PART II, EVALUATION OF THE PALLMANN TECHNIQUE IN TWO GEOTHERMAL AREAS OF WEST-CENTRAL NEVADA

By F. H. OLMSTED, IRVING FRIEDMAN, and DANIEL R. NORTON

CONTENTS

ILLUSTRATIONS

TABLES

ABSTRACT

The Pallmann method, which derives an integrated temperature on the basis of the hydrolysis of sucrose to invert sugar, was tested as a means of geothermal exploration at shallow depths in two adjoining geothermal areas of west-central Nevada. Integrated Pallmann temperatures for a 12-month period and a 3-month, midwinter, period at depths of 1 and 2 meters (m) are compared with temperatures at 15 m obtained by more conventional methods at 15 sites in the Soda Lakes area and 8 sites in the Upsal Hogback area. The field tests suggest that the Pallmann method is useful in mapping temperature anomalies at greater depths and that the method may be superior to a conventional set of synoptic temperature measurements in outlining diffuse temperature anomalies where the areal differences in temperatures at depths of 15 m or more are relatively small. Better results were obtained with data obtained at a depth of 2 m than at 1 m. Correlations between the Pallmann temperatures for the 3-month, midwinter, period and temperatures at 15 m were better than between the Pallmann temperatures for the 12-month period and the 15-m temperatures, probably because of the smaller difference between the Pallmann temperatures (exponential means) and the arithmetic-mean temperatures for the shorter period.

INTRODUCTION

In principle, the utility of temperature measurements at depths of 1 or 2 m in geothermal exploration is enhanced if annual averages rather than single sets of synoptic values are used. Until recently, however, the determination of mean annual temperature generally has involved the use of either frequent periodic measurements with thermometer probes or buried thermometers of various types connected to expensive recording equipment. The cost advantages of many measurements at shallow depths over fewer measurements at greater depths, below the zone of annual temperature fluctuation, are therefore largely lost. Clearly, a measurement technique is needed which is more convenient and less expensive than instrumental methods and which is applicable to remote places where access is difficult.

One such technique, described by Pallmann and others (1940), derives an integrated temperature on the basis of the hydrolysis of sucrose to invert sugar. This method, hereinafter referred to for convenience as the "Pallmann method," has been tested in a variety of settings, summarized by Lee (1969), and particularly in soil-temperature measurements (O'Brien, 1971). O'Brien's results, in a small area near Schenectady, N.Y., were sufficiently encouraging that the method was tested by two of us in Yellowstone National Park (Friedman and Norton, PART III, present paper) and further tests, in a different geologic and climatic setting in west-central Nevada, seemed warranted.

In this paper we describe the results of field tests in two adjoining geothermal areas in west-central Nevada, where abundant temperature data obtained by more conventional methods at depths of 15-30 m are available (Olmsted and others, 1975; Olmsted, 1977).

The theory as well as laboratory and field methods are discussed in PART I, Pallmann Technique, by Norton and Friedman.

AREAS SELECTED FOR FIELD TESTS

Two areas, designated the Soda Lakes and Upsal Hogback geothermal areas, were selected for field tests of the Pallmann method. Both areas are in the west-central Carson Desert, about 100 km east of Reno, Nev. (fig. 2). Abundant information about the geology, hydrology, and the temperature distribution to depths of about 150 m was available from previous studies (Olmsted and others, 1975, p. 99–118; Olmsted, 1977).

The Soda Lakes geothermal area occupies about 21 km^2 (square kilometers) between Soda Lakes to the south-southwest and Upsal Hogback to the north-northeast. Both Soda Lakes and Upsal Hogback are late Pleistocene to Holocene basaltic eruptive centers, probably alined along a concealed fault or fault system. The Soda Lakes thermal anomaly probably results from upward leakage of hot water along a steeply inclined or vertical fault-controlled conduit into shallow sand aquifers, through which the hot water moves north-northeastward, in the direction of the near-surface hydraulic gradient (Olmsted and others, 1975, p. 104). Previous data from synoptic temperature measurements at a depth of 1 m indicated relatively high temperatures and large heat flows in the hottest part of the thermal anomaly. Conditions seemed especially favorable for the application of the Pallmann method.

The Upsal Hogback geothermal area lies several kilometers north-northeast of the Soda Lakes area, generally east and north of Upsal Hogback. Although somewhat more extensive than the Soda Lakes geothermal area, the Upsal Hogback area is characterized by much lower near-surface temperatures and smaller heat flows. Correlation of synoptic temperatures at 1-m depth and temperatures at 30 m is poor, owing to the relatively small amplitude of the thermal anomaly and the relatively large perturbing effects of nongeothermal factors (Olmsted, 1977, p. B21, B24). Conditions, therefore, seemed much less favorable for application of the Pallmann method than in the Soda Lakes area. However, we hoped that the temperatures obtained with the Pallmann method at shallow depth would show a better correlation with those at greater depth than did the synoptic measurements at 1 m reported by Olmsted (1977).

