in locating our probes. Three distinct probe emplacement programs were conducted to:

- Attempt to make comparison with the contours of Lachenbruch *et al*. (1976).
- Measure spatial variability of 2-m temperatures.
- Measure temperature variations in an obvious spring discharge area.

Only the first program will be discussed in this Semi-Annual Report. The other programs will be covered in the following semi-annual report.

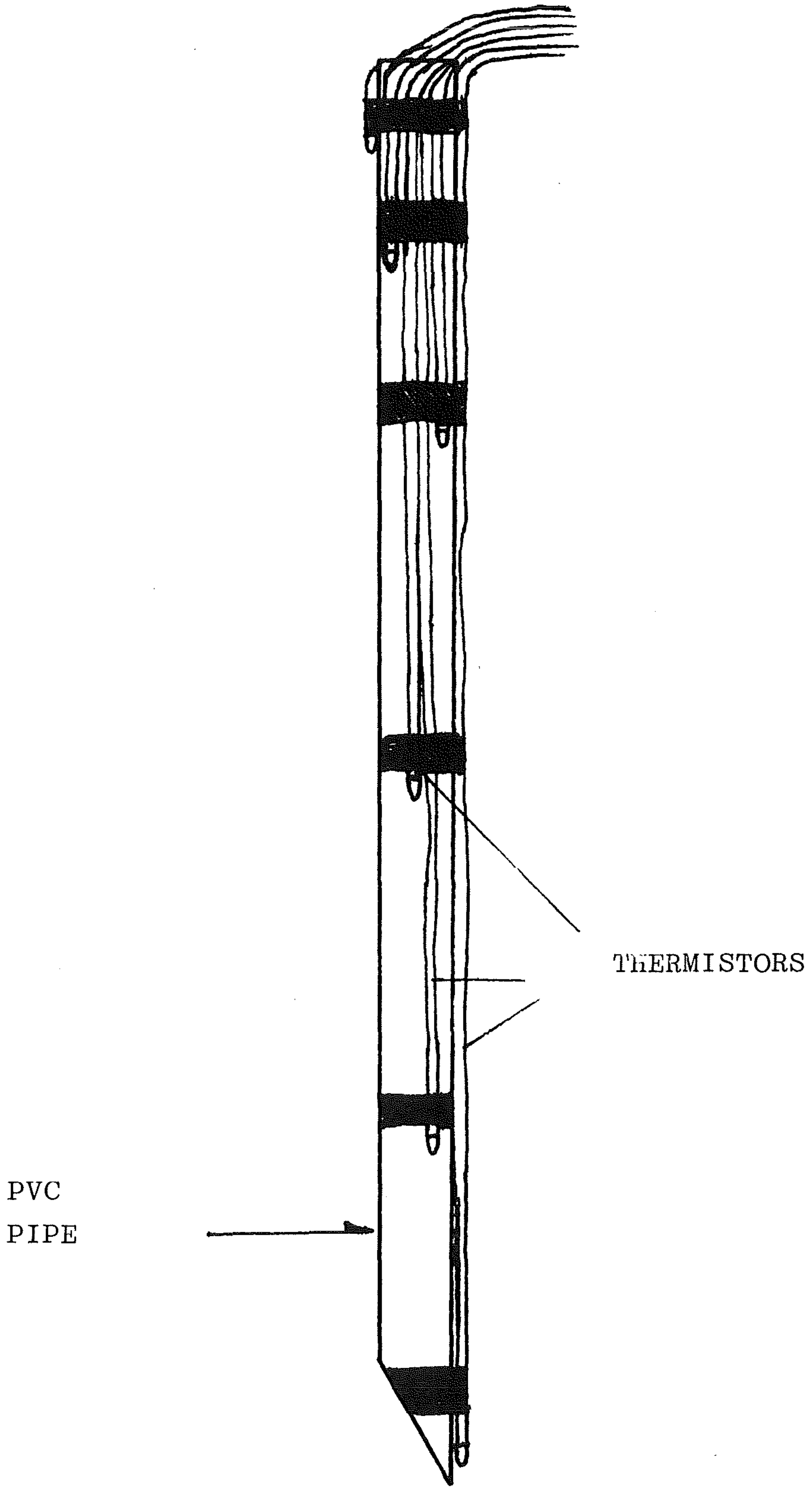


FIGURE 3: Thermistors mounted on a 6-element probe made of 0.5 in (1.3 cm) PVC pipe. Typical depths are 0.1, 0.25, 0.5, 1.0, 1.5 and 2.0 m.

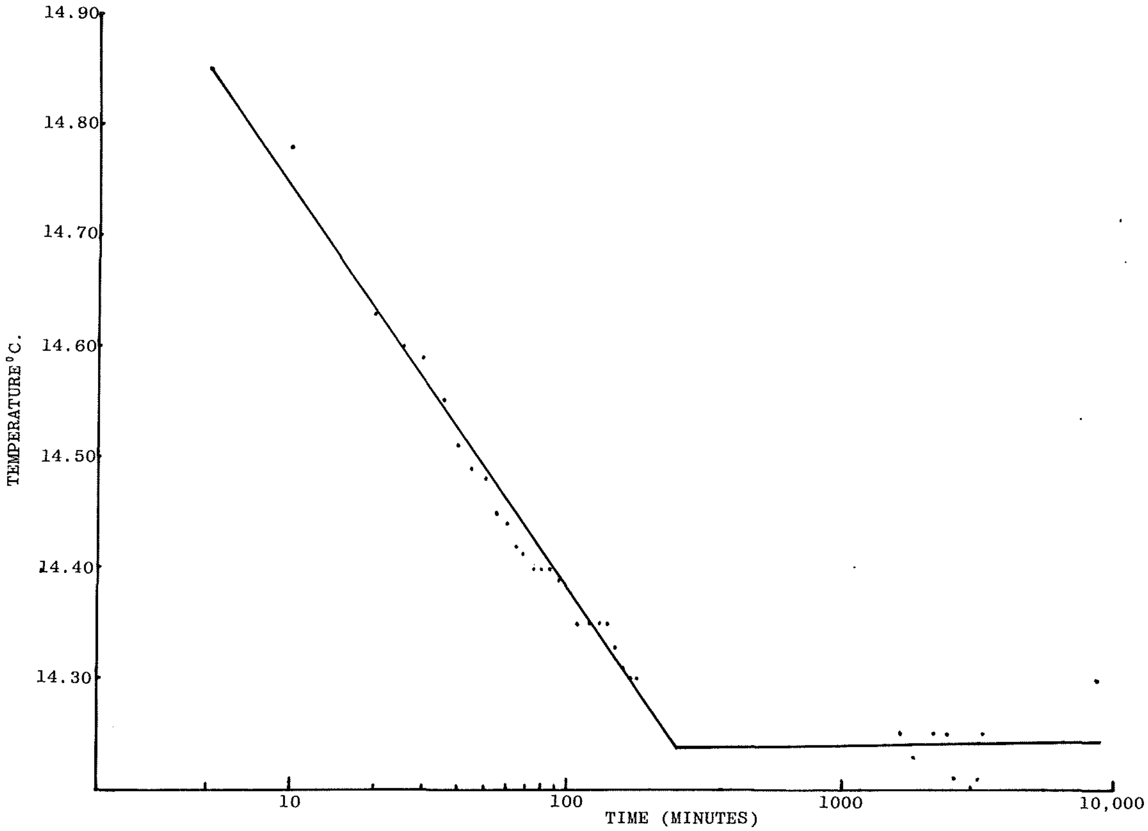


FIGURE 4: Equilibrium is reached at Station 25, Long Valley in approximately 300 minutes (5 cm hole). 25-30 June 1977. Temperatures at 2-m depth.

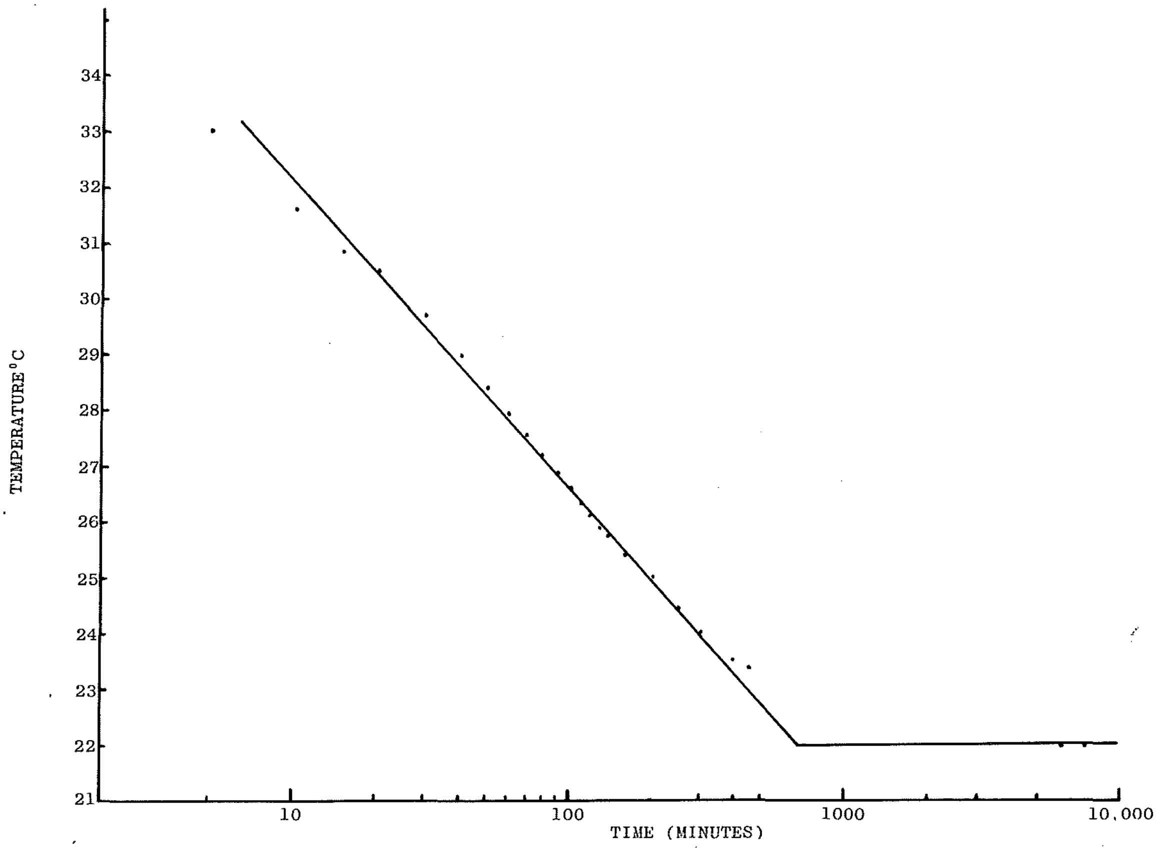


FIGURE 5: Equilibrium is reached at Station 13, Coso in approximately 700-1000 minutes (18 cm hole). 29 July - 3 August 1977. Temperatures at 2-m depth.

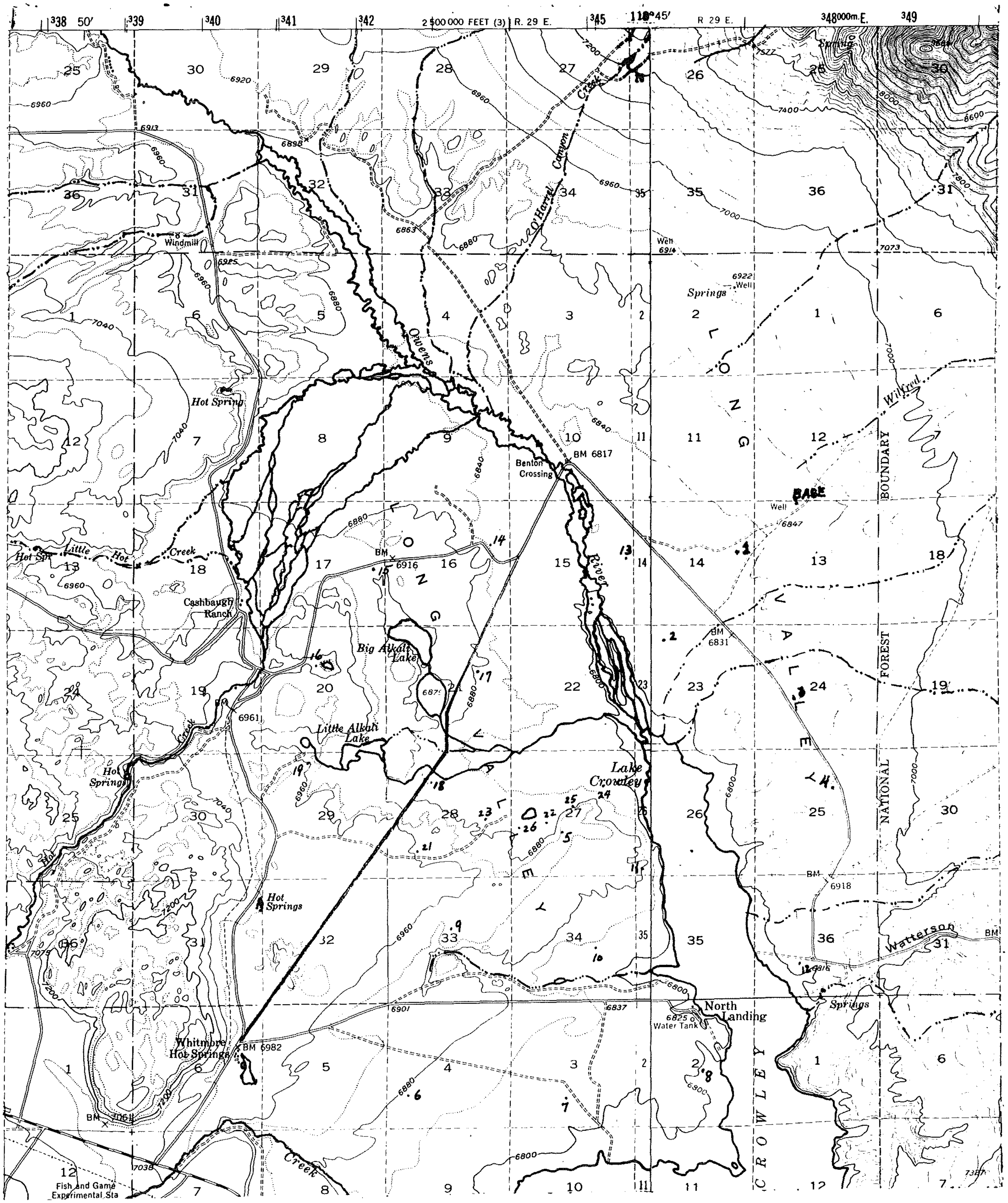


FIGURE 6: Locations of 2-m temperature stations at Long Valley (Mt. Morrison and Casa Diablo Quadrangles).

