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Ground-Temperature Measurements

Part I, Pallmann Technique

By DANIEL R. NORTON and IRVING FRIEDMAN

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

Part III, Ground Temperatures in and near Yellowstone National Park

By IRVING FRIEDMAN and DANIEL R. NORTON

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Doyle G. Frederick, *Acting Director*

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ABSTRACT

The measurement of integrated ground temperatures by the use of the Pallmann method was investigated in the laboratory and in the field. The method makes use of the fact that the rate of inversion of a solution of sucrose to invert sugar is temperature-dependent and can be easily monitored. The rate, which is also a function of the pH of the solution, can be adjusted so that the reaction is only partially completed during the time that the temperature is to be monitored. Laboratory calibration of the solution is necessary if accuracies of 0.25° Celsius (C) are to be achieved.

Probes containing Pallmann solution at 1-meter (m) and 2-m depths were designed for insertion into the ground. A method for making 2-m-deep holes in the ground was developed that combines pounding a small steel rod into the ground and then enlarging this small hole by blasting with Primacord.

Field tests using these techniques show that the effective temperature, integrated over the annual temperature cycle at soil depths of 1 and 2 m can be measured with an accuracy of about 0.25°C. Differences in temperature between 1 and 2 m, and between adjacent probes can be measured to about 0.05°C.

Figures are given which allow Pallmann-effective temperatures to be converted to arithmetic-mean temperatures, obsidian-hydration effective temperatures, and Ambrose-effective temperatures. In order to use these figures, the range in temperature experienced by the sample for the time period under consideration must be known, or estimated. A novel method of determining the temperature range utilizes two cells containing materials whose activation energy differs. These cells are buried side by side.

PARTS II and III of the present paper describe field use of the Pallmann method.

INTRODUCTION

Ground-temperature data are needed to date rhyolite flows and glacial moraines that contain rhyolite glass by the obsidian-hydration method and to date organic materials by the amino-acid-racemization dating technique. Shallow ground temperatures may also be useful in detecting and delineating thermal anomalies in potential geothermal-resource areas.

For a number of years, the authors measured ground temperatures by burying temperature sensors in the soil and connecting them to various types of recorders. At many places this method was not feasible because electric power was not available, and access for servicing in the winter was difficult. In addition, malfunctions of the recorders and the necessity of changing recorder charts required frequent visits. In addition, thousands of points had to be read from the charts and then transferred to a computer to calculate average or integrated annual temperatures. The total cost of this method of temperature measurement is high.

A method for temperature measurement more convenient and less expensive than continuous recording, and applicable to remote areas, is the Pallmann method of temperature measurement, first described by Pallmann and others (1940). This method makes use of the fact that an aqueous solution of sucrose slowly hydrolyzes to invert sugar (mixture of glucose and fructose). The rate of this reaction is temperature- and pH-dependent. The higher the temperature the more rapidly the reaction proceeds. The reaction is easily monitored inasmuch as the sucrose has a different angle of rotation of polarized light than the invert sugar, and the rotation can be measured with a polarimeter. Pallmann and others (1940) investigated this reaction extensively and proposed its use for measuring temperatures in the soil for biological investigations. Other investigators (Schmitz, 1964; Schmitz and Volkert, 1959; Lee, 1969; O'Brien, 1971) used the Pallmann method and reported precision on the order of a few hundredths of a degree Celsius. These results, plus convenience, prompted us to investigate the technique as a replacement for the continuous-recording method.

PREPARATION OF PALLMANN SOLUTIONS

The Pallmann solution is a sucrose solution in aqueous media using a citric acid-sodium citrate buffer. Reagent-grade chemicals and distilled water were used. Formaldehyde was added to prevent deterioration of the solution by bacterial growth. Because the sucrose hydrolysis reaction is catalyzed by acid, it was necessary to adjust the pH of the solution to ±0.02 pH units. The Pallmann solutions were made according to the technique given by Schmitz (1964). The solutions were immediately bottled in ampoules or polypropylene bottles, and stored in a freezer at −32°C. The glass ampoules were made of 15-mm o.d. (millimeters outside diameter) tubing with a narrow neck for sealing, and contained 4 ml (milliliters) of solution.

TEMPERATURE PROBE

In order to measure effective ground temperatures by the Pallmann method it is necessary to bury small amounts of sucrose solution sealed in glass ampoules and to be able to retrieve these ampoules after a suitable period of time. Our ampoules were about 15 mm in diameter and contained 4 ml of solution. These ampoules were inserted into probes for insertion into the ground. Our probes were constructed of plastic water pipe (½-inch (12.7-mm) diameter water pipe). One vial was placed at the bottom of the 2-m long probes in a small brass container and another vial was placed at the 1-m position of the same probe enclosed in a brass sleeve to make good thermal contact with the ground. Styrofoam pellets were packed inside the pipe to prevent convection currents. The plastic probe was capped by a metal pipe cap. The probe was buried just below the surface of the ground and the earth was well tamped around it to eliminate air space between soil and probe. In order to locate the probe we mapped its location and then used a metal detector to detect the metal pipe cap at the top of the probe. This technique proved highly successful and we have had no difficulty in locating probes in remote, and in some places featureless, terrain.

When the probes were removed from the ground the Pallmann ampoules were retrieved from the probes and were immediately placed upright in a container of dry ice to freeze. Freezing in the upright position prevented stresses that might have cracked the ampoule.

EMPLACEMENT OF TEMPERATURE PROBE

Different methods of drilling holes to emplace the probes containing Pallmann solution, as well as different designs of probes, were evaluated. Hand augering of the 1-in. (2.5-cm) diameter holes to 2-m depth was of marginal usefulness. It was slow and extremely difficult because the soil often contained pebbles and cobbles. However, this method of emplacing probes has been used on a few occasions. We also investigated the use of lightweight portable gasoline-driven drills. The problem with this technique was the plugging of the 2-m-long auger bit. In addition, the difficulty of handling the 2-m-long drill bits added complications. Small pebbles or cobbles also defeated this device.

The most successful method of emplacing the probes has been to use Primacord[1] to enlarge a small hole. The Primacord method was to first pound into the ground a steel device consisting of an outer thin steel tube $\frac{5}{16}$ in. o.d. and $\frac{1}{4}$ in. i.d. (inside diameter) and an inner steel rod having a diameter slightly less than $\frac{1}{4}$ in. The inner rod was then withdrawn and Primacord (50 grains per foot) was threaded down the tube to the bottom of the hole. The outer steel tube was then withdrawn, leaving the Primacord in place in the soil.

Upon detonation, the Primacord enlarges the hole from its initial $\frac{5}{16}$-in. diameter to approximately 1.5 in. in diameter. The Primacord is a relatively safe explosive because it cannot be detonated without the use of powerful detonators. The exploding bridgewire detonator that we are using is also relatively safe because it contains no sensitive explosive but is detonated by the shock wave produced by an exploding wire. This thin (0.001 in.) gold wire is exploded by passing a high current (approximately 1000 amperes) at high voltage (approximately 3000 volts) through the wire for a short period (1 microsecond). These detonators can only be activated by the use of a special detonation box. We have emplaced several hundred probes using this technique without incident. The noise made by the detonating Primacord is equivalent to that of a 12-gauge shotgun and it can be sufficiently muffled so that a person standing 50 m away can hardly hear the detonation.

MEASUREMENT OF OPTICAL ROTATION

Optical rotation was measured with a Rudolph Model 52A2 Polarimeter with a mercury lamp at 546.07 nm (nanometer). Digital readout of optical rotation was read to the nearest 0.01 degree. Water-jacketed polarimeter sample cells 200 mm long with a capacity of 2.5 ml were used throughout this study. Special glass filters were used to isolate the 546.07-nm line. The optical rotation of an NBS (National Bureau of Standards) quartz control plate was determined with each group of measurements. Over a 2-year period we found that the standard deviation of the measurement of the quartz plate was a 0.05-degree rotation. All optical rotation measurements reported by our method are the average values for 10 readings corrected for instrument zero.

Prior to measurements, the ampoules were removed from the freezer, held in the hand to melt the solution, and constantly shaken. As soon as the crystals melted completely the ampoules were placed in a circulator-water bath at 20.00°C and were kept there for 10 minutes with intermittent shaking. During this period the water-jacketed polarimeter tube sample cell was equilibrated to 20.00°C. Immediately after this equilibrium period the ampoules were opened and the Pallmann solutions were transferred with a narrow glass pipette into the polarimeter cell. It is important that the Pallmann solution, which is viscous, be introduced from the bottom of the cell to avoid air entrapment. After securing the cap on the end of the cell, another 5-minute period was allowed for temperature equilibrium. Readings were then immediately taken to reduce errors due to continued hydrolysis.

EFFECTIVE TEMPERATURE

The rate of the Pallmann reaction, in common with many chemical and physical processes, responds in a nonlinear manner to temperature. A positive temperature change will speed up the cumulative reaction more than an equivalent negative temperature change will slow it down. Therefore, if the sucrose solution experiences a fluctuating temperature, the reaction will be the same as if the sucrose was exposed to a constant temperature that is higher than the arithmetic-mean temperature. This calculated constant temperature is referred to as the "effective temperature".

Because the Pallmann reaction responds nonlinearly with respect to temperature, the values calculated by this method are not arithmetic means but are logarithmic-integrated temperatures. These can be converted to arithmetic means if the range in temperature is known, as shown by Lee (1969). For many purposes, including obsidian and amino-acid dating, integrated (effective) temperatures are more actually useful than arithmetic means, because the reactions being monitored (diffusion of water into volcanic glass, racemization of amino acids) also respond to temperature changes exponentially, not linearly. The closer the activation-energy rate constant of the monitoring method is to that of the reaction being monitored, the more accurate the integrated temperature will be. This can be illustrated as follows.

Given a temperature that varies sinusoidally between +5° and −5°C. The arithmetic average temperature is 0°C. The integrated or effective temperature for a reaction having an activation energy of 20 kcal/mole (kilocalories per mole) is +0.74°C; if the activation energy is 10 kcal/mole, the integrated temperature is +0.43°C. If the amplitude of the temperature variation is doubled to +10°, or to −10°, the mean temperature will remain zero but the two integrated temperatures will now be 2.75°C and 1.66°C, respectively.

In the previous example of a sinusoidally varying temperature, the integrated or effective temperature is

---

[1] Primacord is a high-explosive (pentacrythrotrol trinitrate) filled cord manufactured by Ensign Bickford Co., Simsbury, Conn. 06070. The exploding bridgewire detonators and the special detonating box are made by Reynolds Industries, Inc., P.O. Box 1176, Marina Del Ray, Calif. Any trade names and trademarks found in this publication are used for descriptive purposes only and do not constitute endorsement by the U.S. Geological Survey.

seen to vary mainly as a function of the temperature range and the activation energy of the reaction. The activation energies of the reactions to be considered in this paper are shown in table 1.

TABLE 1.—*Activation energy of several reactions*

Reaction	Activation energy, in kcal/mole
Water diffusion through plastic (Ambrose cell)	[1]11.7
Water diffusion into obsidian-hydration dating)	[2]19 to 22
Inversion of sucrose (Pallmann solution)	[3]27.0
Isoleucine amino-acid racemization (amino-acid dating)	[4]27.5

[1] Ambrose (1976); F. Trembour, (oral commun., 1978).
[2] Friedman and Long (1976).
[3] Lee (1969).
[4] Bada and Schroeder (1972).

The rate at which the sucrose inverts to invert sugar is dependent upon the pH of the solution as well as upon temperature. By adjusting the initial pH, we prepared solutions that were useful for different effective-temperature ranges. The basic equation, as originally proposed by Pallmann and others (1940) is:

$$T\ (^{\circ}K) = \frac{-a}{\mathrm{pH}-b-\log t+\log\left[\log(R_o-R_\infty)-\log(R_t-R_\infty)\right]}, \tag{1}$$

where T = integrated temperature in degrees Kelvin (K)
a = constant
b = constant
t = time, in days
R_o = rotation angle of sucrose solution at time $t = 0$
R_t = rotation angle of sucrose solution at time $= t$
R_∞ = rotation angle of sucrose solution at time $= \infty$ (infinity). This is the rotation angle when all of the sucrose has inverted to invert sugar.
K = Temperature in degrees Kelvin.

ACCURACY OF THE PALLMANN METHOD

In the pH range used in our investigation (pH 1.5-3.0), a difference of 0.01 pH unit corresponds to an annual temperature increment of 0.13°C. It is difficult to measure pH with an accuracy of ±0.01 units. The pH changes slightly with temperature and also changes as the reaction proceeds (Lee, 1969). Therefore, we calibrated our Pallmann solutions by measuring the change in rotation when aliquots of the solutions were kept in constant temperature baths for known time periods. The baths used were constant to ±0.01°C, and the temperatures were read to ±0.05°C using thermometers calibrated against NBS standards. The sealed vials containing the solutions were kept in the water baths for periods of time from 1 day to 3 months at temperatures from 20° to 45°C. The rotation angles were measured and corrected according to figure 2*d* of Schmidt and Volkert (1959), recalculated for mercury light. At the conclusion of the experiment, reaction-rate constants were calculated using the corrected rotations, the known time, and the measured pH. The constants proposed by Pallmann and others (1940) and those calculated by us are given in table 2.

Temperatures calculated for the pH 1.93 solution using our constants are about 1°C lower than those using the original Pallmann constants. On the other hand, the temperatures calculated for the pH 2.51 solution with our constants are within 0.2°C of those calculated using the Pallmann constants. This discrepancy may be due to errors in our pH measurements. The pH meter had to be calibrated using pH 7 and 4 buffers. The buffer values were known to ±0.01. The farther the pH to be measured is from this pH range, the greater the error in the pH measurement. If the actual pH of the low pH Pallmann solution was 1.87 rather than the measured value of 1.93, the Pallmann constants would yield exact temperature values.

A check on the accuracy to be expected using the Pallmann method was carried out in the field using probes buried in the ground and placed 1 m apart. These probes contained vials of Pallmann solution at 1- and 2-m depths.

Four probes were spaced in an array where two of the probes contained solutions of pH 1.93 and the other two contained solutions of pH 2.51. All the probes were buried at one time, and all were removed 1 year later. The results are shown in table 3. The pH 1.93 solutions yielded temperatures that are about 0.25°C higher than those of the pH 2.51 solutions. The accuracy of the Pallmann method is about 0.25°C, and is limited primarily by the difficulty in determining the pH to closer than 0.02 unit.

TABLE 2.—*Constants for the Pallmann equation*

pH[2]	Constants[1]	
	a	*b*
Pallmann and others (1940)	−5856.6	20.1988
Present authors:		
1.93	−5857.5	20.2725
2.51	−5913.5	20.3913
3.08	−5755.0	19.8171

[1] *a* and *b* are constants given in equation 1.
[2] Constants derived by Pallmann and others (1940) are independent of pH.

PRECISION OF THE METHOD

The precision of the method—that is how precisely can small temperature differences be measured—is far better than 0.25°C. Under laboratory conditions, using a constant temperature bath, temperature differences as small as 0.05°C can be resolved. Under natural conditions, the limiting factor is the inherent "noise" because there are ground-temperature differences between sites as closely spaced as 1 m due to inhomogenieties in soil diffusivity, surface albedo, thermal inertia, and other variables.

In addition to the array given in table 3, two other arrays with multiple probes containing the pH 1.93 solution were emplaced 1 m apart and were measured after being buried for 1 year. The results are given in table 4. The 0.12°C difference at the Bunsen Peak site 1-m depth may be real, inasmuch as a difference of 0.16°C was found the previous year at the same site (see table 3). The temperatures at 2-m depth were the same for both years at this site. From the above data it can be seen that a precision of ±0.02°C can be realized by the Pallmann method.

The many curves shown in figure 1 (at end of PART I) define the relationships among the three parameters: (1) arithmetic-mean temperature, (2) effective temperature, and (3) temperature range for the different processes of sucrose inversion, obsidian hydration, and diffusion of water through methyl methacrylate plastic. The data for this figure were calculated assuming that the temperature varied sinusoidally (harmonically) through the temperature range plotted on the abscisa. From this figure, if the temperature range is approximately known, then Pallmann or Ambrose-effective temperature can be converted to obsidian-hydration or amino-acid effective temperatures, or to arithmetic-mean temperatures. Plots are given for 2°C-increments in arithmetic mean temperature from 0° to 30°C.

