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MEASUREMENT OF HEAT FLOW BY A DOWNHOLE PROBE TECHNIQUE IN THE SAN JOAQUIN VALLEY, CALIFORNIA

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

ABSTRACT

During the drilling of five shallow (120 to 150 m) wells in the central San Joaquin Valley, 18 successful penetrations were made using the downhole heat-flow probe. Eighteen values of thermal conductivity measured in situ ranged from 1.19 to 2.07 with mean of 1.65 $Wm^{-1} K^{-1}$ ± 0.23 s.d. When compared with grain conductivity measurements on adjacent ditch samples, the in situ values yielded interpreted values of porosity ranging from 7% to 44% with mean of 28.8 ± 9.1 s.d. Heat flows at the five sites were between 44 and 64 mWm^{-2} (1.05 and 1.53 HFU). This is in the same range as heat flows obtained from deep oil wells in the southwestern part of the San Joaquin Valley. It is inconsistent with predictions of high heat flows (85 to 105 mWm^{-2} and greater) from silica geotemperatures of non-thermal waters presented by C. A. Swanberg and Paul Morgan.

INTRODUCTION

Wang and Munroe (1982) have published a great deal of information on temperatures and temperature gradients in the near-surface (upper ~300 meters) Tertiary and Quaternary material of the Central Valley of California. Lack of thermal conductivity data has thus far made it impossible to make realistic estimates of heat flow for these sites. We have recently drilled five holes (ranging from 120 to 152 meters deep) in the central San Joaquin Valley between the Coast Ranges and Fresno (Figure 1). Temperatures and thermal conductivities were measured in situ during the drilling process using the technique described by Sass and others (1981). In this report, we present the thermal data from those wells.

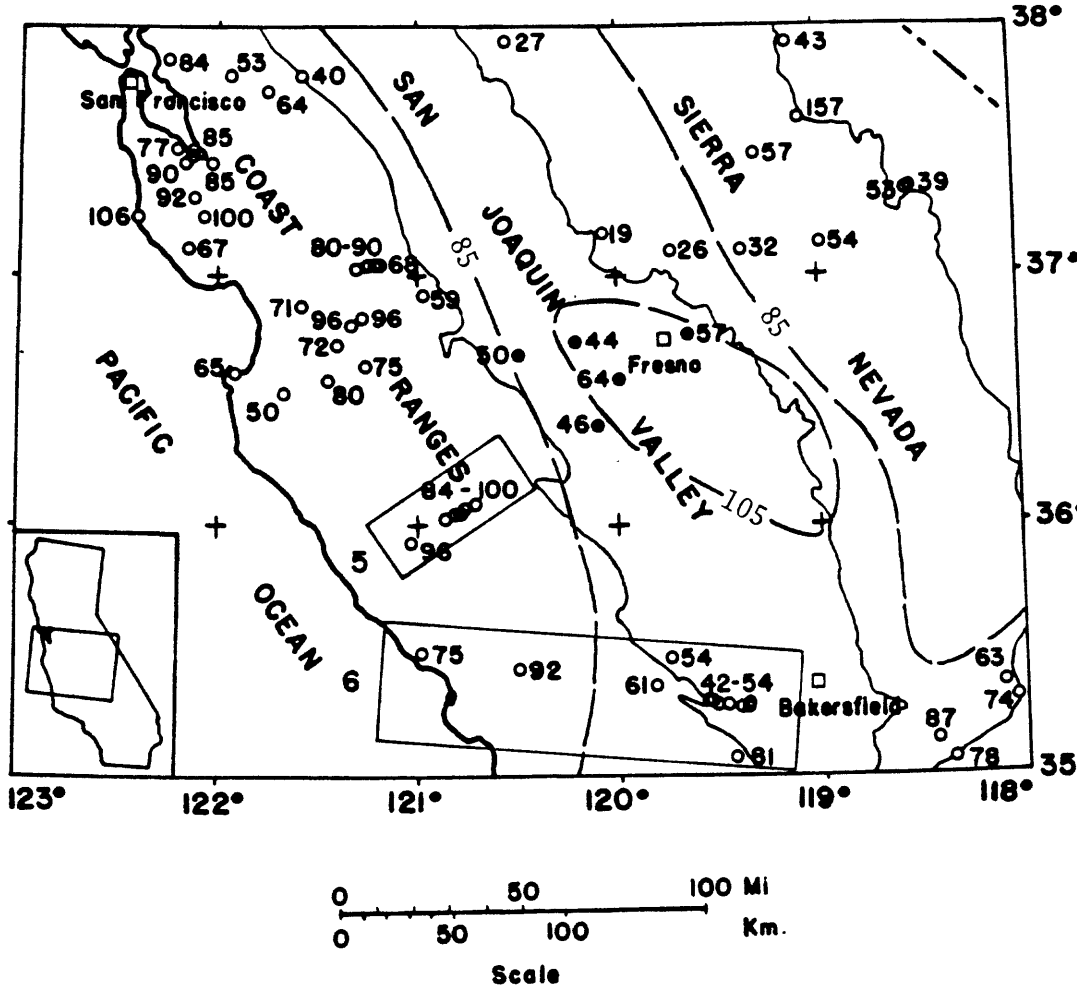

Figure 1. Map showing physiographic boundaries of the San Joaquin Valley and neighboring tectonic provinces in central California. Inset: Map of California showing study area. Rectangles outline regions 5 and 6 of Lachenbruch and Sass (1980) (see text). Open circles are previously published values, and dots, present work. Dashed contours are heat flows predicted by silica temperatures (Swanberg and Morgan, 1978).