Twenty-seven 6-element thermistor probes were emplaced at the Long Valley site, as shown in Figure 6. Elements were at depths of 0.1, 0.25, 0.5, 1.0, 1.5 and 2.0 m. Emplacement was made generally in a stratified random fashion. The stratification was made on a 1-mile section basis within which a random site* was chosen. The hole was usually drilled within 100-300 m of a road or trail. We tried to emplace at least one hole per 1-mile section, and if the randomly chosen location was not drillable, we kept searching for some location nearby that was.

The probes were allowed to equilibrate and were then read. Between midnight 8-9 July, 1977, and midnight 9-10 July, 1977, they were read at approximately six-hour intervals so that diurnal variation could be determined. Twenty-three of the probes were read at least six additional times between 9 July and 15 August, 1977. Four representative probes have been left at Long Valley so that one complete annual cycle can be determined.

At each of the 27 sites surface albedo and surface roughness were measured. Soil samples were collected at the surface and at a depth of 40-50 cm. A base station was established at which surface weather observations, mean wind speed, incoming solar radiation and net radiation were measured. The base station (Figure 7), located in Section 13, northeast of Lake Crowley (see Figure 6), was chosen because, according to Lachenbruch _et al_. (1976), it was in an area with close-to-normal heat flow. The base station equipment included a meteorograph to record surface temperature, humidity and pressure; a Lintronic pyronometer to measure incoming solar radiation; a net all-wave radiometer to measure net radiation at the surface; an inverted Lintronic pyronmeter to measure albedo; casella anemometers to measure average daily wind speed, and soil heat flux plates.

3.2 Coso

On 28 and 29 July, 1977, 24 1-element probes were emplaced at Coso as shown in Figure 8. The criteria for emplacement was easy accessibility, i.e., along roads or trails, and knowledge that a geothermal anomaly, already identified with deep reconnaissance drilling (Combs), 1975; Combs 1976), could be covered. These 24 probes were read on 2-3 August, 1977. The results were so encouraging we returned on 14 September, 1977. Between 14 and 18 September, 78 more probes were inserted to better delineate the anomaly area. Of these, 24 had elements at 1.5 m in addition to an element at 2 m; four were six-element probes.

Albedo, surface roughness and soil samples from a depth of 30-40 cm were collected at each of the original 24 sites. A base surface weather station was established in Section 11 west

---

*A random number generator was used to generate a mileage value to proceed to upon entering each new 1-mile section.

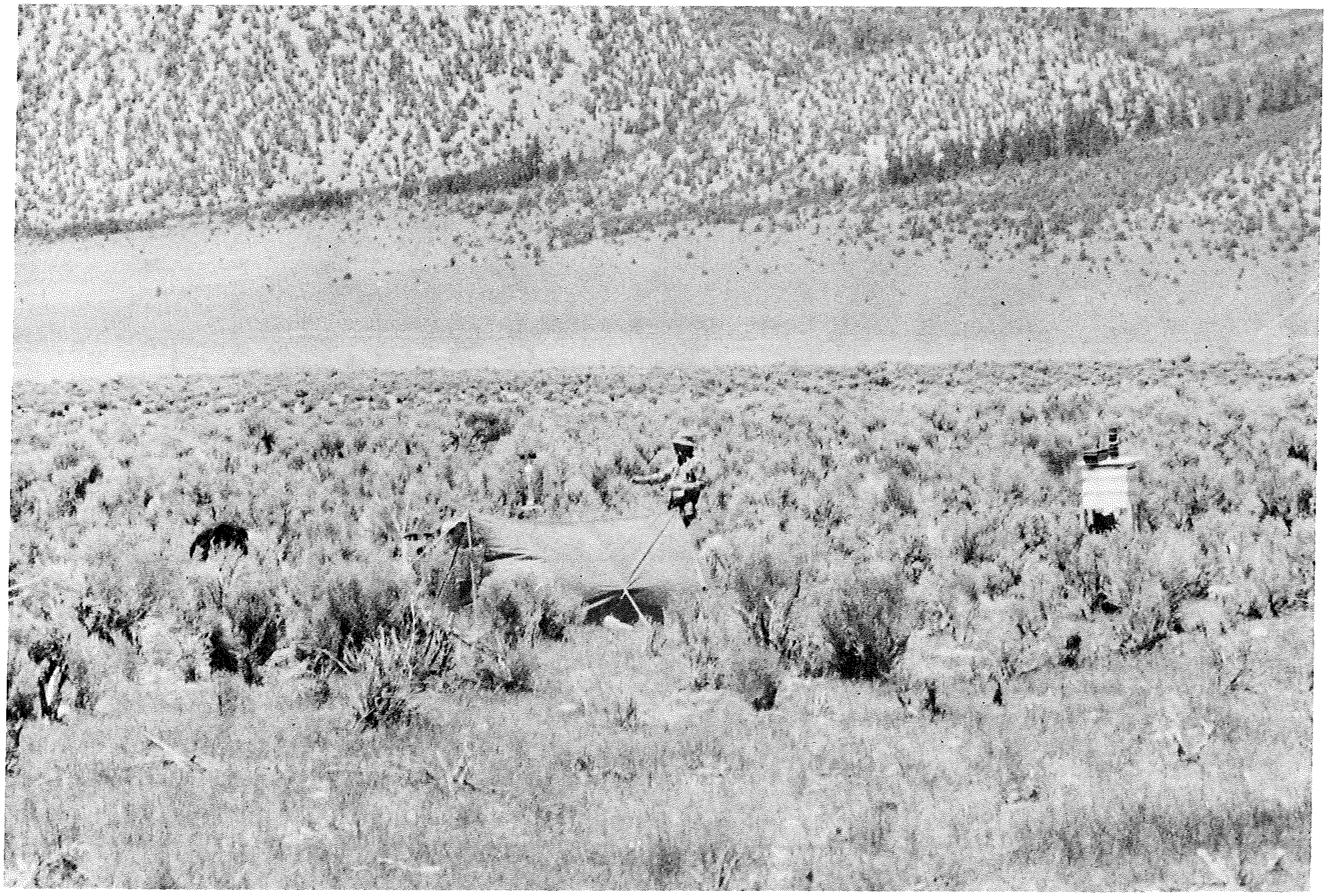


FIGURE 7: The Base Station at Long Valley, California is located in Section 13, northeast of Lake Crowley. View is toward northeast.

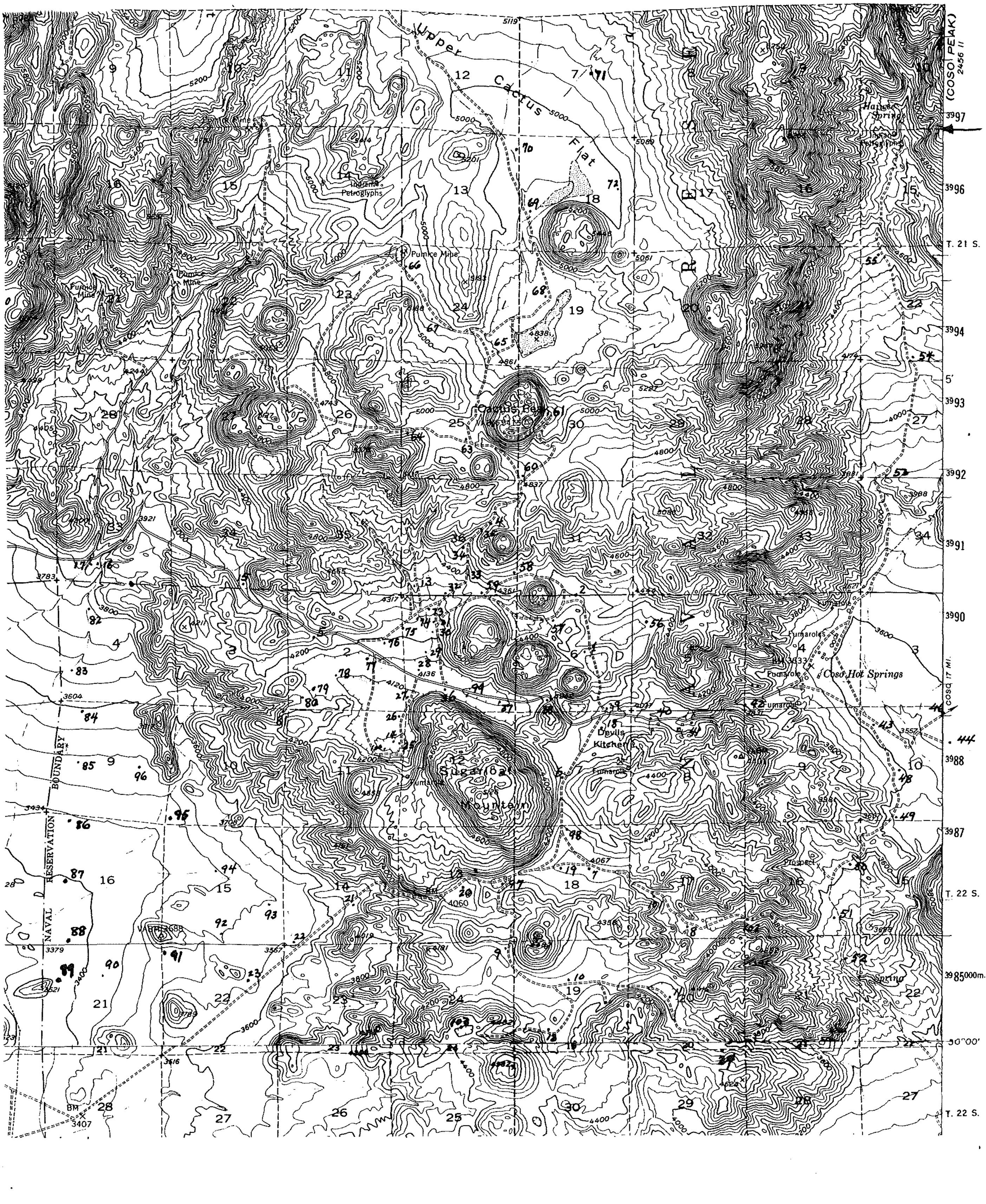


FIGURE 8: Locations of 2-m temperature stations at Coso. The first 24 were emplaced in July 1977, the rest in September 1977. (Haiwee Reservoir and Little Lake Quadrangles).

of Sugarloaf Mountain. The four 6-element probes, emplaced at representative locations around the anomaly, were read approximately every six hours between noon of 24 September to noon of 25 September, 1977. These probes have been left in place at Coso.

4. Examining the Data

As expected from Birman (1969), Poley and Van Steveninck (1970) and Sabins (1976), emplacement of probes at a 2-m depth avoided completely the effect of diurnal variations of solar input. At Long Valley most of our probes had six elements. At Coso four of our probes had six elements. As a result, it was possible to obtain a detailed soil temperature profile at locations where these probes were emplaced. Figures 9 and 10 show the soil temperature variations over one diurnal cycle for four representative sites at Long Valley and Coso, respectively. It can be seen, therefore, that at these sites diurnal variation is negligible below a depth of 1 m (see Appendix A for Long Valley diurnal measurements).

At a depth of 2 m, however, our probes are well within the range of the annual solar cycle which can usually be observed to a depth of some 20 m. Empirically, we determined the daily change due to the annual variation at our sites ranged from 0.01-0.08^{o}C per-day. A quarter of the annual cycle has been observed at four representative sites at Long Valley (Figure 11). Though it is clear the annual effect is significant, if a survey for a given area is completed within a few days after its commencement, corrections to the 2-m temperatures will be minimal. The effect of aperiodic solar variations of any period have been deemed negligible as far as our data are concerned because they can be assumed to cause temperature changes during a typical survey less than those caused by the annual variation.