The Ambrose technique is another method for temperature integration (Ambrose, 1976). It is based upon the temperature dependence of the rate of diffusion of water into a plastic cell.

Figure 1 shows that the Pallmann effective temperatures are somewhat higher than the obsidian-hydration effective temperatures.

Because the activation energy of the isoleucine amino-acid racemization is close to that of the Pallmann reaction (27.5 kcal versus 27.0 kcal), the effective temperatures measured by the Pallmann method will be close approximations to the amino-acid effective temperatures. The Ambrose method yields effective temperatures that are lower than both the Pallmann and obsidian temperatures.

If the temperature range can be determined, the Ambrose and Pallmann effective temperatures can be converted to amino-acid or obsidian-hydration effective temperatures, or to arithmetic-mean temperatures.

By burying a Pallmann vial next to an Ambrose cell, the effective temperature for each can be measured, and then the temperature range can be calculated from the difference in effective temperatures. For example, if the Pallmann vial yields an effective temperature of 15.1°C, and the Ambrose cell gives an effective temperature of 12.5°C, the range in temperature is 26.0°C, and the mean temperature is 10.0°C (see fig. 1). PARTS II and III of the present paper give applications of the Pallmann technique.

TABLE 3.—*Pallman temperatures during 1977 at Bunsen Peak site*[1] *as measured using two solutions of different pH*

Depth (m)	pH 1.93		pH 2.51	
	Probe a	Probe b	Probe c	Probe d
1 ·······	4.77°C	4.61°C	4.55°C	4.53°C
2 ·······	4.33°C	4.31°C	4.05°C	4.07°C

[1] See PART III for description of this site.

TABLE 4.—*Pallmann temperatures during 1978 at two sites as measured using solutions of pH 1.93*

Depth (m)	Bunsen Peak site[1]		Turbid Lake site[1]	
	Probe a	Probe b	Probe a	Probe b
1 ·········	4.54°C	4.42°C	5.34°C	5.36°C
2 ·········	4.35°C	4.31°C	5.44°C	5.46°C

[1] See PART III for description of this site.

ACKNOWLEDGMENTS

We owe a great debt of thanks to William Long who designed and constructed the steel device used to emplace the Primacord. He also designed the plastic probe and was most helpful at all stages of the research. Gary Giarratano and Mary Robison assisted in the laboratory phase of the research.

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FIGURE 1

Plots of the temperature range experienced by a sample versus the effective temperatures calculated for the Pallmann reaction, the obsidian-hydration reaction, and the Ambrose method. In making the calculations we used equation 2 and assumed a harmonic or sinusoidal temperature variation with an amplitude given by the "temperature range", and an activation energy for each reaction as follows: Pallmann (27 kcal/mole), obsidian-hydration (19.7 kcal/mole), Ambrose (11.7 kcal/mole). Sets of curves are given for different arithmetic means from 0° to 30° Celsius in 2°-intervals. The effective temperature equals the arithmetic mean temperature when the temperature range equals zero.

$$t = e^{\frac{-E}{RT}} + 273.2, \tag{2}$$

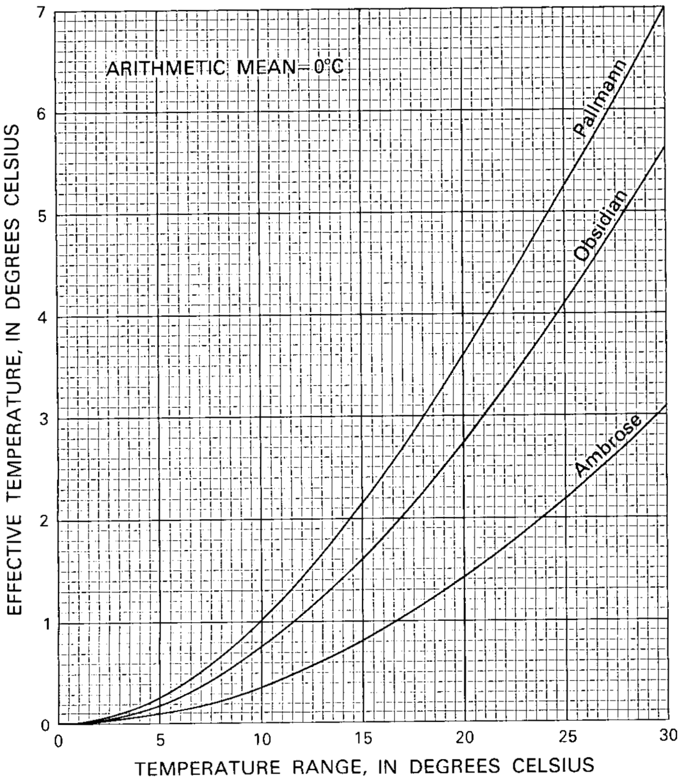
where t = effective temperature in degrees Celsius

e = base of natural logarithms

E = activation energy

R = gas constant, 1.98 cal/mole

T = temperature in degrees Kelvin. This temperature varies sinusoidally with an amplitude given by "temperature range".


ARITHMETIC MEAN=0°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
0
1
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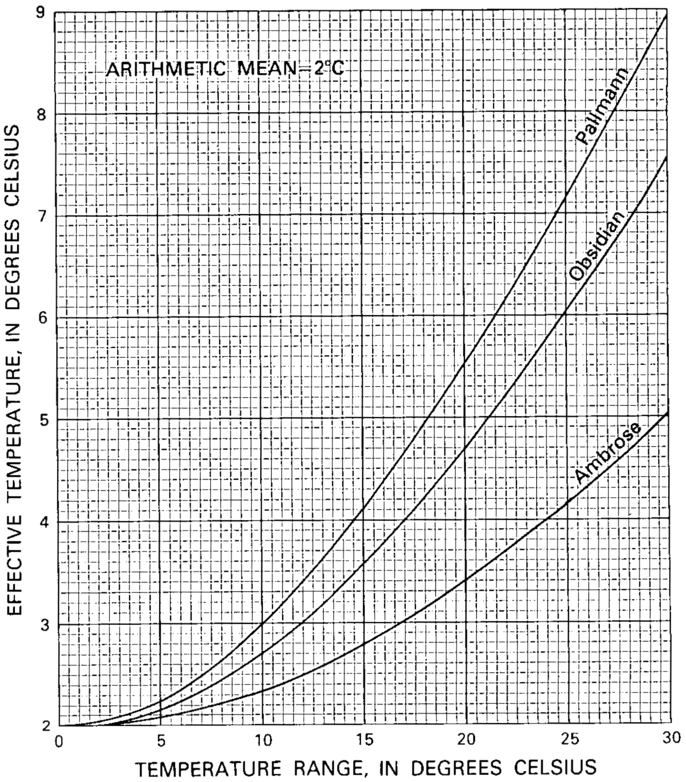
4
5
6
7
0
5
10
15
20
25
30
TEMPERATURE RANGE, IN DEGREES CELSIUS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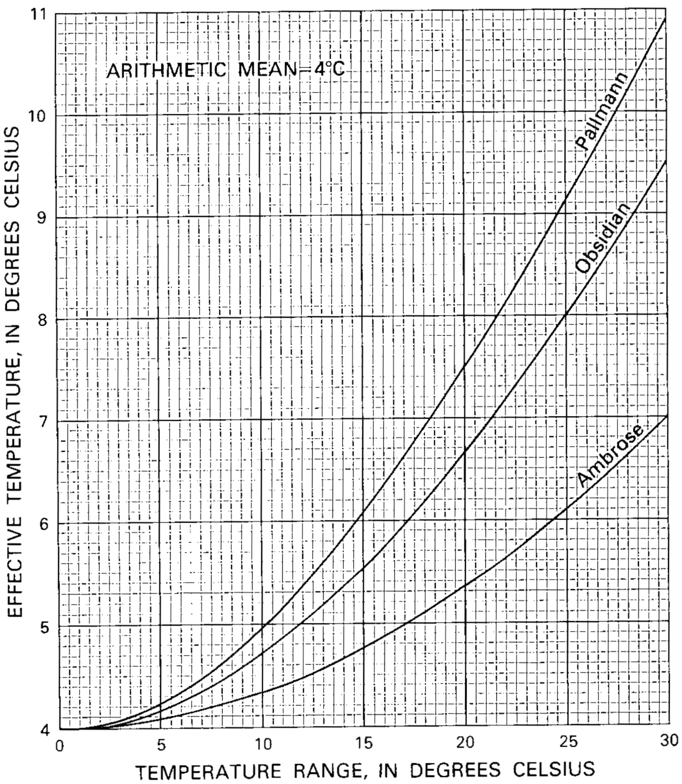
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30
TEMPERATURE RANGE, IN DEGREES CELSIUS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Pallmann
Obsidian
Ambrose
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5
6
7
8
9
10
11
0
5
10
15
20
25
30
TEMPERATURE RANGE, IN DEGREES CELSIUS

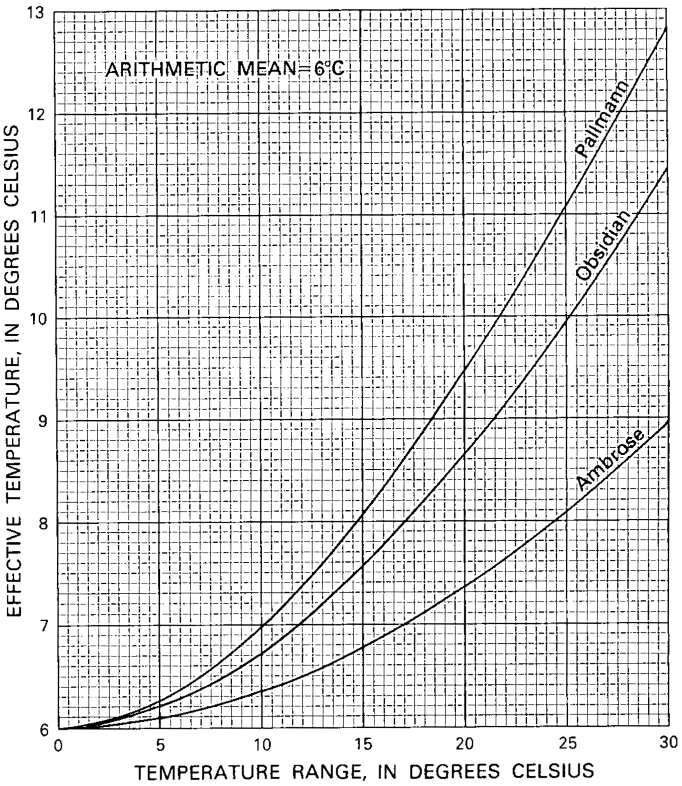
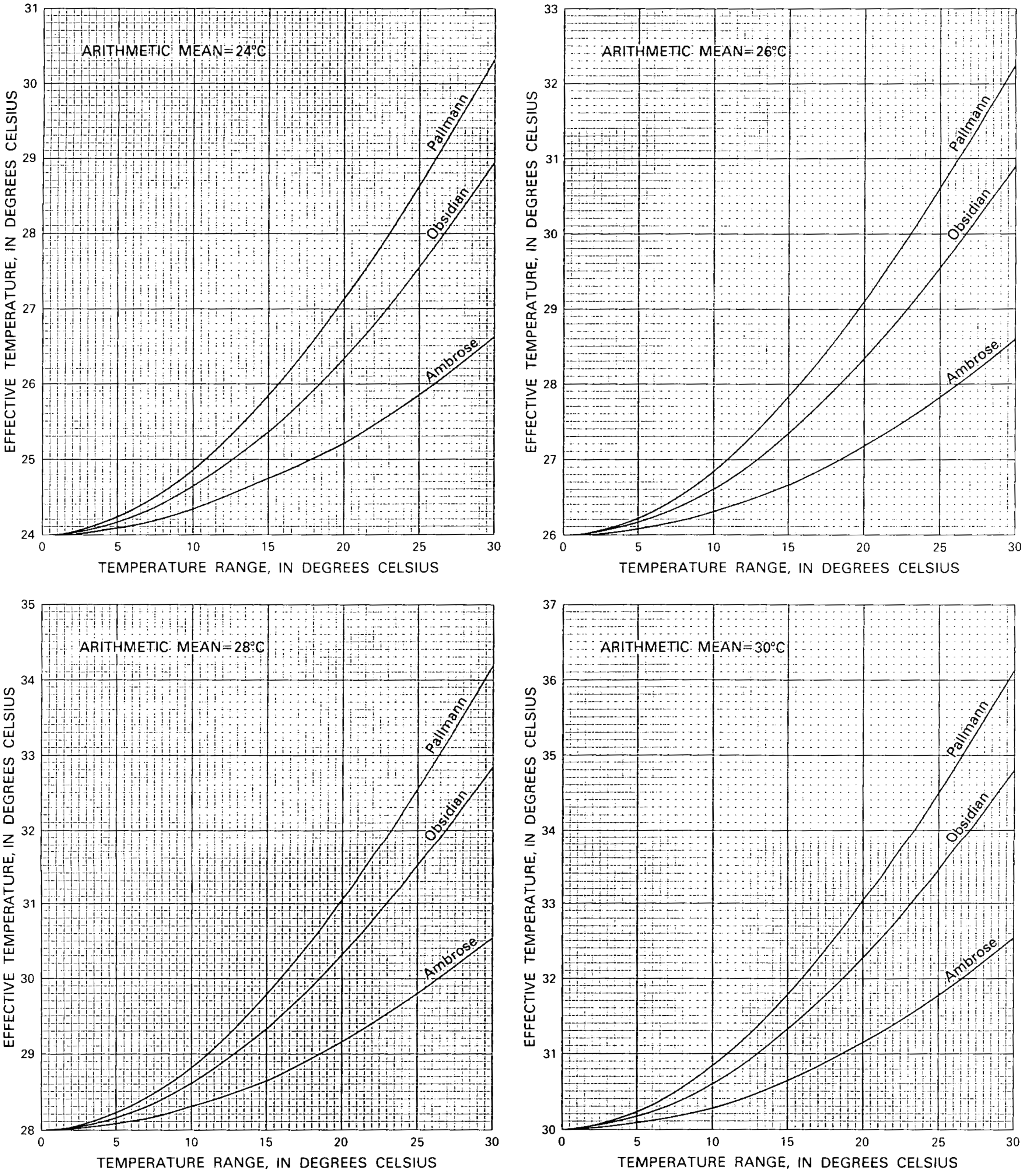

ARITHMETIC MEAN=6°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
6
7
8
9
10
11
12
13
0
5
10
15
20
25
30
TEMPERATURE RANGE, IN DEGREES CELSIUS

FIGURE 1


ARITHMETIC MEAN=24°C
ARITHMETIC MEAN=26°C
ARITHMETIC MEAN=28°C
ARITHMETIC MEAN=30°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
TEMPERATURE RANGE, IN DEGREES CELSIUS
0
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10
15
20
25
30
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28
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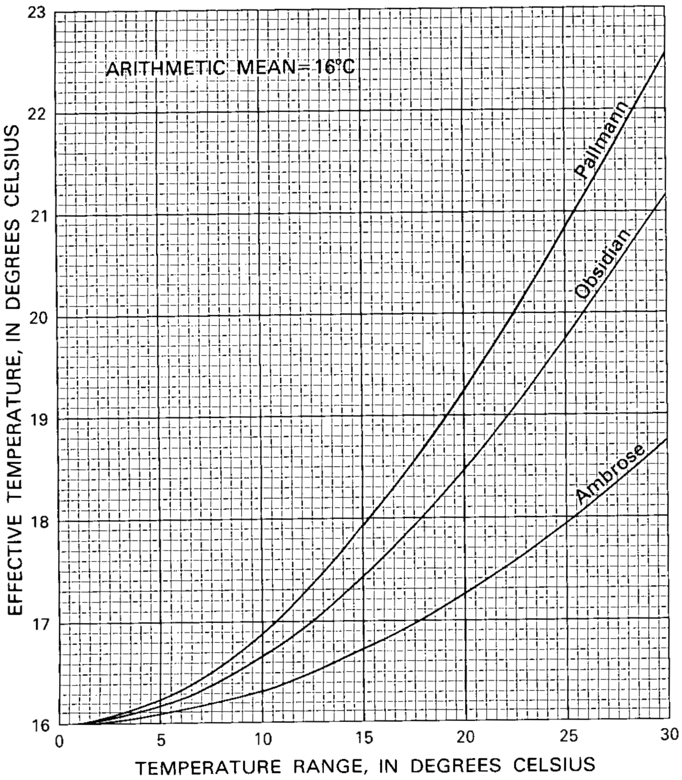
33
34
35
36
37