FIELD TECHNIQUES AND INSTRUMENTATION

Most of the Pallmann samples were placed near sites of earlier U.S. Geological Survey or U.S. Bureau of Reclamation test wells, or 1-m temperature-measurement sites used by Olmsted (1977). Criteria for site selection included: (1) Level or nearly level ground; (2) absence of nearby vegetation which could shade the site for significant periods of time; (3) sufficient distance (generally at least 10 m) from nearby test wells to avoid possible perturbing effects; and (4) alinement of sites along and across the long axes of the two thermal anomalies so as to check the previous interpretation (Olmsted, 1977) of the extent and configuration of the anomalies. A total of 15 sites in the Soda Lakes area and 8 sites in the Upsal Hogback area were occupied for the 1-year period from mid-December 1976, to mid-December 1977. Additional samples were placed at 19 of the 23 sites for the 3-month period from mid-December 1977, to mid-March 1978.

In order to provide data for comparison with and adjustment of some of the Pallmann-method temperatures, monthly measurements were made with a 1-m thermistor probe at four sites in the Soda Lakes area and four sites in the Upsal Hogback area from mid-December 1976, to mid-March 1978. Measurement techniques were those described by Olmsted (1977, p. B5).

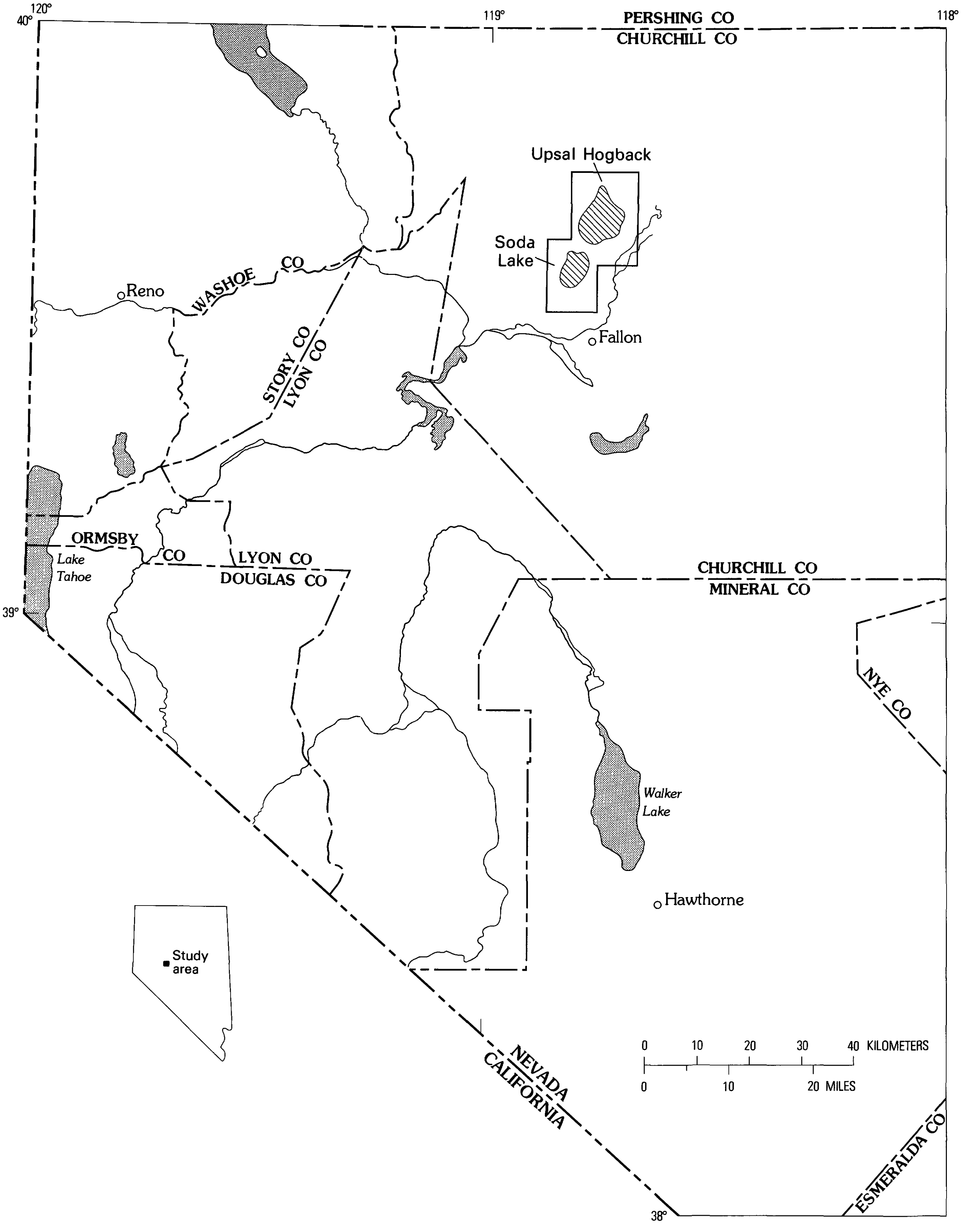


FIGURE 2.—West-central Nevada, showing the location of Soda Lakes and Upsal Hogback geothermal areas.

DATA REDUCTION AND INTERPRETATION

Pallmann temperatures at depths of 1 and 2 m were determined by the method described by Norton and Friedman in PART I of the present paper. As discussed by them and by Lee (1969) and O'Brien (1971), the Pallmann method consistently overestimates integrated arithmetic-mean temperature for the period of measurement because the rate of sucrose hydrolysis varies exponentially instead of linearly with temperature. The magnitude of the difference between the measured exponential-mean temperature and the arithmetic-mean temperature increases with increasing temperature range but decreases slightly with increasing mean temperatures. Lee (1969, p. 427) and Norton and Friedman (PART I, fig. 1) have calculated the corrections to the measured Pallmann temperatures, assuming harmonic temperature fluctuation for the period of interest and using an activation energy of 27 kcal/mole (kilocalories per mole) for the Pallmann reaction. The larger corrections associated with the larger ranges in temperature fluctuation account for the higher measured Pallmann temperatures at 1 m than at 2 m at many sites in the Soda Lakes and Upsal Hogback areas. Actually, at most places net heat flow for a yearly cycle is upward, and the integrated arithmetic-mean annual temperature at 1 m is therefore less, not greater, than that at 2 m.

