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NEAR-SURFACE HYDROTHERMAL REGIME OF THE LASSEN "KNOWN GEOTHERMAL RESOURCES AREA", CALIFORNIA

by

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Abstract

Thermal data have been obtained for 11 holes (~200 m depths), 9 within the Lassen KGRA and 2 regional holes located adjacent to it. Conductive segments of temperature profiles from two holes within the KGRA and two regional holes to the south and east are consistent with a regional transition between low heat flow (~40 mWm^{-2}) in the Klamath Mountains and Coastal provinces to high heat flow (70-100 mWm^{-2}) within the Modoc Plateau, a subprovince of the Basin and Range. The remaining temperature profiles indicate a complex three-dimensional structure dominated by hydrothermal circulation within the KGRA. The circulatory systems are driven primarily by elevation differences, therefore, the movement of ground water must extend to a depth of several kilometers. This is necessary if the cell patterns are to be effectively forced by surface topography with horizontal wavelengths of that order.

INTRODUCTION

As part of the U.S. Geological Survey's geothermal resource assessment of Lassen "Known Geothermal Resources Area", we conducted a heat-flow reconnaissance of the KGRA and its environs. In the first phase of the study nine holes were drilled in volcanic rocks within the area and two holes in granitic rock outside of it (Figures 1 and 2). The holes were completed according to established procedures which include a "10 sack grout" around the casing (Moses and Sass, 1979); however, early temperature measurements indicated that for holes drilled within volcanic rocks, most of the cement was lost in fractures and that at most, a few meters of casing near the bottom of the hole were grouted off. Preliminary temperature measurements, thermal conductivity determinations, and estimated heat flows have been completed and are presented in this report. Since temperature profiles in the majority of the holes obviously are non-linear and show the effects of ground water movement, we shall analyze the data from both a conductive and convective point of view.

The following symbols and units are used in the remainder of this report:

- T, temperature, °C
- K, thermal conductivity, 1 W $m^{-1}K^{-1}$ = 2.39 mcal $cm^{-1}s^{-1}°C^{-1}$
- z, depth, m positive downwards
- v_z, volume flux of water or vertical (seepage) velocity m s^{-1} or mm y^{-1}
- Γ, vertical temperature gradient, °K km^{-1} = °C km^{-1}
- q, vertical conductive heat flow, mWm^{-2} = kW km^{-2}, or HFU (10^{-6} cal cm^{-2} s^{-1}): 1 HFU = 41.8 mWm^{-2}

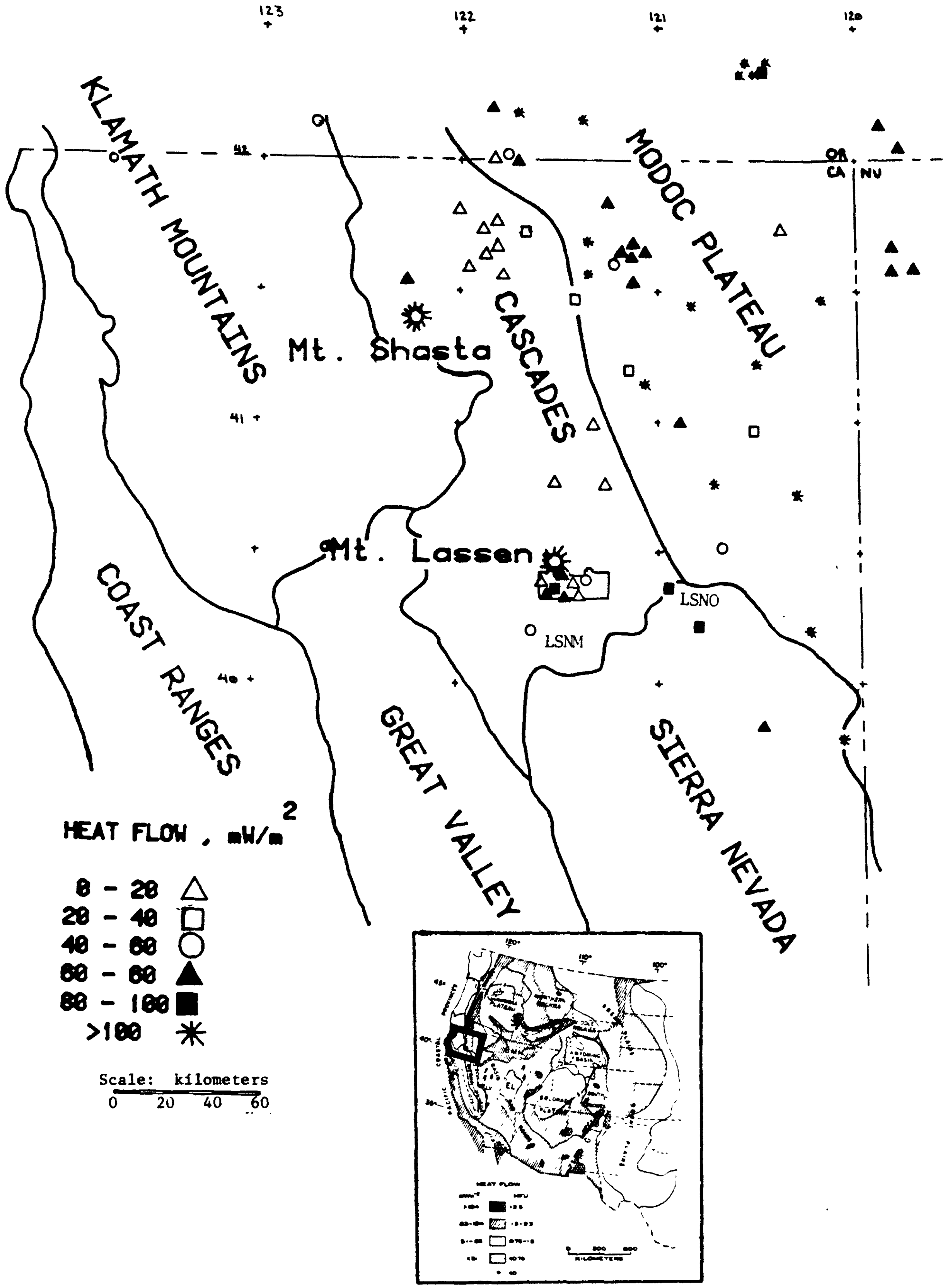

Figure 1. Major physiographic-tectonic provinces in Northern California and adjacent areas of Oregon and Nevada (after Fenneman, 1928). Heat-flow control is shown as coded symbols. LSNM and LSNO are discussed in the text.