ARITHMETIC MEAN=16°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
16
17
18
19
20
21
22
23
TEMPERATURE RANGE, IN DEGREES CELSIUS
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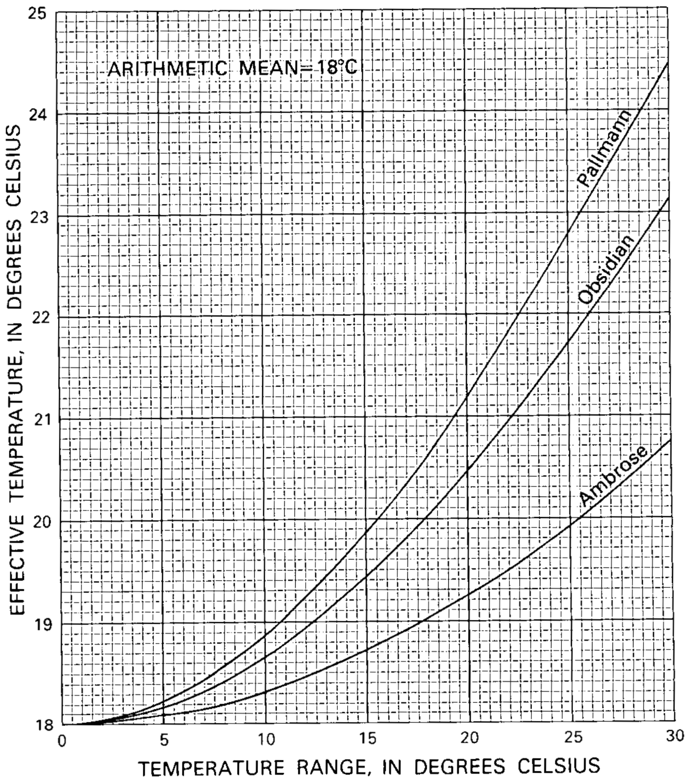
5
10
15
20
25
30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Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
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19
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22
23
24
25
TEMPERATURE RANGE, IN DEGREES CELSIUS
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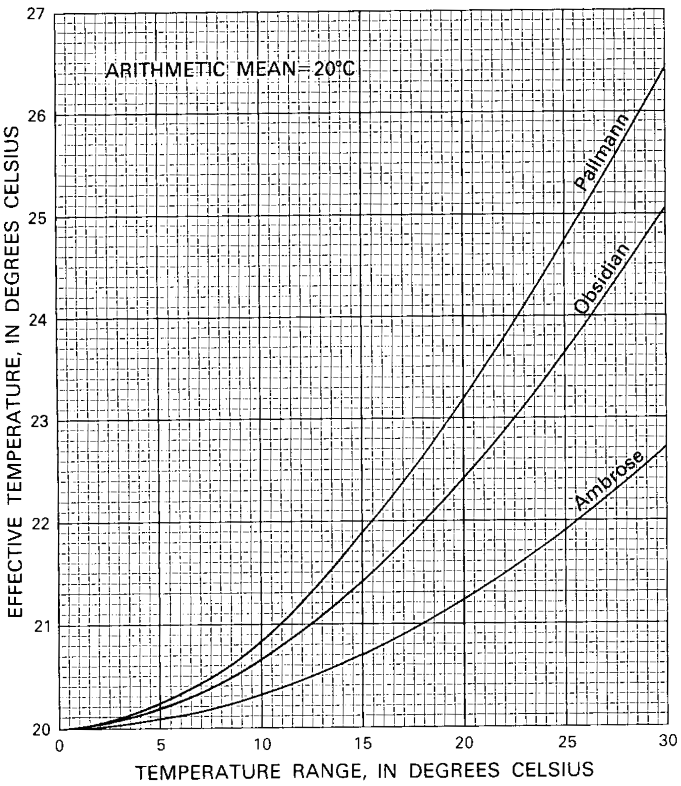
5
10
15
20
25
30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Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
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23
24
25
26
27
TEMPERATURE RANGE, IN DEGREES CELSIUS
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5
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15
20
25
30

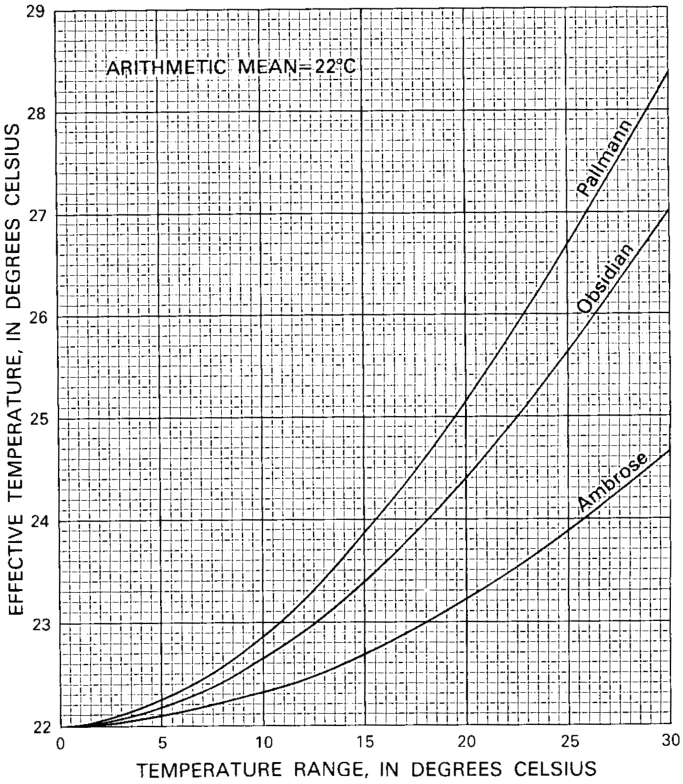
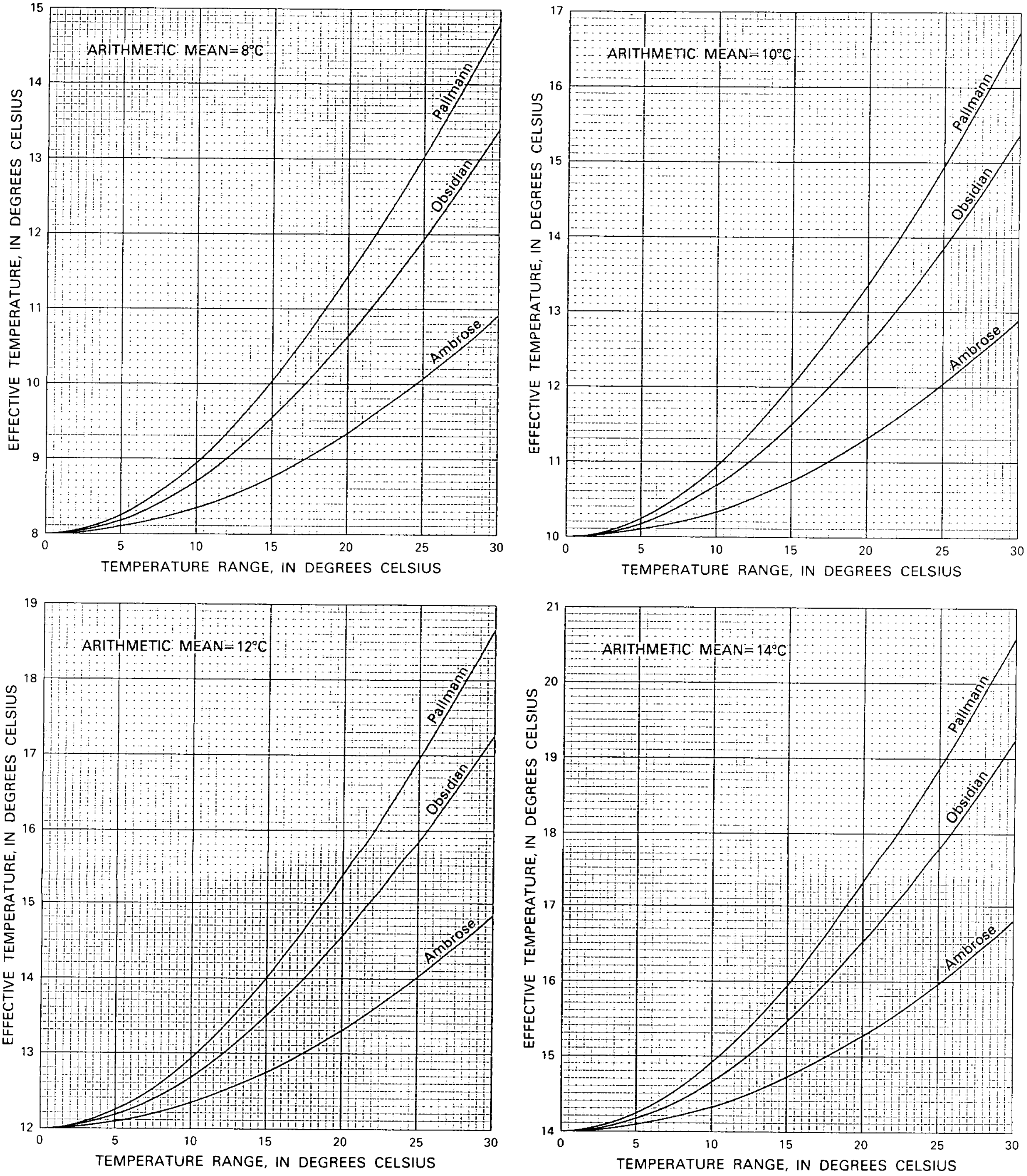

ARITHMETIC MEAN=22°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
22
23
24
25
26
27
28
29
TEMPERATURE RANGE, IN DEGREES CELSIUS
0
5
10
15
20
25
30

FIGURE 1


ARITHMETIC MEAN=8°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
8
9
10
11
12
13
14
15
TEMPERATURE RANGE, IN DEGREES CELSIUS
0
5
10
15
20
25
30
ARITHMETIC MEAN=10°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
10
11
12
13
14
15
16
17
TEMPERATURE RANGE, IN DEGREES CELSIUS
0
5
10
15
20
25
30
ARITHMETIC MEAN=12°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
12
13
14
15
16
17
18
19
TEMPERATURE RANGE, IN DEGREES CELSIUS
0
5
10
15
20
25
30
ARITHMETIC MEAN=14°C
Pallmann
Obsidian
Ambrose
EFFECTIVE TEMPERATURE, IN DEGREES CELSIUS
14
15
16
17
18
19
20
21
TEMPERATURE RANGE, IN DEGREES CELSIUS
0
5
10
15
20
25
30

GROUND TEMPERATURE MEASUREMENTS

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

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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).

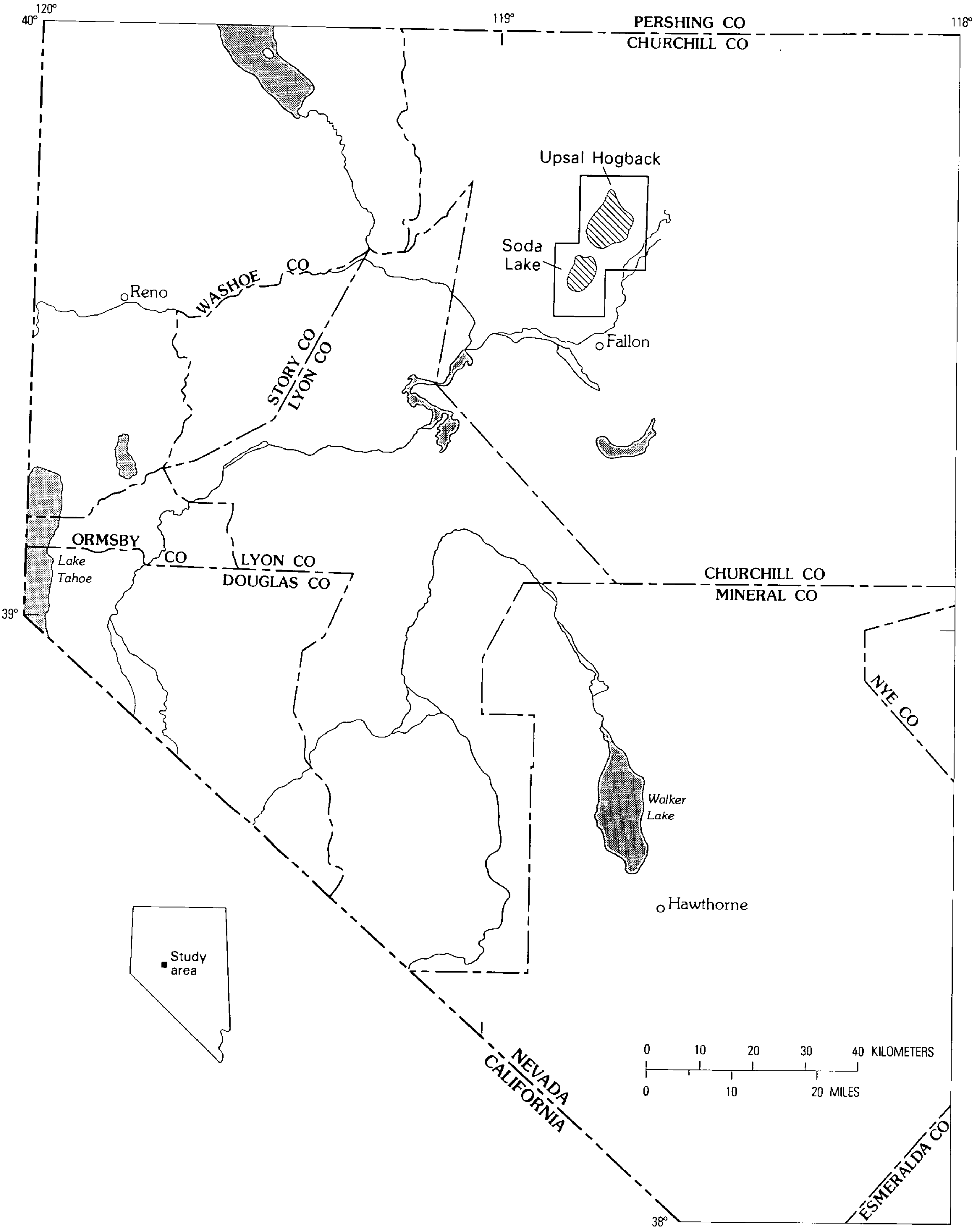


FIGURE 2.—West-central Nevada, showing the location of Soda Lakes and Upsal Hogback geothermal areas.

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.

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.

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.

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.