Comparisons between adjusted Pallmann temperatures—integrated arithmetic means—and means determined by thermistor measurements at monthly intervals at a depth of 1 m at eight sites in the Soda Lakes and Upsal Hogback areas are presented in table 5. Two periods of comparison were used: (1) The 3 months from December 15, 1977, to March 15, 1978; and (2) the 12 months from December 15, 1976, to December 15, 1977. For each of these periods the measured Pallmann temperatures were adjusted to integrated arithmetic-mean temperatures, using the temperature ranges and mean temperatures measured by thermistor and the corrections given by Norton and Friedman (PART I, fig. 1). Because the Pallmann solution ampoule at 1 m was broken upon recovery in December 1977, at one site (72) in the Upsal Hogback area, and another site (62), in the Soda Lake area, was not reoccupied during the ensuing 3 months, only seven of the eight Pallmann sites provided temperature data for comparison with the concurrent thermistor temperatures.

For the 3 months from December 15, 1977, to March 15, 1978, the corrections to the measured Pallmann temperatures at the seven sites were only −0.1 to −0.3°C because of the relatively small temperature fluctuation for this midwinter period (3.3-5.9°C). Except for two of the sites, where the Pallmann probe was inadvertently buried about 0.5 and 0.2 m too deep, agreement is good between the adjusted Pallmann temperatures and the thermistor temperatures: the differences are only a few tenths of a degree Celsius.

For the preceding 12-month period, larger corrections to the measured Pallmann temperatures were required (1.7°-3.6°C) because of the larger fluctuations in temperature (14.0°-21.6°C) for this period. In spite of the larger corrections, agreement between adjusted Pallmann temperatures and thermistor temperatures is as good for the annual period as for the 3-month period.

Because of the absence of concurrent thermistor temperature measurements the temperature-fluctuation data required for calculating adjusted Pallmann temperatures were not obtained at most of the Pallmann sites. For this reason, we use measured (unadjusted) Pallmann temperatures in the following discussions of results in the two geothermal areas. As described above, these measured temperatures may be several degrees Celsius higher than the integrated arithmetic-mean temperatures, especially for longer periods such as a year and at depth of only 1 m. However, the feasibility of the Pallmann method as a geothermal exploration tool depends in large part on the usefulness of the uncorrected temperatures in delineating areas underlain by abnormal temperatures at greater depth.