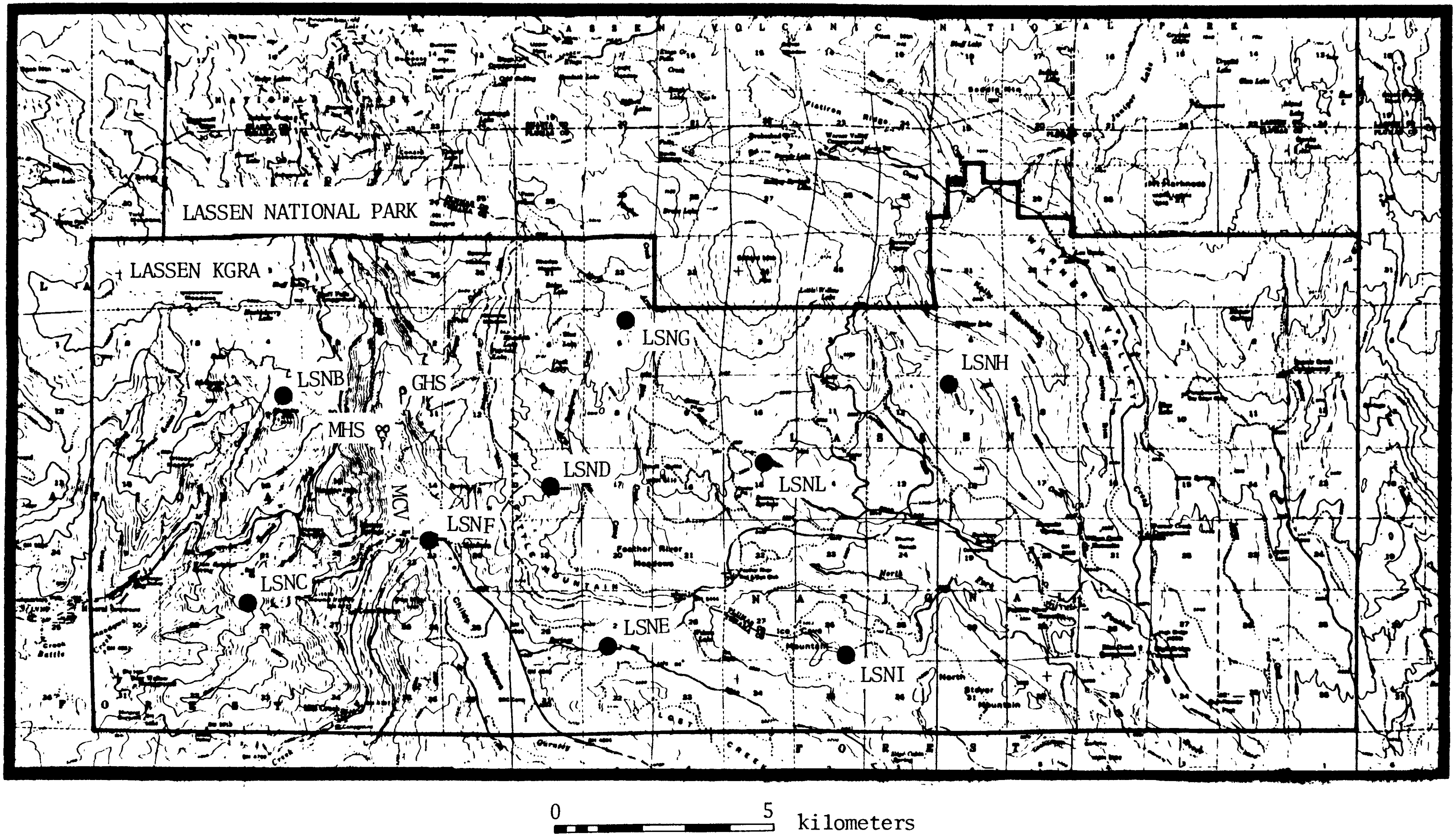

Figure 2. Location of heat-flow sites within Lassen KGRA. GHS, Growler hot spring, MHS, Morgan hot springs, and MCV, Mill Creek Valley are discussed in the text.

REGIONAL TECTONIC AND THERMAL SETTING

Mount Lassen is the southernmost of the Cascade volcanoes. It is situated near the boundaries of the Cascade physiographic province with the Klamath, Great Valley, Sierra Nevada, and Modoc Plateau provinces (Figure 1). The regional thermal setting (including a discussion of the granite holes, LSNM and LSNO) is the subject of a separate study (Mase and others, 1980); however, we shall summarize it briefly here. There are no heat-flow data from the Northern Great Valley and very few for the Northern Sierra Nevada. Such data as do exist for the latter province are in the northeastern part, and they suggest a transition to the high values (>60 mWm^{-2}) characteristic of the Basin and Range province. Control in the Klamath province also is poor but suggests a region of uniformly low heat flow characteristic of the entire western coastal region north of Cape Mendocino. The Modoc Plateau has variable but generally high heat flow. In contrast to the interpretation of the heat flow to the north (Blackwell and others, 1978, 1980), heat flow in the uppermost few hundred meters of a large area of the California Cascades is uniformly low (Figure 1). We attribute the observed low heat flow, contrasting with the high heat flow expected along a magmatic arc, to regional circulation of ground water. This low heat flow indicates that the surficial thermal regime of the California Cascades is dominated by convective heat transfer. The transition zones bounding the Cascades are effectively masked by hydrothermal circulation.

GEOTHERMAL DATA

The most recent temperature-depth profiles for 10 new heat-flow sites in the Lassen area are shown in Figure 3. It is common for temperature-depth curves in or near strongly convecting zones to exhibit thermal gradients that are quite variable with depth, making any downward extrapolations on the basis of these curves speculative. The consistent tendency for the temperature gradient to increase downward in LSNB, LSND, LSNG, LSNH, and LSNI can be attributed only to a vertical component of downward water movement, making any estimates of conductive heat-flow for these boreholes meaningless. The upper segment of the profile from LSNF (0-85 m) is undulant, suggesting a combination of upward, downward, and lateral movement of ground water. Below 85 m the gradient decreases consistently with increasing depth. This curvature could indicate an increase of thermal conductivity with depth, topographic effects, lateral heat conduction away from a strongly convecting system or broad upward convection. As detailed conductivity measurements indicate no increase in thermal conductivity with depth and removal of topographic effects does not decrease the curvature significantly, the cause of the curvature is probably either lateral heat conduction or broad upward convection. The temperature profile for LSNL shows the influence of upward movement of water characteristic of areas of regional ground water discharge. The upper segments of the remaining boreholes (LSNC, LSNE, LSNM, and LSNO) all show the influence of water movement in a shallow subsystem but yield consistent gradients below that zone, suggesting that heat transfer in the lower segments is primarily by conduction.

Heat-flow data for the 10 sites are summarized in Table 1. For linear segments of the temperature profiles, the vertical component of heat flow, q,

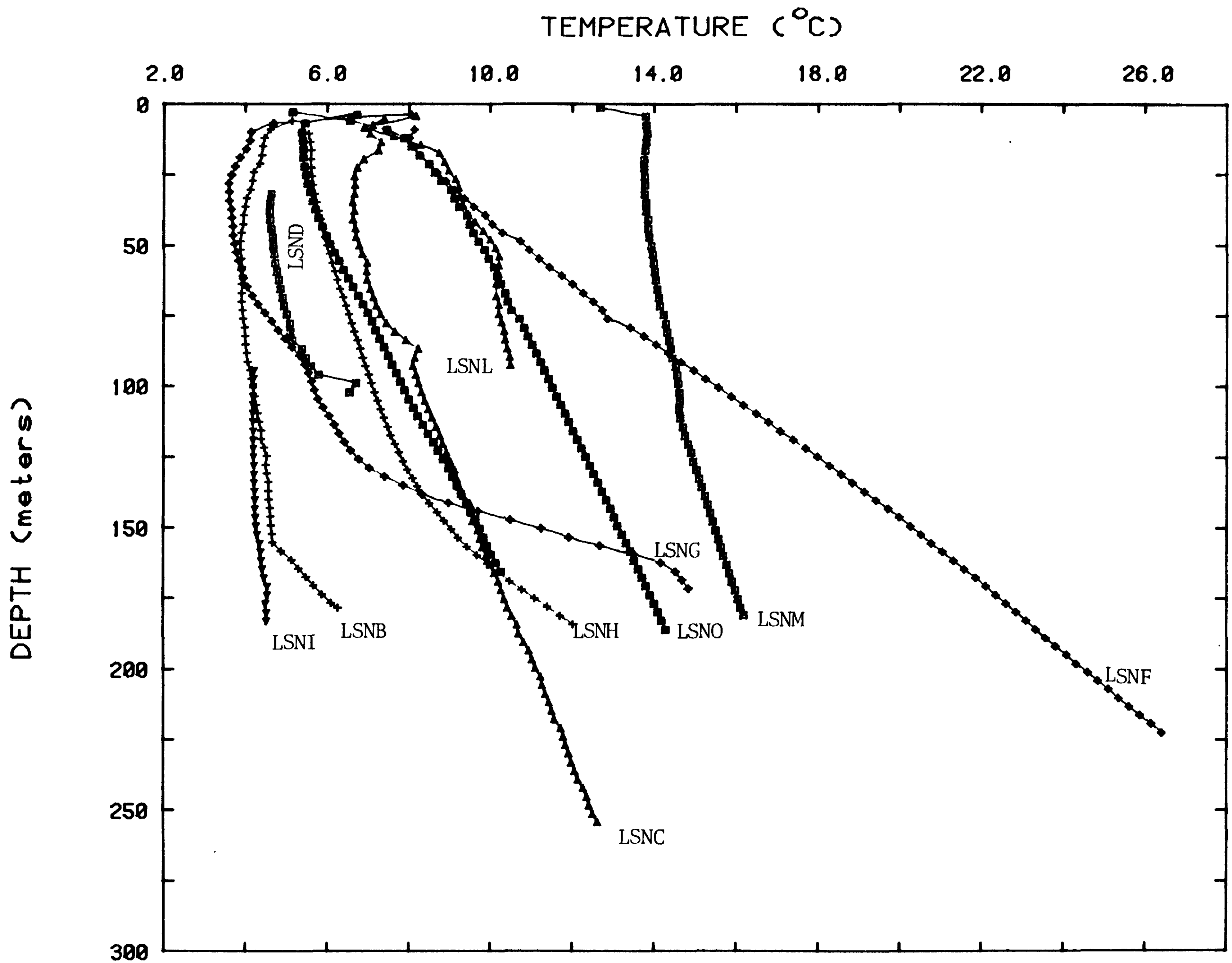

Figure 3. Temperature profiles from USGS wells in the Lassen area.