5. Corrections to the Data

5.1 Corrections for Spatial Variations in Surface/Soil Properties

Parameters which effect the surface energy partitioning and heat flow into the soil were measured or estimated at each location (27 sites at Long Valley and 24 at Coso). At each of these sites, albedo, surface roughness and percentage of soil moisture were obtained. Albedo was measured with a Lintronic solarimeter while surface aerodynamic roughness was calculated from geometric characteristics of the surface following the method of Lettau (1969). At each site a soil sample was collected and analyzed in the laboratory for percentage soil moisture content, bulk density, percentage organic carbon and texture class. From the observed 6-level temperature measurements, thermal diffusivity was calculated for four sites at each location using the following formula:

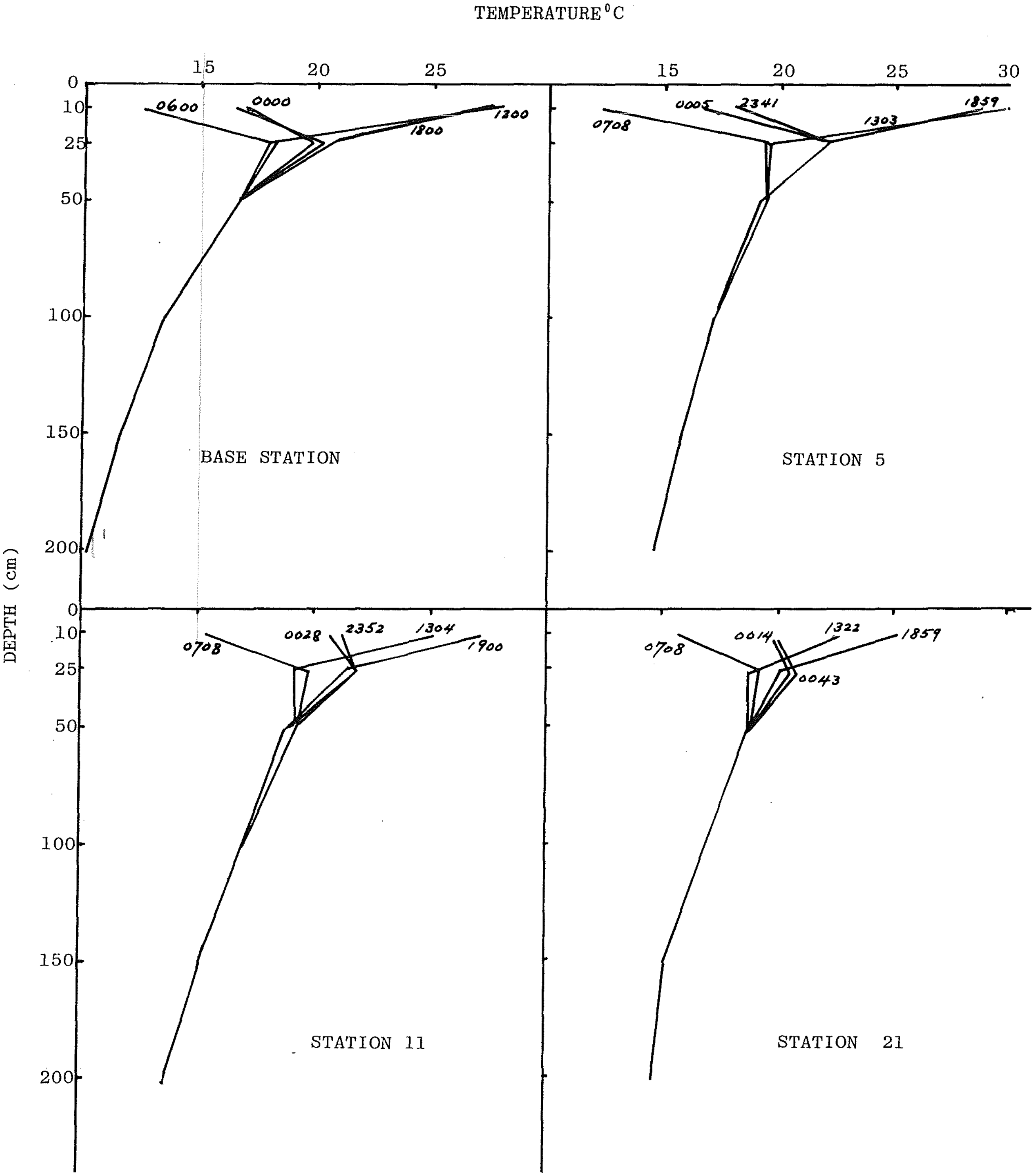


FIGURE 9: Typical diurnal soil temperature variations at Long Valley, 9-10 July 1977. Mean times indicated on profiles.

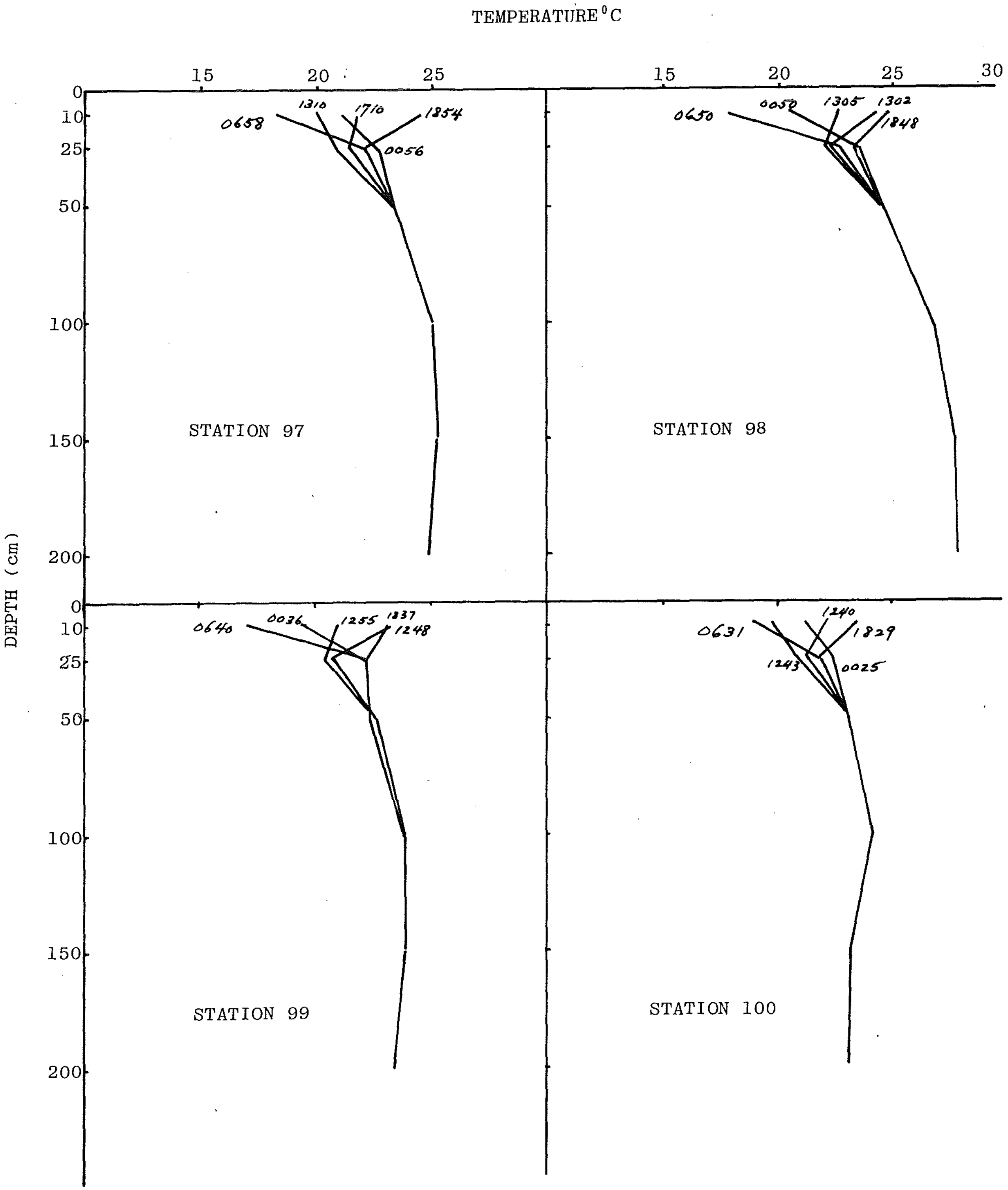


FIGURE 10: Typical diurnal soil temperature variations at Coso, 24-25 September 1977. Mean times indicated on profiles.

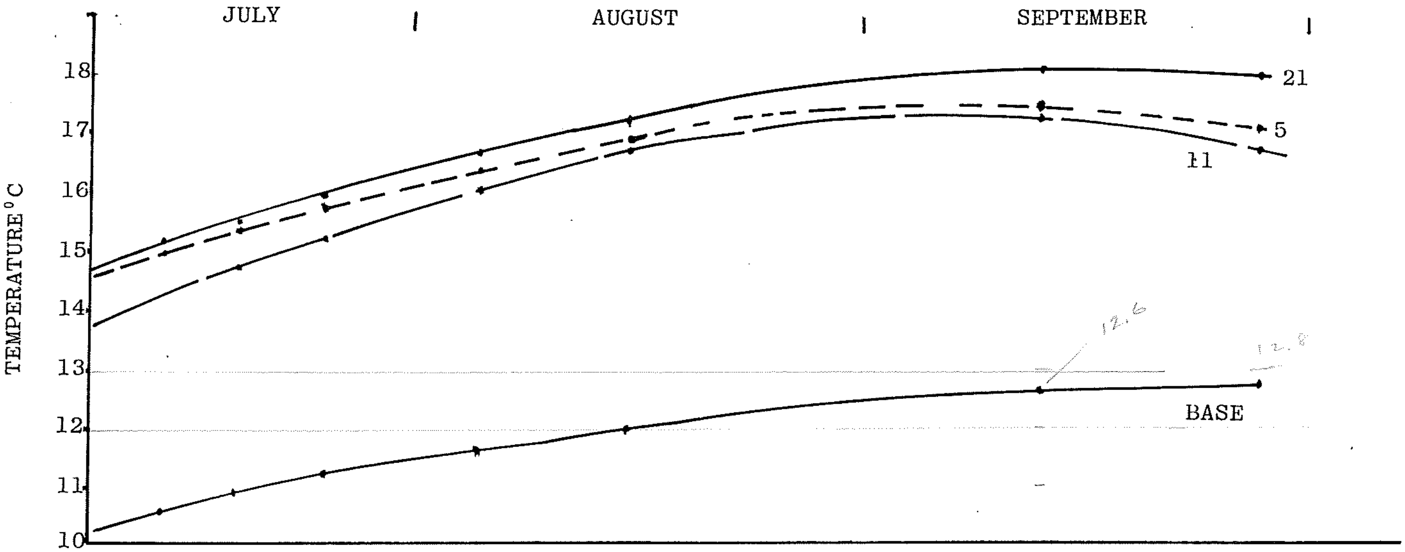


FIGURE 11: Annual variation of typical 2-m temperatures at Long Valley, Summer, 1977. Station numbers are marked on curves.

$$\alpha = \frac{\Delta z(\Delta \overline{T})}{\Delta \overline{T}'(\Delta t)}$$

where

$\Delta \overline{T}$ = change in mean temperature of layer Δz in observation time Δt

$\Delta \overline{T}'$ = mean temperature gradient at two depths in Δt

An independent estimate of thermal diffusivity for the base station at Long Valley using the phase lag of the maximum temperature wave showed good agreement between calculated values. In addition, these values of diffusivity were similar to quoted values in the literature for dry sand soil.

Table 1 shows the values of albedo, surface roughness, and thermal diffusivity for Long Valley and Coso. Tables 2, 3 and 4 are the results of the soil analysis for Long Valley (surface and 40-50 cm depth) and Coso (30-40 cm depth). Table 5 displays the means and standard deviations of the various surface-soil parameters.

We feel the surface-soil properties exhibit a striking degree of homogeneity, especially at Coso. In many ways, this homogeneity is to be expected when one examines Tables 2, 3 and 4. There is a great degree of similarity in the textural class of all the soils at both locations--all having a high content of sand, with many exhibiting high proportions of gravel and low amounts of clay-size particles and organic matter. Two possible exceptions to this uniformity are albedo and percentage moisture content (45-cm depth) for Long Valley. The albedo has 6 of 27 values grouped between 29% and 32% with a break occurring in the distribution at 26%. The sites which fell into the higher percentage group had a cover of white alkali on the surface. These are the same playa areas which influenced the percentage moisture content distribution, producing a sharp break in the classes between 9% and 14% soil moisture, with 8 of the 27 samples having moisture content greater than 14%. In both cases, this higher valued class increased the sampled variance for their respective distributions. This variation could be reduced by sub-dividing the samples into two distinct classes based on dichotomous surface grouping of alkali/no alkali.