EXPERIMENTAL PROCEDURE

The apparatus is described, and field procedures are summarized by Sass and others (1981). The equipment is described in greater detail by Sass and others (1979). Briefly, at intervals of a few tens of meters (30.5 meters or 100 feet in this case), the drilling process is interrupted and the bit is placed on the bottom. A long (~1.5 m), thin (6 mm diameter) probe containing three thermistors either 0.5 or 0.15 m apart and a heating wire is driven ahead of the bit into the formation below it. The passive thermal response of the probe is recorded at the surface for about 30 minutes. A constant current is then supplied to the heating wire and the temperature-time curve is recorded for about 16½ minutes (1000 seconds). Equilibrium temperatures and (in theory) gradients can be obtained from the "passive" temperature-time graphs and thermal conductivity, from the temperature-log time curve obtained during the heating phase. The whole process including penetration of the probe takes about an hour whereupon drilling is continued or (if target depth has been reached), the hole is logged, plugged, and abandoned. Ditch samples at intervals of 5 to 10 meters are retained to permit preparation of lithologic logs and to afford the opportunity of measuring the thermal conductivity of the solid component of the sediments in the laboratory (Sass and others, 1971).

Temperatures. The material most often encountered in this study was a combination of sand, silt, and gravel (see detailed lithologic descriptions, Appendix 2). This proved difficult to penetrate for more than 0.3 to 0.5 meters. Combined with the fact that the gradients were low in comparison to those encountered in geothermal areas, this resulted in very poor determinations of interval thermal gradients. We were able to obtain (in effect) only a single-point determination of temperature for each probe run.

Gradients were then determined between neighboring probe runs (Table 1). Discrete measurements of temperature are plotted as a function of depth for all five wells in Figure 2.

For SJV5, we were unable to achieve penetration at total depth (152.4 m) owing to a mechanical malfunction in the driving system. To obtain a temperature, we cased the well with 32 mm i.d. plastic pipe and returned to log the well two months after completion. This allowed us to compare temperatures obtained conventionally with those measured during drilling (Figure 3). There is an offset of about 0.1°C between the two curves. This can be explained easily in terms of a calibration offset between the downhole probe and the conventional logger. The interval gradients are, however, identical; the mean difference between the two logs at the four points of comparison is 0.105 ± 0.007°C.

Thermal conductivity and porosity. One of the aims of the present investigation was to characterize (if possible) the mean thermal conductivity of the near-surface unconsolidated sedimentary material which, in turn, would allow us to make meaningful estimates of heat flow from the gradient data compiled by Wang and Munroe (1982). These sediments were derived from the neighboring Coast Ranges and Sierra Nevada. We should thus expect thermal conductivities to reflect those of the parent rock, making allowances for porosity and the weathering of feldspathic minerals to clay.

Individual values of in situ thermal conductivities (K_r) are shown in Table 1. Also tabulated are the average conductivity of the solid component (K_s) of ditch samples collected from the 6.1 m intervals immediately above and below the in situ determination. From these two numbers, we "backed out"

TABLE 1. Thermal conductivities, calculated porosities, temperatures, and interval heat flows
San Joaquin Valley

Well #	Depth m	K_r ($Wm^{-1}\ K^{-1}$)	K_s ($Wm^{-1}\ K^{-1}$)	ϕ %	Description	Temp. °C	Interval gradient °C km^{-1}	K $Wm^{-1}\ K^{-1}$	q mWm^{-2}
SJV-1	30.5	1.75	3.03	33	Silt, clay, gravel	21.115			
							47.86	1.64	78
	61.0	1.52	2.39	32	Silt, clay, minor gravel	22.574			
							30.91	1.60	50
	91.4	1.69	2.71	31	Sand, silt, fine gravel	23.516			
							25.75	1.88	48
	121.9	2.07	2.66	16	Gravel, coarse sand, minor silt	24.301			
							27.52	1.84	51
	152.4	1.62	2.62	32	Gravel	25.140			
							Average 61-152		50
SJV-2	42.7	1.56	2.25	27	Silt, sand, minor gravel	20.532			
							35.1	1.78	62
	61.0	2.01	2.22	7	Sand, silt, gravel	21.174			
							32.6	1.60	52
	121.9	1.19	1.90	39	Silt, sand, minor gravel	23.162			
							Average 43-122		57
SJV-4	85.3	1.65	3.04	37	Very coarse sand	22.915			
							35.8	1.80	64
	134.1	1.95	3.08	27	Medium to coarse sand	24.663			
SJV-5	30.5	1.56	2.39	30	Fine sand, silt, clay	21.179			
							50.9	1.62	82
	61.0	1.67	2.15	19	Fine sand, silt, clay	22.732			
							32.0	1.62	52
	97.5	1.57	2.20	25	Fine sand, silt, clay	23.899			
							27.2	1.48	40
	121.9	1.38	2.45	40	Fine sand, silt, clay	24.564			
							Average 61-122		46
SJV-8	61.0	1.86	2.86	27	Fine sand to silt	21.148			
							24.6	1.76	43
	91.4	1.66	2.68	31	Very coarse sand	21.897			
							24.4	1.48	36
	121.9	1.30	2.44	44	Fine sand to silt	22.640			
							35.1	1.48	52
	152.4	1.67	2.20	21	Fine sand to silt	23.711			
							Average 61-152		44