TABLE 1. Locations, conductive temperature gradients, lithologies, conductivities, and estimated heat flows for holes in Lassen KGRA

Designation	Latitude	Longitude	Elev. (m)	Depth range (m)	Γ(°C km^{-1})	Type Γ†	Lithology	Conductivity¶ (Wm^{-1} K^{-1})	Uncor. q(mWm^{-2})	Cor. q(mWm^{-2})
LSNB	40° 23.5'	121° 32.2'	1890	0-158	**	r	dacite	2.34 (.08)	**	**
				158-165	63.93 (.27)	c	dacite	2.06 (.03)	132 (2)	**
LSNC	40° 20.9'	121° 33.0'	1735	91-256	29.68 (.03)	c	dacite	2.29 (.09)	68 (3)	72 (3)
LSND	40° 22.4'	121° 28.0'	1828	0-105	**	r	andesite	1.88 (.10)	**	**
LSNE	40° 20.4'	121° 27.0'	1770	46-168	36.45 (.03)	c	andesite	2.00 (.03)	73 (1)	65 (1)
LSNF	40° 21.3'	121° 29.9'	1500	30-224	91.93 (.13)	c,d	andesite	2.51 (.15)	231 (14)	
LSNG	40° 24.4'	121° 26.8'	1905	0-165	**	r	andesite	1.64 (.03)	**	**
				165-172	51.88 (.86)	c	andesite	1.64 (.03)	85 (3)	**
LSNH	40° 23.6'	121° 21.6'	1786	0-185	**	r	andesite	1.87 (.04)	**	**
LSNI	40° 20.4'	121° 23.1'	1817			r	andesite	2.15 (.11)		**
LSNL	40° 22.6'	121° 24.5'	1740	0-93	**	d	andesite	2.36 (.05)	**	**
LSNM	40° 10.0'	121° 30.3'	975	0-122	**	r	granodiorite	2.43 (.05)	**	**
				122-182	22.20 (.04)	c	granodiorite	2.43 (.05)	54 (1)	46 (1)
LSNO	40° 21.9'	120° 56.7'	1585	76-187	32.63 (.08)	c	granite	1.97 (.03)	97 (1)	93 (1)

†Type of Γ: C = conductive regime; d = discharge and/or upward movement of water; r = recharge and/or downward movement of water.

¶Conductivities were estimated on the basis of the harmonic mean of the solid component, $\langle K_s \rangle$, as measured from drill cuttings using the "chip method" (Sass and others, 1971). No correction has been applied for formation porosity (see text).

**Gradient and heat flow have not been estimated for boreholes exhibiting easily identifiable hydrologic disturbances.

was computed as the product of the least-squares temperature gradient, Γ, and the harmonic mean thermal conductivity $\langle K \rangle$. Solid component thermal conductivities were measured from drill chips in a divided-bar apparatus following the methods described by Sass and others (1971). From measurements of surface samples, an average porosity of $<1\%$ was determined; therefore, no correction for porosity was applied to the solid component conductivity. For those boreholes whose temperature profiles exhibited substantial curvature not related to lithologic changes, we assumed a dominance of convective processes and did not estimate a conductive heat flow.

DISCUSSION

From Figure 3 it is obvious that a substantial part of the near-surface heat transfer is non-conductive owing to hydrothermal convection in permeable near-surface strata. The low thermal gradient in the upper part of most temperature profiles suggests that heat from a greater depth is being absorbed by downward percolation of ground water, a condition characteristic of regions of hydrologic recharge. The next step is to examine how pervasive (both laterally and vertically) is the recharge, and the extent to which it modifies conductive heat transfer in the upper crust. For systematically non-linear segments displaying curvature in the temperature-depth profile, a one-dimensional flow model similar to that described by Lachenbruch and Sass (1977, equations 10 and 11) or Bredehoeft and Papadopulos (1965) was used to estimate the vertical volume flux of water (positive downward). Estimates of seepage velocity varied from a few centimeters to a few tenths of a meter per year. For this model, we assumed broad vertical flow within the formation. An ambiguity exists in this assumption since the lack of a barrier between casing and borehole wall can result in fluid flow within the borehole which is indistinguishable in a temperature profile from fluid flow in the formation. Although we have assumed simple one-dimensional vertical flow, more complex patterns (two- and three-dimensional) can be envisioned to explain the temperature data.

LSNG and LSNH exhibit systematic curvature which we attribute to downward percolation of ground water. If the circulatory system is driven primarily by elevation differences between the ridges and surrounding valleys, the fluid flow field may be approximated by a single vertical component since both boreholes lie along ridge axes (Domenico and Palciauskas, 1973). A one-dimensional flow model provides reasonably good fits (Figures 4 and 5) and results in an estimated downward flow with a seepage velocity of .38 and .19 m/y, respectively. The model yields only a velocity estimate and provides no information on the depth of circulation; however, some insight may be gained by examining the curvature of the profiles (Figure 3). The high degree of curvature exhibited by the boreholes could not extend much past the depth of the borehole without unreasonable temperatures being obtained; therefore, it is unlikely that circulation as pictured by these models could extend to great depths. Drilling records for LSNG indicated that the water table was encountered at 165 m, while in LSNH no ground water was encountered. It is possible that the profiles represent percolation of ground water through a zone of aeration and that below the water table vertical flow velocities are reduced to the point where, at least locally, there is an essentially conductive thermal regime. An example of this may be seen in LSNC (Figure 3) in which the water table was encountered at 91 m; above the water table, curvature is consistent with downward percolation of ground water; below the water table, the profile is apparently conductive. The lowermost 7 m of LSNG may represent a conductive gradient and yields a plausible extrapolated surface temperature and heat flow (Figure 3 and Table 1).

Apart from boreholes with substantial hydrologic disturbances, LSNF is the only borehole to exhibit an anomalous heat flow within the KGRA. The youngest volcanism in the vicinity of the hole is the dacite dome of Doe Mountain, which has an estimated age of 1.2-1.5 m.y. (Patrick Muffler, personal communication, 1980) and is, therefore, too old to serve as a source for the anomalous heat flow. The profile (Figure 3) exhibits a consistent decrease in the temperature gradient with depth. One possible explanation is

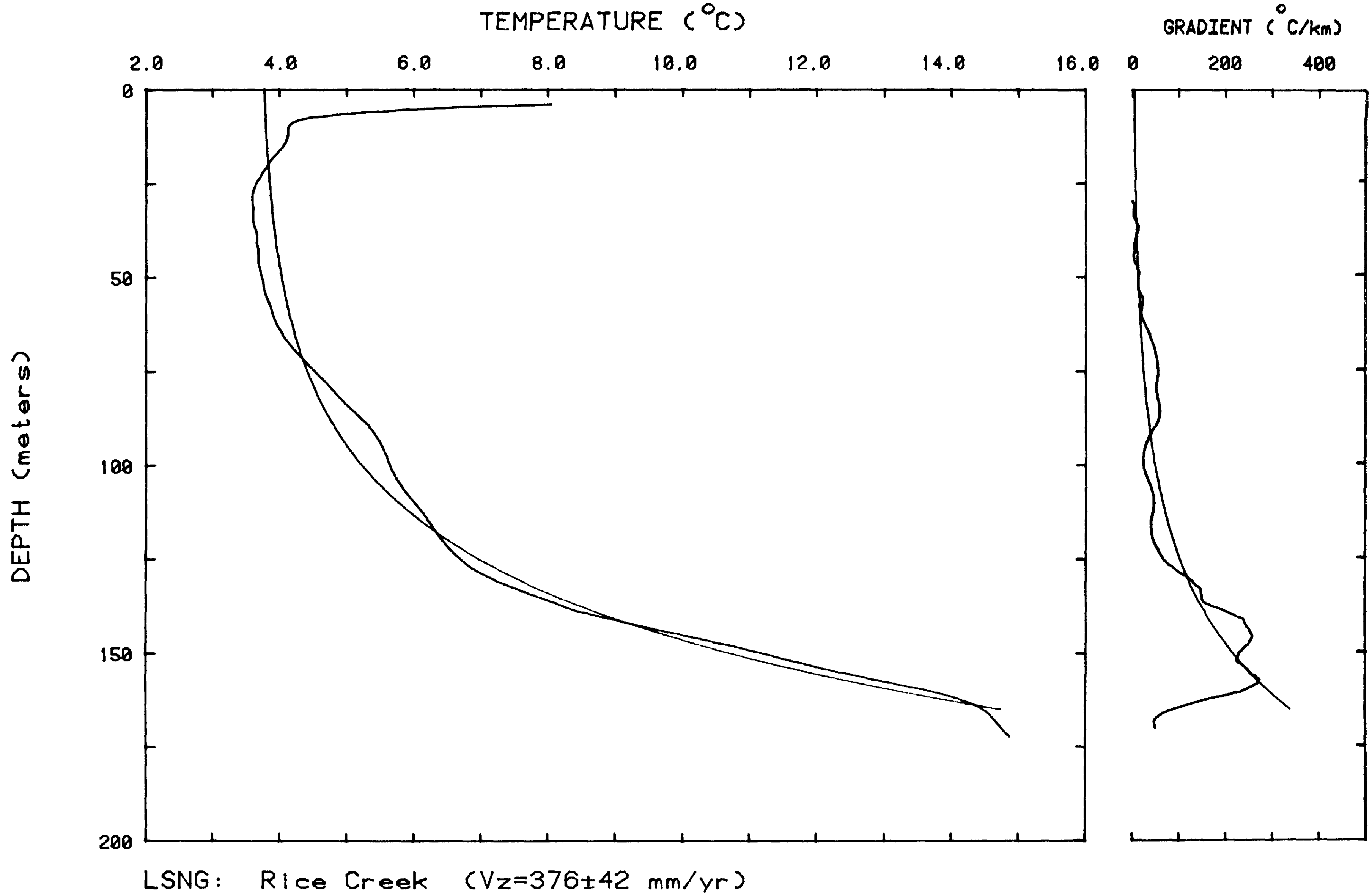

Figure 4. Temperature profile for hole LSNG, Rice Creek, together with theoretical model for downward vertical water movement.