TABLE 5.—*Comparison of measured and adjusted Pallmann temperatures with thermistor temperatures at a depth of 1 m*

[Leaders (- - -) indicate no data]

Pallmann site number	Temperature, in degrees Celsius			
	Measured Pallmann	Adjusted Pallmann	Thermistor	Difference[1]
3 months				
57	8.8	8.6	7.9	[2]0.7
58	26.6	26.3	21.8	[2]4.5
60	16.5	16.2	16.0	[3]0.2
72	12.7	12.5	10.7	[3]1.8
73	9.1	9.0	8.7	0.3
74	9.7	9.6	10.1	−0.5
76	9.9	9.7	9.6	0.1
12 months				
57	19.0	15.5	15.8	−0.3
58	>26.8	>24.8	26.6	- - -
60	23.8	22.1	22.2	−0.1
62	21.0	17.4	17.4	0.0
73	18.5	15.7	16.2	−0.5
74	17.5	15.0	15.5	−0.5
76	18.9	16.3	16.0	0.3

[1]Adjusted Pallmann temperature minus thermistor temperature.
[2]Pallmann probe ~ 0.5 m too deep; adjusted temperature probably ~ 4°-5°C too high.
[3]Pallmann probe ~ 0.2 m too deep; adjusted temperature probably ~ 1°C too high.

RESULTS IN SODA LAKES GEOTHERMAL AREA

Measured Pallmann temperatures for 12 months at 1 and 2 m at 15 sites in the Soda Lakes area outline in a general way the thermal anomaly defined by temperatures at 15 m in test wells (fig. 3). Temperatures at 15 m range from more than 100°C (boiling temperatures at hydrostatic depth) in the southwest part of the anomaly to less than 20°C on the margins of the anomaly. The general north-northeasterly alinement of the anomaly is delineated clearly by the Pallmann temperatures, but the temperatures at 1 m delineate only the hottest area (more than 40°C at 15 m). Temperatures at 1 m in the hottest area probably are more than 10°C higher than the background values, which range from less than 19°C to more than 18°C.

Temperatures at 2 m for the same period at the same 15 sites appear to define the north-northeasterly elongation of the deeper, 15-m anomaly somewhat better than do the 1-m temperatures. At many sites the 2-m temperatures are less than the measured 1-m temperatures for the same 12-month period because of the smaller fluctuation and correspondingly smaller negative correction at the 2-m depth.

Correlation of temperatures at a depth of 15 m—below the range of significant annual temperature fluctuation—with temperatures at depths of 1 or 2 m affords a useful index of the reliability of the shallower measurements in outlining deeper thermal anomalies. The correlation of temperature at 15 m with temperature at 2 m measured by the Pallmann method for the 12-month period at nine sites is shown in figure 4. The coefficient of determination, r^2 (a measure of variance), is 0.93, which indicates a fairly good fit to the least-mean-squares regression. Similar correlations for depths of 15 and 1 m and for the 3-month period are summarized in table 2. As might be expected because of larger range in annual temperature fluctuations at 1 m than at 2 m, the correlation of temperature at 15 m with that at 1 m is poorer than for 15 m versus 2 m (r^2 = 0.77 instead of 0.93). The similar correlations for the 3-month period indicate a somewhat better fit (larger values of r^2) for these data, probably because of the smaller temperature fluctuations during the 3-month period as compared to the 12-month period.

RESULTS IN UPSAL HOGBACK GEOTHERMAL AREA

As shown in figure 5, the areal range in temperature at a depth of 15 m is only about 5°C in the Upsal Hogback area, as compared to a range of more than 80°C in the Soda Lakes area. The corresponding ranges in 12-month Pallmann temperatures at 1 and 2 m are even smaller and do not correlate well with the temperatures at a greater depth. The highest temperature at 2 m (18.4°C) does occur at a site immediately southeast of the hottest part of the thermal anomaly at 15 m, but the temperatures at the other Pallmann sites show no consistent pattern related to the deepter anomaly. Unfortunately, the Pallmann-solution ampoule at 1 m was broken upon recovery from the hottest site at 2 m, so no pattern at all is apparent from the 1-m data.