We expect the observed variations in the surface/soil properties will not affect the temperature at 2 m within the errors of measurement. For example, Kappelmeyer and Haemel (1974) quote (on table 3.14) differences of $\simeq 1.0^{\circ}$C in mean annual temperature and 2.3°C maximum difference of temperature at 2 m between adjacent forest and meadow cover. One may assume approximately a 10% variation in albedo and at least an order of magnitude difference in surface roughness between the two surfaces. However, it remains to be definitively stated how sensitive, on an annual time frame, temperature changes at 2 m are to variations in the surface soil

TABLE 1: Surface Condition - Long Valley

	Albedo %	Surface Roughness (cm)	Thermal Diffusivity (cm^2/sec)
BS	30	8.7	.0024
1	23	9.0	
2	29	7.8	
3	24	14.2	
4	20	11.0	
5	23	11.0	.0027
6	18	2.6	
7	19	5.8	
8	20	5.8	
9	19	7.1	
10	32	1.6	
11	18	7.7	.0036
12	18	21.9	
12	21	8.4	
14	19	9.6	
15	19	11.0	
16	23	9.7	
17	25	12.9	
18	30	10.3	
19	32	2.6	
20	23	7.7	
21	21	6.1	.0034
22	18	9.0	
23	20	4.2	
24	29	1.8	
25	25	9.7	
26	24	9.0	

Surface Condition - Coso

1	35	5.8	
2	32	5.8	.0021 Station 99
3	24	5.8	
4	30	4.9	
5	33	7.6	.0020 Station 100
6	31	6.7	
7	34	7.6	
8	35	8.1	.0021 Station 97
9	32	11.6	
10	32	0.1	
11	33	7.1	.0019 Station 98
12	30	16.1	
13	35	6.2	
14	40	4.6	
15	33	14.5	
16}	34	3.9	
17	35		
18	31	6.5	
19	32	6.7	
20	32	7.7	
21	30	7.1	
22	34	10.3	
23	34	6.8	
24	31	6.7	

TABLE 2: Soil Surface Samples - Long Valley *

Site Sample No.	% Water of Oven Dried Soil	% Gravel	Bulk Density (gm/cm^3)	% Organic C.	% Clay	% Silt	% Sand
Base Station	0.94	13.6	1.14	.391	0	15.5	84.5
1	2.80	8.9	0.92	.316	0	27.0	73.0
2	1.65	1.5	1.35	.293	0	38.5	61.5
3	0.92	27.5	1.43	.272	0.3	11.0	88.7
4	0.58	25.7	1.32	................Not Calculated...........			
5	1.85	9.3	1.12	1.270	0.4	19.0	80.6
6	22.46	17.5	0.99	3.23	0.4	17.6	82.0
7	7.05	18.7	1.09	.906	0	15.5	84.5
8	1.00	17.0	1.24	.375	0.5	11.5	88.0
9	1.47	11.0	1.45	.316	0.3	7.3	92.4
10	17.85	1.0	1.08	.339	5.3	17.7	77.0
11	0.64	27.0	1.29	1.021	1.4	14.2	84.4
12	1.13	16.5	1.39	.587	1.9	10.1	88.0
13	6.31	2.2	1.02	.386	3.3	19.5	77.2
14	1.17	3.7	1.24	.730	3.2	30.8	66.0
15	1.17	13.8	1.32	.481	0.5	10.1	89.4
16	2.93	6.2	1.13	.271	3.5	14.1	82.4
17	0.89	16.0	1.51	.750	0	22.0	78.0
18	11.36	3.6	1.01	.156	10.0	38.0	52.0
19	21.77	4.7	1.21	0	9.0	19.5	71.5
20	32.01	4.1	0.91	.501	4.8	21.7	73.5
21	2.26	2.7	1.03	.309	3.5	21.5	75.0
22	2.03	0.7	0.76	.156	0	8.4	91.6
23	1.13	3.5	1.22	.462	3.2	17.8	79.0
24	11.71	3.9	1.09	.347	0.5	28.2	71.3
25	1.03	5.8	1.31	.539	3.0	27.5	70.5
26	4.50	3.2	1.08	................Not Calculated...........			

TABLE 3: Soil Samples at 40 to 50-cm Depth - Long Valley *

Site Sample No.	% Water of Oven Dried Soil	% Gravel	Bulk Density (gm/cm^3)	% Organic C.	% Clay	% Silt	% Sand
Base Station	3.4	7.6	1.05	3.2	2.5	23.3	74.2
1A	3.4	18.8	1.02	17.4	1.8	15.2	83.0
2A	19.7	9.3	0.95	12.2	12.4	30.1	57.5
3A	6.8	29.3	0.80	12.0	0.0	6.1	94.8
4A	3.3	30.3	1.42	12.0	2.8	16.0	81.8
5A	2.3	12.9	1.29	.3	3.5	14.9	81.6
6A	15.7	15.3	1.68	6.0	10.5	25.5	64.0
7A	7.7	16.2	1.12	2.4	4.8	16.9	78.3
8A	2.2	22.3	1.39	7.4	2.1	13.6	84.3
9A	3.0	18.7	1.26	7.0	3.0	6.9	90.1
10A	21.5	2.0	1.29	6.8	15.1	10.9	74.0
11A	1.9	33.7	1.23	4.0	6.6	22.4	71.0
12A	5.2	16.8	0.95	4.2	2.4	8.3	80.3
13A	9.1	19.0	0.98	4.8	3.1	23.9	73.0
14A	8.8	3.9	0.95	4.2	6.0	33.3	60.7
15A	4.8	23.1	1.07	4.0	0.5	8.5	91.0
16A	7.0	5.5	1.11	4.6	5.2	15.8	79.2
17A	2.2	13.6	1.28	0.3	1.8	16.6	81.6
18A	19.1	2.2	0.74	0.3	19.0	36	45.0
19A	20.1	6.8	1.33	0.3	5.2	10.6	84.2
20A	30.4	10.6	0.98	0.3	7.5	27.5	65.0
21A	2.6	8.3	1.21	0.8	7.5	27.5	65.0
22A	6.4	1.6	1.09	0.3	4.4	7.6	88.0
23A	2.3	19.5	1.20	0.2	7.0	20.0	73.0
24A	14.7	3.8	1.47	0.1	1.5	10.3	88.2
25A	1.4	6.6	1.34	0.4	5.4	26.4	68.2
26A	14.4	1.4	1.35	0.2	6.4	9.4	84.2

---

* See Appendix B for details.

TABLE 4: Soil Samples at 30 to 40-cm Depth - Coso*

Site Sample No.	% Water of Oven Dried Soil	% Gravel	Bulk Density (gm/cm^3)	% Organic.	% Clay	% Silt	% Sand
1	6.05	8.74	1.17	0.060	5.0	10.6	84.4
2	6.21	17.24	1.16	0.002	6.0	14.0	80.0
3	5.33	13.33	1.34	0.002	6.0	10.0	84.0
4	4.46	19.75	1.38	0.090	4.2	10.4	85.4
5	2.96	36.09	1.34	0.090	4.2	16.8	79.0
6	6.65	17.60	1.13	0.090	7.0	23.0	70.0
7	6.91	15.38	1.42	0.002	9.0	15.0	76.0
8	5.65	12.84	1.14	0.080	3.3	12.7	84.0
9	6.14	17.04	1.01	0.040	1.5	23.0	75.5
10	6.58	17.55	1.17	0.002	7.0	33.5	59.5
11	5.94	12.68	1.11	0.090	3.0	19.4	77.6
12	4.92	17.16	1.16	0.020	4.6	15.6	79.8
13	2.91	16.89	1.31	0.130	3.0	5.2	91.8
14	3.15	23.73	1.02	0.020	4.4	16.8	79.8
15	3.04	9.72	1.49	0.060	4.0	6.5	89.5
16	3.69	24.84	1.11	0.060	7.8	15.6	76.6
17	3.69	24.84	1.11	0.060	7.8	15.6	76.6
18	7.50	15.26	1.10	0.020	8.5	21.5	70.0
19	6.51	12.14	1.17	0.020	7.0	19.5	73.5
20	5.12	22.37	1.07	0.090	3.0	17.3	79.7
21	3.00	31.24	1.32	0.060	4.0	1.3	94.7
22	3.47	20.72	1.18	0.060	3.0	14.6	82.4
23	4.15	6.97	1.28	0.060	8.2	7.6	84.2
24	5.79	12.18	1.37	0.090	3.0	14.2	82.8

TABLE 5: Means and Standard Deviations of Surface/Soil Properties

		Albedo	Surface Roughness	Thermal Diffusivity	Percent Moisture
Long Valley	- Mean =	23%	8.37 cm	.003 cm^{2}sec^{-1}	8.9%
	Standard Deviation =	±4.5	±4.13	±.0005	±7.6
Coso	- Mean =	33%	7.2 cm	.002 cm^{2}sec^{-1}	5.0%
	Standard Deviation =	±2.2	±3.3	$\pm 8 \cdot 10^{-5}$	±1.4

---

* See Appendix B for details.

properties. This statement must await the development of an annual surface climate energy budget model.

In summary, our surface and near-surface data indicate that perturbations owing to differences in albedo, surface roughness and thermal diffusivity over the areas encompassed in our two case history surveys are small compared to the size of our anomalies and can be neglected at these sites. This does not imply the above effects are always negligible. These parameters should be examined at each new site where shallow temperature surveys are undertaken.

5.2 Elevation Corrections to 2-m Temperature Data

It would be expected the temperature at 2-m depth would be affected by the mean annual temperature at the surface. Assuming an adiabatic lapse rate of -1.0^{o}C/100 m of elevation, it is clear that a noticeable mean annual surface temperature difference would be experienced between the highest and lowest sites at least at the Coso site, if not at the Long Valley site. We tested this by computing the correlation coefficient for the 2-m temperature-elevation sets at Long Valley (Table 6) and at Coso (Tables 7 and 8).

Table 6 lists the temperatures and the elevations observed at Long Valley, as determined from the USGS Topographic sheet. No significant temperature-elevation correlation was observed. However, the variation in elevation is small (the standard deviation is only 16 m or 52 ft). Table 7 lists the 24 original temperature-elevation sets for the Coso site. Here, too, there is no meaningful correlation. But the standard deviation of elevations is still relatively small, i.e., 77 m (251 ft). A wider range of elevations is shown in Table 8. In this case, we chose two relatively flat areas--one to the west of the anomaly, the other to the north--where there was a large difference in mean elevation but relatively little temperature or elevation variation within each of the areas.

When temperature-elevation correlations are made among the data for each of the data sets independently, i.e., the western set and the northern set, the standard deviations of elevations are small and there is no significant correlation for the northern set and a modest positive correlation for the western set. However, when the correlation is made with the western and northern set combined, the standard deviation in elevations is several times larger than in previous cases and the correlation coefficient is -0.87, indicating a significant negative correlation among temperature and elevation. This negative correlation would be expected if the temperatures were affected by temperature change due to elevation (i.e., the adiabatic change). The +0.78 correlation for the western set may be indicative of a shallow soil layer thinning in the direction of higher elevation. Such a thinning layer could bring

TABLE 6: Temperature-Elevation Correlation, Long Valley, California

10 July 1977

Station	Temperature °C	Elevation (ft)
B	10.10	6860
1	10.32	6835
2	9.98	6815
3	11.15	6870
4	11.60	6920
5	14.45	6920
6	17.78	6865
7	16.59	6815
8	14.59	6800
9	18.25	6920
10	11.70	6840
11	13.55	6880
12	12.60	6800
13	11.77	6815
14	9.35	6840
15	11.60	6930
16	20.15	6920
17	10.25	6880
18	12.07	6860
19	11.79	6960
20	20.92	7000
21	14.55	6950
22	18.60	6865
23	32.75	6870
24	12.52	6820
25	14.75	6920
26	16.70	6870

Mean temperature = 14.46°C
Standard deviation = ±4.9°C

Mean elevation = 6876 ft (2096 m)
Standard deviation = ± 52 ft (16 m)

Correlation coefficient, rxy = + 0.25

TABLE 7: Temperature-elevation correlation, first 24 sites, Coso, California

2-3 August 1977

Station	Temperature °C	Elevation (ft)
1	22.82	4350
2	21.25	4360
3	22.60	4160
4	21.75	4640
5	24.10	4280
6	29.80	4240
7	26.80	4070
8	23.50	3870
9	23.82	4140
10	21.61	4100
11	23.39	4000
12	21.70	4130
13	21.99	4320
14	20.05	4070
15	21.83	4150
16	23.70	3860
17	24.50	3860
18	25.38	4125
19	26.00	4090
20	22.78	4060
21	24.13	3660
22	23.30	3560
23	23.32	3580
24	22.85	4020

Mean temperature = 23.46°C
Standard deviation = ±2.05°C

Mean elevation = 4071 ft (1241 m)
Standard deviation = 251 ft (77 m)

Correlation Coefficient, rxy = -0.13

TABLE 8 : Temperature-elevation correlations for western area, northern area and western and northern areas combined, Coso, California

22-23 September 1977

WEST

Station	Temperature °C	Elevation (ft)
16	24.93	3860
17	25.38	3860
22	24.55	3560
23	24.60	3580
82	25.72	3750
83	24.98	3660
84	24.65	3600
85	24.39	3510
86	24.41	3440
87	24.39	3400
88	23.25	3380
89	23.46	3430
90	23.65	3420
91	23.79	3500
92	23.79	3520
93	24.71	3530
94	23.61	3480
95	24.53	3460
96	24.50	3510

Mean temperature = 24.38°C
Standard deviation = ± 0.65°C
Mean elevation = 3550 ft (1082 m)
Standard deviation = 142 ft (43 m)
Correlation coefficient, rxy = + 0.78

NORTH

Station	Temperature °C	Elevation (ft)
60	22.31	4840
61	21.60	5170
62	20.91	5100
63	22.01	4940
64	21.51	4960
65	20.20	4880
66	20.39	4930
67	20.57	4920
68	19.41	4850
69	18.34	4960
70	19.39	4990
71	20.71	5080
72	20.05	5000

Mean temperature = 20.57°C
Standard deviation = ±1.13°C
Mean elevation = 4971 ft (1516 m)
Standard deviation = 98 ft (30 m)
Correlation coefficient, rxy = +0.11

Combined Correlation

Mean temperature = 22.83°C
Standard deviation = ± 2.09°C
Mean elevation = 4127 ft (1258 m)
Standard deviation = ± 720 ft (220 m)
Correlation coefficient, rxy = -0.87

the more conductive bedrock relatively so much closer to the probes at the higher elevations than at the lower elevations as to significantly increase the temperature recorded at these higher elevations. A shallow, thinning soil layer is consistent with the alluvial nature of this area.