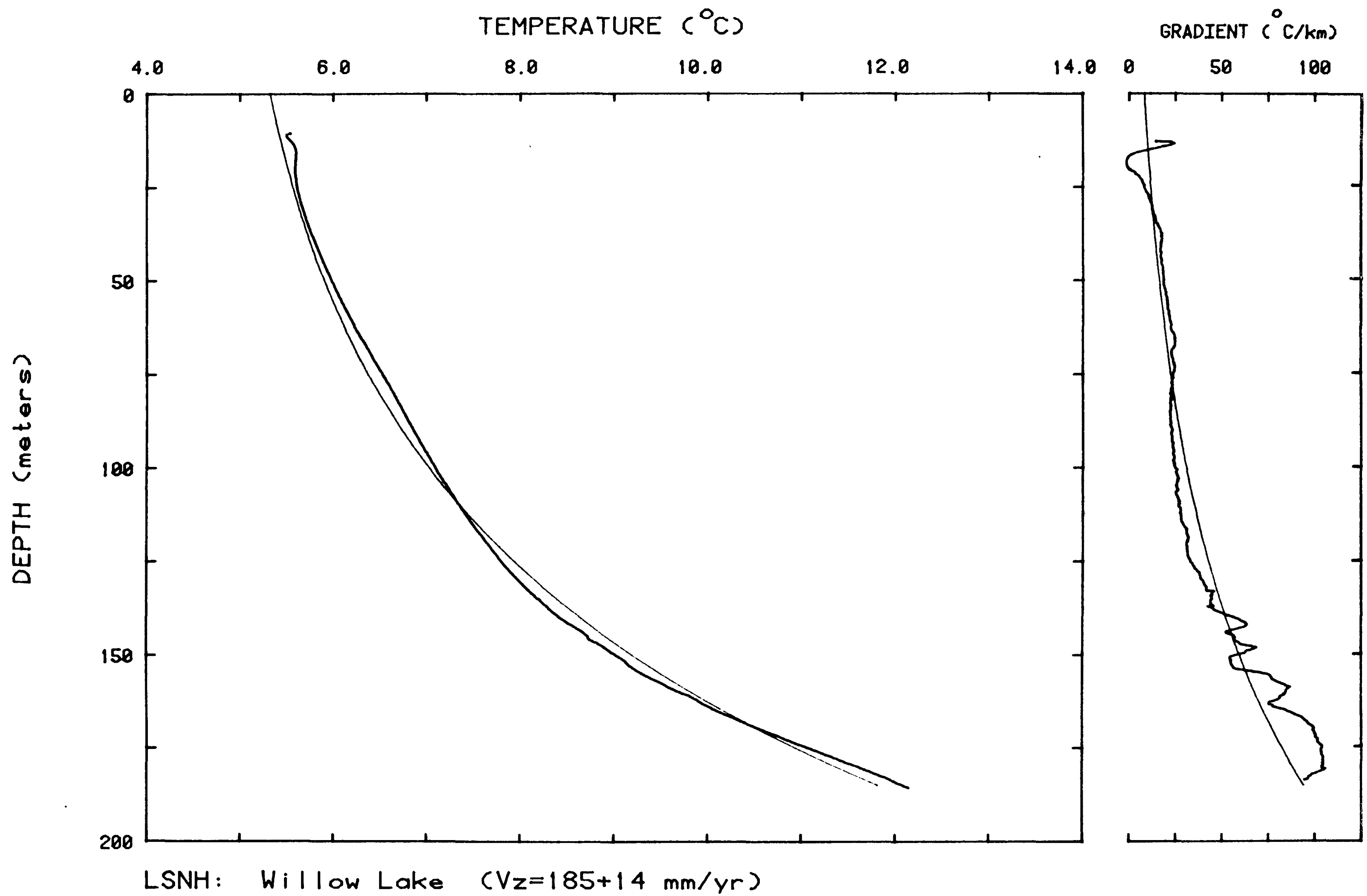

Figure 5: Temperature profile for hole LSNH, Willow Lake, together with theoretical model for downward vertical water movement.

lateral heat conduction away from southward migrating thermal fluids contained within streambed deposits of Mill Creek Valley. Evidence for this is seen in the presence of Growler and Morgan hot springs located to the north of LSNF along Mill Creek (Figure 2) and the high conductive gradient observed in the lowermost portion of LSNB (Figure 3 and Table 1). The thermal fluids are believed to have their sources within the Little Hot Springs Valley, Bumpass Hell area, immediately south of Lassen Peak, based on available hydrologic information and geochemical analysis of hot spring waters (primarily light stable isotopes, Nancy Nehring, personal communication, 1980). Figure 6 illustrates another possible explanation for the temperature-profile from LSNF. Over the depth of the hole, the temperature-depth curve is indistinguishable from the theoretical curve for broad upward flow calculated from a one-dimensional model. From the parameters of this theoretical curve, the interpretation would imply a vertical flow of $\sim$30 mm y^{-1}, which would yield a constant temperature reservoir of 75°C if extrapolated to 2 km depth. The only way to resolve the ambiguity raised by the two explanations is by further drilling.

Based on thermal considerations, the boreholes within Lassen KGRA may be divided into three distinct groups. The first group (LSNC, LSNE) yields a gradient and heat flow consistent with a regional transition between low heat flow ($\sim$40 mWm^{-2}) in the Klamath Mountains and Coastal Provinces to high heat flow (70-100 mWm^{-2}) within the Modoc Plateau, a subprovince of the Basin and Range (Mase and others, 1980). The upper plarts of the temperature profiles from these boreholes show the influence of downward water movement probably due to recharge in a shallow subsystem. The remaining two groups are considered to be characteristic of regions with hydrologic recharge (LSNB, LSND, LSNG, LSNH, LSNI) and regions of hydrologic discharge (LSNF, LSNL). In all instances, the regions of apparent recharge are associated with topographic highs and the regions of discharge are associated with topographic lows. If the circulatory systems are driven primarily by elevation differences, then the movement of ground water must extend to a depth of several kilometers; this is necessary if the cell patterns are to be effectively forced by surface topography with horizontal wavelengths of that order. The present lack of deeper thermal data and correlative geochemical and hydrologic information precludes a more thorough quantitative assessment of the hydrothermal regime of this region.