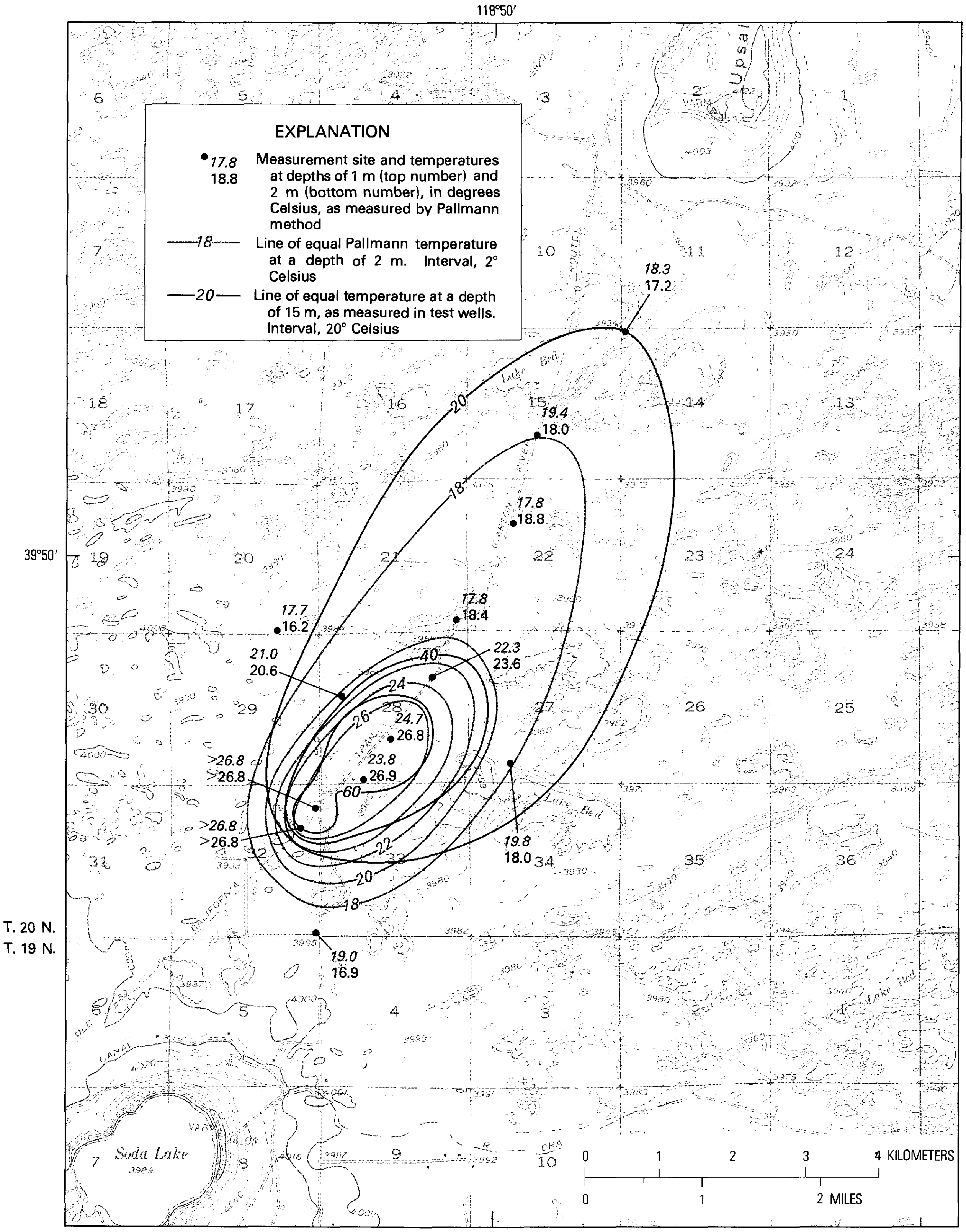
Coefficients of determination (r^2) for the least-mean-squares linear regressions of temperatures at 15 m versus temperatures at 1 and 2 m corroborate the generally poor correlations described above (see table 6). As in the Soda Lakes area, the temperatures at 2 m show a somewhat better correlation with temperatures at 15 m than do the temperatures at 1 m, but the improved correlation for the 2-m data results entirely from the single value southeast of the hottest part of the 6 thermal anomaly, where the measurement at 1 m was lost because of the broken Pallmann ampoule (see fig. 6). Coefficients of determination are significantly higher for the 3-month period than for the 12-month period for both 1- and 2-m data, most likely because of the smaller amplitudes of temperature fluctuation during the shorter period.