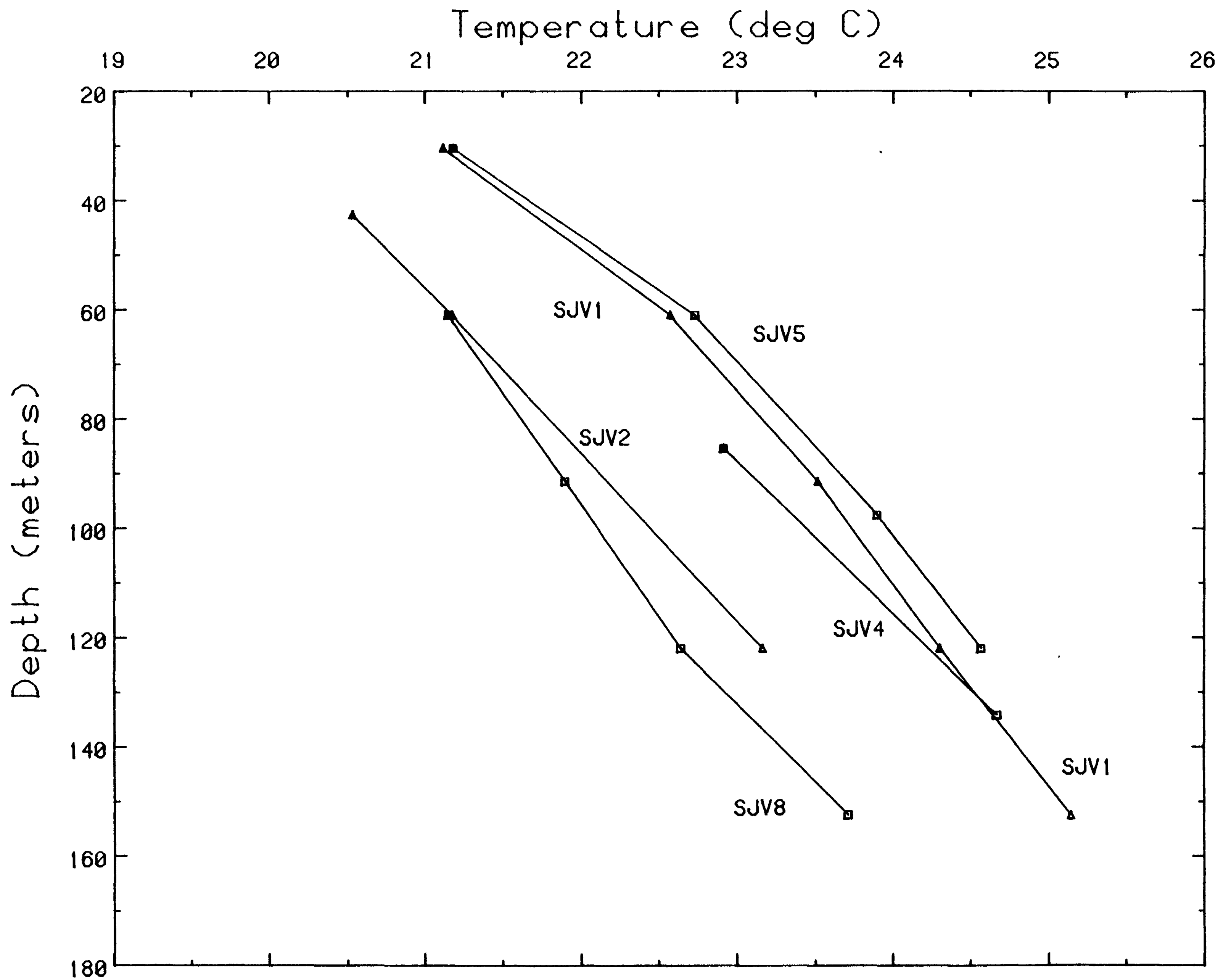

Figure 2. Formation temperatures measured during drilling using the USGS downhole probe for holes drilled in the central San Joaquin Valley.