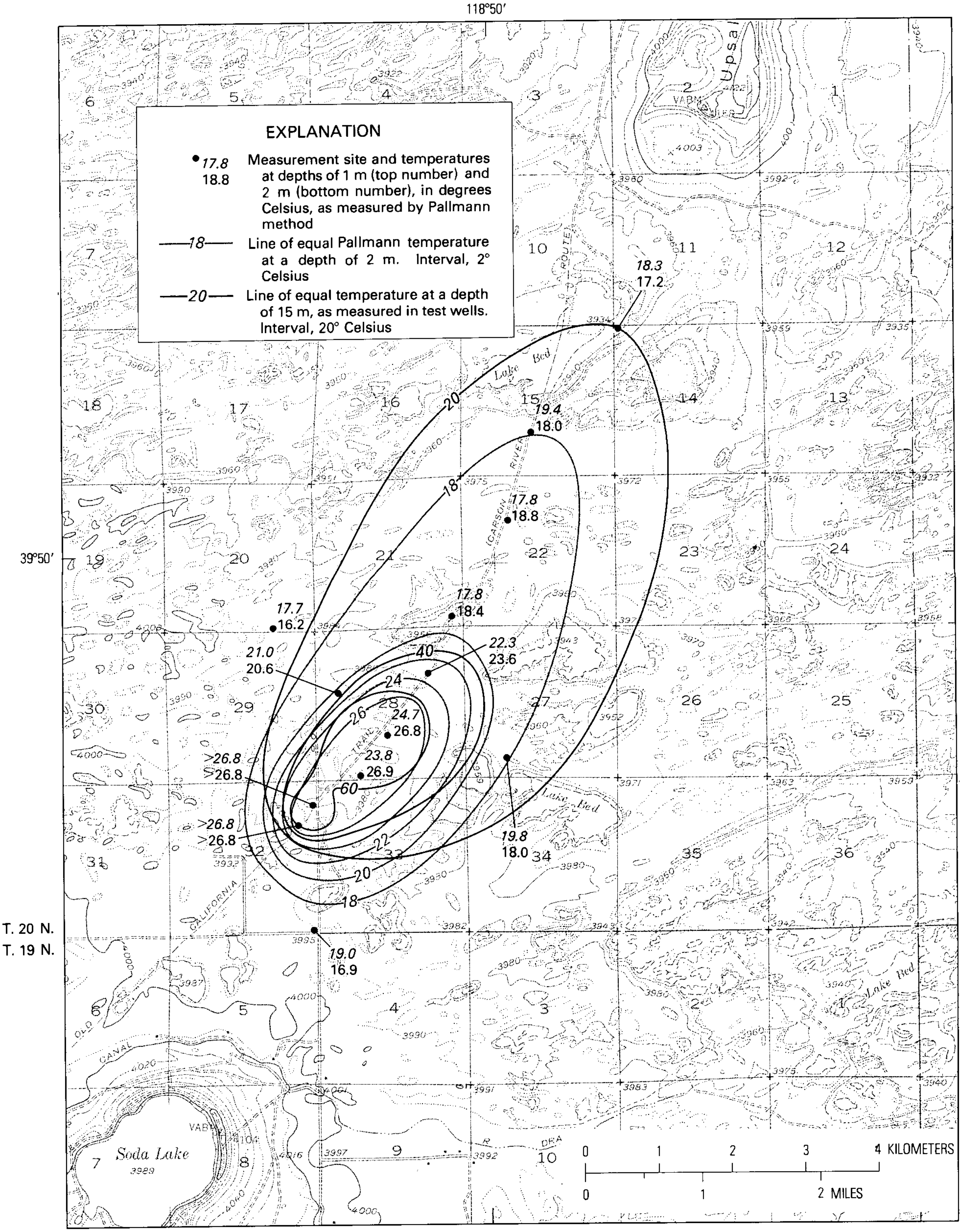
Coefficients of determination (r^2) for the least-mean-squares linear regressions of temperatures at 15 m versus temperatures at 1 and 2 m corroborate the generally poor correlations described above (see table 6). As in the Soda Lakes area, the temperatures at 2 m show a somewhat better correlation with 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*

		Soda Lakes area		Upsal Hogback area	
Depths (m)	Period (months)	No. of sites	Coefficient of determination (r^2)	No. of sites	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.

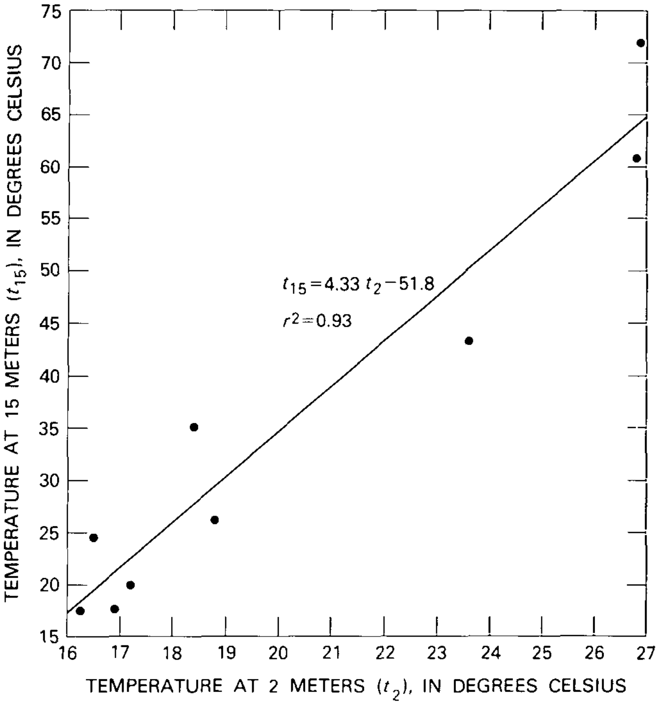


FIGURE 4.—Correlation of temperature at 15 m in test wells with measured Pallmann temperatures at 2 m for December 15, 1976, to December 15, 1977, Soda Lakes area, Nevada.

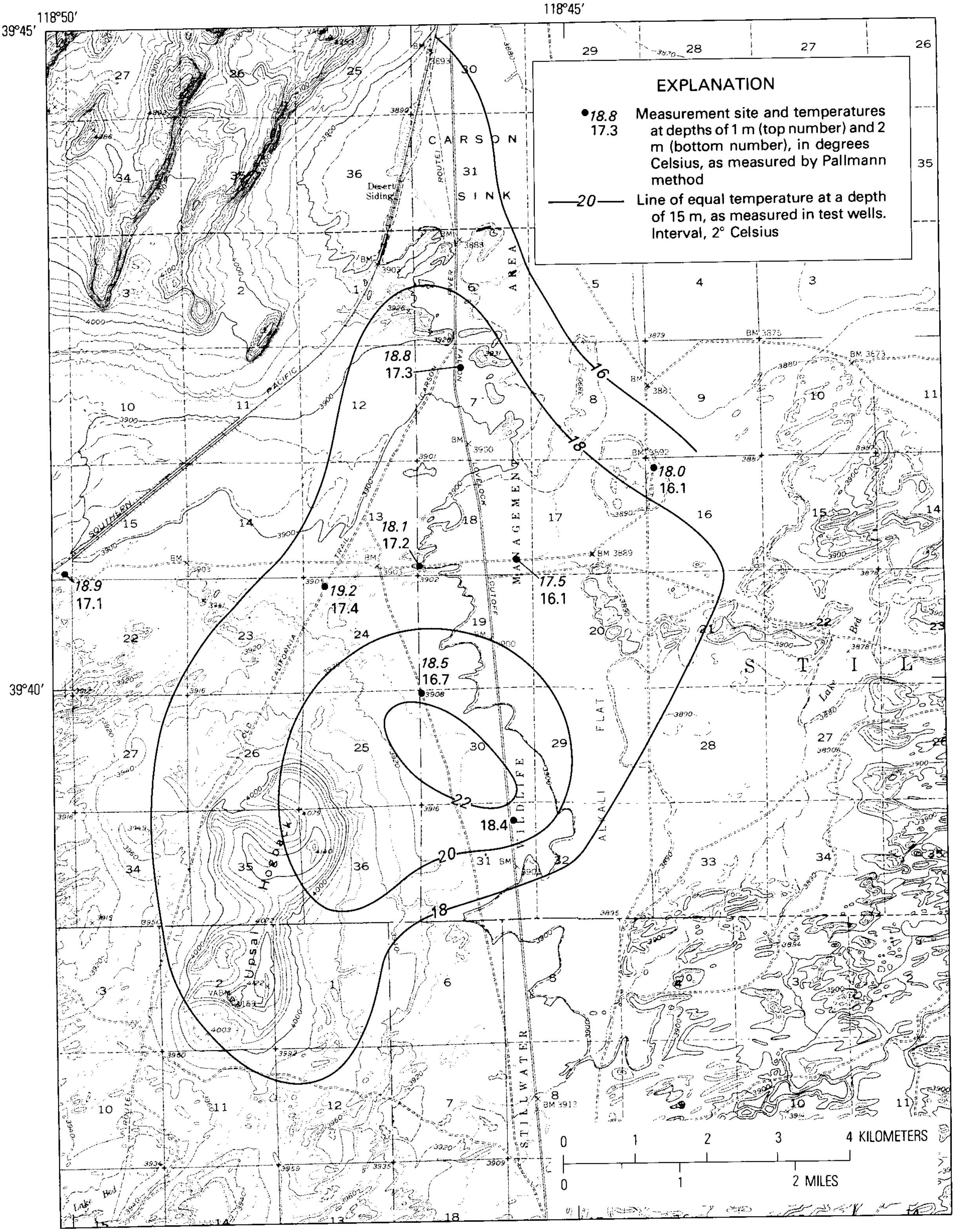
In principle, the chief advantage of the Pallmann method over single sets of synoptic temperature measurements should be in minimizing the perturbing effects of areal differences in thermal diffusivity, degree of stratification of materials, and depth to the water table. All these factors affect both 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.

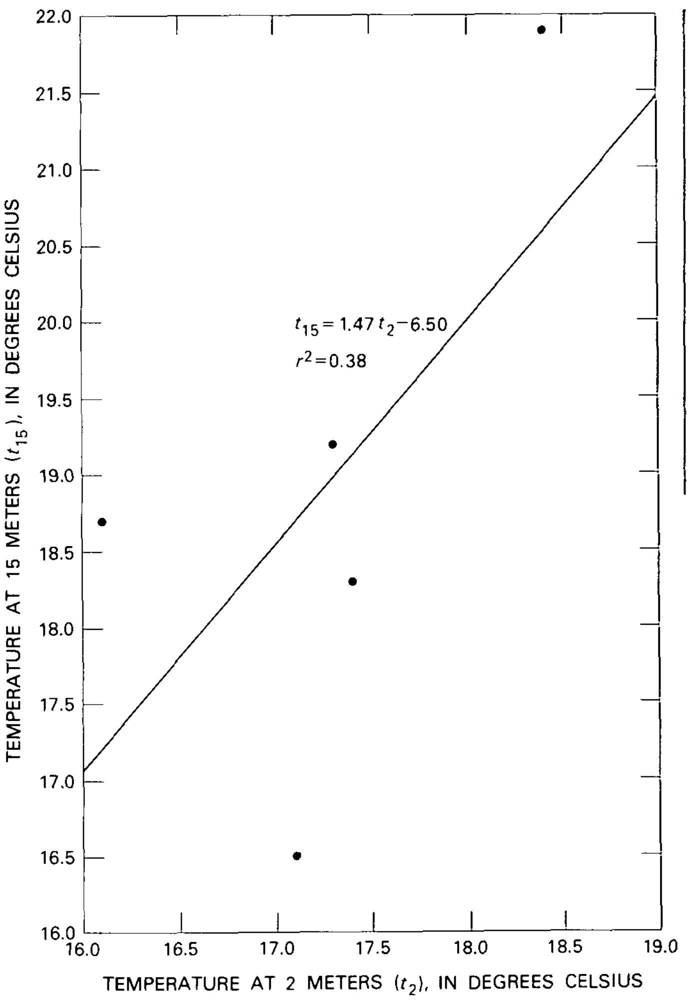


FIGURE 6.—Correlation of temperature at 15 m in test wells with measured Pallmann temperatures at 2 m for December 15, 1976, to December 15, 1977, Upsal Hogback area, Nevada.

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GROUND TEMPERATURE MEASUREMENTS

PART III, GROUND TEMPERATURES IN AND NEAR YELLOWSTONE NATIONAL PARK

By IRVING FRIEDMAN and DANIEL R. NORTON

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ILLUSTRATIONS

TABLES

ABSTRACT

The Pallmann method was used to determine ground temperatures at 1- and 2-meter (m) depths at 57 sites in Yellowstone National Park and vicinity for several annual periods. These measurements were used for determining rates of obsidian hydration for dating. In order to utilize these measurements for heat-flow comparisons of the different sites, the 2-m data points were normalized to a common altitude and degree of shade. Using these corrected Pallmann temperatures, we were able to define areas of anomalous heat flow at sites distant from known geothermal influence. In addition to Pallmann measurements, we made instantaneous ground-temperature measurements at most Pallmann sites at or near the temperature maximum and minimum for the year. These instantaneous measurements were made to determine the temperature range in order to convert Pallmann temperatures to arithmetic-mean annual temperatures.

INTRODUCTION

Ground-temperature measurements were made in order to calculate rates of hydration of obsidian collected from locations in and near Yellowstone National Park. These rates of hydration were used to date volcanic flows and other geologic features containing obsidian. Our first attempt at temperature measurements utilized continuous recorders to record the temperature of thermocouples buried in the ground. This technique severely limited the location of the sites where temperature could be measured, inasmuch as electric power and a shelter had to be available for the recorder. The difficulty of servicing the equipment during the winter proved to be another limitation. The Pallmann technique seemed well suited for these measurements. In September of 1975, Irving Friedman and Daniel R. Norton, assisted by Fred Cater, emplaced forty-five 2-m probes containing Pallmann solution in various parts of the park (fig. 7). Some of the sites selected for probe emplacement were located adjacent to those places previously used to collect obsidian which was used to date volcanic flows and glacial events. Another group of probes was placed both inside and outside of the Yellowstone caldera in an attempt to determine if there was a measurable difference in ground temperature between these two areas. Previous analysis of data from obsidian-hydration measurements of K-Ar dated obsidian flows had suggested a higher ground temperature at 2-m depth inside of the caldera as compared with the outside. We tried to place all our probes as far as possible from known thermal areas. The probes were all emplaced in level ground. Where possible, we selected areas that would remain in the sun all day. A description of the location of the sites is given in table 7.

FIELD INVESTIGATIONS

In September 1976, the first group of probes was removed after having been in place for 1 year, and was reemplaced with new Pallmann solutions. In addition to these initial 45 sites, 12 new sites were added in September and October of 1976. In October 1977, the Pallmann vials were retrieved from all sites and most sites were then abandoned. All the vials containing the Pallmann solution were frozen in dry ice immediately upon removal from the probe. The rotation of polarized light of the solutions were all measured within a day or two with equipment set up in the park. The results are given in table 8.

In late September and early October of 1978, instantaneous ground-temperature measurements at 0.5- , 1-, and 2-m depth were made at all sites. In February of 1979, ground temperatures at these same depths were measured at a group of selected Pallmann sites. These instantaneous measurements taken in September 1978, and February 1979, at or near the maximum and minimum of the annual temperature cycle allow us to convert Pallmann-effective annual temperatures to obsidian-effective temperatures, and also to arithmetic-mean annual temperatures (see PART I).

A description of the Pallmann probes and the techniques used to emplace them are given in PART I. The instantaneous temperatures were obtained using thermistor probes (Enviro Labs Model[1] DT101) which were allowed to remain in place until the temperature stabilized to within 0.05°C (Celsius) when read at 10-minute intervals. The time to reach a constant temperature was minimized by adjusting the thermistor probe to the approximate ground temperature before inserting it into the ground. In the autumn, the thermistor probes reached equilibrium within ½ to ¾ hour.

In the winter the above procedure was modified because of temperature changes in the holes caused by penetration of cold air. To minimize this effect, the probes were inserted in the ground as soon as possible after the holes were completed. The temperature of the probes was initially adjusted to be slightly cooler than that of the ground. Upon insertion into the ground, the temperature rapidly increased to a maximum, and then began to decrease as cold air penetrated into the freshly opened soil. When this occurred, we pounded the probes about 2-4 cm (centimeter) farther into the ground and observed a rise in temperature as fresh warm soil was penetrated by the probe. This second maximum was recorded as the actual ground temperature. The results of these instantaneous temperature measurements are given in table 9 and plotted in figure 8.

DISCUSSION

The annual integrated ground temperature is a function of the soil thermal diffusivities plus the:

1. Heat flow from the surface downward.
2. Heat flow from the interior upward.

The heat flow downward will be determined by the hours of sunlight, amount of shade received by the site, the type of ground cover, the albedo of the soil, the amount and duration of snow cover as well as the air temperature and wind velocity, both of which are somewhat dependent upon elevation.

If we desire to determine the effective annual temperature at a particular site for obsidian or amino-acid dating studies, then the Pallmann measurements will yield the necessary data. However, if we desire to

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[1] Use of trade name in this paper is for descriptive purposes only and does not constitute endorsement of the product by the U.S. Geological Survey.