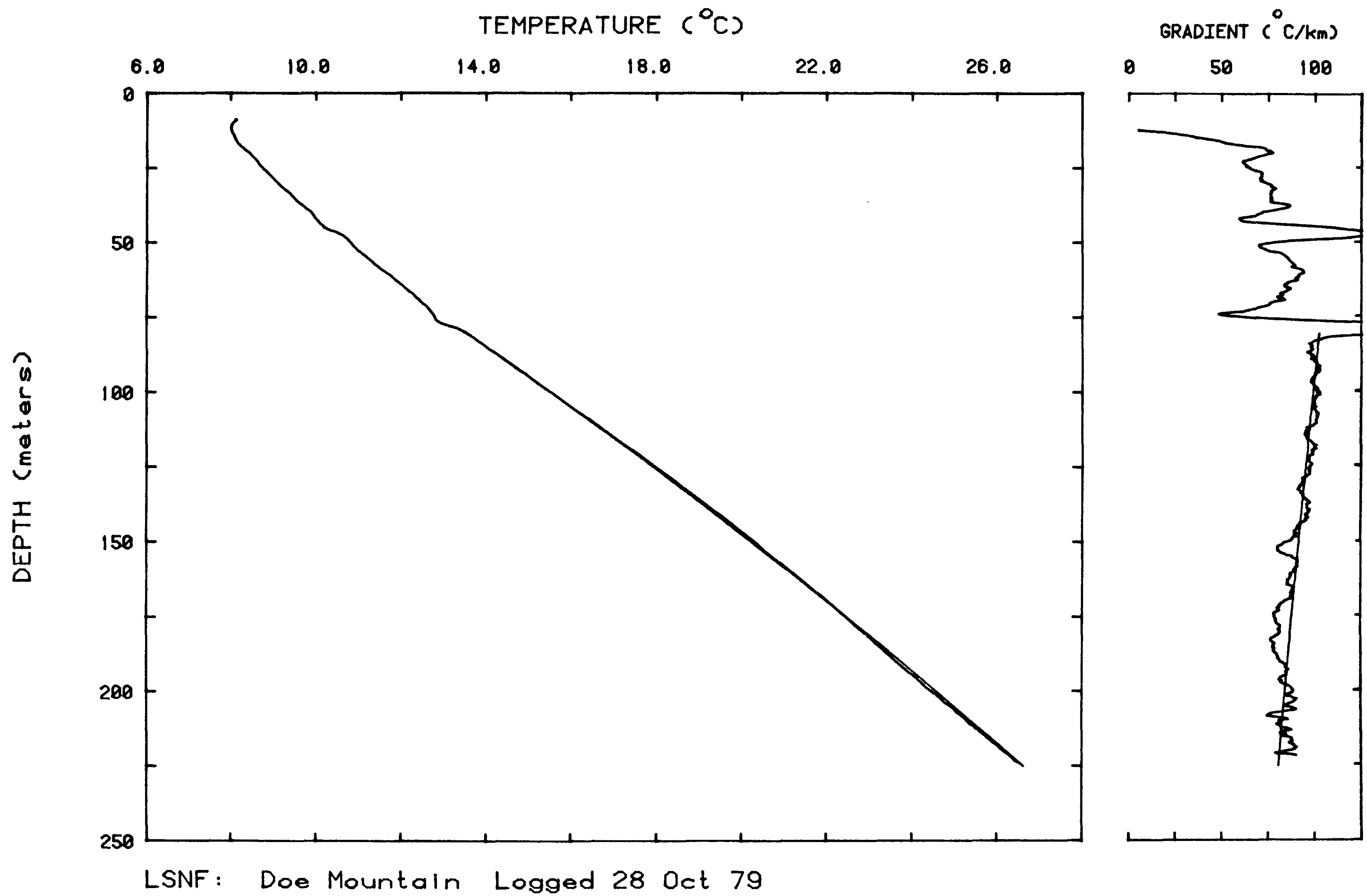

Figure 6. Temperature profile for hole LSNF, Doe Mountain, together with theoretical model for upward vertical water movement.

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APPENDIX A

Temperature measurements were made in boreholes of 105 to 256 m depths drilled using conventional air-hammer and/or mud rotary techniques. Well completion involved lowering 33 mm I.D. steel pipe to within a meter of bottom, then pumping about 0.7 m^3 of cement-bentonite grout through the pipe, followed by a wiping plug and clear water (for detailed description, see Moses and Sass, 1979). This amount of grout is usually sufficient to seal off the lowermost 50 m of the annulus around the pipe in these 130 mm nominal diameter holes; however, early temperature measurements indicated that for holes drilled within volcanic rock most of the cement was lost in fractures and at the most, a few meters of casing near the bottom of the hole were grouted off. An additional $\sim$3 m of cement plug was emplaced at the top of the well after the remainder of the hole had been backfilled with mud and cuttings. Upon completion of the well, the steel pipe was then filled with water and allowed to equilibrate to facilitate temperature measurements (better heat transfer between probe and surrounding rock). Chip samples for thermal conductivity measurements were made at 6 m intervals in all holes.

Temperatures were measured repeatedly to a few millidegrees at intervals of either .3 or 1.52 m until all transient disturbances resulting from drilling had vanished. Temperature profiles are presented graphically in Figures 7 through 17. A smoothed average gradient over 3 m intervals is also shown on each of these figures.

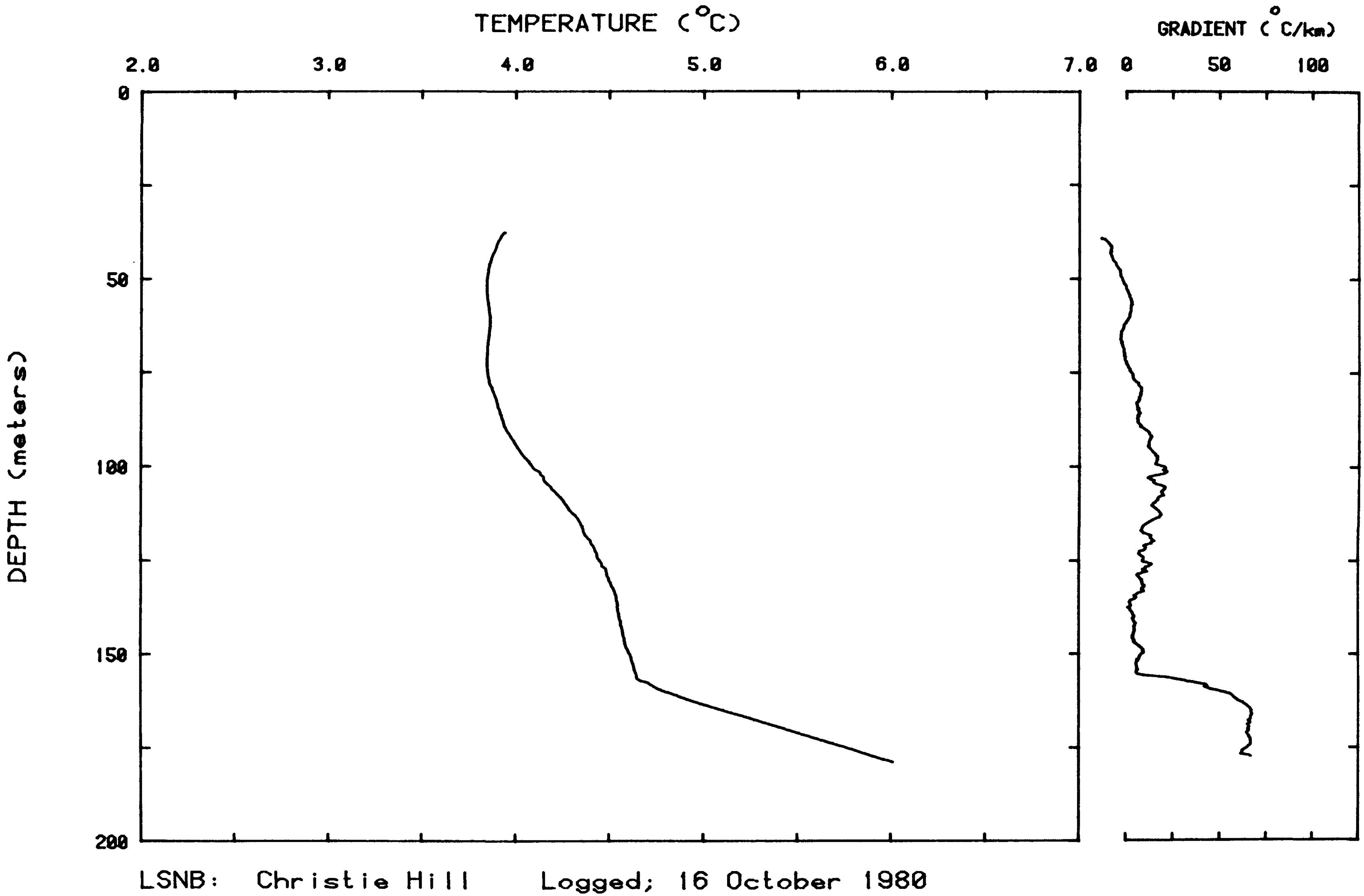


Figure 7. Temperature and gradients for borehole LSNB.