TABLE 6.—*Comparison of coefficients of determination* (r^2) *for least-mean-squares linear regressions of temperature at 15 m versus temperatures at 1 m and 2 m*

Depths (m)	Period (months)	Soda Lakes area: No. of sites	Soda Lakes area: Coefficient of determination (r^2)	Upsal Hogback area: No. of sites	Upsal Hogback area: Coefficient of determination (r^2)
1, 15	3	9	0.84	5	0.48
2, 15	3	8	.96	4	.58
1, 15	12	9	.77	4	.06
2, 15	12	9	.93	5	.38

CONCLUSIONS

The results of our field test in the Soda Lakes and Upsal Hogback areas indicated that the Pallmann method of temperature integration, when used at depths of only 1 or 2 m, is useful in mapping temperature anomalies at greater depths, below the range of significant seasonal temperature fluctuation. As is true of more conventional synoptic measurements, the Pallmann method works best where areal differences in temperature at greater depths are large, as in the Soda Lakes area (more than 80°C at 15 m), and is least useful where the areal differences are small, as in the Upsal Hogback area (only about 5°C at 15 m).



Base from USGS 15' topo series. Soda Lake, Nevada

FIGURE 3.—Soda Lakes area, Nevada, showing measured Pallmann temperatures at 1 and 2 m for December 15, 1976, to December 15, 1977, and temperatures at 15 m in test wells for fall 1975.

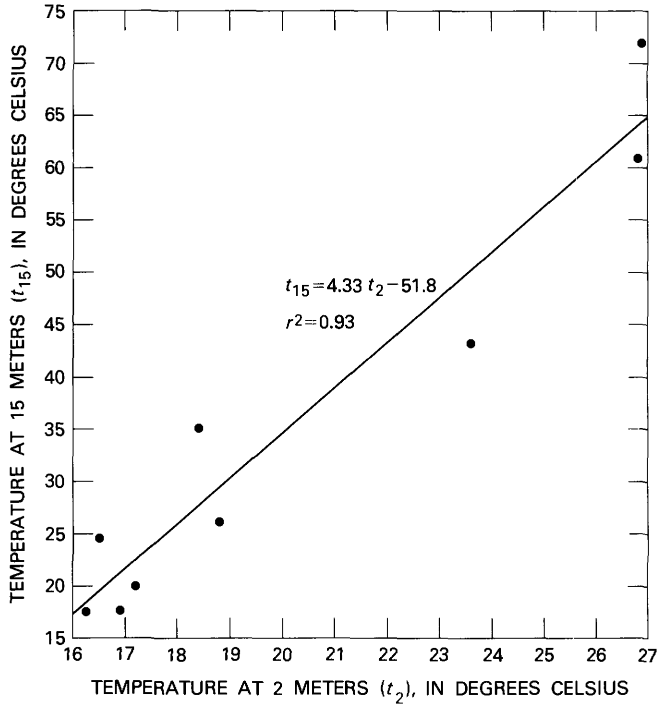


FIGURE 4.—Correlation of temperature at 15 m in test wells with measured Pallmann temperatures at 2 m for December 15, 1976, to December 15, 1977, Soda Lakes area, Nevada.