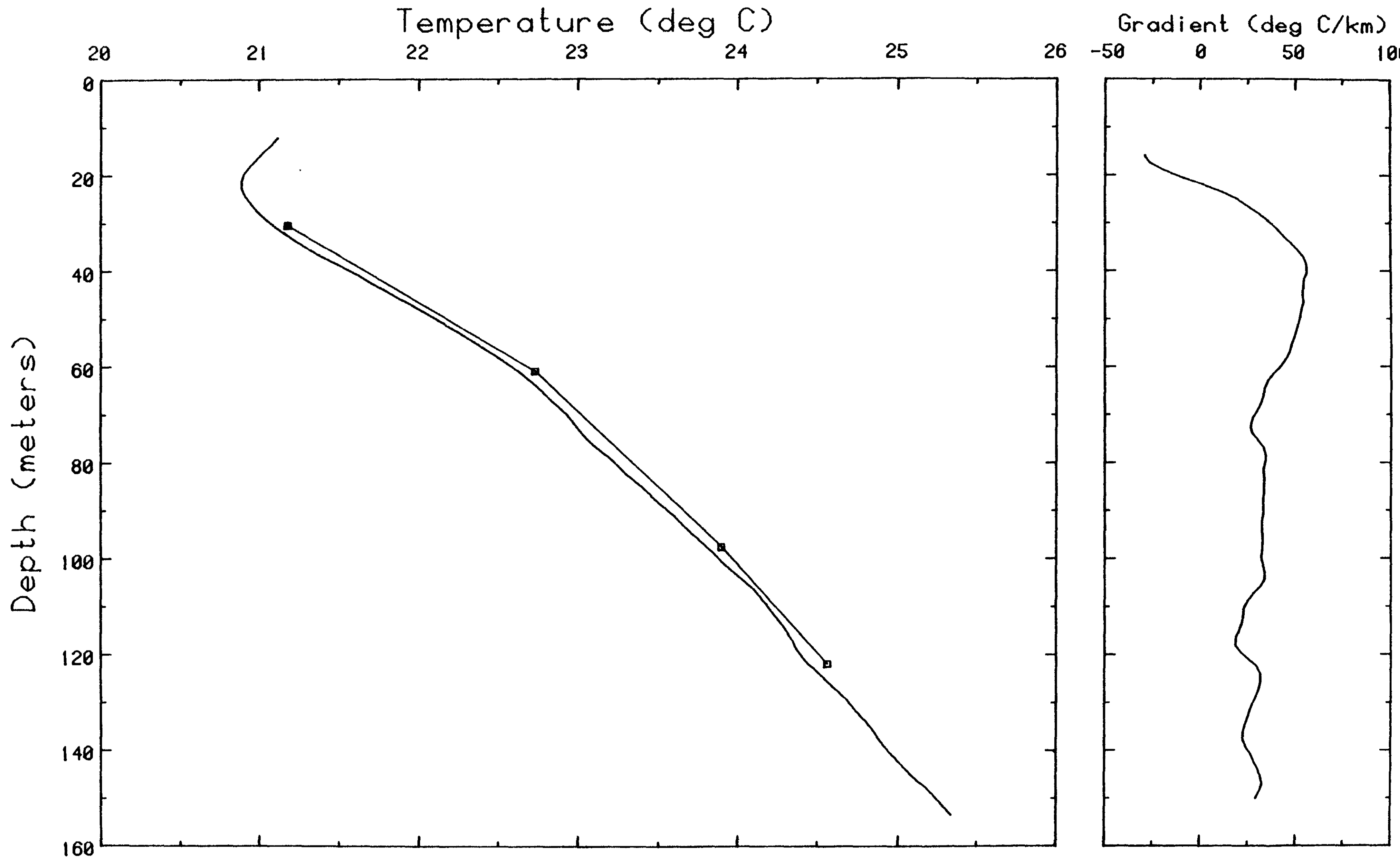

Figure 3. Temperatures measured during drilling (squares joined by straight lines) and two months post-drilling in well SJV-5.

an estimate of porosity (ϕ) using the geometric mean relation, i.e.,

$$K_r = K_s^{(1-\phi)} \cdot 0.58^{\phi}$$

where 0.58 represents the thermal conductivity of liquid water in $Wm^{-1}\ K^{-1}$ at about 20°C. Taking natural logarithms and rearranging terms, the fractional porosity may be represented as

$$\phi = \frac{\ell n\ K_s - \ell n\ K_r}{\ell n\ K_s - \ell n\ 0.58}$$

These values are tabulated as percentage porosity in Table 1. The conductivity distribution is normal (Figure 4) and the mean thermal conductivity of 1.65 $Wm^{-1}\ K^{-1}$ ± 0.23 s.d. (3.94 ± 0.55 mcal/cm sec °C) is reasonable for unconsolidated sediments containing substantial amounts of quartz. The distribution of calculated porosity (Figure 5) also is quasi-normal with a mean that is not unusual for this type of material. The strong concentration of porosity values around a mean of about 30% is encouraging in terms of calculating formation conductivity from measurements on chips from other holes.

Heat flow. As mentioned above, it was difficult to achieve complete penetration for most runs and the low gradients (Figures 2 and 3) made gradient determinations over 0.5 to 1 m intervals very inaccurate. We thus made all of our heat-flow determinations over the 30- to 60-meter intervals between neighboring probe runs (Table 1). The gradient was determined simply by dividing the temperature difference between succeeding runs by the depth difference. This was, in turn, multipled by the average conductivity (K, Table 1) for the two runs to give a component value of heat flow (q, Table 1). The high values between 30 and 60 meters in SJV1 and SJV5 are apparently related to the thermal transients associated with a century of agriculture and irrigation. They were not included in the average heat