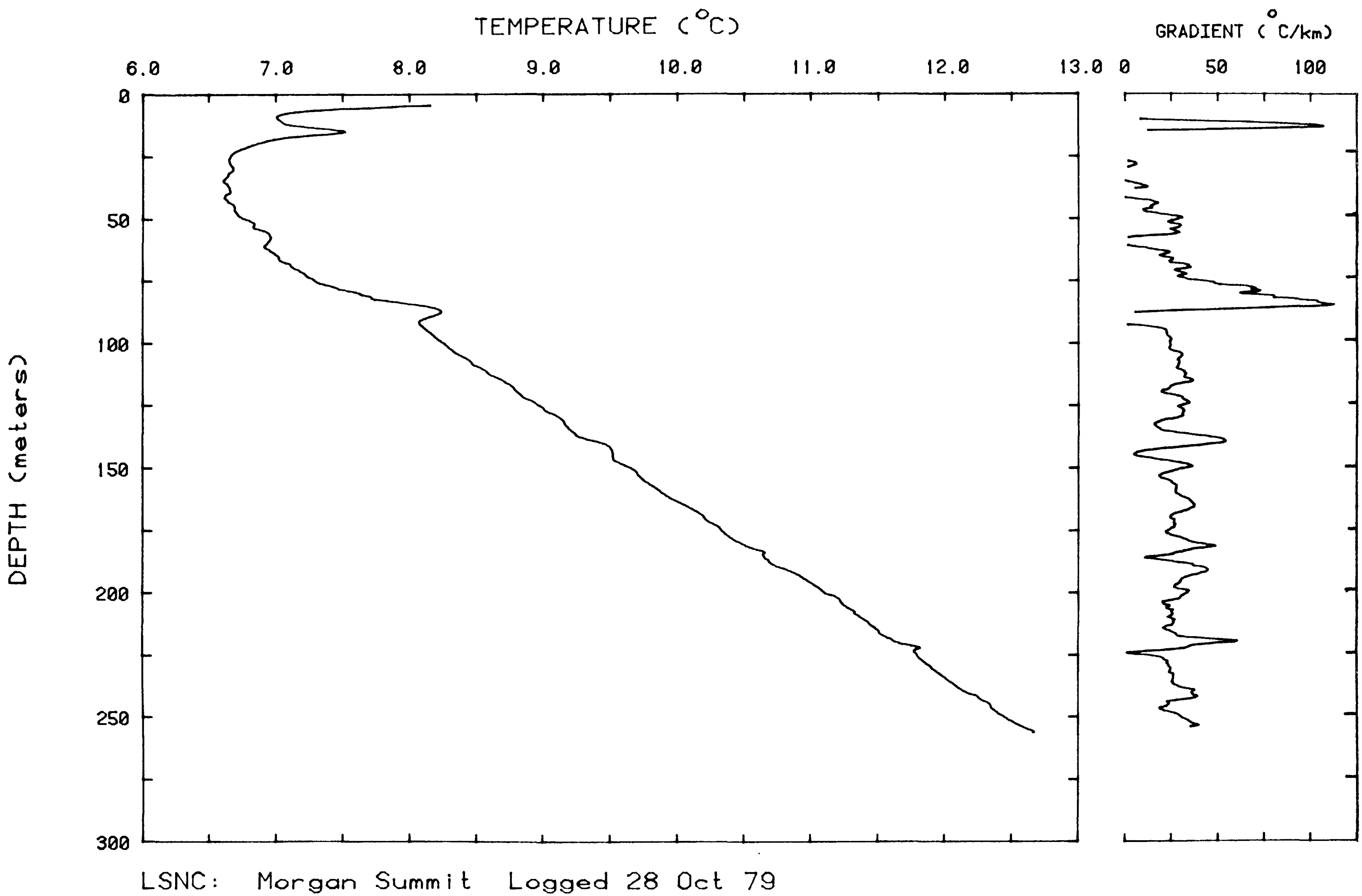


Figure 8. Temperature and gradients for borehole LSNC.

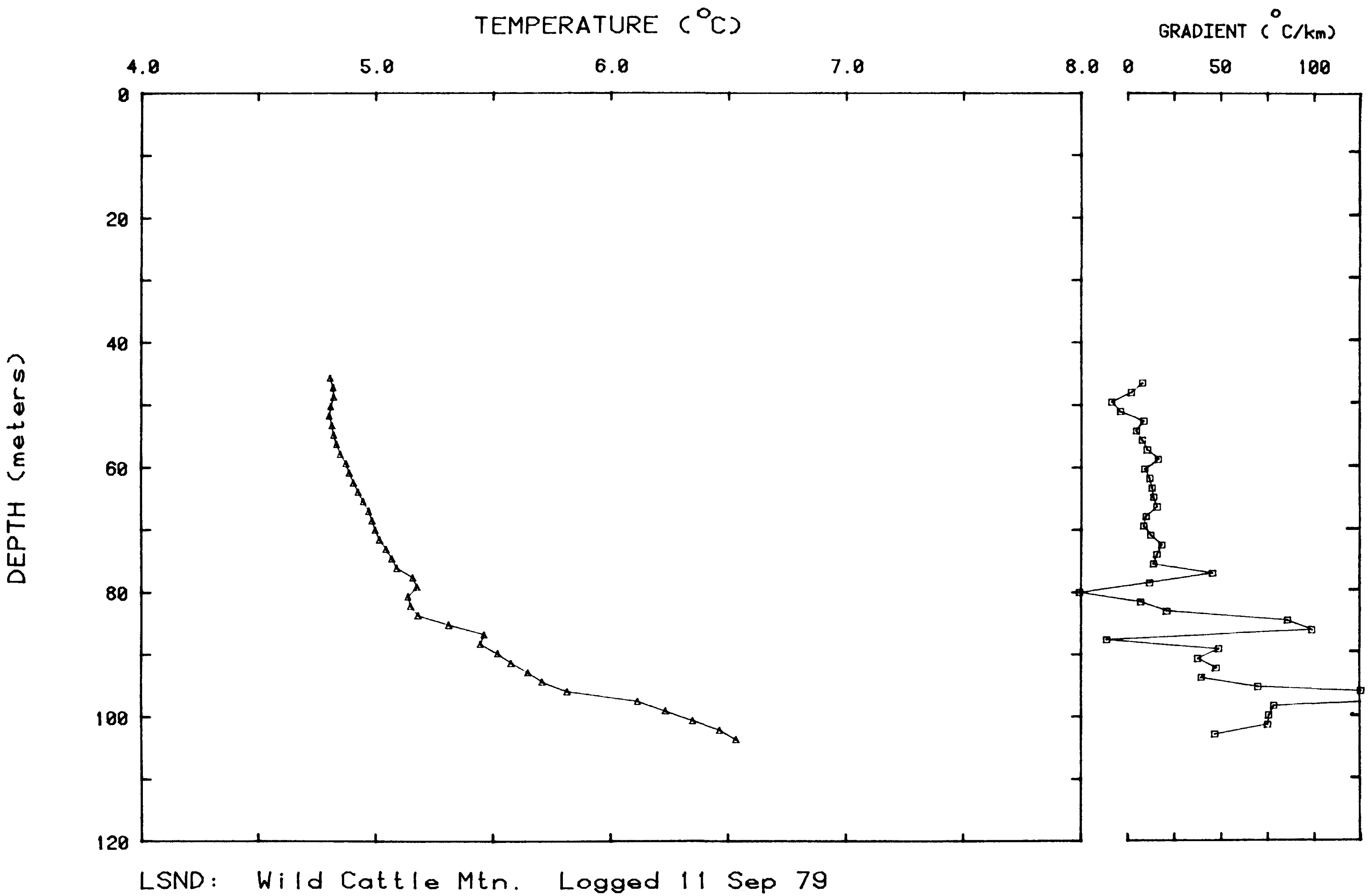
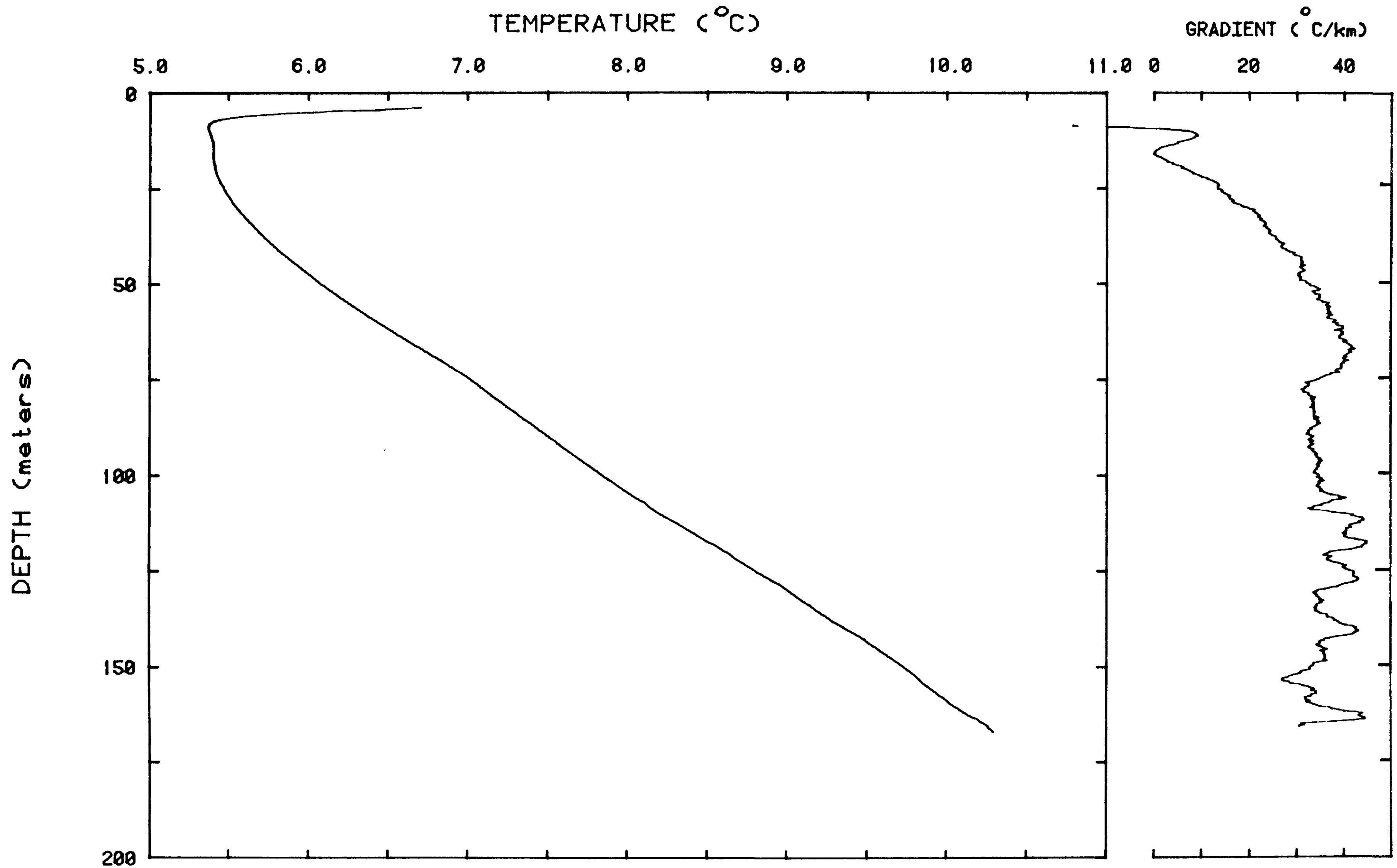