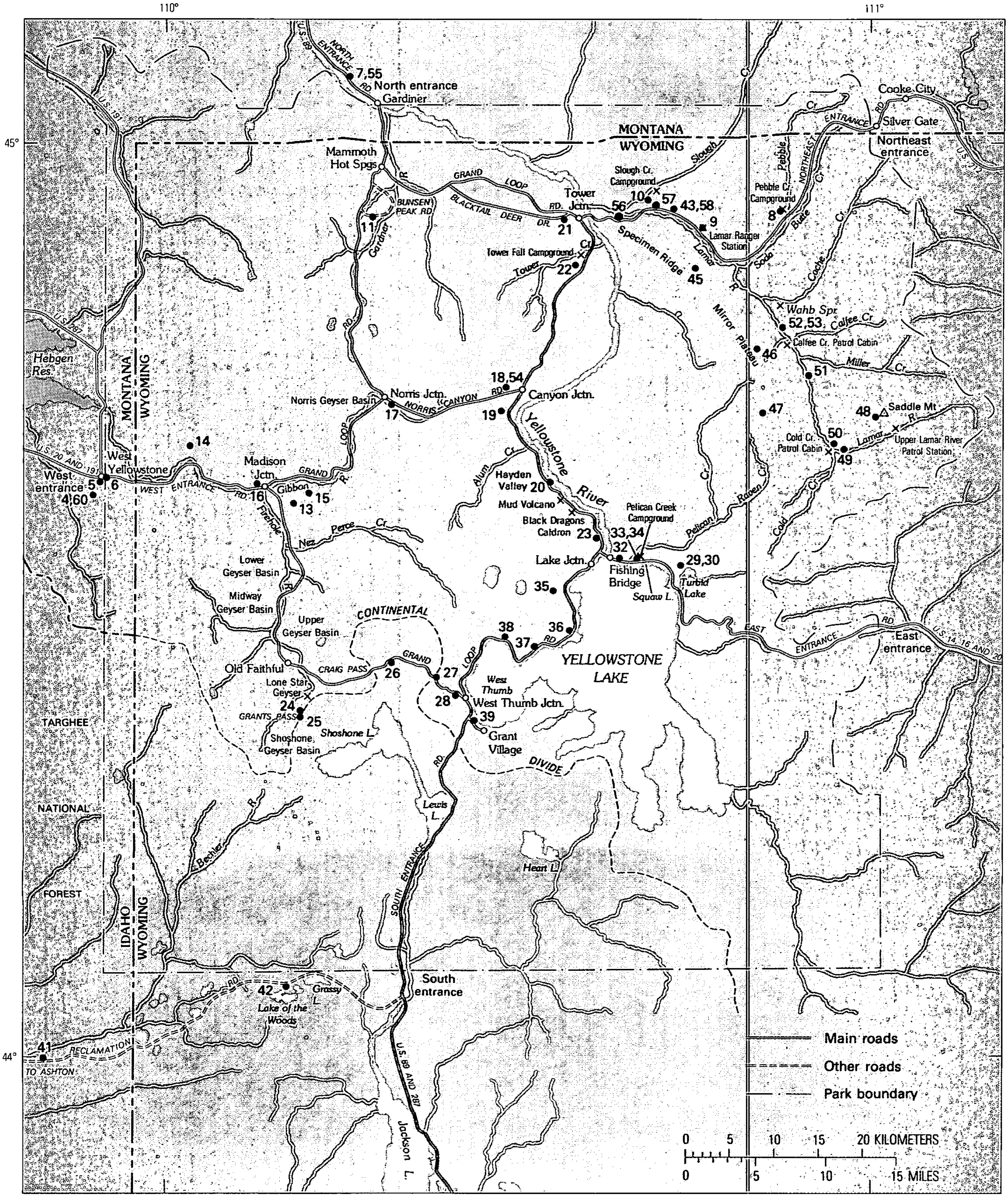

FIGURE 7.—Generalized sketch map of Yellowstone National Park and vicinity showing site localities and numbers.

TABLE 7.—*Description of sites*

Site (geographic order)		Topographic quadrangle name[1]	Latitude, N.			Longitude, W.			Altitude[2]		Directions to site[3]
No.	Name		deg	min	s	deg	min	s	ft	m	
1.	Teton Pass	Teton Pass (7.5′)	43	29	31	110	57	17	8630	2630	0.7 mi S. on service road from Teton Pass to transmission tower; 20 yd W. from tower to site (not shown on fig. 7).
2.	Snake River	Jackson (7.5′)	43	27	53	110	52	20	6160	1880	2.6 mi S. on secondary road from Wilson; 10 yd E. from road to site (not shown on fig. 7).
3.	Mosquito Creek	Teton Pass (7.5′)	43	26	24	110	56	39	6780	2065	4.4 mi S. on secondary road from Wilson; 4.5 mi W. on dirt road; 5 yd N. from road to site (not shown on fig. 7).
4.	West Yellowstone Flow (shade).	West Yellowstone	44	35	29	111	8	39	7540	2300	6.6 mi S. on Madison Plateau Rd. from W. Yellowstone; 40 yd W. from road to site.
60.	W. Yellowstone Flow (sun).	do	44	35	29	111	8	39	7540	2300	15 yd E. of site 4.
5.	Madison Plateau Rd.	do	44	39	14	111	6	39	6660	2030	0.4 mi S. on Madison Plateau Rd. from W. Yellowstone; 15 yd E. from road to site.
6.	West Entrance	do	44	39	9	111	5	0	6660	2030	0.3 mi S. on service road from W. Entrance; 10 yd from rear of pumphouse.
7.	Miller Garden	Miner	45	5	14	110	46	33	5120	1560	4.9 mi NW. on Rt. 89 from Gardiner to Miller property; 60 yd N. of residence at end of garden.
55.	Miller Field	do	45	4	40	110	46	34	5120	1560	4.9 mi NW. on Rt. 89 from Gardiner to Miller property; 120 yd SW. of residence to site.
8.	Pebble Creek	Abiathar Peak	44	55	4	110	6	54	7040	2145	40 yd N. of parking lot of Pebble Creek Campground.
9.	Lamar Ranger Station	do	44	53	46	110	13	27	6740	2055	0.4 mi NW. on unimproved dirt road from Lamar Ranger Station; 60 yd W. from road to site.
10.	Slough Creek	Tower Junction	44	45	35	110	18	58	6220	1895	0.4 mi N. on Slough Creek Campground road from its intersection with NE. Entrance road; 10 yd E. from road to site.
11.	Bunsen Peak	Mammoth	44	55	28	110	43	21	7280	2220	0.6 mi S. on Bunsen Peak Rd., from its intersection with Grand Loop Rd.; original site No. 11, 4 yd SW. from road; site Nos. 11a, b, c, and d, 13 yd SW. from road.
13.	Mesa Road I	Madison Junction	44	37	11	110	49	42	7180	2190	1.3 mi E. on Mesa Rd. from its intersection with Grand Loop Rd.; 10 yd S. from road to site.
14.	Cougar Creek	do	44	40	49	110	57	57	6900	2105	1.5 mi NW. on trail starting from E. side of bridge crossing Madison R. at a point 7.4 mi E. of the W. Entrance on W. Entrance Rd.; 10 yd N. 80°E. from trail-marker sign to site.
15.	Mesa Road II	do	44	38	20	110	48	15	7180	2190	3.1 mi E. and NE. on Mesa Rd. from its intersection with Grand Loop Rd.; 5 yd E. from road to site.
16.	Harlequin Lake	do	44	38	27	110	53	30	6800	2075	11.7 mi E.on W. Entrance Rd. from W. Entrance; 30 yd N. from road to site.
17.	Norris Junction	Norris Junction	44	43	30	110	40	54	7500	2285	0.8 mi W. on Norris-Canyon Rd. from Norris Jct.; 50 yd. S. from road to site.
18.	Cascade Meadows (shade).	do	44	44	7	110	30	57	7950	2425	1.2 mi E. on Norris-Canyon Rd. from Canyon Jct.; 40 yd. N. from road to site.
54.	Cascade Meadows (sun).	do	44	44	7	110	30	46	7880	2400	1.1 mi W. on Norris-Canyon Rd. from Canyon Jct.; 20 yd N. from road to site.
19.	Upper Falls	do	44	42	57	110	30	57	7960	2425	0.6 mi W. on service road from its intersection with Grand Loop Rd.; 40 yd S. from road to site.

TABLE 7.—*Description of sites*—continued

Site (geographic order)		Topographic quadrangle name[1]	Latitude, N.			Longitude, W.			Altitude[2]		Directions to site[3]
No.	Name		deg	min	s	deg	min	s	ft	m	
20.	Elk Antler Creek	Canyon Village	44	38	18	110	26	59	7720	2355	8.4 mi S. on Grand Loop Rd. from Canyon Jct.; 70 yd NW. from road to site.
21.	Blacktail Deer Dr.	Tower Junction	44	55	36	110	27	19	6840	2085	0.6 mi W. on Blacktail Deer Dr. from its eastern intersection with Grand Loop Rd.; 20 yd S. from road to site.
22.	Tower Fall	do	44	51	56	110	23	37	7080	2160	2.3 mi S. on Grand Loop Rd. from its intersection with Tower Falls Campground; 40 yd W. from road to site.
23.	LeHardys Rapids	Canyon Village	44	36	15	110	23	0	7800	2375	2.6 mi N. on Grand Loop Rd. from Lake Jct.; 50 yd W. from road to site.
24.	Grants Pass I	Old Faithful	44	23	17	110	49	53	7900	2410	2.4 mi S. on trail from footbridge over the Firehole R. located near Lone Star geyser; 10 yd W. from trail to site.
25.	Grants Pass II	do	44	22	56	110	49	36	8000	2440	2.9 mi S. on trail from footbridge over the Firehole R. located near Lone Star geyser; 5 yd SW. of trail to site at Continental Divide.
26.	DeLacy Creek	West Thumb	44	27	4	110	41	15	8000	2440	7.9 mi W. on Grand Loop Rd. from W. Thumb Jct.; 30 yd SW. from road to site.
27.	Divide Lake	do	44	26	5	110	38	17	8380	2555	4.1 mi W. on Grand Loop Rd. from W. Thumb Jct.; 10 yd N. of road to site.
28.	Little Thumb Creek	do	44	25	14	110	36	11	8200	2500	2.1 mi W. on Grand Loop Rd., from W. Thumb Jct.; 20 yd SW. from road site.
29.	Turbid Lake (shade).	Canyon Village	44	33	7	110	16	1	7920	2415	3.0 mi E. on service road from its intersection with E. Entrance Rd. at Squaw Lake; 15 yd NE. from road to site (22 yd SE. of site No. 30).
30.	Turbid Lake (sun).	do	44	33	10	110	16	3	7910	2410	20 yd NW. of site No. 29.
31.	Mummy Cave	Clayton Mountain (7.5′)	44	27	33	109	42	57	6130	1868	17.4 mi E. on Wyoming Rt. 16 from E. Entrance; 15 yd SE. from road to site. (not shown on fig. 7).
32.	Fishing Bridge	Canyon Village	44	33	42	110	21	49	7780	2370	1.0 mi E. on E. Entrance Rd. from Fishing Bridge; 10 yd N. from road to site.
33.	Pelican Creek Campground-(sun).	do	44	36	16	110	20	49	7760	2365	0.4 mi N. on Pelican Creek Campground road from its intersection with E. Entrance Rd.; 15 yd W. of parking turnout.
34.	Pelican Creek Campground-(shade).	do	44	36	16	110	20	50	7760	2365	0.4 mi N. on Pelican Creek Campground road from its intersection with E. Entrance Rd.; 5 yd E.of parking turnout.
35.	Natural Bridge	do	44	31	42	110	26	45	7820	2385	0.7 mi W. on Natural Bridge road from its intersection with Grand Loop Rd.; 25 yd N. from road to site.
36.	Sand Point	Frank Island	44	29	36	110	25	26	7880	2400	3.6 mi S. on Grand Loop Rd. from its intersection with Natural Bridge road; 35 yd NW. from road to site.
37.	Pumice Point	West Thumb	44	27	47	110	28	45	7760	2365	9.9 mi N. on Grand Loop Rd. from W. Thumb Jct.; 10 yd NW. from road to site.
38.	Arnica Creek	do	44	28	40	110	31	56	7760	2365	5.8 mi N. on Grand Loop Rd. from W. Thumb Jct.; 30 yd N. from road to site.
39.	Grant Village	do	44	23	24	110	33	57	7840	2390	0.2 mi E. on Grant Village road from its intersection with S. Entrance Rd.; 15 yd N. from road to site.
41.	Falls River	Warm River Butte	44	3	1	111	11	39	5935	1810	0.3 mi E. on Reclamation Rd. from Targhee National Forest boundary; 10 yd NE. from road to site.

TABLE 7.—*Description of sites*—continued

Site (geographic order)		Topographic quadrangle name[1]	Latitude, N.			Longitude, W.			Altitude[2]		Directions to site[3]
No.	Name		deg	min	s	deg	min	s	ft	m	
42.	Grassy Lake	Grassy Lake Reservior	44	7	34	110	50	35	7300	2225	1.1 mi W. on Reclamation Rd. from the W. end of the Grassy Lake Dam; 5 yd SW. from road to site.
43.	Lamar Canyon East I	Tower Junction	44	54	53	110	15	49	6560	2000	2.6 mi E. on NE. Entrance Rd. from its intersection with Slough Creek Campground road; 20 yd N. from road to site.
58.	Lamar Canyon East II	do	44	54	53	110	15	49	6560	2000	10 yd E. of site No. 43 to site No. 58
45.	Fossil Forest	Abiathar Peak	44	51	28	110	14	20	8400	2560	2.7 air miles S.4°12'W. from Lamar Ranger Station; 15 yd SW. from edge of forest.
46.	Flint Creek	do	44	46	5	110	10	15	9025	2750	2.9 air miles S.77°48'W. from Calfee Creek Patrol Cabin; 180 yd N. of Flint Creek tributary.
47.	Timothy Creek	Pelican Cone	44	42	54	110	9	47	8520	2595	5.5 air miles N.67°0'W. from Cold Creek Patrol Cabin; 30 yd. E. from buffalo wallow.
48.	Saddle Mountain	Sunlight Peak	44	42	6	110	59	31	9820	2995	2.1 air miles N.63°30'W. from Upper Lamar R. Ranger Station; 70 yd S. from saddle between Little Saddle Mountain and Hayne Mountain.
49.	Little Lamar River	Pelican Cone	44	40	20	110	1	32	7440	2270	1.8 air miles N.66°0'W. from Cold Creek Patrol Cabin; 25 yd NE. from edge of forest.
50.	Cold Creek	do	44	41	0	110	3	22	7250	2210	0.2 air miles E. from Cold Creek Patrol Cabin to forest edge; 20 yd E. from forest edge to site.
51.	Miller Creek	Abiathar Peak	44	45	16	110	5	51	7160	2180	1.8 air miles S.27°36'E. from Calfee Creek Patrol Cabin.
52.	Cache Creek (sun)	do	44	47	59	110	7	38	6870	2095	1.6 air miles N.26°24'W. from Calfee Creek Patrol Cabin to campsite 34 signpost; 40 yd NE. from signpost to site.
53.	Cache Creek (shade)	do	44	47	59	110	7	38	6870	2095	30 yd E. from site No. 52 to site No. 53.
56.	Gravel Pit	Tower Junction	44	54	28	110	20	46	6180	1885	4.2 mi E. on NE. Entrance Rd. from Tower Jct.; 20 yd N. from road to site.
57.	Lamar Canyon West	do	44	55	13	110	18	12	6360	1940	6.6 mi E. on NE. Entrance Rd. from Tower Jct.; 15 yd N. from road to site.
59.	Ashton	Warm River (7.5')	44	4	19	111	21	16	5565	1695	6.3 mi E. on Rt. 67 from Ashton to junction with Reclamation Rd.; site is in northerly part of triangular junction, 5 yd from Reclamation Rd. (not shown on fig. 7).

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[1] All quadrangles are 15 minute unless otherwise noted.

[2] Altitudes given to ±20 ft and ±5 m.

[3] Odometer mileage; paced yards. A 1-yd pace equals about 1 m.