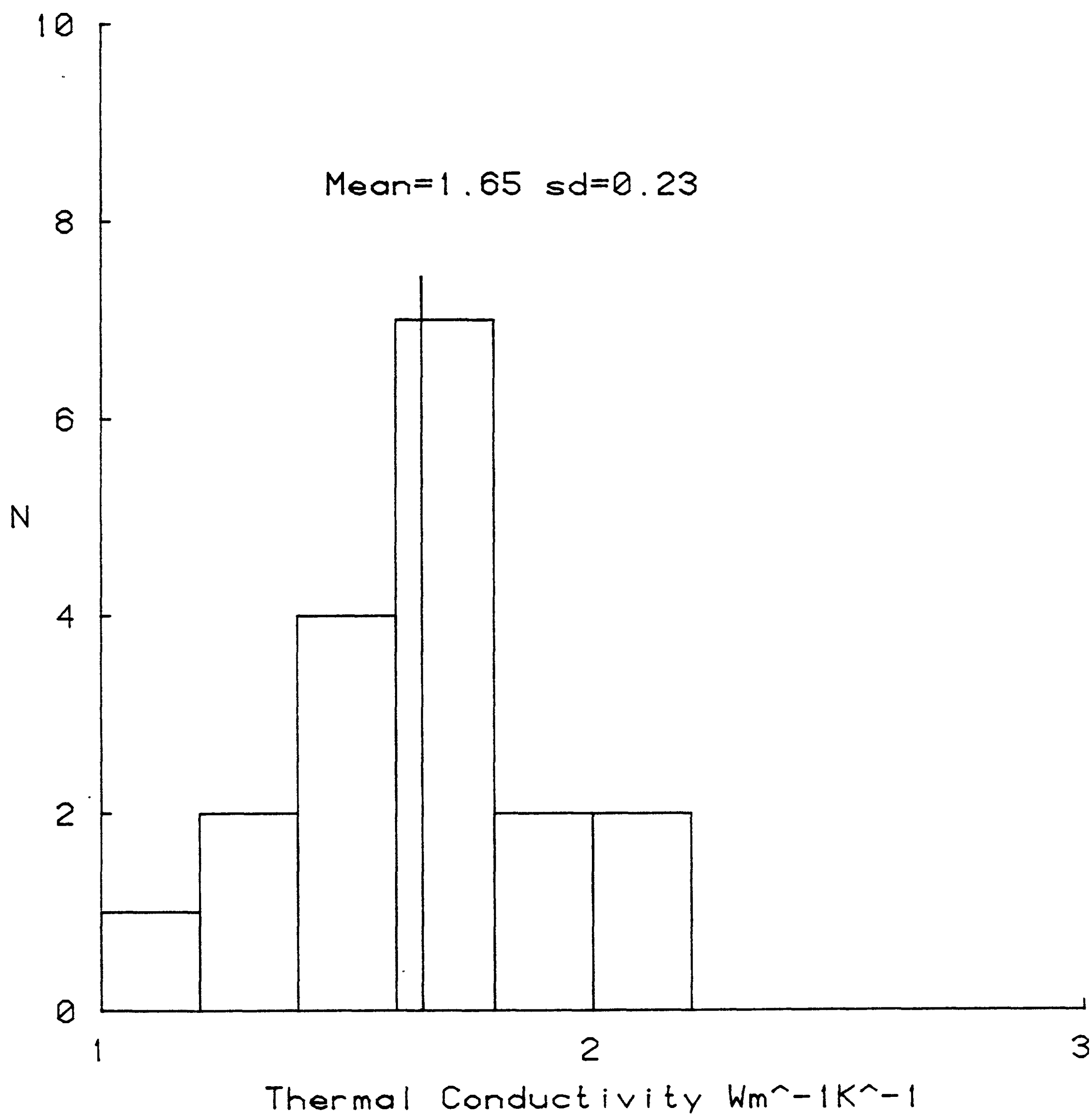

Figure 4. Histogram of 18 thermal conductivities determined in situ in the central San Joaquin Valley.