Examination of the mean elevation difference between the northern data set and the western data set is 434 m (1424 ft). With an adiabatic lapse rate of -1.0°C/100-m elevation change, the calculated mean temperature difference should be 4.34°C. The measured mean temperature difference is 3.81°C. It therefore seems clear the change of temperature with elevation becomes significant with elevation differences of 100-200 m or more. If this range of elevations appears, the 2-m temperatures should be corrected. Using the adiabatic lapse rate of -1.0°C/100 m, we have corrected to an arbitrarily picked datum of 3400 ft, all the 2-m temperatures gathered at the Coso site and have listed them on Table 9.

5.3 Corrections for Topographic Effects

At Long Valley and at Coso we took care to see that topographic disturbances were kept to a minimum. We made every attempt to gather our data where the slope of the terrain was close to zero and therefore the exposure of this surface to the sun would vary little from place to place. Most of our data were collected in areas where the data sites were out of shadow zones. Although some of our data were collected at locations where they were in the shadow of large hills at some time during the day (sites 6 and 14 at Coso are examples), they were sufficiently far away so that the shadow effect occurred only in the early morning or the late afternoon when there is relatively little solar input.

With one exception we kept our sites far enough away from large topographic features, i.e., hills, gorges etc., so that topographic effects as estimated according to the techniques described by Lachenbruch (1968) would be minimal. In the one exception, site 16 at Coso was deliberately chosen close to a sharp drop-off. Site 17, its neighbor 15 m away, was sufficiently removed to be unaffected. The measured temperature difference between the sites, 0.5°C, was consistent with the value estimated according to Lachenbruch's technique.

In summary, it can be seen from the 2-m temperature contour plots of the Long Valley or Coso sites (Figures 12 and 13) that there is no observable correlation between them, and the topographic contours (Figures 6 and 8), and the corrections due to topographic effects are negligible at these two case history sites. Where the temperature anomalies are not as great as they are in our two case histories, quantitative evaluation of these topographical effects might be necessary, even with the precautions of site location that we took in gathering the present data.

TABLE 9: Corrected and Uncorrected 2-m Temperatures at Coso, 22-23 September 1977

Station	Uncorrected	Corrected	Elevation
1	24.10	27.0	4360
2	22.61	25.5	4360
3	23.65	26.0	4160
4	23.19	27.0	4640
5	24.94	27.7	4300
6	30.69	33.2	4220
7	28.00	30.1	4080
8	24.79	26.2	3880
9	25.10	27.3	4140
10	23.50	25.6	4110
11	24.53	26.6	4100
12	23.05	25.3	4130
13	23.02	25.8	4320
14	21.50	23.5	4070
15	23.33	25.6	4150
16	24.93	26.3	3860
17	25.38	26.7	3850
18	26.40	28.6	4125
19	27.30	29.4	4080
20	24.21	26.1	4060
21	25.45	26.3	3660
22	24.55	25.0	3560
23	24.60	25.1	3580
24	23.83	25.7	4020
25	22.05	23.5	3870
26	23.84	26.0	4110
27	22.90	25.0	4110
28	23.50	25.7	4130
29	23.60	25.9	4165
30	24.20	26.7	4220
31	23.98	26.5	4240
32	23.99	26.7	4280
33	25.80	28.8	4385
34	23.20	26.5	4495
35	22.40	26.0	4600
36	23.15	25.4	4140
37	24.67	26.9	4120
38	25.48	28.0	4220
39	26.85	29.1	4140
40	29.87	31.7	4015
41	31.69	33.3	3940
42	30.00	31.2	3800
43	24.44	25.0	3580
44	22.57	23.1	3570
45	23.10	23.5	3550
46	24.28	24.7	3550
47	---------------No Hole-------------		
48	24.11	24.8	3620
49	24.80	25.3	3560
50	29.20	29.9	3620
51	30.30	30.8	3580
52	33.58	33.8	3480
53	23.61	25.1	3880
54	23.95	26.2	4130
55	24.83	28.0	4450
56	25.39	28.3	4350
57	24.00	26.9	4360
58	24.27	27.6	4480
59	23.74	26.7	4390
60	22.31	26.7	4838
61	21.60	27.0	5190
62	20.91	26.1	5095
63	22.01	26.7	4950
64	21.51	26.3	4960
65	20.20	24.7	4880
66	20.39	25.0	4930
67	20.57	25.2	4920
68	19.41	23.8	4850
69	18.34	23.1	4950
70	19.39	24.3	5000
71	20.71	25.7	5050
72	20.05	24.9	5000
73	24.31	26.9	4250
74	24.06	26.6	4240
75	22.41	24.9	4220
76	23.21	25.6	4180
77	23.38	25.6	4150
78	23.40	25.6	4125
79	24.30	26.6	4150
80	24.29	26.6	4160
81	23.14	25.4	4160
82	25.72	26.8	3750
83	24.98	25.7	3650
84	24.65	25.2	3590
85	24.39	24.7	3500
86	24.41	24.5	3440
87	24.39	24.3	3390
88	23.25	23.2	3380
89	23.46	23.5	3430
90	23.65	23.7	3420
91	23.79	24.1	3500
92	23.79	24.1	3520
93	24.71	25.1	3530
94	23.61	23.8	3480
95	24.53	24.7	3450
96	24.50	24.8	3500
97	24.98	27.2	4120
98	27.98	30.2	4120
99	23.46	25.6	4120
100	23.25	25.3	4080
101	25.01	26.7	3960
102	24.65	26.0	3840
103	23.25	26.3	4400

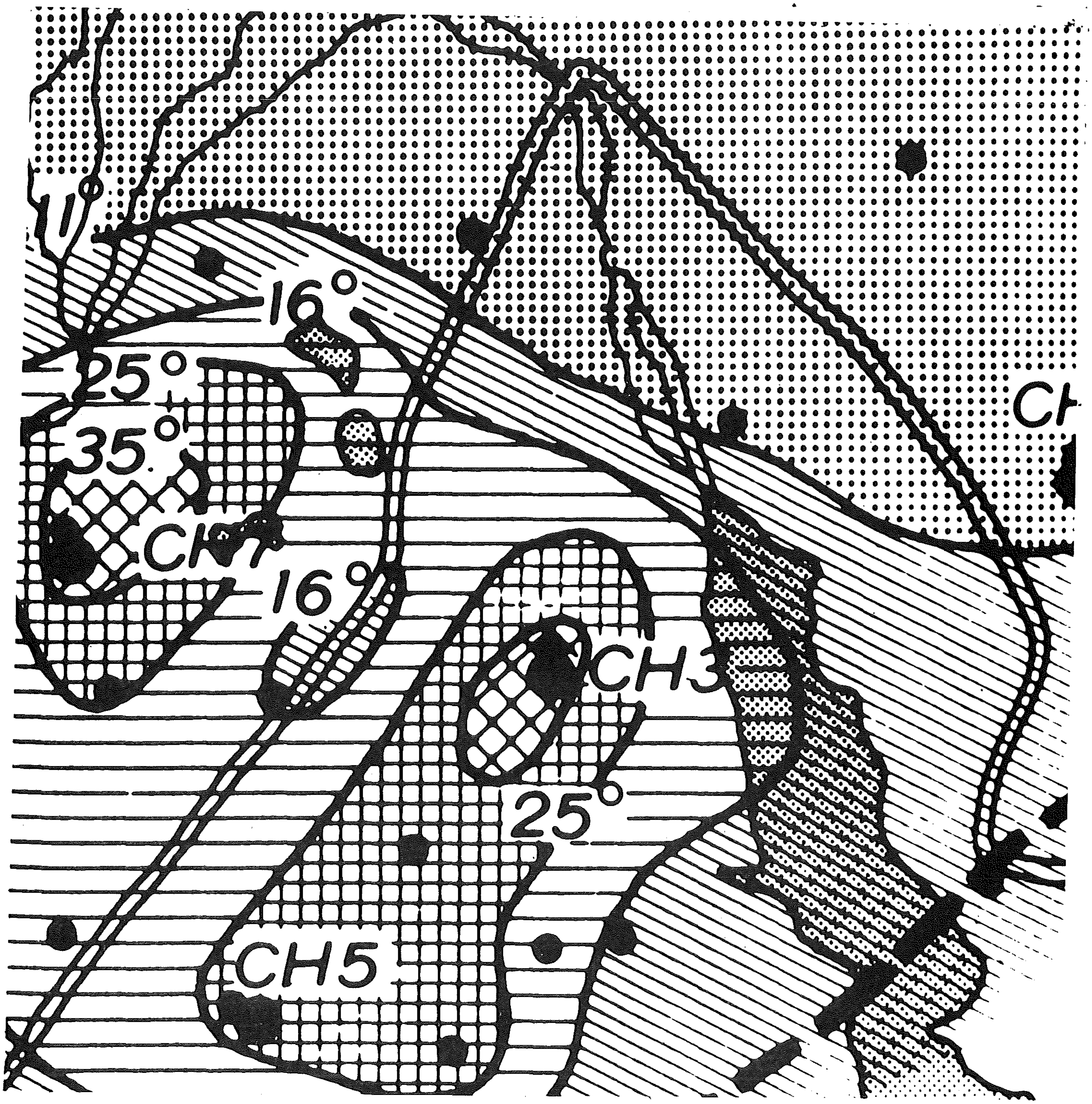


FIGURE 12 (a, above): A section of the 10-m temperature contour map at Long Valley in June (after Lachenbruch, et al., 1976) is compared with a computer-generated 2-m temperature contour map based on our data (b, right). We used 26 of the 27 data points collected on 10 July 1977; site 20 was not used because it was sufficiently high to have produced another anomaly in a location at which USGS did not drill, thus reducing the strong similarity in the two contour maps.