TABLE 8.—*Pallmann temperatures*

[*t*, temperature; Δ*t*, difference in temperature between 1-m and 2-m values; leaders (- - -) indicate no data]

Site (geographic order) No.	Name	Depth (m)	1976 *t*°C	1976 Δ*t*	1977 *t*°C	1977 Δ*t*	Correction (both 1 and 2 m) Alt[1]	Correction (both 1 and 2 m) Site[2]	Corrected temp °C 1976	Corrected temp °C 1977	Corrected temp °C Avg 1976-77 at 2 m
1.	Teton Pass	1	2.68	0.30	2.64	0.24	+1.6	+2.0	6.3	6.2	
		2	2.38		2.40				6.0	6.0	6.0
2.	Snake River	1	- - -	- - -	7.58	1.32	−.8	+.5	- - -	7.3	
		2	5.99		6.26				5.7	6.0	5.9
3.	Mosquito Creek	1	4.98	.36	5.24	0.65	−.2	+1.0	5.8	6.0	
		2	4.62		4.59				5.4	5.4	5.4
4.	W. Yellowstone Flow (shade)	1	3.13	.30	3.05	.30	+.5	+2.0	5.6	5.6	
		2	2.83		2.75				5.3	5.3	5.3
5.	Madison Plateau Rd.	1	- - -	- - -	6.25	.99	−.3	+1.0	- - -	7.0	
		2	4.56		5.26				5.3	6.0	5.7
6.	West Entrance	1	5.86	.43	- - -	- - -	−.3	+1.0	6.6	- - -	
		2	5.23						5.9	- - -	5.9
7.	Miller Garden	1	11.40	−.28	[3]10.99	−.75	−1.9	0	9.5	9.1	
		2	12.08		[3]11.74				10.2	9.8	10.0
55.	Miller Field	1	- - -	- - -	[3]9.34	.32	−1.9	0	- - -	7.4	
		2	- - -		[3]9.02				- - -	7.1	7.1
8.	Pebble Creek	1	5.22	1.18	- - -	- - -	0	+.5	5.7	- - -	
		2	4.04		4.35				4.5	4.9	4.7
9.	Lamar Ranger Station	1	4.83	.71	5.02	.76	−.3	0	4.5	4.7	
		2	4.12		4.26				3.8	4.0	3.9
10.	Slough Creek	1	6.49	−1.63	- - -	- - -	−.8	0	5.7	- - -	
		2	8.12		- - -				7.3	- - -	7.3
43.	Lamar Canyon East I	1	- - -	- - -	7.02	.99	−.4	0	- - -	6.6	
		2	- - -		6.03				- - -	5.6	5.6
11.	Bunsen Peak	1	4.88	0.24	5.05	0.40	+.3	0	5.2	5.4	
		2	4.64		4.65				4.9	5.0	5.0
13.	Mesa Road I	1	4.71	.24	- - -	- - -	+.2	+1.5	6.4	- - -	
		2	4.47		- - -				6.2	- - -	6.2
14.	Cougar Creek	1	6.72	.66	7.02	.88	−.1	0	6.6	6.9	
		2	6.06		6.14				6.0	6.0	6.0
15.	Mesa Road II	1	4.23	−.13	4.01	−.28	+.2	+.5	4.9	4.7	
		2	4.36		4.29				5.1	5.0	5.1
16.	Harlequin Lake	1	4.20	.04	4.57	.38	−.2	+2.0	6.0	6.4	
		2	4.16		4.19				6.0	6.0	6.0
17.	Norris Junction	1	5.92	−.38	6.15	−.33	+.5	+1.0	7.4	7.7	
		2	6.29		6.48				7.8	8.0	7.9
18.	Cascade Meadows (shade).	1	- - -	- - -	3.32	.12	+1.0	+1.5	- - -	5.8	
		2	3.26		3.20				5.8	5.7	5.8
54.	Cascade Meadows (sun).	1	- - -	- - -	6.08	.53	+.9	0	- - -	7.0	
		2	- - -		5.54				- - -	6.4	6.4
19.	Upper Falls	1	4.53	.10	4.68	.4	+1.0	+.5	6.0	6.2	
		2	4.43		4.64				5.9	6.1	6.0
20.	Elk Antler Creek	1	3.82	.16	3.72	.03	+.7	0	4.5	4.4	
		2	3.66		3.69				4.4	4.4	4.4
21.	Blacktail Deer Dr.	1	5.59	.64	5.30	.39	−.2	0	5.4	5.1	
		2	4.95		4.91				4.8	4.7	4.8
22.	Tower Fall	1	6.07	.99	5.95	.96	+.1	+.5	7.6	7.5	
		2	5.08		4.99				6.6	6.5	6.6
23.	LeHardys Rapids	1	3.04	.78	2.68	.36	+.8	+1.5	5.3	5.0	
		2	2.25		2.32				4.6	4.6	4.6
24.	Grants Pass I	1	2.57	.30	2.52	.25	+.9	+1.5	5.0	4.9	
		2	2.27		2.27				4.7	4.7	4.7
25.	Grants Pass II	1	2.81	.72	3.03	.70	+1.0	+1.5	5.3	5.5	
		2	2.09		2.33				4.6	4.8	4.7
26.	DeLacy Creek	1	4.05	.15	3.77	−.09	+1.0	+1.5	6.6	6.3	
		2	3.90		3.86				6.4	6.4	6.4
27.	Divide Lake	1	3.22	.56	3.61	.62	+1.4	+1.5	6.1	6.5	
		2	2.56		2.99				5.5	5.9	5.7
28.	Little Thumb Creek	1	- - -	- - -	- - -	- - -	+1.2	+2.0	- - -	- - -	
		2	2.44		- - -				5.6	- - -	5.6
29.	Turbid Lake (shade)	1	3.65	−.31	3.41	−.30	+.9	+2.0	6.6	6.3	
		2	3.96		3.71				6.9	6.6	6.8
30.	Turbid Lake (sun)	1	- - -	- - -	5.72	.18	+.9	0	- - -	6.6	
		2	5.62		5.54				6.5	6.4	6.5
32.	Fishing Bridge	1	3.54	.32	3.44	.15	+.8	+1.5	5.8	5.7	
		2	3.22		3.29				5.5	5.6	5.6
33.	Pelican Creek Campground (sun).	1	7.17	−.33	7.17	−.72	+.8	+.5	8.5	8.5	
		2	7.50		7.89				8.8	9.1	9.0
34.	Pelican Creek Campground (shade).	1	4.79	−1.02	4.50	−1.20	+.8	+2.0	7.6	7.3	
		2	5.81		5.70				8.6	8.5	8.6
35.	Natural Bridge	1	5.35	−.73	5.44	−.69	+.8	+1.0	7.2	7.2	
		2	6.08		6.13				7.9	7.9	7.9

TABLE 8.—*Pallmann temperatures*—continued

Site (geographic order)		Depth	1976		1977		Correction (both 1 and 2 m)		Corrected temp °C		
No.	Name	(m)	t°C	Δt	t°C	Δt	Alt[1]	Site[2]	1976	1977	Avg 1976-77 at 2 m
36.	Sand Point	1	4.00	.27	3.90	- - -	+.9	+1.5	6.4	6.3	
		2	3.73		- - -				6.1	- - -	6.1
37.	Pumice Point	1	5.09	−.59	5.00	−.60	+.8	+1.5	7.4	7.3	
		2	5.68		5.60				8.0	7.9	8.0
38.	Arnica Creek	1	4.76	.20	4.96	−.06	+.8	+1.5	7.1	7.3	
		2	4.56		5.02				6.9	7.3	7.1
39.	Grant Village	1	6.85	−1.24	7.04	−1.41	+.8	+1.5	9.2	9.3	
		2	8.09		8.45				10.4	10.8	10.6
41.	Falls River	1	6.24	.39	7.55	.82	−1.1	0	5.1	6.5	
		2	5.85		6.73				4.8	5.6	5.2
42.	Grassy Lake	1	3.54	.36	4.14	.63	+.3	+1.0	4.8	5.4	
		2	3.18		3.51				4.5	4.8	4.7
45.	Fossil Forest	1	- - -	- - -	4.13	.70	+1.4	0	- - -	5.5	
		2	- - -		3.43				- - -	4.8	4.8
46.	Flint Creek	1	- - -	- - -	- - -	- - -	+2.0	0	- - -	- - -	
		2	- - -		3.95				- - -	6.0	6.0
47.	Timothy Creek	1	- - -	- - -	- - -	- - -	+1.5	0	- - -	- - -	
		2	- - -		3.74				- - -	5.2	5.2
48.	Saddle Mountain	1	- - -	- - -	2.91	.45	+2.8	0	- - -	5.7	
		2	- - -		2.46				- - -	5.3	5.3
49.	Little Lamar River	1	- - -	- - -	4.18	.72	+.4	+1.0	- - -	5.6	
		2	- - -		3.46				- - -	4.9	4.9
50.	Cold Creek	1	- - -	- - -	4.76	.24	+.3	0	- - -	5.1	
		2	- - -		4.52				- - -	4.8	4.8
51.	Miller Creek	1	- - -	- - -	6.28	.39	+.2	0	- - -	6.5	
		2	- - -		5.89				- - -	6.1	6.1
52.	Cache Creek (sun)	1	- - -	- - -	6.87	−.07	−.1	0	- - -	6.8	
		2	- - -		6.94				- - -	6.8	6.8
53.	Cache Creek (shade).	1	- - -	- - -	- - -	- - -	−.1	2.0	- - -	- - -	
		2	- - -		5.92				- - -	7.8	7.8

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[1] All sites are normalized to an altitude of 7000 ft (2133 m) by applying a lapse rate of 1°C per 1000 feet of altitude.

[2] All sites normalized to a condition where site receives full sun all day.

[3] Solution of pH=3.51 used for these probes. All other probes contained pH=1.93 Pallmann solution.

TABLE 9.—*Instantaneous temperature measurements in degrees Celsius*

[Data in italics are estimated. Leaders (- - -) indicate no data. Last column, Δ*t*, 2 m is the temperature difference between 1978, 2m and 1979, 2m]

Site		Sept.-Oct. 1978			Feb. 1979			Δ*t*.
No.	Name	0.5 m	1 m	2 m	0.5 m	1 m	2 m	2 m
4.	W. Yellowstone Flow (shade)	5.4	5.1	4.7	0	0.6	1.7	*3.0*
7.	Miller Garden	12.1	13.5	14.8	−.1	1.3	7.2	*7.6*
8.	Pebble Creek	6.7	7.4	6.4	- - -	- - -	- - -	*3.0*
9.	Lamar Ranger Station	7.6	7.5	6.4	- - -	- - -	- - -	*3.0*
10.	Slough Creek	10.3	9.9	8.9	- - -	- - -	- - -	*3.0*
11.	Bunsen Peak	7.0	7.0	6.7	.7	1.7	3.7	3.0
14.	Cougar Creek	8.8	8.6	8.4	- - -	- - -	- - -	*3.0*
15.	Mesa Road II	4.2	5.1	6.1	- - -	- - -	- - -	*3.0*
16.	Harlequin Lake	5.8	6.5	6.7	−1.0	.9	4.1	2.6
18.	Cascade Meadows (shade)	5.2	5.1	4.9	−.2	1.2	2.3	2.6
19.	Upper Falls	5.4	5.7	6.2	- - -	- - -	- - -	*3.0*
20.	Elk Antler Creek	5.0	5.7	5.4	−1.5	−.3	4.1	1.3
21.	Blacktail Deer Dr.	7.2	7.5	6.9	0	2.1	4.4	2.5
22.	Tower Fall	7.2	7.7	7.3	- - -	- - -	- - -	*3.0*
23.	LeHardys Rapids	4.9	4.7	- - -	- - -	- - -	- - -	- - -
24.	Grants Pass I	4.0	4.5	3.9	- - -	- - -	- - -	*2.0*
25.	Grants Pass II	5.3	5.3	4.3	- - -	- - -	- - -	*2.0*
26.	DeLacy Creek	3.3	5.0	6.2	- - -	- - -	- - -	*2.0*
27.	Divide Lake	5.8	5.5	4.8	−.3	−.6	3.3	1.5
28.	Little Thumb Creek	4.5	4.6	4.8	- - -	- - -	- - -	*1.5*
29.	Turbid Lake (shade)	4.4	5.0	5.4	- - -	- - -	- - -	*3.0*
30.	Turbid Lake (sun)	5.5	6.7	7.3	- - -	- - -	- - -	*3.0*
32.	Fishing Bridge	4.8	5.5	5.2	- - -	- - -	- - -	*3.0*
33.	Pelican Creek Campground (sun)	7.5	8.9	9.8	- - -	- - -	- - -	*1.5*

Site		Sept.-Oct. 1978			Feb. 1979			Δ*t*,
No.	Name	1.5 m	1 m	2 m	0.5 m	1 m	2 m	2 m
34.	Pelican Creek Campground (shade)	5.5	6.8	7.7	- - -	- - -	- - -	*2.0*
35.	Natural Bridge	6.0	7.3	8.2	- - -	- - -	- - -	*1.5*
36.	Sand Point	5.5	5.4	5.4	- - -	- - -	- - -	*3.0*
37.	Pumice Point	5.2	6.1	7.0	- - -	- - -	- - -	*2.0*
38.	Arnica Creek	6.1	6.2	- - -	- - -	- - -	- - -	- - -
39.	Grant Village	6.6	8.1	9.5	2.7	4.9	8.6	0.9
41.	Falls River	9.4	9.6	8.5	- - -	- - -	- - -	*3.0*
42.	Grassy Lake	4.5	4.9	5.0	- - -	- - -	- - -	*3.0*
45.	Fossil Forest	6.4	6.7	6.0	- - -	- - -	- - -	3.0
47.	Timothy Creek	5.3	6.0	6.2	- - -	- - -	- - -	*3.0*
48.	Saddle Mountain	3.4	4.3	4.3	- - -	- - -	- - -	*3.0*
49.	Little Lamar River	6.2	6.7	5.1	- - -	- - -	- - -	*3.0*
50.	Cold Creek	6.5	7.3	6.4	- - -	- - -	- - -	*3.0*
51.	Miller Creek	8.0	8.7	8.7	- - -	- - -	- - -	*2.0*
52.	Cache Creek (sun)	9.0	9.5	9.4	- - -	- - -	- - -	*1.5*
53.	Cache Creek (shade)	6.0	6.9	7.4	- - -	- - -	- - -	*1.5*
54.	Cascade Meadows (sun)	7.5	7.6	7.5	.5	1.6	4.4	3.1
55.	Miller Field	10.4	11.5	11.9	−.6	1.7	5.4	6.5
56.	Gravel Pit	12.2	11.9	10.6	- - -	- - -	- - -	*1.5*
57.	Lamar Canyon West	9.8	9.5	9.8	−1.8	.6	5.5	4.3
58.	Lamar Canyon East II	9.9	9.4	8.4	- - -	- - -	- - -	*1.5*
59.	Ashton	9.9	10.8	10.4	1.1	3.4	6.7	3.7
60.	W. Yellowstone Flow (sun)	6.9	6.8	6.7	.8	1.3	2.5	4.2