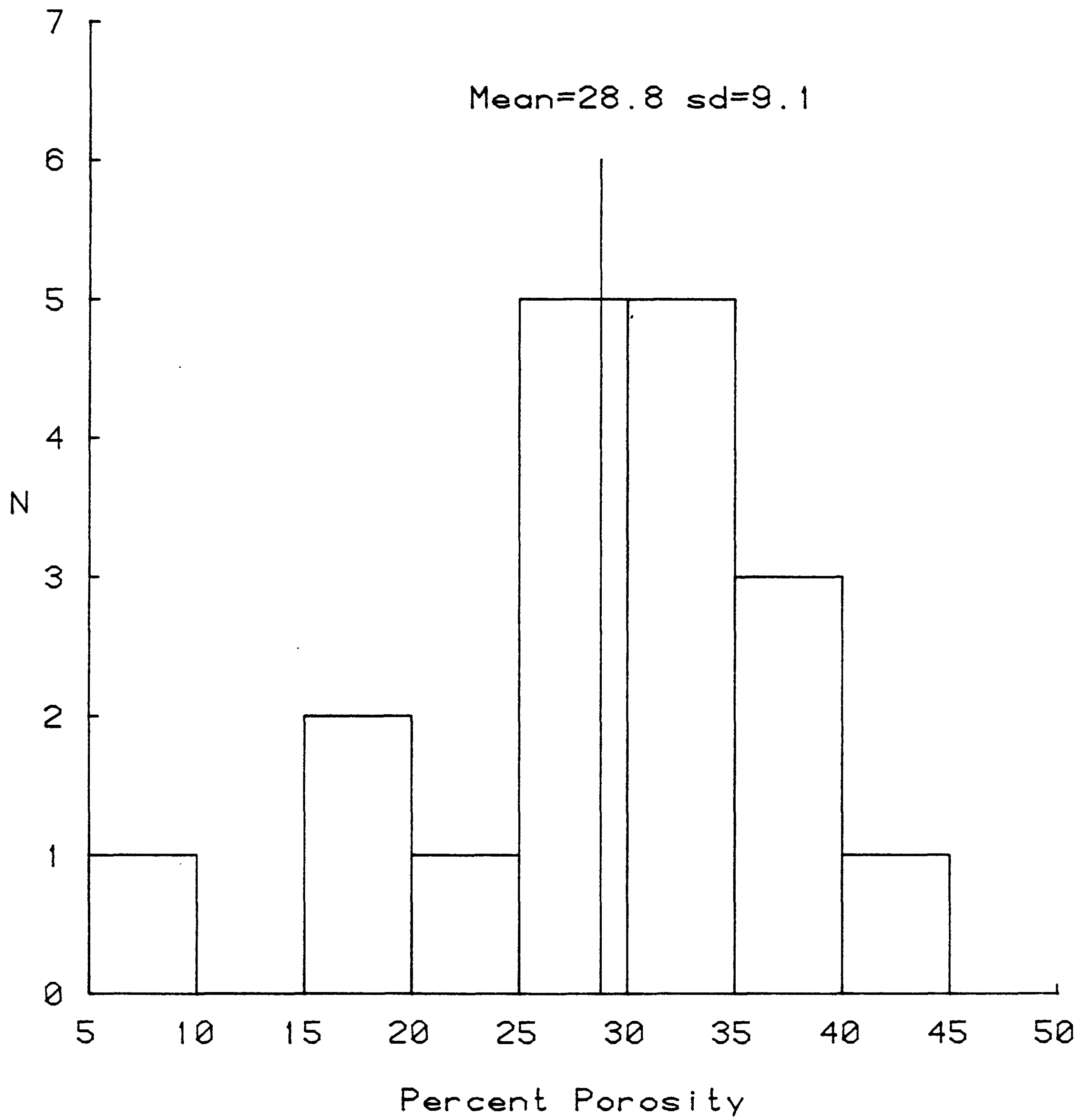

Figure 5. Histogram of 18 values of porosity calculated from in situ determinations of thermal conductivity and laboratory measurements on ditch samples (see text).

flows. Values range from 44 mWm^{-2} (1.05 HFU) at SJV8 to 64 mWm^{-2} (1.53 HFU) at SJV4 (Figure 1, Table 1). Some upward revision of these numbers is probably required to take account of the rapid sedimentation rates that have been characteristic of the great Central Valley throughout its history.

DISCUSSION

The heat-flow values obtained in this study may be placed in context by comparison to Regions 5 and 6 of Lachenbruch and Sass (1980) for the Coast Ranges and to the Sierra Nevada profile of Lachenbruch (1968). The Region 6 heat-flow falls abruptly from a mean of 77 mWm^{-2} in the Coast Ranges to values in the same range as the present ones in deep oil wells at Elk Hills. To the east in the Sierra Nevada, heat flows are generally lower than those of the present study although the ranges do overlap (Figure 1).

The present study was made in a region within which, on the basis of silica temperatures of non-thermal waters, Swanberg and Morgan (1978) predicted very high heat flows (85 mWm^{-2} or greater; see silica contours, Figure 1). The prediction of Swanberg and Morgan is not substantiated by the present work.

Because of the rather restricted range of thermal conductivities (1.65 Wm^{-1} K^{-1} ±14%) over a large area, it should be possible to make reliable heat-flow estimates from other wells (most particularly those compiled by Wang and Munroe) in the San Joaquin Valley. Based on the consistent mean of ~30% calculated for porosity of the near-surface sedimentary material, it should also be possible to estimate formation conductivity from measurements on drill cuttings of other wells.

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APPENDIX A. Thermal Conductivities of Ditch Samples

The individual conductivity samples in the following tables A1-A5 were measured from ditch samples collected every 6.1 m. The measurements were made following the procedure described in Sass and others (1971). All conductivities were measured at ~25°C.

TABLE A-1. Thermal conductivities from SJV-1

Depth m	K_s $Wm^{-1} K^{-1}$
24.4 - 30.5	2.47
30.5 - 36.6	3.60
54.9 - 61.0	2.34
61.0 - 67.1	2.44
85.3 - 91.4	2.59
91.4 - 97.5	2.83
115.8 - 121.9	2.90
121.9 - 128.0	2.42
146.3 - 152.4	2.62

TABLE A-2. Thermal conductivities from SJV-2

Depth m	K_s Wm^{-1} K^{-1}
36.6 - 42.7	2.39
42.7 - 48.8	2.11
54.9 - 61.0	2.14
61.0 - 67.0	2.29
91.4 - 97.5	2.23
97.5 - 103.6	2.38
115.8 - 121.9	2.54
121.9 - 128.0	1.90

TABLE A-3. Thermal conductivities from SJV-4

Depth m	K_s Wm^{-1} K^{-1}
79.2 - 85.3	3.32
85.3 - 61.0	2.75
109.7 - 115.8	2.33
115.8 - 121.9	2.09
128.0 - 134.1	3.29
134.1 - 140.2	2.88

TABLE A-4. Thermal conductivities from SJV-5

Depth m	K_s $Wm^{-1}\ K^{-1}$
24.4 - 30.5	2.31
30.5 - 36.6	2.47
54.9 - 61.0	2.10
61.0 - 67.1	2.20
91.4 - 97.5	2.13
97.5 - 103.6	2.26
115.8 - 121.9	2.56
121.9 - 128.0	2.24
134.1 - 140.2	2.74
146.3 - 152.4	3.27

TABLE A-5. Thermal conductivities from SJV-8

Depth m	K_s $Wm^{-1} K^{-1}$
54.9 - 61.0	2.89
61.0 - 67.1	2.82
85.3 - 91.4	2.59
91.4 - 97.5	2.78
115.8 - 121.9	2.34
121.9 - 128.0	2.53
146.3 - 152.4	2.20