Figure 9. Temperature and gradients for borehole LSND.



LSNE: Wilson Lake Logged 27 Oct 79

Figure 10. Temperature and gradients for borehole LSNE.

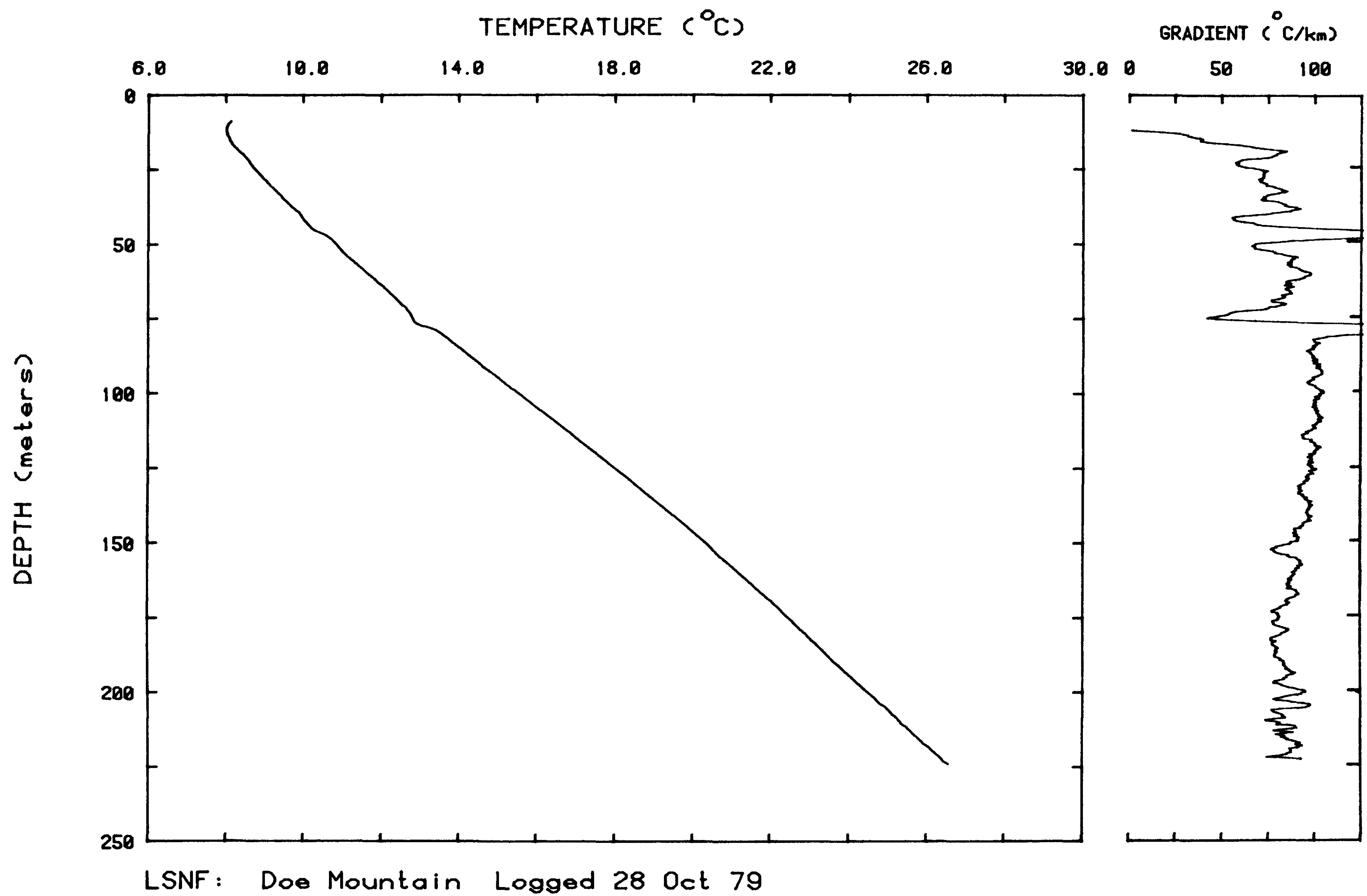


Figure 11. Temperature and gradients for borehole LSNF.

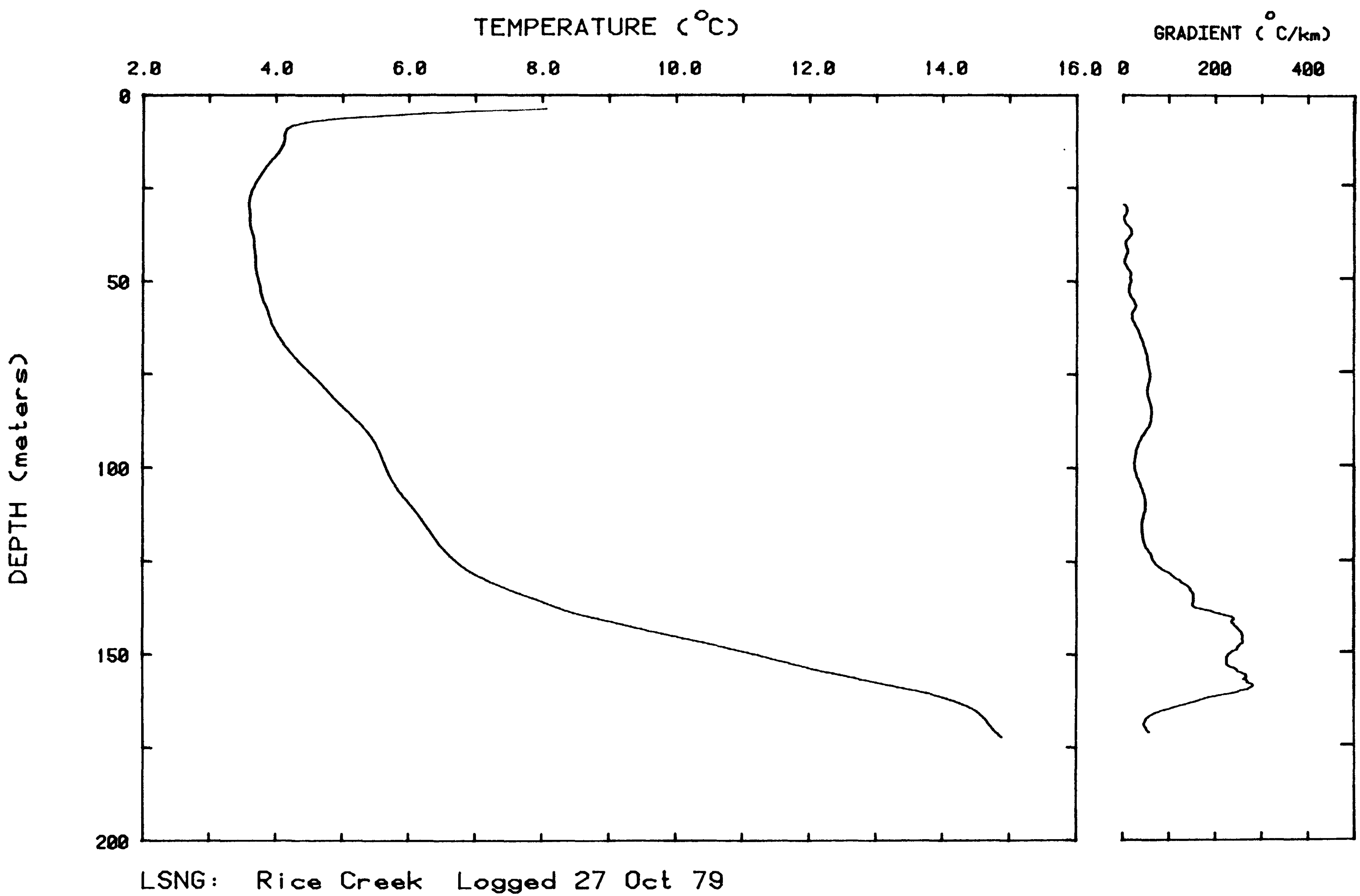


Figure 12. Temperature and gradients for borehole LSNG.