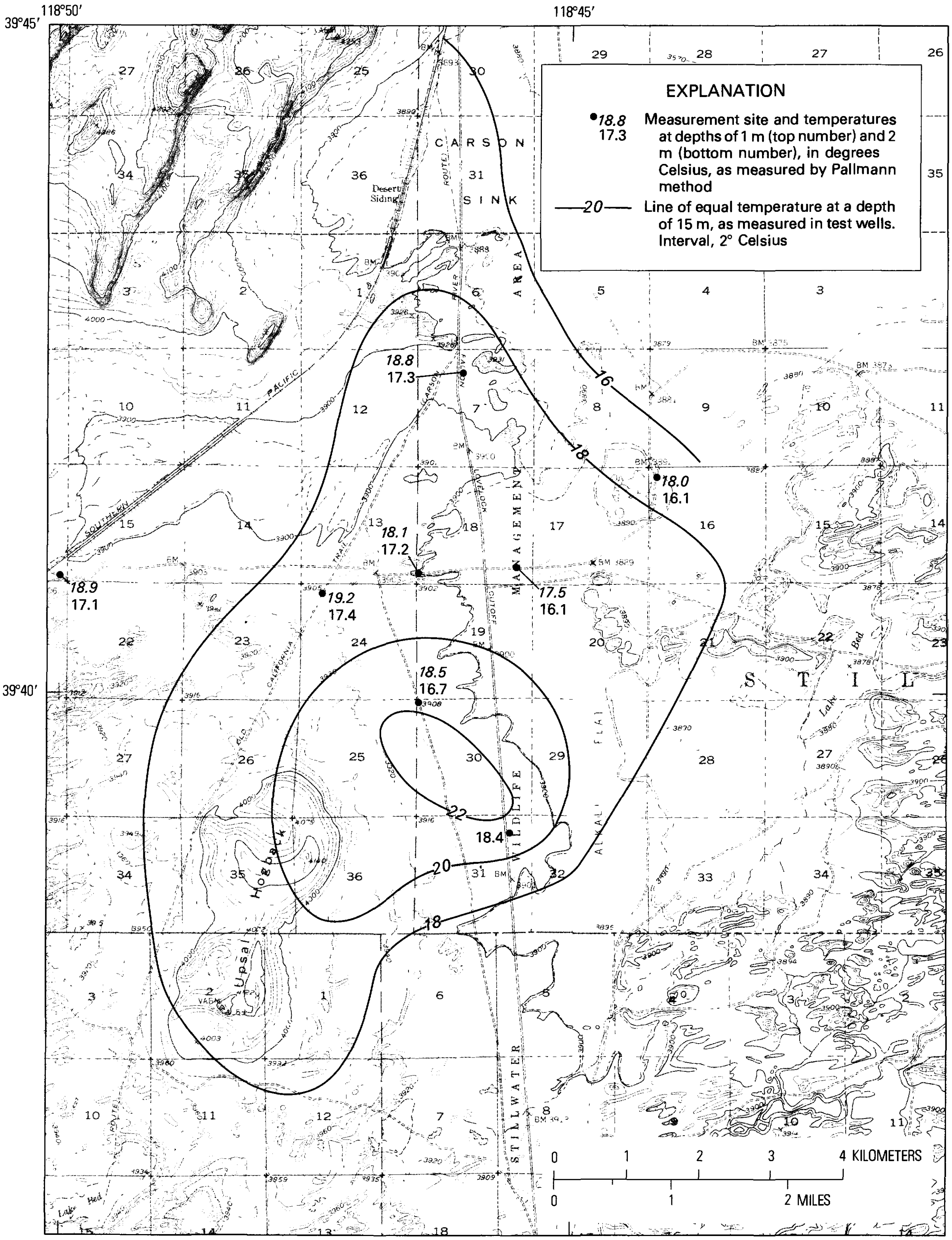
In principle, the chief advantage of the Pallmann method over single sets of synoptic temperature measurements should be in minimizing the perturbing effects of areal differences in thermal diffusivity, degree of stratification of materials, and depth to the water table. All these factors affect both the amplitude and the phase lag of the annual temperature wave but do not significantly affect the average annual temperature at a given depth, which is indicated approximately by the Pallmann temperature. The perturbing effects of the other nongeothermal factors, such as nonuniform topography, albedo, and vegetative cover, would be expected to affect both Pallmann-method and conventional synoptic-method temperature measurements equally because these factors control the average annual temperature at land surface at a site. In principle, therefore, the Pallmann method should be a better exploration tool than a single set of synoptic temperature measurements in mapping diffuse temperature anomalies like that near Upsal Hogback.

Our field test, however, suggested but did not unequivocally demonstrate the superiority of the Pallmann method over conventional synoptic measurements in the Upsal Hogback area. The coefficient of determination (r^2) for the least-mean-squares linear regression of temperatures at 15 m versus temperatures at 1 m for the period December 15, 1977, to March 15, 1978, is 0.48 (table 6); r^2 for the equivalent regression using temperatures measured December 2, 1975, with a thermistor at 1 m at the same sites is only 0.20. For the 12-month period December 15, 1976, to December 15, 1977, r^2 for temperatures at 15 m versus temperature at 1 m by the Pallmann method is only 0.06, but this value represents only four of the five data pairs used in the other correlations; the measurement was lost at the critical site near the hottest part of the 15-m temperature anomaly.

In both the Soda Lakes and the Upsal Hogback areas, Pallmann temperatures at 2 m correlate better with temperatures at 15 m than do the Pallmann temperatures at 1 m. In large part, the improved correlation is a consequence of the smaller variation, at 2 m than at 1 m, in the differences between the Pallmann integrated-mean temperature (an exponential mean) and the true integrated arithmetic-mean temperature. In addition, the temperatures at greater depths are affected less than are the temperatures at shallower depths by other surface and near-surface nongeothermal influences. Insofar as these influences affect the average annual temperature, a part of the advantage of deeper over shallower temperature measurements is common to both synoptic and Pallmann integrated temperatures.

Although in principle a period of a year might appear to be optimum for application of a temperature-integration method, in our field tests the Pallmann temperatures at both 1 and 2 m for a 3-month midwinter period showed a somewhat better correlation with temperatures at a greater depth than did the Pallmann temperatures for a 12-month period at the same depths. The most likely explanation involves the fact that the Pallmann temperatures are integrated exponential means rather than arithmetic means. The smaller temperature flucuation for the shorter period results in smaller difference between the Pallmann temperatures and the arithmetic-mean temperatures. This factor apparently outweighs the effects of the areal differences in the amplitude and phase lag of the annual temperature wave, which would tend to produce more scatter in the 3-month data and a poorer correlation of these shorter term data with temperatures at 15 m or more.