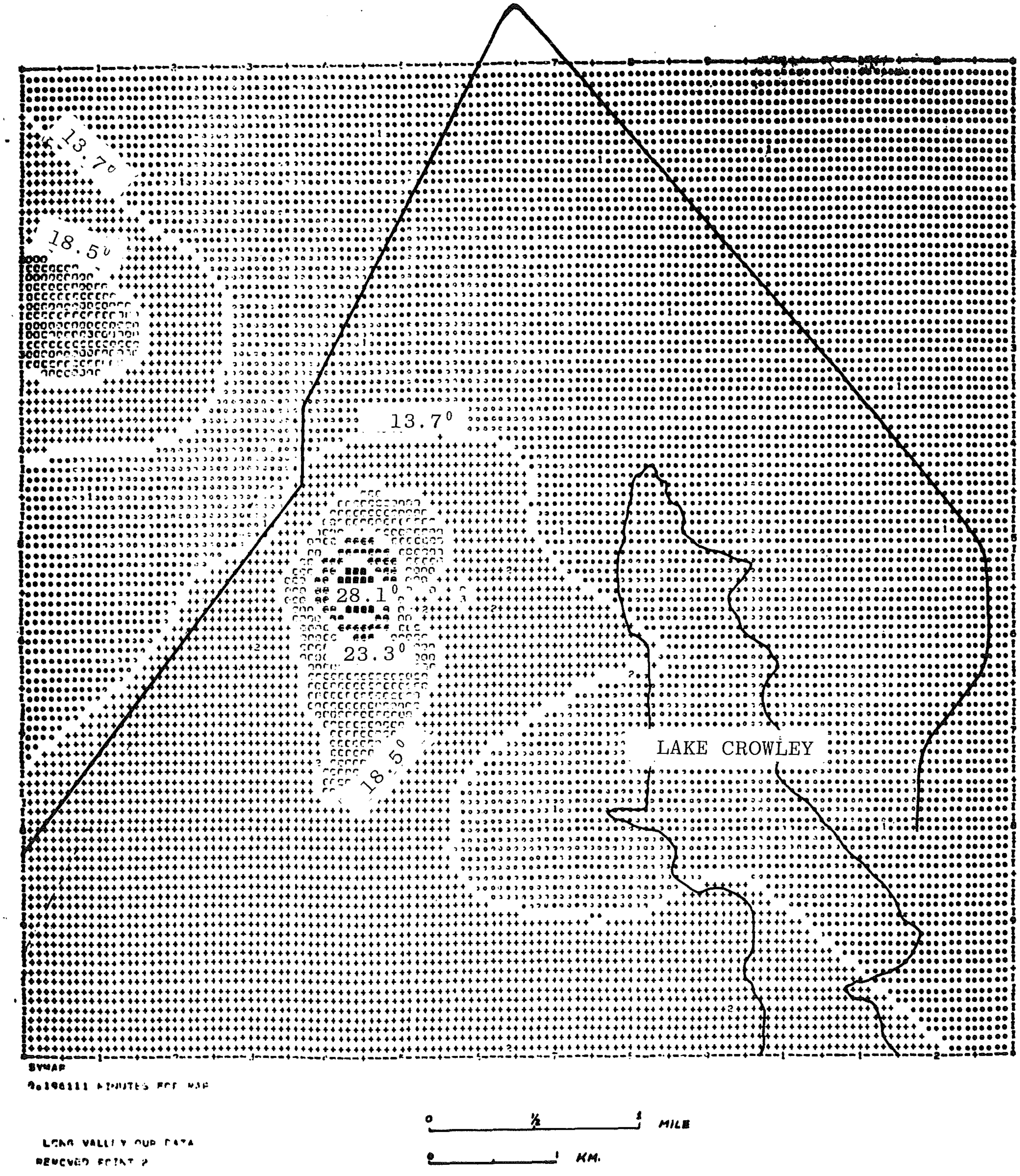
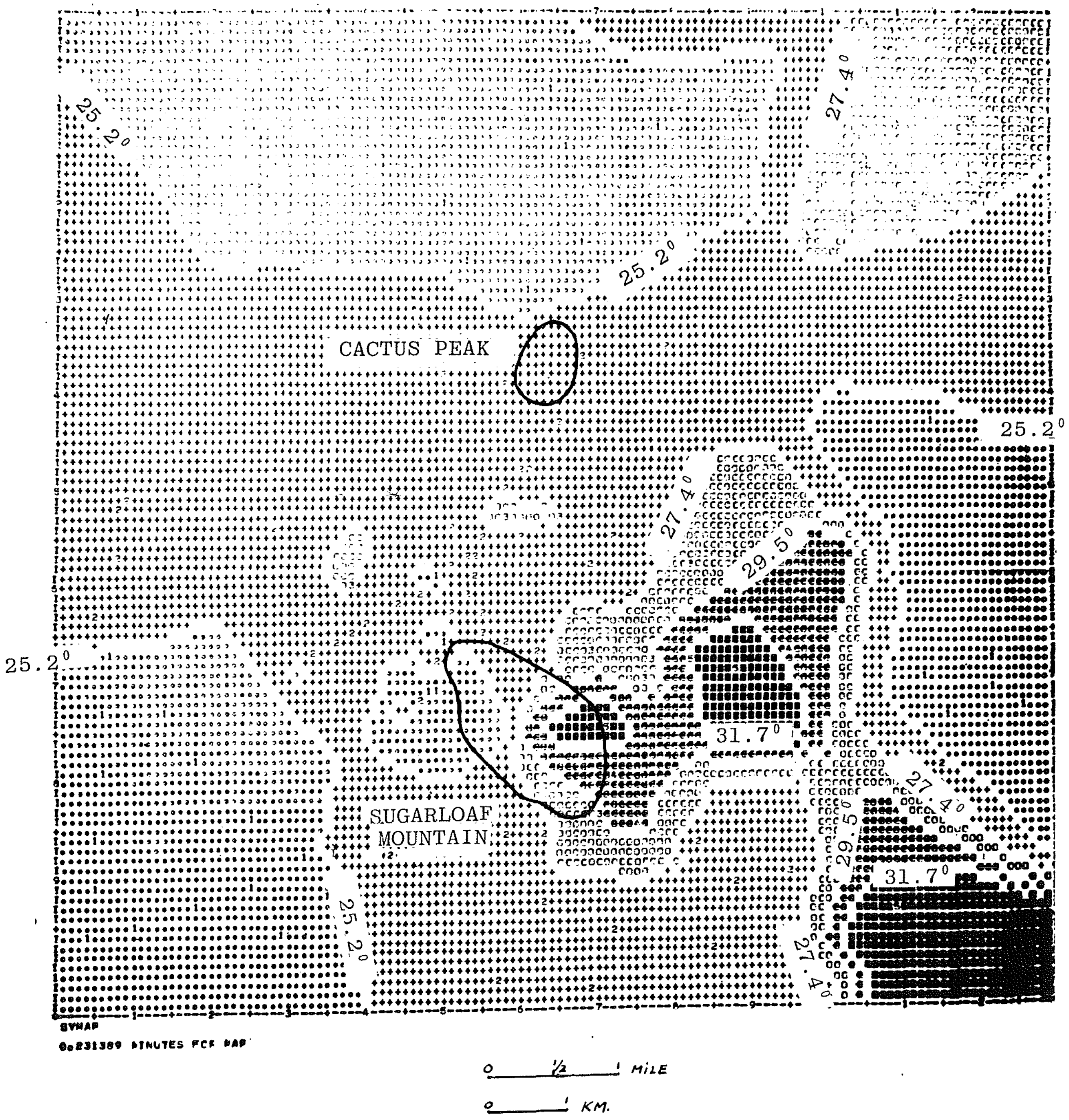

13.7°
18.5°
13.7°
28.1°
23.3°
18.5°
LAKE CROWLEY
SYMAP
0.196111 MINUTES PER MAP
LONG VALLEY OUR DATA
REMOVED POINT 2
0 ½ 1 MILE
0 1 KM.

FIGURE 13 (a, above): A computer-generated 30-m temperature contour map at Coso based on the 21 drill sites of Combs (1975) and Combs (1976) is compared with a similarly constructed map based on our 102 2-m temperatures recorded on 22-23 September 1977 (b, right). Our data were corrected as described in the text. A clear similarity of the anomaly patterns can be seen.


25.2°
27.4°
25.2°
CACTUS PEAK
25.2°
27.4°
29.5°
25.2°
31.7°
SUGARLOAF MOUNTAIN
27.4°
29.5°
31.7°
25.2°
27.4°
SYMAP
0.231389 MINUTES FOR MAP
0 ½ 1 MILE
0 1 KM.

6. Comparison of our 2-m Temperature Contours with Deeper Reconnaissance Data

Figure 12a presents the 10-m temperature contour data recorded by the U.S.Geological Survey at Long Valley as illustrated in Figure 1 of Lachenbruch et al. (1976). It is compared with a computer-generated contour map* (Figure 12b) based on our 2-m temperature data recorded at the same location. Figures 13a and 13b are computer-generated contour maps of the Coso site using the 30-m temperature data of Combs (1975) and Combs (1976) and our corrected 2-m data, respectively. Examination of these two sets of contour maps shows clearly the plots are nearly similar geometrically, and that any value to a geothermal exploration program that would accrue from a standard deep reconnaissance drilling program at either of the sites would also accrue from our shallow temperature survey.

7. Locating Faults at Coso

The shallow soil temperature survey technique enabled Poley and Van Steveninck (1970) to locate near-surface faults that otherwise had no surface expression. They showed there were several characteristic profile signatures which could identify where the profile had crossed the near-surface extension of the fault. Since the Coso area has many faults associated with it (O'Hara, 1977; Duffield and Bacon, 1977), we attempted to identify a few of them by establishing two intersecting profile lines with relatively close spacing between the probes.

Figure 14 shows the faulting at Coso as indicated by the field work and photointerpretation efforts of O'Hara (1977). Superimposed are our profile lines A-A' and B-B' with probes located at intervals of 320 m. Figure 15 shows the temperature profiles recorded along lines A-A' and B-B'. We note that one of the characteristic signatures identified by Poley and Van Steveninck (1970) is observed at three locations along both of the intersecting lines. We have postulated faults across our profile lines as indicated in Figure 14. These faults appear to be essentially coincident with those suggested by O'Hara (1977). We therefore observe that in some areas useful structural information can be provided when a shallow temperature survey is employed to assist in the identification of geothermal anomalies.

8. A Discussion of the Shallow Temperature Survey Method

Kappelmeyer and Haenel in their monograph "Geothermics," stated:

> "Before the locations of deep exploratory wells

---

*SYMAP, Version 5.20, Laboratory for Computer Graphics and Spatial Analysis, Graduate School of Design, Harvard University, Cambridge Massachusetts 02138.

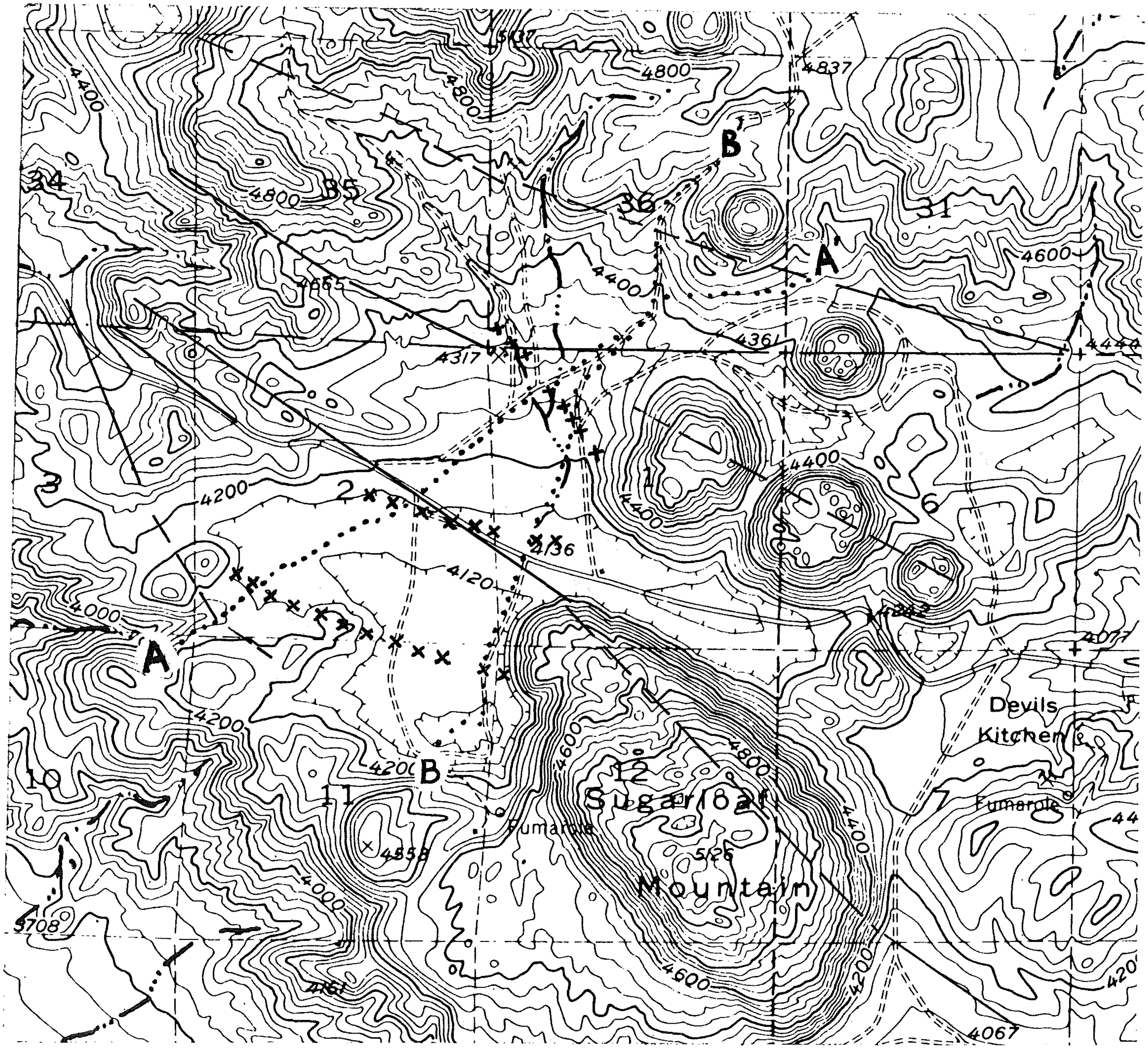


FIGURE 14: Faults at Coso suggested by O'Hara (1977) are indicated by solid and dashed lines. Profiles A-A' and B-B' are indicated by dotted lines. X-lines are faults suggested by correlation of temperature peaks (Figure 15) according to the method of Poley and Van Steveninck (1970).