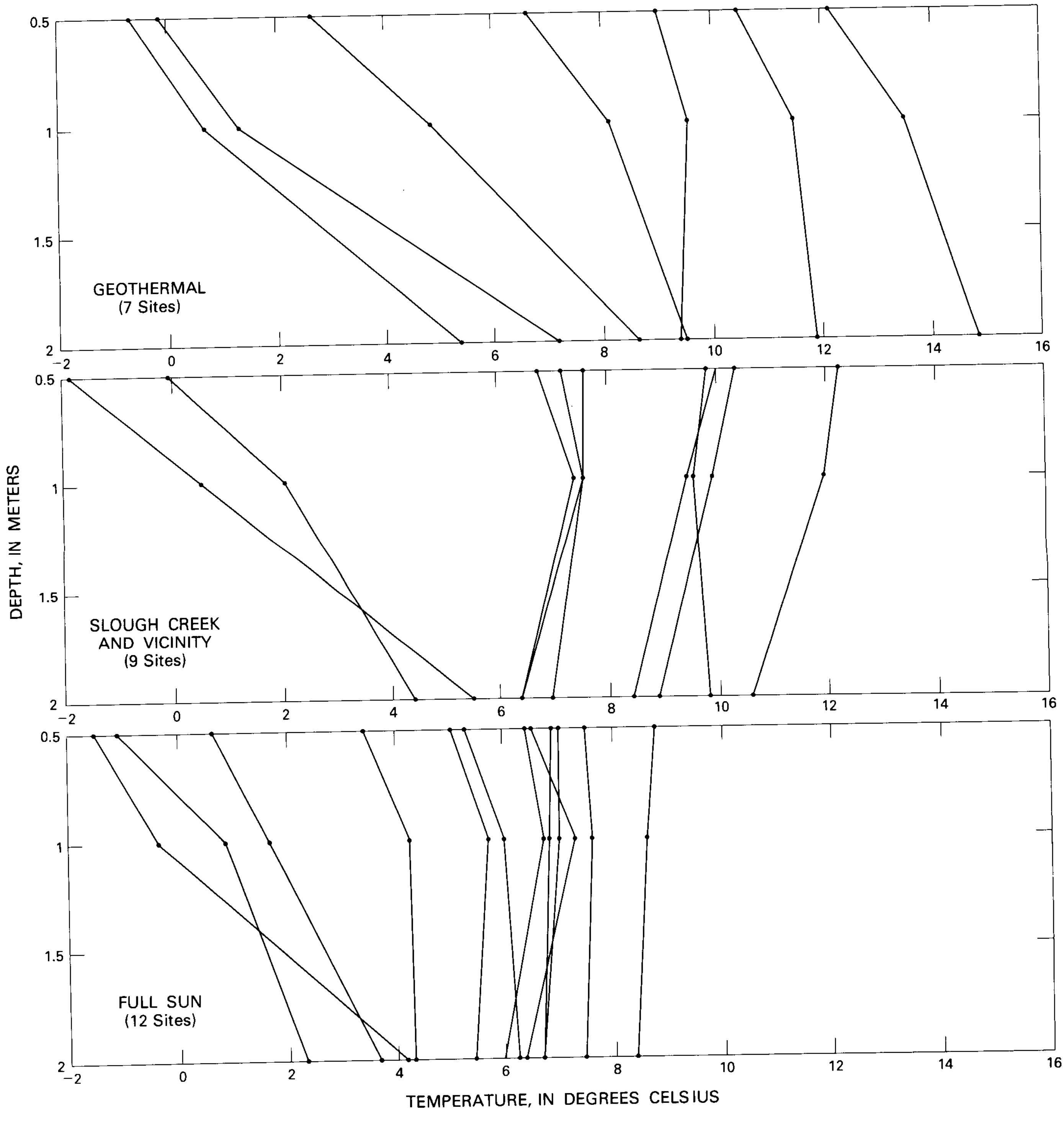
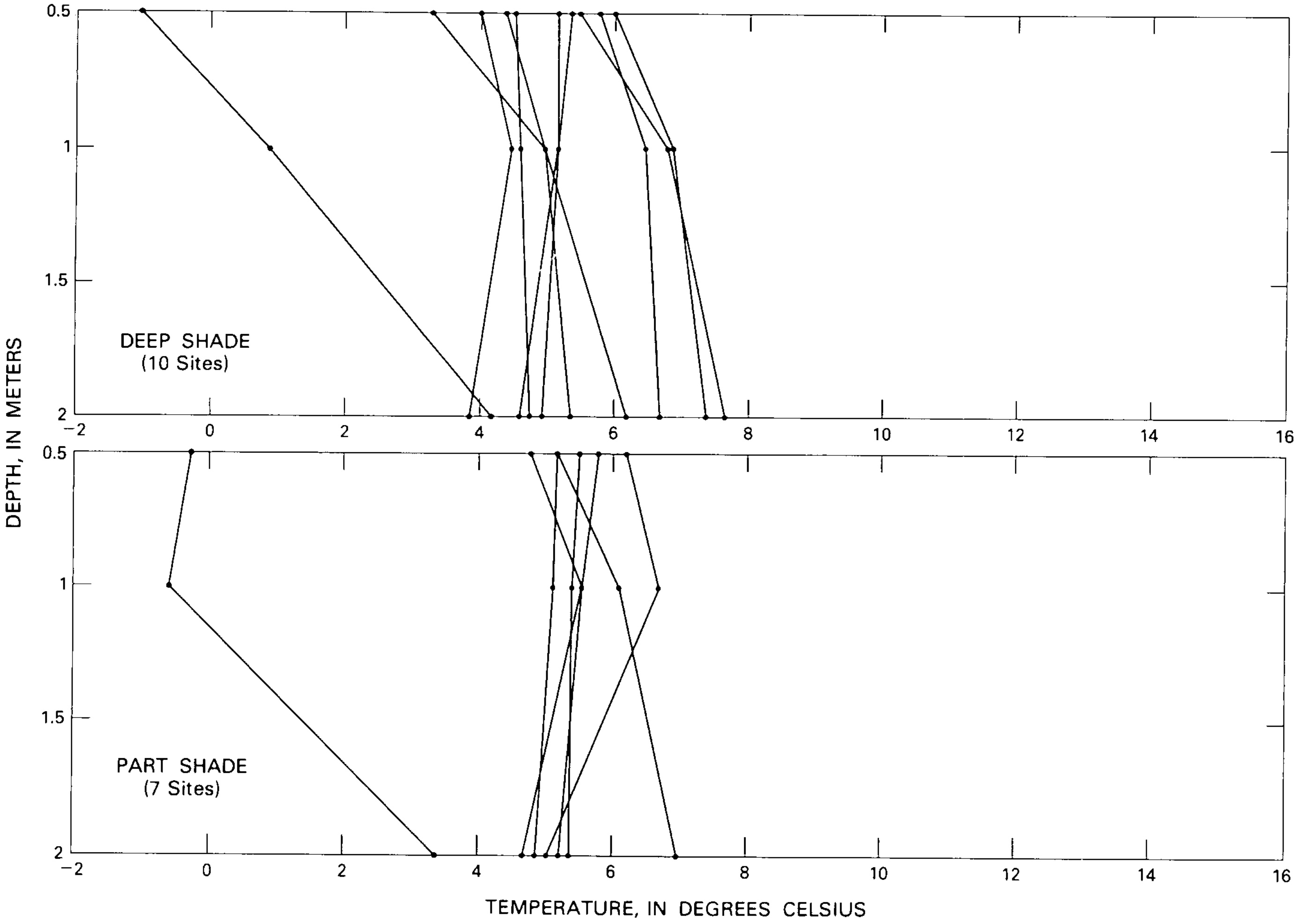


FIGURE 8.—Above and facing page. Plot of instantaneous ground-temperature measurements made in late September 1978, and mid-February 1979. The sites plotted under "geothermal" are those sites that fall in the temperature groupings 3, 4, 5, 6 and 7 in figure 9. Slough Creek plot is from areas of possible anomalous heat flow.


DEPTH, IN METERS
0.5
1
1.5
2
DEEP SHADE
(10 Sites)
−2
0
2
4
6
8
10
12
14
16
0.5
1
1.5
2
PART SHADE
(7 Sites)
−2
0
2
4
6
8
10
12
14
16
TEMPERATURE, IN DEGREES CELSIUS

determine the relative heat flow upward from the interior of the Earth, then we must have a method of normalizing all sites to the same net heat flow downward from the ground surface. We attempted to do this for the Yellowstone sites by first making an altitude correction normalizing all sites to an altitude of 7,000 feet. This was first attempted by applying the pseudoadiabatic lapse rate of 2°C/1000 ft elevation. This altitude correction, when applied to pairs of stations differing only in altitude, did not give corrected temperatures that were equal at the two sites. A correction of 1°C per 1,000 feet of elevation yielded corrected temperature values in better accord in each of the paired stations. A lower lapse rate may be due to the sinking of cold air to the valley bottom. This effect, most noticeable in winter, will tend to reduce the normal lapse rate. These corrections are given in table 8.

The second correction applied to the data was for degree of shade received by the site. A completely open site—one that received all of the available sun all year long—was found to have an effective annual temperature that was 2°C higher at a depth of 2 m than a nearby completely shaded site. After estimating the degree of shade on a scale of 1 through 5, all sites were normalized to the completely open site condition by adding the appropriate correction (see table 8) to the altitude-corrected temperature. These corrections are considered to be a first approximation. Other corrections, such as soil thermal diffusivity, snow cover, and soil albedo, are not easily made, and were not evaluated. The corrected Pallmann temperatures are listed in table 8. Figure 9 is a map of the area under investigation with the 2-m corrected Pallmann temperatures shown for each site.

To convert Pallmann-effective temperatures to obsidian-effective temperatures and to arithmetic-mean temperatures, the plots (16) in figure 1, PART I were used. The minimum ground temperatures could not be obtained for many sites, and therefore we have estimated the minimum temperature for these sites. These estimated temperatures are shown in italic type in table 9.

The temperature spread between summer maximum and winter minimum at 2 m is small, 3°C or less for most sites. As a result, the difference between Pallmann- and obsidian-hydration effective temperature is 0.1°C or less at 2 m for all sites in the park. This will not be true for obsidian exposed at depths shallower than 2 m. For these samples, the constants used to convert from Pallmann- to obsidian-hydration effective temperature can be computed from the 1-m data given in tables 8 and 9, together with plots in figure 1, PART I.

In terms of snow depth, the winter of 1975–76 was normal. However, the winter of 1976–77 was extremely dry with about one-third the normal snow depth. In 1977–78, about two to three times the normal snow depth was recorded in the park. The 1978–79 winter was extremely cold with no respite through February, 1979. The snowfall was normal, and the ground was insulated from the cold by the snow (1–2 m snow depth by early February).

RESULTS

As discussed in PART I, the Pallmann temperatures given in table 8 differ from arithmetic-mean annual temperatures. In general, they will show higher readings than "arithmetic" mean annual, because the Pallmann solutions react in a nonlinear manner, that is, the reaction rate is an exponential, rather than a linear, function of temperature. In addition, in areas of normal heat flow, the upper vial will indicate a higher integrated temperature than the lower, again due to the higher temperatures experienced by the upper solutions as compared to the lower. Several sites must have been close to sources of high geothermal heat flow. At these places, extremely high temperatures were recorded at 2 m and these temperatures were higher than those recorded at 1 m. The Pallmann site near Grant Village was particularly hot, and we understand that wells drilled in the vicinity of Grant Village have encountered extremely hot water at rather shallow depths. Anomalously high Pallmann temperatures were also recorded at other sites, including the Slough Creek site and the Norris Junction site.

As mentioned previously, the Slough Creek site (10) yielded anomalously high Pallmann temperatures as compared to similar sites nearby. Additional Pallmann probes were placed at sites adjacent to Slough Creek (sites 43, 58), and the results are shown in figure 9. In addition to these Pallmann probes, instantaneous temperature measurements (in September 1978, and February 1979) were made at three places close to the Slough Creek site (sites 56, 57, 58). These results are given in table 9. All of these results suggest an area of high heat flow in the Slough Creek area.

The winter of 1978–79 was one of the coldest on record. Not only were extremely low temperatures recorded (−56° Fahrenheit at Old Faithful) but the cold persisted without letup from mid-November 1978, through February 1979. In spite of this, the frost level did not penetrate deeply into the ground. At all but one site, the freezing line was between 0.5 and 1 m. The exception was Elk Antler Creek in Hayden Valley where the freezing line was just below 1 m. This site was exposed to the wind, and the snow depth when we visited in February 1979, was only about 0.25 m, in contrast to the 1–2 m of snow cover at all the other sites. Evidently, the low-density abundant snow fell early enough in the fall to act as an effective thermal insulation at most sites.

In figure 10 we have plotted the corrected effective annual Pallmann temperatures at 2 m. Inasmuch as the corrections that we have applied to the measured tem-

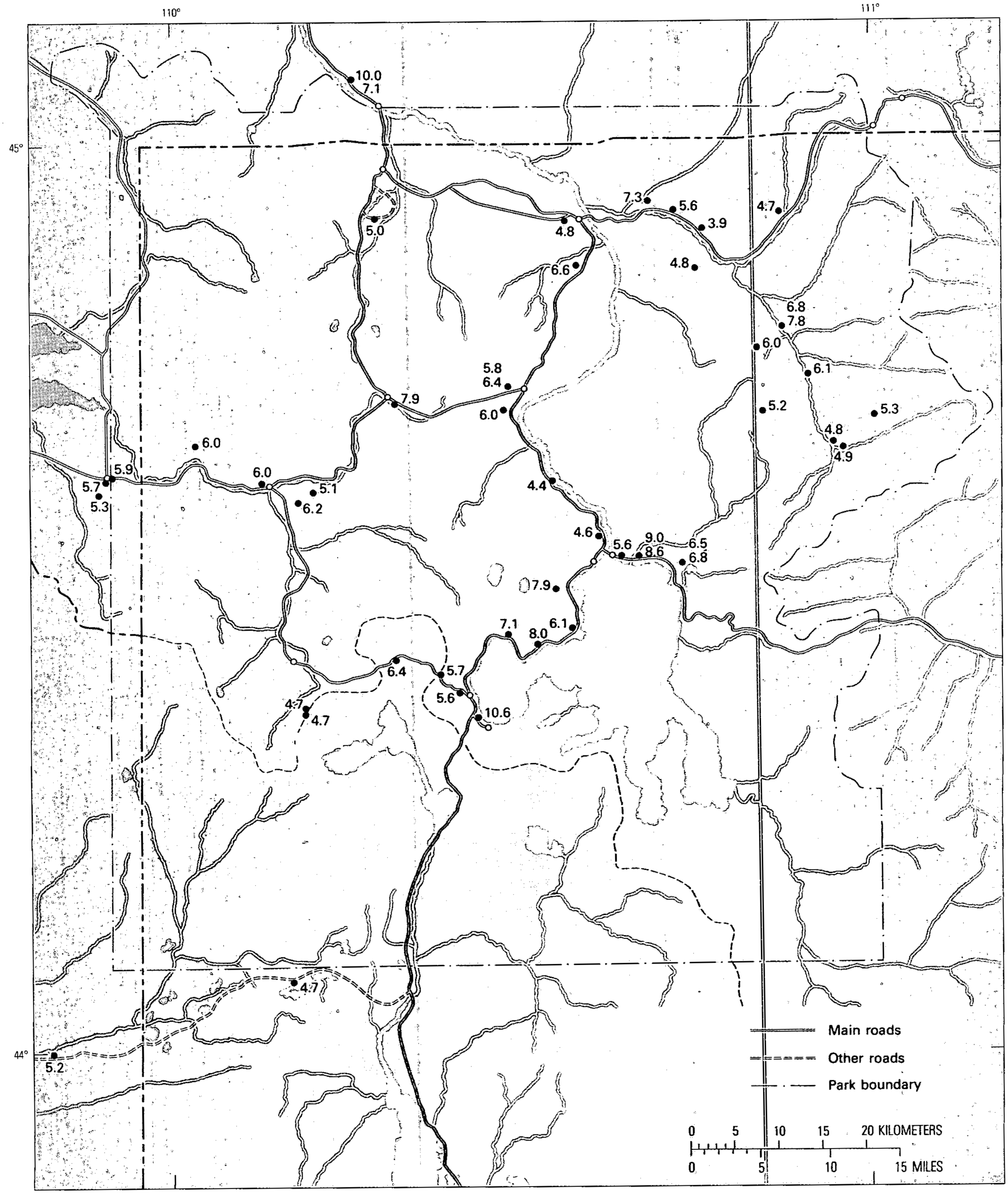


FIGURE 9.—Yellowstone National Park and vicinity with the average corrected 2-m Pallmann temperature for 1976 -1977 shown for each site. These temperatures, in degree Celsius, have been normalized to 7000 ft (2133 m) and to a site that received all available sun (unshaded).