APPENDIX B. Lithologic Descriptions

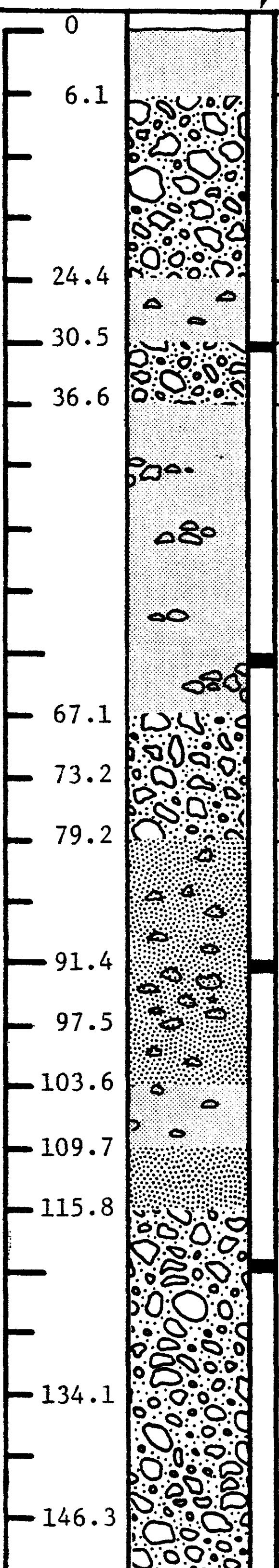
During drilling of the five holes, ditch samples were collected every 6.1 meters. The samples were brought to the laboratory and examined using a 0.5 to 30x binocular microscope; size and grade names were noted (Wentworth Scale) as was wet-sample color (Geological Society of America Rock Color Chart). Where percentages are indicated, values should be taken as approximate, since the samples are contaminated with drilling mud.

A predominantly western source is indicated for the sediment in Holes 1 and 5 (chert and sandstone clasts) and an eastern source for Holes 2, 4, and possibly 8 (granitic clasts).

Hole: SJV-1

Latitude: 36° 41.6' N Longitude: 120° 30.7' W

Elevation: 92 m Notes by: P.G. Sheet 1 of 1



Depth (m)	Lithology
0 – 6.1	Silt and clay (light olive brown, 5y5/5)
6.1 – 24.4	Gravel and coarse sand (gravel clasts: 3-8 mm avg.; subangular to rounded; predom. chert and sandstone)
24.4 – 30.5	Silt and clay (light olive brown, 5y5/5), minor gravel (3-8 mm)
30.5 – 36.6	Gravel and coarse sand (avg. 2-5 mm, max. ∿12 mm)
36.6 – 67.1	Silt and clay (light olive brown, 5y5/5), minor gravel interbeds
67.1 – 73.2	Gravel (avg. 10-20 mm; subangular to rounded; predom. sandstone and chert)
73.2 – 79.2	Gravel (avg. 3-8 mm; 60%) and coarse sand to silt (40%)
79.2 – 91.4	Coarse sand to silt (70%) and gravel (30%)
91.4 – 97.5	(50%) (50%)
97.5 – 103.6	(80%) (20%)
103.6 – 109.7	Silt and clay (5y4/2) with minor gravel (∿10%)
109.7 – 115.8	Coarse sand
115.8 – 134.1	Gravel (subrounded to well rounded; predom. chert and sandstone): avg. 2-7 mm, max. ∿15 mm
134.1 – 146.3	avg. 5-15 mm, max. ∿20 mm
146.3 – 152.4 (T.D.)	avg. 2-4 mm, max. ∿10 mm

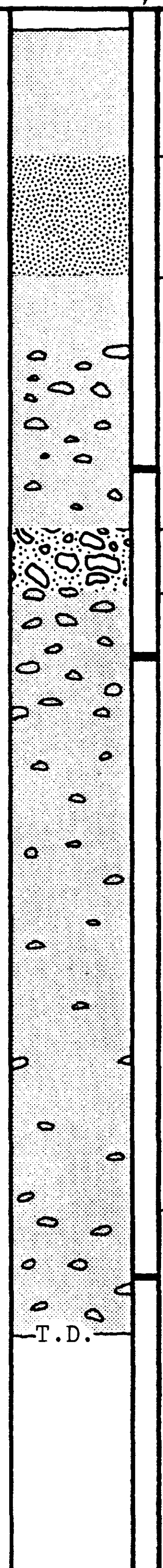
Hole: SJV-2

Latitude: 36° 45.8' N — Longitude: 119° 39.4' W

Elevation: 104 m — Notes by: P.G. — Sheet 1 of 1

Depth (m)	Lithology
0	Silt and clay (moderate brown, 5YR4/4)
12.2	Sand (coarse to fine; granitic) with silt
24.4	Silt and sand (5YR4/4)
	with 20% gravel (2-4 mm avg.; granitic)
	with 10% gravel
	with 5% gravel
48.8	Gravel (4-12 mm avg., max. ∿25 mm; angular; predom. greenschist, minor granite)
54.9	Silt and sand (5YR4/4) with 20% gravel (2-5 mm avg., ∿10 mm max.)
	with ∿5% gravel
115.8	Silt and sand (light olive gray, 5Y5/2) with 15% gravel (2-5 mm avg., ∿12 mm max.)
128.0	T.D.