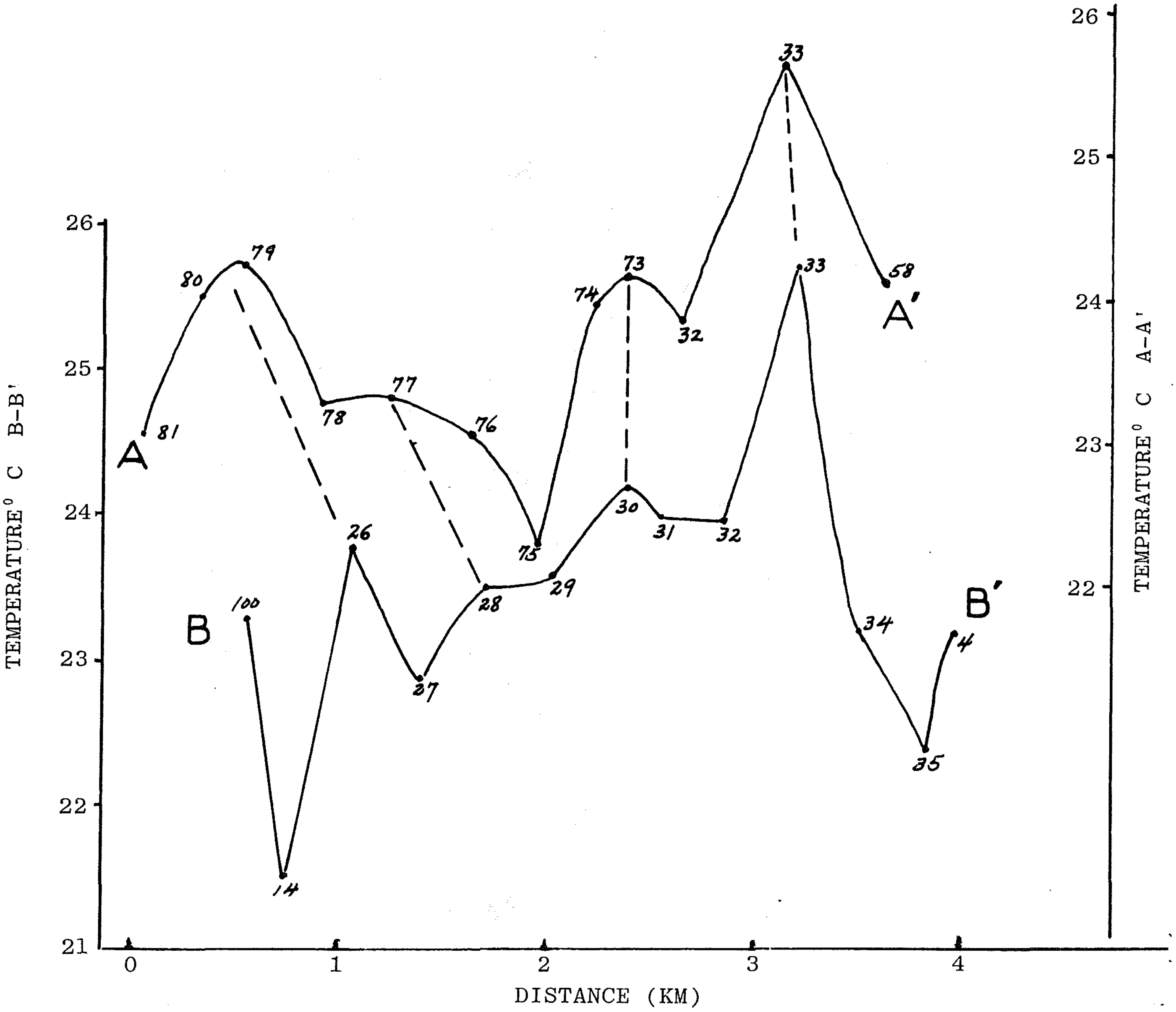


FIGURE 15: Temperature profiles for A-A' and B-B' are correlated. Stations 32 and 33 are common. Dashed lines indicate suggested correlation of temperature peaks caused by faulting. Station numbers are indicated on curves.

> are chosen a more detailed picture of the subsurface should be obtained by geophysical methods. The chances for success are much better if the location of the deep bore holes is planned with the assistance of geophysical data.
>
> "The most useful geophysical exploration methods for geothermal resources are geothermics and geoelectrics. Both methods indicate the existence of hyperthermal zones. Geothermal investigations are performed in bore holes; the information is naturally better from deeper bore holes but for economic reasons the depth is limited. It is usually difficult to decide if a limited budget should be spent on a few deep bore holes or many shallow bore holes."

From the two case histories we have presented here, it seems clear that at the Long Valley and Coso sites there is much redundancy in the data gathered by standard reconnaissance drilling techniques compared with those gathered by the shallow soil temperature technique. With the benefit of hindsight, the dilemma posed above by Kappelmeyer and Haenel could, with respect to either of our sites, be easily solved. Drill many 2-m holes to obtain the outlines of the anomaly and use this shallow survey to choose optimum locations for a few deeper reconnaissance holes. The deeper holes can provide the temperature gradient and thermal conductivity data necessary for a more thorough evaluation of the potential of the geothermal prospect. But the combined cost for the "mixed survey" would be significantly less than a standard reconnaissance survey of the type conducted by Combs (1975) and Combs (1976). Furthermore, in the case of Coso, the results of the combined survey would produce much the same results as the more expensive deep reconnaissance survey.

From the data derived from the deep reconnaissance survey at Coso (Combs, 1975, and Combs, 1976) there is little variation in thermal conductivity vertically or laterally, and there is a close positive correlation between the geothermal gradient and the heat flow. At Coso the heat flow pattern derived from the deep reconnaissance survey could be closely approximated by the shallow soil temperature survey. In short, the shallow temperature survey cannot produce all the specific data of a deep reconnaissance survey, but it can, at our case history sites, provide sufficient data so that the same conclusions about the anomalies could be reached at much less cost.

The Long Valley and Coso sites are quite different because there is moving ground water close to the surface at Long Valley, while the water table is approximately 100 m below the surface at Coso. However, there appears to be an important similarity between the two: Both roughness, albedo and near surface thermal diffusivity. This suggests our techniques will be more successful in similar regions than in humid ones where these variables have potentially greater range. Even though this can be evaluated by more case history studies, there are a large number of geothermal prospects in the western United States that are in arid areas similar to those at Long Valley and at Coso where our technique appears immediately applicable.

From the data presented, we see that the shallow soil temperature survey was able to replicate the anomaly patterns developed from the deeper, more expensive survey. In no way do we imply that this will always be the case. Ground-water movement at various depths between 2 m and 50-100 m could alter the anomaly patterns to be derived from these respective depths. On the other hand, anomaly patterns observed at a depth of 100 m can, owing to structure or fluid movement, disappear at deeper depths. Accordingly, it is unsafe to project downward to any great extent the anomaly patterns obtained at 2-m depth just as anomalies at deeper reconnaissance survey depths sometimes can be misleading. Yet the anomaly patterns obtained at a 2-m depth can be useful in planning a larger, more costly exploration program, especially in areas where there are no visible surface expressions of subsurface geothermal activity. If there is little geothermal activity in the area the data will certainly show this, as in the case of the data gathered by Birman (1969) 180 km south of Coso where the deviations from the mean of his shallow soil temperatures were minimal. Where there is geothermal activity, however, the 2-m data appears to show it and will provide useful insights to further exploration programs at a minimal cost.

9. Summary

Shallow (2-m) soil temperature data have been collected at 27 sites at Long Valley, Calif. and at 102 sites at Coso, Calif. These are locations where traditional deep reconnaissance geothermal survey bore holes have been emplaced, allowing us to compare directly our shallow temperature results with standard geothermal exploration techniques. We have considered the effects of surface roughness, albedo, soil thermal diffusivity, topography and elevation in making corrections to our 2-m temperature data. The corrected data for both locations have been plotted by computer to avoid any personal bias, and have been compared with the published 10-m contour data at Long Valley and the 30-m contour data for Coso. Close geometrical similarity has been observed. We have identified previously located faults with our survey. Due to the relative inexpensiveness of our technique, we conclude the shallow temperature survey method should be one of the first geophysical surveys initiated at a geothermal prospect to help guide the development and expenditure of financial resources when embarking on a detailed exploration program.

10. References

Birman, J.H., 1969, Geothermal Exploration for Ground Water, G.S.A. Bull. V80, pp 617-630.

Birman, J.H., 1977, Pers. Comm., Dept. of Geology, Occidental College, Los Angeles, Ca.

Cartwright, K., 1968, Thermal Prospecting for Ground Water, Water Resources Res., V4, N2, pp 395-401.

Combs, J., 1975, Heat Flow and Microearthquake Studies, Coso Geothermal Area, China Lake, California, Final Report, July 1965, Inst. for Geosciences, Univ. of Texas at Dallas, Richardson, Tx 75080, under contract N00023-74-C-2099, sponsored by the Advanced Research Projects Agency, ARPA Order No. 2800.

Combs, J., 1976, The Coso Geothermal Project, Tech. Rept. No. 3, Dec. 1976, Heat Flow Determinations in the Coso Geothermal Area, California, Battelle Northwest Laboratories, Richland, Wash. 99352 and Center for Energy Studies, Univ. of Texas at Dallas, Richardson, Tx 75080 under Contract E(45-1)-1830, ERDA.

Duffield, W.A., and Bacon, C.R., 1977, Preliminary Geologic Map of the Coso Volcanic Field and Adjacent Aaeas, Inyo County, California, U.S. Geol. Surv. Open File Map 77-311, Sheet 1.

Kappelmeyer, O. and Haenel, R., 1974, Geothermics--with Special Reference to Application, Gebrüder Borntraeger, Berlin-Stuttgart.

Kintzinger, P.R., 1956, Geothermal Survey of Hot Ground Near Lordsburg, New Mexico, Science, 5 Oct V 124, No 3223, pp 629-630.

Lachenbruch, A.H., 1968, Rapid Estimation of the Topographic Disturbance to Superficial Thermal Gradients, Reviews of Geophysics, V.6, No. 3, pp 365-400.

Lachenbruch, A.H., Sorey, M.L., Lewis, R.E., and Sass, J.H., 1976, The Near-Surface Hydrothermal Regime of Long Valley Caldera, J. of Geophs. Res., V 81, No 5. pp 763-768.

Lee, Tien-Chang, 1977, On Shallow-Hole Temperature Measurements--A Test Study in the Salton Sea Geothermal Field, Geophysics, V 42, No 3, pp 572-583.

Lettau, H.H., 1969, Note on Aerodynamic Roughness--Parameter Estimation on the Basis of Roughness--Element Description, J. Applied Meteorology, V8, No.5, pp 828-832.

Lovering, T.S. and Goode, H.D., 1963, Measuring Geothermal Gradients in Drill Holes Less Than 60 Feet Deep East Tintic District, Utah, U.S. Geol. Survey Bul. 1172.

Noble, J.W. and Ojiambo, S.B., 1975, Geothermal Exploration in Kenya, Proc. 2nd U.N. Symposium on Use of Geothermal Resources, San Francisco, Calif. 20-29 May 1975, pp 189-204.

O'Brien, P.J., 1970, Aquifer Transmissivity Distribution as Reflected by Overlying Soil Temperature Patterns, Ph.D. Thesis, The Pennsylvania State Univ. (Geology) 1970.

O'Hara, N.W., 1977, Pers. Comm, based on unpublished data, Dept. of Oceanography and Ocean Engineering, Florida Inst. of Tech. Melbourne, Fla.

Poley, J. Ph. and Van Steveninck, J., 1970, Geothermal Prospecting--Delineation of Shallow Salt Domes and Surface Faults by Temperature Measurements at a Depth of Approximately 2 Meters, Geophs. Prospecting, V18, pp 666-700.

Sabins, F., 1976, Pers. Comm., Chevron Oil Field Research, La Habra, Calif.

Whelan, J.A., 1977, Thermal Gradient and Heat Flow Drilling, Final Report, (V5), under Nat'l Sci. Foundation Contract GI-43741, Univ. of Utah, Salt Lake City, Utah 84112

APPENDIX A

Tabulation of Diurnal Temperature Measurements Made at Long Valley California, 9-10 July 1977

Measurements were made from midnight 9 July to midnight 10 July 1977 at nominally 6-hour intervals. The three readings conducted during daylight hours were mean values, i.e., a given series of stations was read 1,2,3....n, the time between stations being 5-10 minutes, and then were re-read, n-1, n-2, n-3....1; the temperature values for both readings at each station were then averaged, thereby approximating values read simultaneously. For logistic reasons the midnight readings were made only once; however, the rate of change of temperature was small at this time. Temperature is in °C.