In general, the use of the Pallmann method at depths of 1 or 2 m will have many of the problems common to more conventional temperature measurements at shallow depths. However, the method is convenient and it eliminates the need for the frequent visits to sites that would be required to obtain data of similar quality from sets of synoptic measurements by thermistor or thermocouple probes.



Base from USGS 15' topo series.
Desert Peak, 1951; Carson Sink, 1951;
Soda Lake, 1951; Stillwater, 1950.

FIGURE 5.—Upsal Hogback area, Nevada, showing measured Pallmann temperatures at 1 and 2 m for December 15, 1976, to December 15, 1977, and temperatures at 15 m in test wells for September 1975.

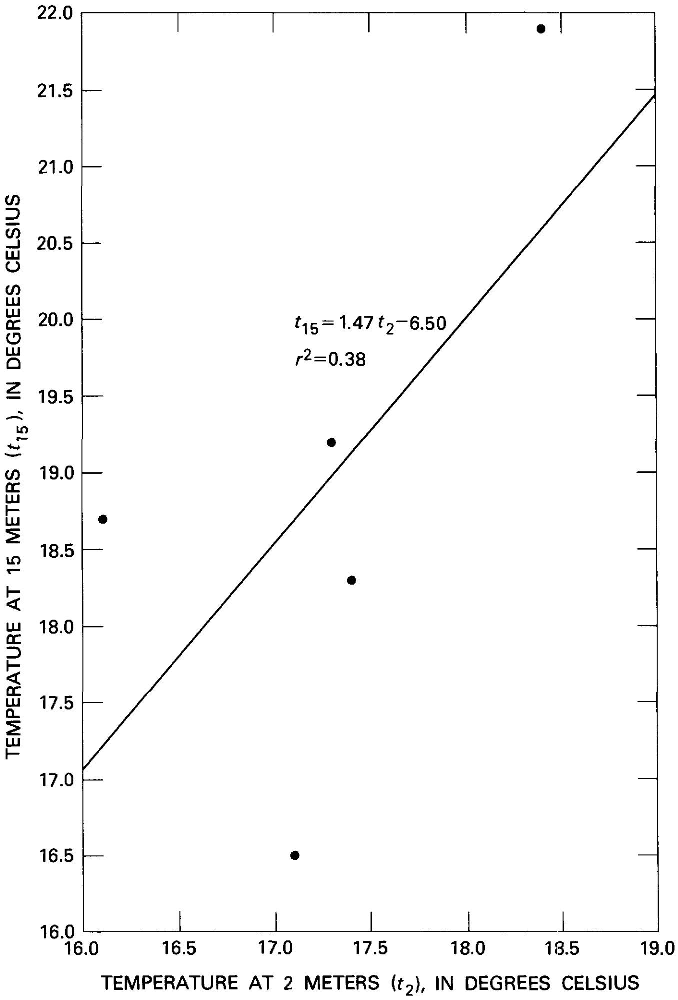


FIGURE 6.—Correlation of temperature at 15 m in test wells with measured Pallmann temperatures at 2 m for December 15, 1976, to December 15, 1977, Upsal Hogback area, Nevada.

REFERENCES CITED

Lee, Richard, 1969, Chemical temperature integration: Journal of Applied Meteorology, v. 8, p. 423-430.

O'Brien, P. J., 1971, Pallmann method for mass sampling of soil, water, or air temperatures: Geological Society of America Bulletin, v. 82, no. 10, p. 2927-2932.

Olmsted, F. H., 1977, Use of temperature surveys at a depth of 1 meter in geothermal exploration in Nevada: U.S. Geological Survey Professional Paper 1044-B, 25 p.

Olmsted, F. H., Glancy, P. A. Harrill, J. R., Rush, F. E., and VanDenburgh, A. S., 1975, Preliminary hydrogeologic appraisal of selected hydrothermal systems in northern and central Nevada: U.S. Geological Survey Open-file Report 75-56, 360 p.

Pallmann, H. E., Eichenberger, E., and Hasler, A., 1940, Eine neue Methode der Temperaturmessung bei okologischen oder bodenkundlichen Untersuchungen [A new method of temperature measurement in ecological or pedological investigations]: Berichte der Schweizerischen Botanischen Gesellschaft p. 337-362.