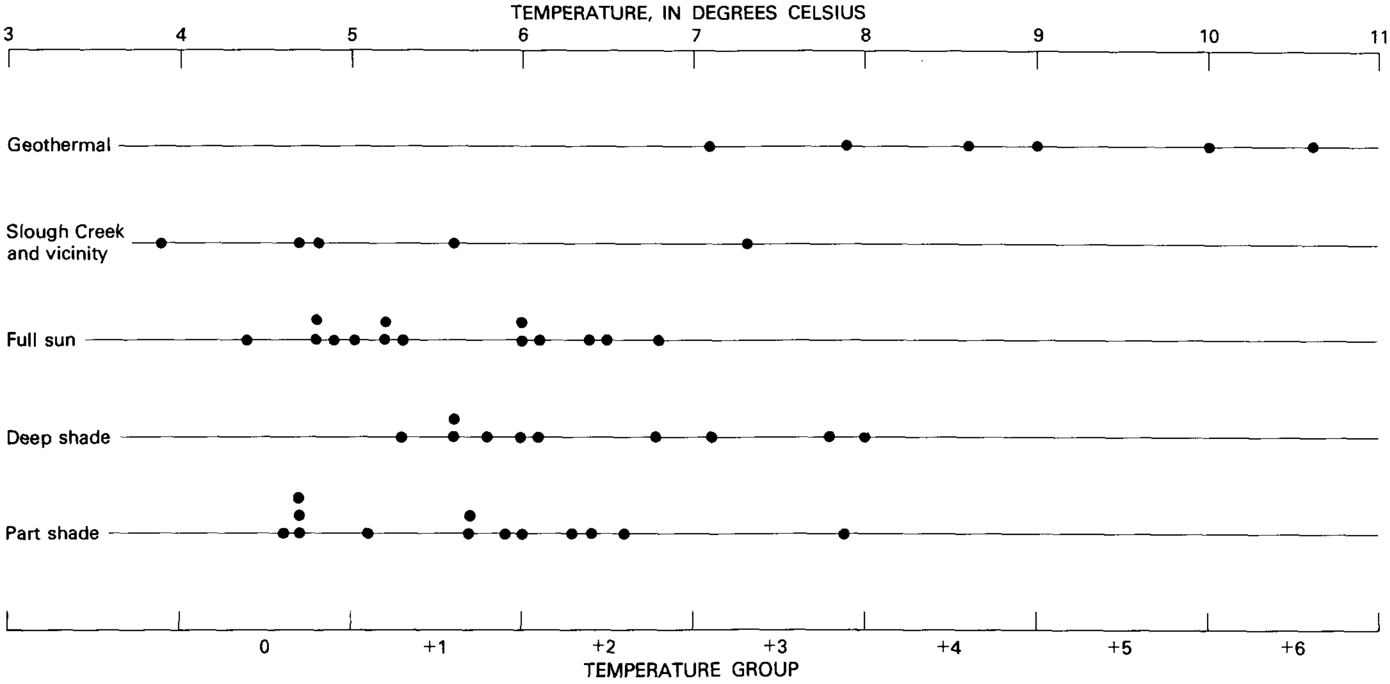


FIGURE 10.—Plot of 2-m corrected Pallmann temperatures, arranged by types of sites: geothermal, Slough Creek and vicinity, full sun, deep shade, and part shade.

peratures have served to normalize these temperatures to a common heat flux from the surface downward, the variations in corrected temperatures at a depth of 2 m will be due to variable heat flux upward. If the sites with the lowest temperatures, (between 4° and 5°C) are taken as a base, the corrected temperatures at all other sites can be compared to this group. The sites in the temperature range 5°-6°C will be designated +1, those in the range 6°-7°C, +2, and so forth. These groupings, from 0 to +6, are a measure of the amount of geothermal heat flux received by members of each group. The group number is plotted on a map of the Yellowstone area (fig. 11). Areas of high heat flow are also shown enclosed by dotted lines.

Although sites inside the Yellowstone caldera tend to show greater geothermal heat flux than do those outside the caldera, the relatively small number of total sites does not allow us to make a more definitive statement in this regard. The area of high heat flow near Slough Creek is somewhat surprising inasmuch as the closest known hot springs are those on the Yellowstone River, about 4.4 mi (miles) west of the site. The hot area near Cache Creek is about 2 mi southwest from Wahb Springs (hot) while the Pelican Creek Campground sites are about 2.5 mi from known hot springs. On the other hand, both the LeHardy Rapids and Elk Antler Creek sites are close (LeHardy, 2 mi, Elk Antler, 1 mi) to large thermal areas, and neither site shows any geothermal influence. The two sites at Grants Pass also do not show geothermal effects, even though they are 2 mi from the Shoshone Geyser Basin. Obviously, mere geographic proximity to a geothermal feature is not a sufficient criterion to predict geothermal contribution at a site. The ground-water regime must be the important link in order for a site to display a high geothermal heat flow at 2-m depth. In fact, the areas containing cool sites are probably places where ground water is moving downwards, whereas the hot sites are caused by warm ascending ground water.

It is interesting to note that site 7 is about 25 yd from a small warm-spring orifice. Site 55 is about 125 yd from site 7 and approximately 150 yd from the spring. The temperature at 2-m depth at site 55, while still high, is 2.9°C less than at site 7 (see table 8).

In figure 12, we have plotted the 2-m corrected Pallmann temperatures versus the difference in Pallmann temperature recorded by the 1- and 2-m Pallmann vials. In addition to the sites in Yellowstone Park, we have also plotted data from eight sites outside the park; sites that we believe to be remote from the high geothermal heat flow associated with the park. These latter sites define a line (A) shown on the diagram, of positive slope. This means that those sites having the highest temperatures at 2 m also have the highest positive Pallmann temperature gradient (1-m vial higher Pallmann temperature than the 2-m vial). This is in keeping with the higher heat flux downward at these sites. On the other hand, the sites in Yellowstone define a line of negative slope (B). This indicates the greater contribution of upward heat flux at these sites.

The instantaneous temperature measurements made in late September and early October 1978, can be used to aid in delineating the extent of the area of possible

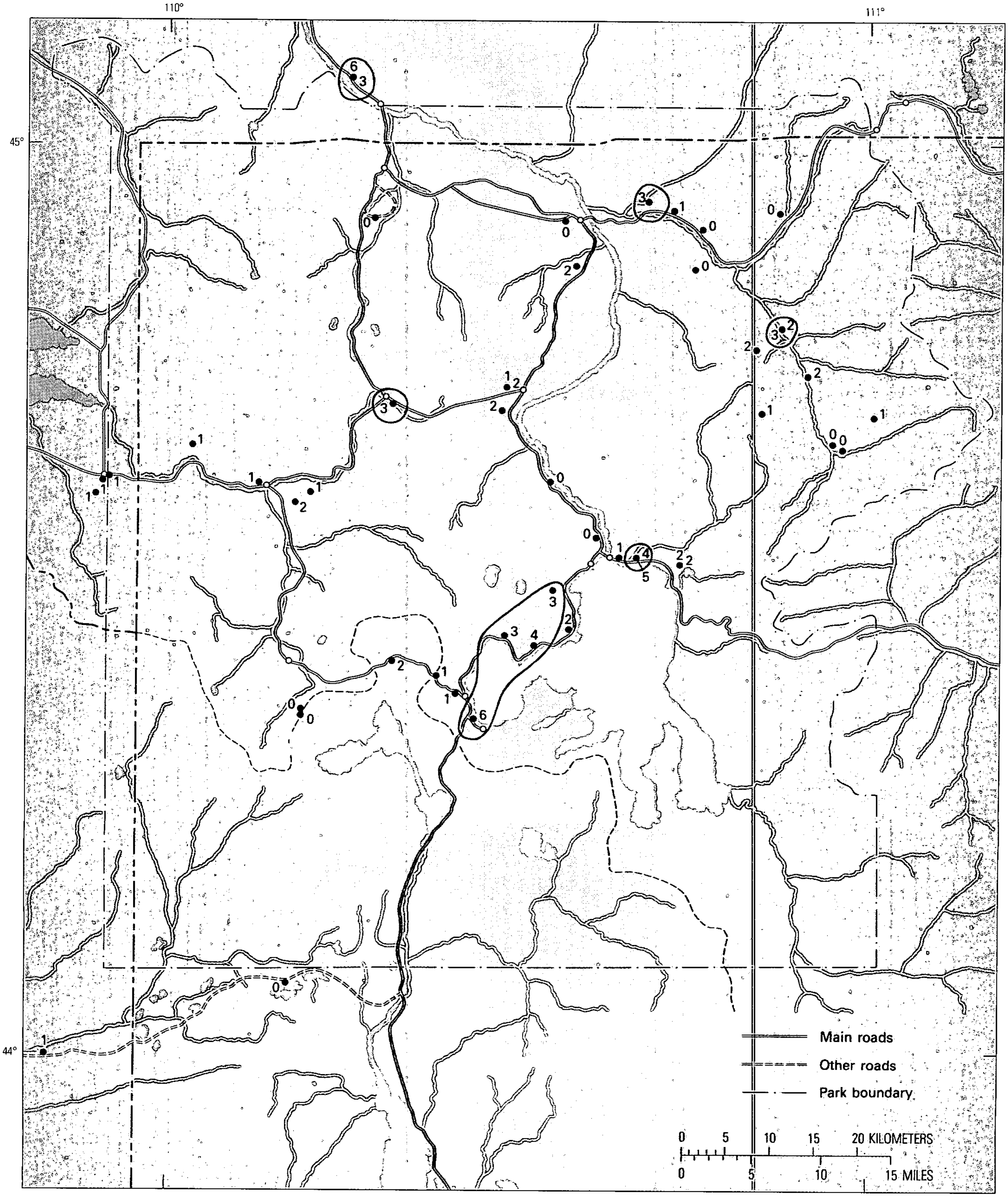


FIGURE 11.—Yellowstone National Park and vicinity showing temperature group (from 0 to +6 degrees Celsius; each group represents a range of 1°, +1= 5° −6°C; +2= 6° −7°C . . .) at 48 sites. Areas of high heat flow containing sites with high temperature group values (+3 or greater) are shown enclosed by dashed lines.

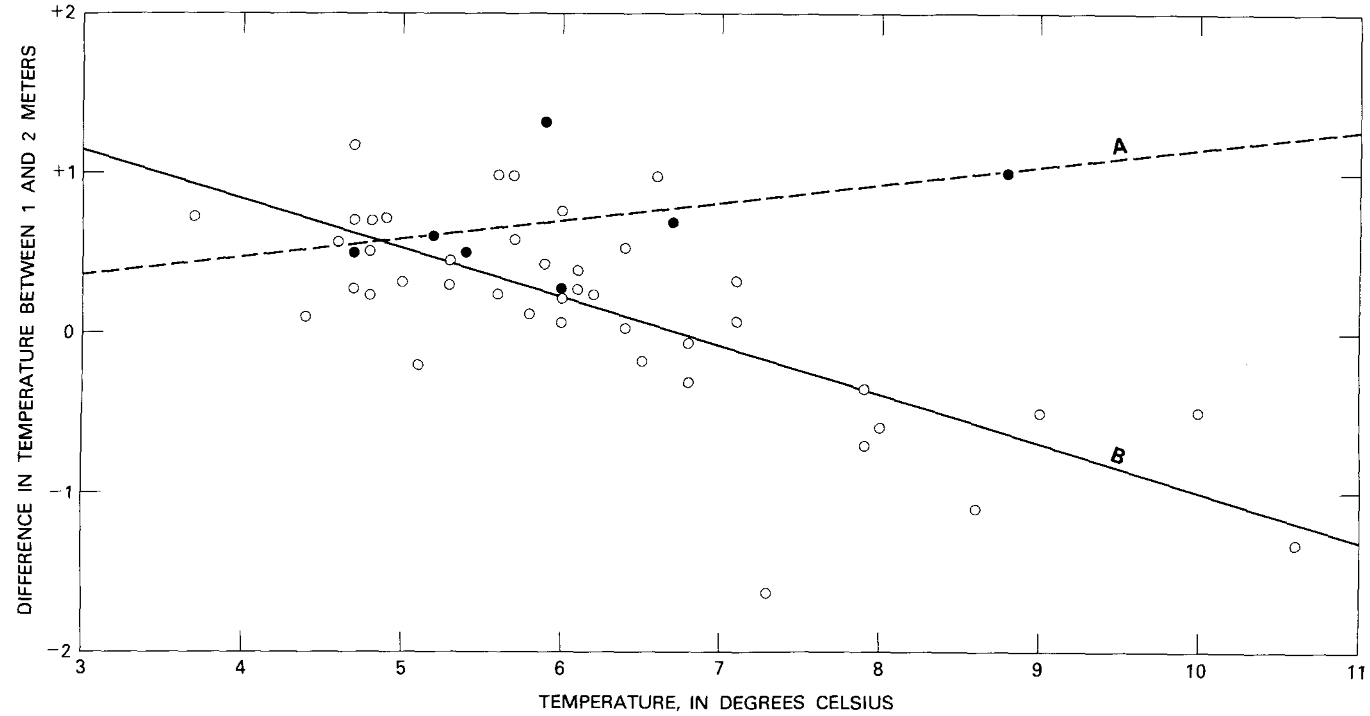


FIGURE 12.—Plot of 2-m corrected Pallmann temperatures versus difference in temperature between 1 and 2 m. Solid circles are from data for sites outside Yellowston National Park that are believed to be remote from geothermal influence. Open circles are data for sites in and adjacent to the park. Lines A and B are least-mean-square fits to the two sets of data points.

anomalous heat flow adjacent to Slough Creek. In figure 13 we have plotted the instantaneous 2-m temperatures, corrected for altitude using the 1°C per 1000 feet (305 m) lapse rate. The data is grouped by whether the sites were in full sun, partial shade, or deep shade. In addition to these groups, the sites that fall in the +3, +4, +5, and +6 categories of figure 9 have been plotted as a separate group labeled "geothermal". The group labeled "Slough Creek" are sites adjacent to Slough Creek. Note that sites 8 and 9 which are east of Slough Creek (Pebble Creek and Lamar Ranger Station) as well as site 21, (Blacktail Deer Drive) west of Slough Creek, all fall in the "normal" group having relatively low 2-m instantaneous temperatures. On the other hand, the sites from just east of Lamar Canyon (site 58) to the gravel pit on the highway west of Slough Creek (site 56) all showed high ground temperatures in the range of the "geothermal" group, the temperature increasing from east to west.

CONCLUSIONS

In conclusion, the Pallmann measurements made at 1- and 2-m depths in and adjacent to Yellowstone National Park can be used to calculate effective obsidian-hydration temperatures for dating. The measurements have also been useful in locating and defining areas of

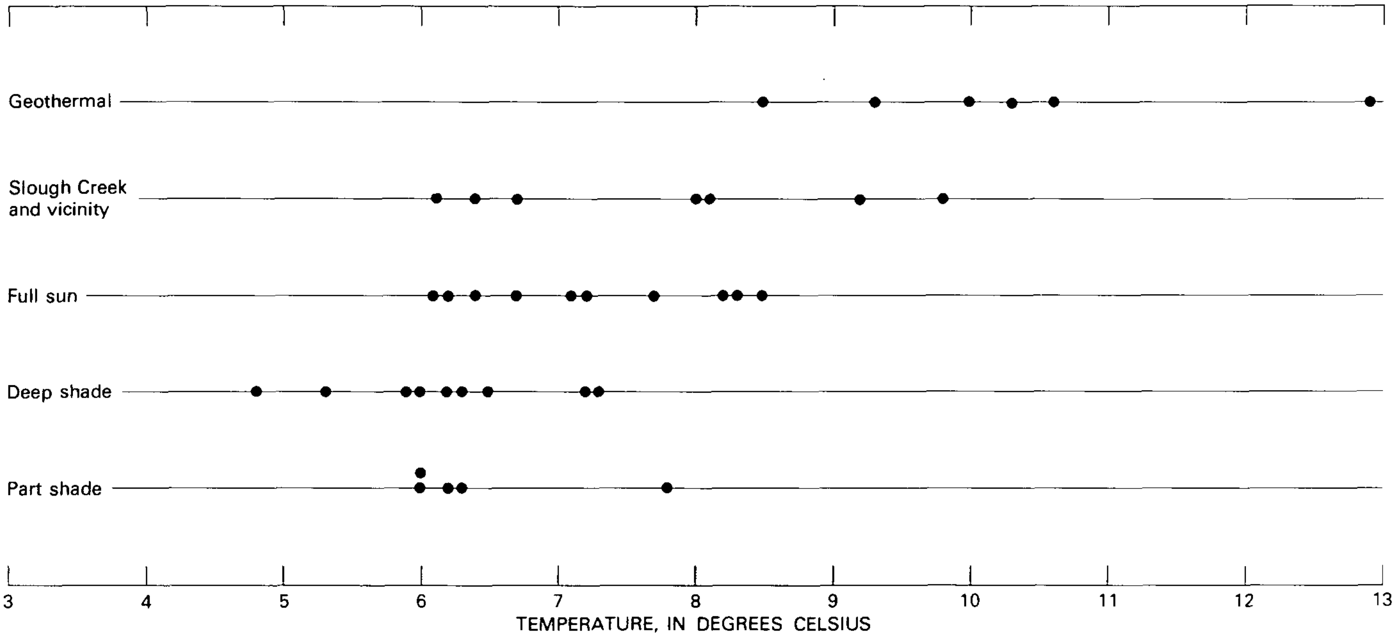


FIGURE 13.—Plot of 2-m instantaneous maximum temperatures made in late September 1978, and normalized to a 7000-ft (2133-m) altitude. Sites are arranged by type: geothermal, Slough Creek and vicinity, full sun, deep shade, and part shade.

anomalous heat flow. Not only did the Pallmann annual effective temperatures measured at 2 m, corrected for altitude and site condition, allow us to locate areas of anomalously high heat flow, but also the temperature gradient between the 1- and 2-m Pallmann vials gave additional indication of such anomalous heat flow.

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