Base Station

	Depth (m)					
Time	.10	.25	.50	1.0	1.5	2.0
0052	16.99	19.86	16.58	13.48	11.65	10.20
0749	12.38	17.80	16.71	13.44	11.61	10.23
1324	27.69	18.02	16.66	13.48	11.66	10.24
1905	27.02	20.63	16.55	13.52	11.69	10.27
0052	16.84	20.33	16.70	13.58	11.73	10.30

Station 1

	Depth (m)					
Time	.10	.25	.50	1.0	1.5	2.0
0100	14.33	21.74	18.52	14.19	11.68	10.40
0650	10.80	18.52	18.72	14.16	11.64	10.41
1324	31.36	18.85	18.56	14.20	11.68	10.42
1932	26.94	22.68	18.40	14.21	11.73	10.42
0043	14.70	21.98	18.62	14.26	11.77	10.45

Station 2

	Depth (m)					
Time	.10	.25	.50	1.0	1.5	2.0
0121	16.45	18.99	16.72	13.71	11.60	10.04
0845	13.08	17.53	16.80	13.68	11.56	10.07
1324	25.82	17.58	16.79	13.71	11.60	10.08
1931	23.48	19.43	16.68	13.77	11.62	10.10
0120	16.38	19.10	16.80	13.80	11.66	10.08

Station 3

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0148	18.32	22.30	20.20	16.77	13.39	11.25
0753	15.79	20.46	20.33	16.75	13.34	11.20
1324	29.58	20.63	20.21	16.80	13.40	11.21
1932	26.94	23.01	20.08	16.83	13.41	11.29
0130	18.53	22.52	20.30	16.88	13.45	11.33

Station 4

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0131	17.71	23.39	19.74	15.98	13.61	11.69
0754	13.88	19.97	19.94	15.96	13.60	11.65
1324	32.67	20.51	19.66	16.00	13.63	11.70
1932	30.16	24.57	19.52	16.02	13.70	11.76
0138	17.32	23.35	19.90	16.09	13.72	11.80

Station 5

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
2341	17.90	22.20	19.02	17.10	15.90	14.60
0708	12.22	19.49	19.30	17.13	15.93	14.61
1303	29.90	19.29	19.13	17.14	15.92	14.60
1859	28.78	22.13	18.95	17.18	15.96	14.62
2405	16.80	22.20	19.12	17.21	15.98	14.65

Station 6

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0103	15.20	19.27	19.35	18.67	18.25	18.01
0710	12.30	17.40	19.21	18.99	18.27	18.15
1307	24.17	18.38	18.67	18.69	18.25	17.88
1857	23.40	21.35	18.90	18.70	18.25	17.95
0136	14.85	19.19	19.42	18.65	18.27	18.05

Station 7

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0054	18.17	22.40	21.00	19.20	17.85	16.70
0711	15.21	19.61	20.84	19.23	17.85	16.74
1306	30.10	20.60	20.35	19.28	17.88	16.76
1857	28.70	24.31	20.56	19.30	17.90	16.78
0127	17.80	22.40	21.22	19.38	17.99	16.81

Station 8

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0040	22.10	22.65	19.99	18.00	16.15	14.59
0710	17.69	21.14	20.19	18.01	16.18	14.60
1307	24.91	20.46	20.05	18.02	16.20	14.59
1858	27.06	22.23	19.88	18.07	16.22	14.60
0114	21.79	22.60	21.28	18.10	16.25	14.62

Station 9

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0020	21.00	24.18	21.50	19.67	18.80	18.35
0709	15.45	21.26	21.69	19.69	18.81	18.35
1300	27.96	21.14	21.43	19.72	18.83	18.38
1858	28.92	24.73	21.30	19.75	18.85	18.38
0056	20.50	24.10	21.62	19.79	18.90	18.41

Station 10

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0008	15.55	19.15	16.60	14.22	12.77	11.95
0710	11.70	16.68	16.80	14.24	12.93	12.03
1335	22.70	16.75	16.62	14.21	12.77	11.92
1900	22.81	19.52	16.50	14.26	12.80	11.99
0044	15.10	18.95	16.65	14.30	12.85	12.01

Station 11

	Depth (m)					
Time	.10	.25	.50	1.0	1.5	2.0
2352	21.25	22.02	19.20	17.05	15.35	13.70
0708	15.43	19.83	19.40	17.08	15.35	13.73
1304	25.07	19.26	19.11	17.09	15.34	13.69
1900	27.32	21.91	18.96	17.13	15.38	13.73
0028	20.78	21.90	19.30	17.19	15.45	13.80

Station 12

	Depth (m)					
Time	.10	.25	.50	1.0	1.5	2.0
0138	18.69	24.13	20.99	16.68	14.26	12.69
0753	13.23	21.01	21.12	16.66	14.21	12.63
1322	33.70	20.75	20.82	16.75	14.25	12.69
1930	30.12	25.02	20.54	16.80	14.32	12.71
0146	18.25	24.31	21.20	16.81	14.38	12.79

Station 13

	Depth (m)					
Time	.10	.25	.50	1.0	1.5	2.0
0050	18.40	19.72	15.80	12.20	10.19	8.88
0749	13.30	17.42	15.93	12.17	10.21	8.87
1224	24.44	17.16	15.83	12.20	10.22	8.88
1933	25.04	19.73	15.69	12.22	10.23	8.90
0033	18.67	19.89	15.81	12.28	10.26	8.94

Station 14

	Depth (m)					
Time	.10	.25	.50	1.0	1.5	2.0
0027	19.20	20.30	16.90	13.80	11.24	9.46
0749	14.89	18.37	17.03	13.80	11.23	9.47
1326	24.93	18.31	16.99	13.80	11.22	9.48
1939	25.33	20.27	16.90	13.84	11.29	9.50
0009	19.40	20.40	17.00	13.90	11.34	9.53

Station 7

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0054	18.17	22.40	21.00	19.20	17.85	16.70
0711	15.21	19.61	20.84	19.23	17.85	16.74
1306	30.10	20.60	20.35	19.28	17.88	16.76
1857	28.70	24.31	20.56	19.30	17.90	16.78
0127	17.80	22.40	21.22	19.38	17.99	16.81

Station 8

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0040	22.10	22.65	19.99	18.00	16.15	14.59
0710	17.69	21.14	20.19	18.01	16.18	14.60
1307	24.91	20.46	20.05	18.02	16.20	14.59
1858	27.06	22.23	19.88	18.07	16.22	14.60
0114	21.79	22.60	21.28	18.10	16.25	14.62

Station 9

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0020	21.00	24.18	21.50	19.67	18.80	18.35
0709	15.45	21.26	21.69	19.69	18.81	18.35
1300	27.96	21.14	21.43	19.72	18.83	18.38
1858	28.92	24.73	21.30	19.75	18.85	18.38
0056	20.50	24.10	21.62	19.79	18.90	18.41

Station 10

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0008	15.55	19.15	16.60	14.22	12.77	11.95
0710	11.70	16.68	16.80	14.24	12.93	12.03
1335	22.70	16.75	16.62	14.21	12.77	11.92
1900	22.81	19.52	16.50	14.26	12.80	11.99
0044	15.10	18.95	16.65	14.30	12.85	12.01

Station 11

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
2352	21.25	22.02	19.20	17.05	15.35	13.70
0708	15.43	19.83	19.40	17.08	15.35	13.73
1304	25.07	19.26	19.11	17.09	15.34	13.69
1900	27.32	21.91	18.96	17.13	15.38	13.73
0028	20.78	21.90	19.30	17.19	15.45	13.80

Station 12

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0138	18.69	24.13	20.99	16.68	14.26	12.69
0753	13.23	21.01	21.12	16.66	14.21	12.63
1322	33.70	20.75	20.82	16.75	14.25	12.69
1930	30.12	25.02	20.54	16.80	14.32	12.71
0146	18.25	24.31	21.20	16.81	14.38	12.79

Station 13

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0050	18.40	19.72	15.80	12.20	10.19	8.88
0749	13.30	17.42	15.93	12.17	10.21	8.87
1224	24.44	17.16	15.83	12.20	10.22	8.88
1933	25.04	19.73	15.69	12.22	10.23	8.90
0033	18.67	19.89	15.81	12.28	10.26	8.94

Station 14

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0027	19.20	20.30	16.90	13.80	11.24	9.46
0749	14.89	18.37	17.03	13.80	11.23	9.47
1326	24.93	18.31	16.99	13.80	11.22	9.48
1939	25.33	20.27	16.90	13.84	11.29	9.50
0009	19.40	20.40	17.00	13.90	11.34	9.53

Station 15

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0021	19.19	21.41	18.61	15.44	13.37	11.74
0752	14.52	19.57	18.78	15.44	13.37	11.75
1326	26.27	19.23	18.72	15.46	13.39	11.74
1941	25.62	21.20	18.60	15.49	13.41	11.77
0003	19.82	21.60	18.64	15.53	13.45	11.81

Station 16

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0013	19.59	22.99	20.99	20.00	19.74	20.20
0749	16.38	20.21	21.16	20.00	19.76	20.22
1327	28.64	20.58	20.98	20.02	19.78	20.22
1942	25.17	23.26	20.84	20.05	19.80	20.20
2354	18.05	22.91	21.00	20.06	19.80	20.26

Station 17

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0033	19.40	22.25	18.08	14.08	11.79	10.38
0750	14.62	19.38	18.34	14.08	11.76	10.40
1326	28.58	19.45	18.28	14.08	11.76	10.40
1938	27.61	22.38	18.05	14.12	11.79	10.41
0015	19.45	22.40	18.21	14.15	11.83	10.43

Station 18

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0039	16.14	17.98	16.36	14.20	12.70	12.20
0749	13.92	16.91	16.40	14.20	12.70	12.20
1325	21.59	17.04	16.39	14.20	12.69	12.20
1936	21.15	17.91	16.31	14.21	12.76	12.23
0021	16.19	17.95	16.30	14.27	12.80	12.26

Station 19

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0000	17.92	20.41	17.72	14.80	13.09	11.94
0748	15.67	18.28	17.83	14.81	13.11	11.95
1326	24.34	18.60	17.34	14.86	13.16	11.99
1945	23.35	20.56	17.67	14.90	13.18	12.00
2342	18.40	20.60	17.79	14.94	13.20	12.00

Station 20

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0102	14.51	18.74	19.33	19.81	20.20	21.08
0748	14.53	17.52	19.38	19.82	20.25	21.05
1326	22.48	18.20	19.32	19.84	20.28	21.08
1945	21.16	19.66	19.28	19.84	20.24	21.11
0057	15.90	19.34	19.37	19.83	20.27	21.10

Station 21

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
0014	19.70	20.59	18.70	16.78	15.40	14.66
0708	15.68	19.35	18.88	16.79	15.40	14.66
1322	22.73	18.88	18.78	16.79	15.40	14.68
1859	25.32	20.31	18.67	16.81	15.45	14.71
0043	19.69	20.69	18.83	16.84	15.46	14.73

Station 22

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
2322	19.80	21.55	19.55	18.72	18.58	18.70
0709	13.79	19.62	19.67	18.75	18.60	18.70
1304	25.61	19.31	19.62	18.76	18.60	18.72
1859	26.29	21.14	19.51	18.77	18.62	18.74
2346	18.97	21.39	19.58	18.80	18.65	18.75

Station 23

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
2315	21.92	26.47	26.35	28.10	30.25	32.90
0708	15.97	24.00	26.55	28.10	30.26	32.93
1304	28.78	23.94	26.29	28.18	30.30	32.89
1800	28.95	26.40	26.18	28.17	30.32	32.95
2339	20.83	26.47	26.43	28.19	30.35	32.99

Station 24

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
2329	17.90	19,62	17.01	15.02	13.60	12.70
0711	12.91	17.03	17.16	15.02	13.63	12.73
1304	23.33	17.34	16.93	15.01	13.60	12.71
1859	23.42	19.73	16.80	15.05	13.64	12.74
2353	17.00	19.30	17.01	15.08	13.70	12.80

Station 25

Depth (m)

Time	.10	.25	.50	1.0	1.5	2.0
2337	20.30	21.29	18.57	16.75	15.50	14.90
0708	14.24	19.21	18.73	16.75	15.53	14.88
1304	24.53	18.49	18.58	16.75	15.49	14.86
1859	27.59	20.88	18.45	16.79	15.55	14.90
2400	19.80	21.40	18.63	16.83	15.58	14.95

Station 26

Time	.10	.25	.50	1.0	1.5	2.0
2319	20.95	21.05	19.43	18.00	17.25	16.82
0709	16.84	19.61	19.58	18.02	17.26	16.84
1305	22.86	19.57	19.52	18.02	17.27	16.81
1858	24.40	20.84	19.45	18.04	17.30	16.91
2343	20.40	21.02	19.49	18.10	17.35	16.90

APPENDIX B

Analytical Methods Used for Soils Analysis

1. Moisture content.

   The sample was oven dried at 105^{o} for 24 hours, and the weight loss expressed as a percentage of the oven dry soil.

2. Bulk density.

   The oven dry soil weight was divided by the volume of the core, to give the bulk density in $g.cm^{-3}$.

3. Particle size analysis.

   The oven dried soil was passed through a 2mm sieve; the portion remaining of the sieve is gravel (> 2mm diameter). A 40 g. sample of the fine earth (< 2 mm) was used in particle size analysis for sand (2 - 0.05 mm), silt (0.05 to 0.002 mm) and clay (< 0.002 mm) by the hydrometer method using sodium hexametaphosphate as a dispersing agent (Day, 1965). The sand, silt and clay contents are expressed as a percentage of the oven dry, < 2mm soil.

4. Organic carbon and organic matter content.

   Organic carbon was determined by the Walkley and Black dichromate oxidation method, using silver nitrate to precipitate chlorides (Allison, 1965). The results are expressed as percentage organic matter in the < 2mm fraction, using a conversion of factor of 2.5 for organic carbon to organic matter.

Allison, L.E. (1965). Organic carbon. pp. 1367-1378 in Black, C.A. (ed.) Methods of Soil Analysis. Amer. Soc. Agron., Madison, Wisc.

Day, P.R. (1965). Particle fractionation and particle size analysis. pp. 545-567 in Black C.A. (ed.) Methods of Soil Analysis. Amer. Soc. Agron., Madison, Wisc.