Graphic column — Probed interval

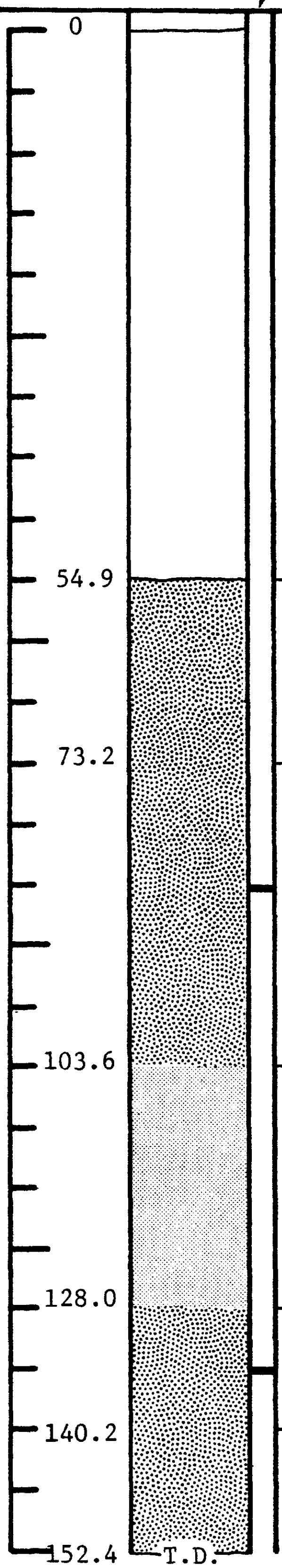


Hole: SJV-4

Latitude: 36° 35.8' N   Longitude: 119° 59.3' W

Elevation: 64 m   Notes by: P.G.   Sheet 1 of 1

Depth (m)	Graphic column	Probed interval	Lithology



No samples collected.

Coarse to very coarse sand (yellowish gray, 5Y7/2; 0.5-1.0 mm avg., 2 mm max.; granitic)

Very coarse sand (light olive gray, 5Y5/2; 1-2 mm avg., 4 mm max.; granitic) with silt interbeds

Fine sand to silt (5Y5/2)

Medium to coarse sand (5Y5/2; granitic)

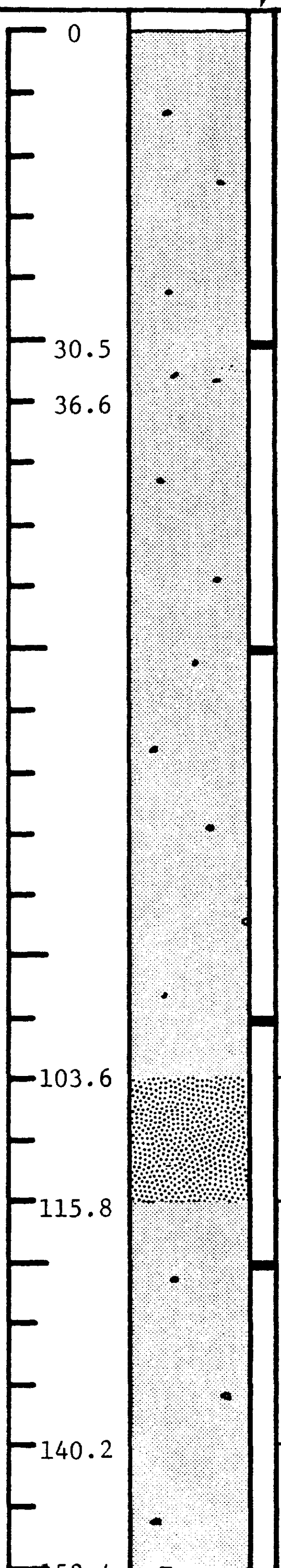
Fine to medium sand (5Y5/2; granitic)

Hole: SJV-5

Latitude: 36° 24.1' N   Longitude: 120° 06.0' W

Elevation: 72 m   Notes by: P.G.   Sheet 1 of 1

Depth (m)	Graphic column	Probed interval	Lithology



Fine sand, silt and clay (light olive brown, 5Y5/5), minor fine gravel (4 mm avg.; predom. quartz and chert)

trace: euhedral authigenic selenite

Medium to coarse sand (.75 mm avg.; 5Y5/5; predom. quartz and chert)

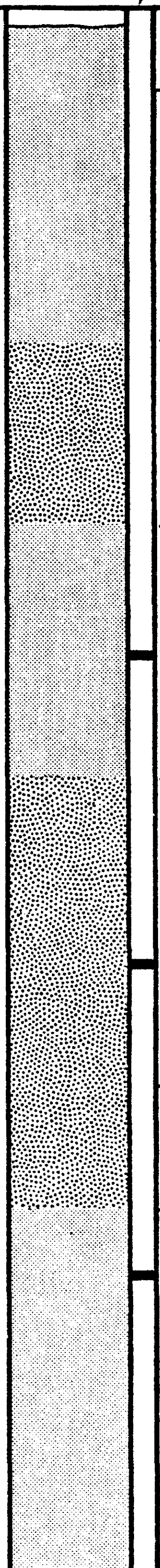
Fine sand, silt and clay (5Y5/5), minor fine gravel

Fine sand, silt and clay (medium olive gray, 5Y4/4), minor fine gravel

Hole: SJV-8

Latitude: 36° 44.1'N   Longitude: 120° 13.3' W

Elevation: 53 m   Notes by: P.G.   Sheet 1 of 1



Depth (m)	Lithology
0 – 6.1	Silt and clay (light olive gray, 5y5/2)
6.1 – 30.4	Medium sand to silt (5y5/2; granitic? source)
30.4 – 48.8	Very coarse sand to silt (5y5/2; granitic? source)
48.8 – 61.0	Medium sand to silt (5y5/2; granitic? source)
61.0 – 73.2	Fine sand to silt (5y5/2; granitic? source)
73.2 – 103.6	Very coarse sand to silt (5y5/2; granitic? source)
103.6 – 115.8	Very coarse to medium sand (5y5/2; granitic? source)
115.8 – 152.4	Fine sand to silt (5y5/2; granitic? source)

Depth (m) | Graphic column | Probed interval | Lithology