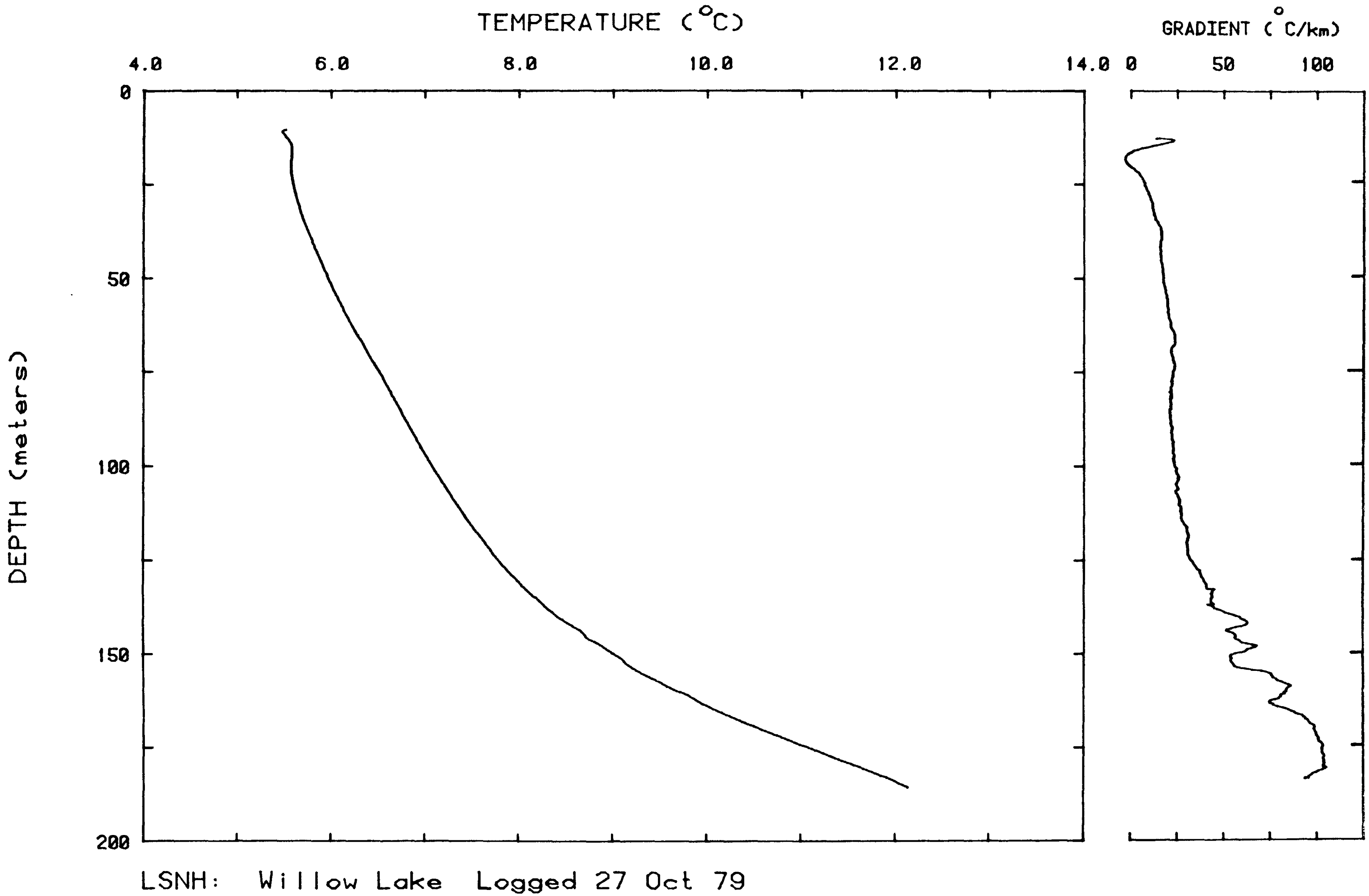


Figure 13. Temperature and gradients for borehole LSNH.

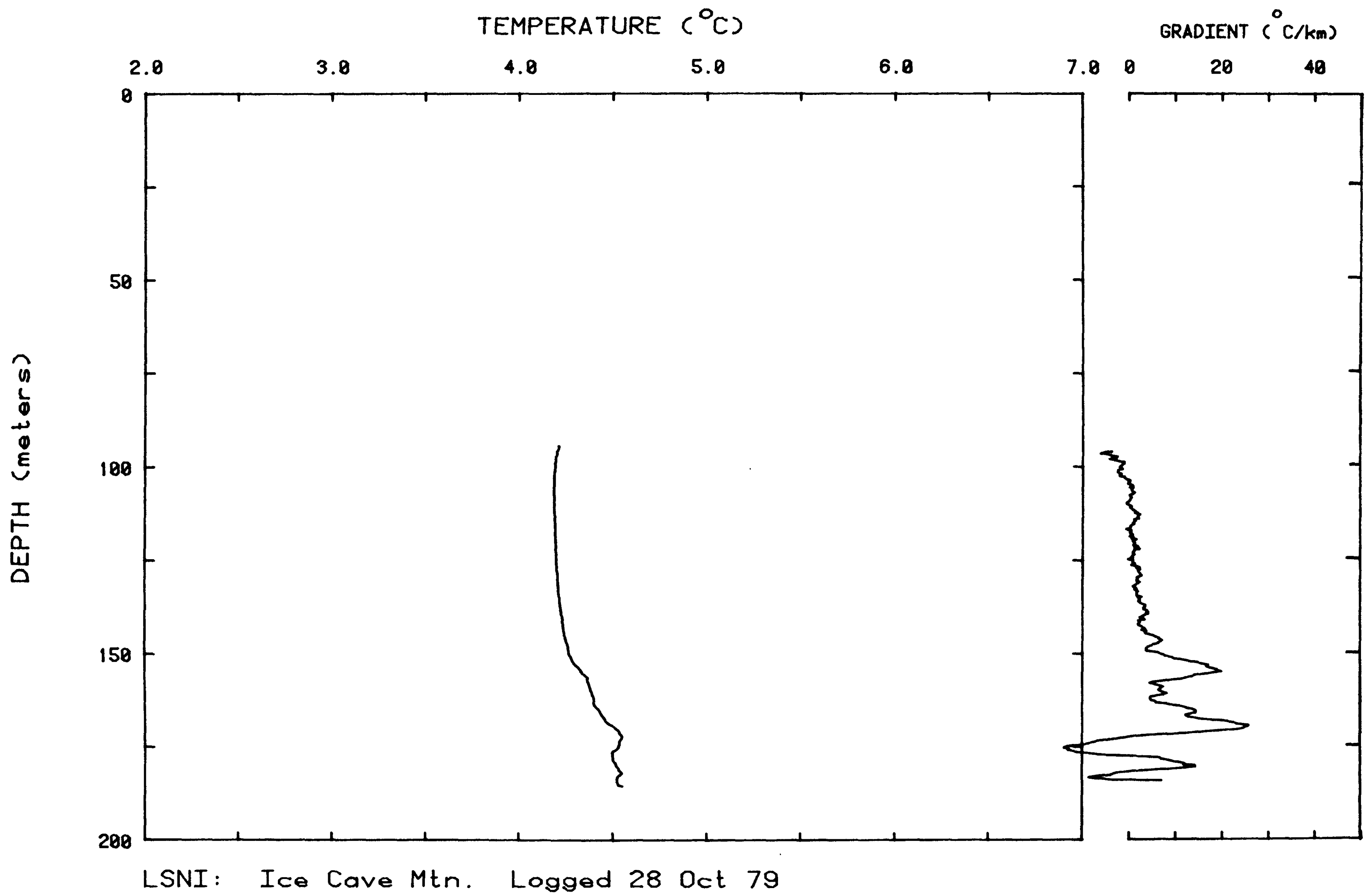


Figure 14. Temperature and gradients for borehole LSNI.

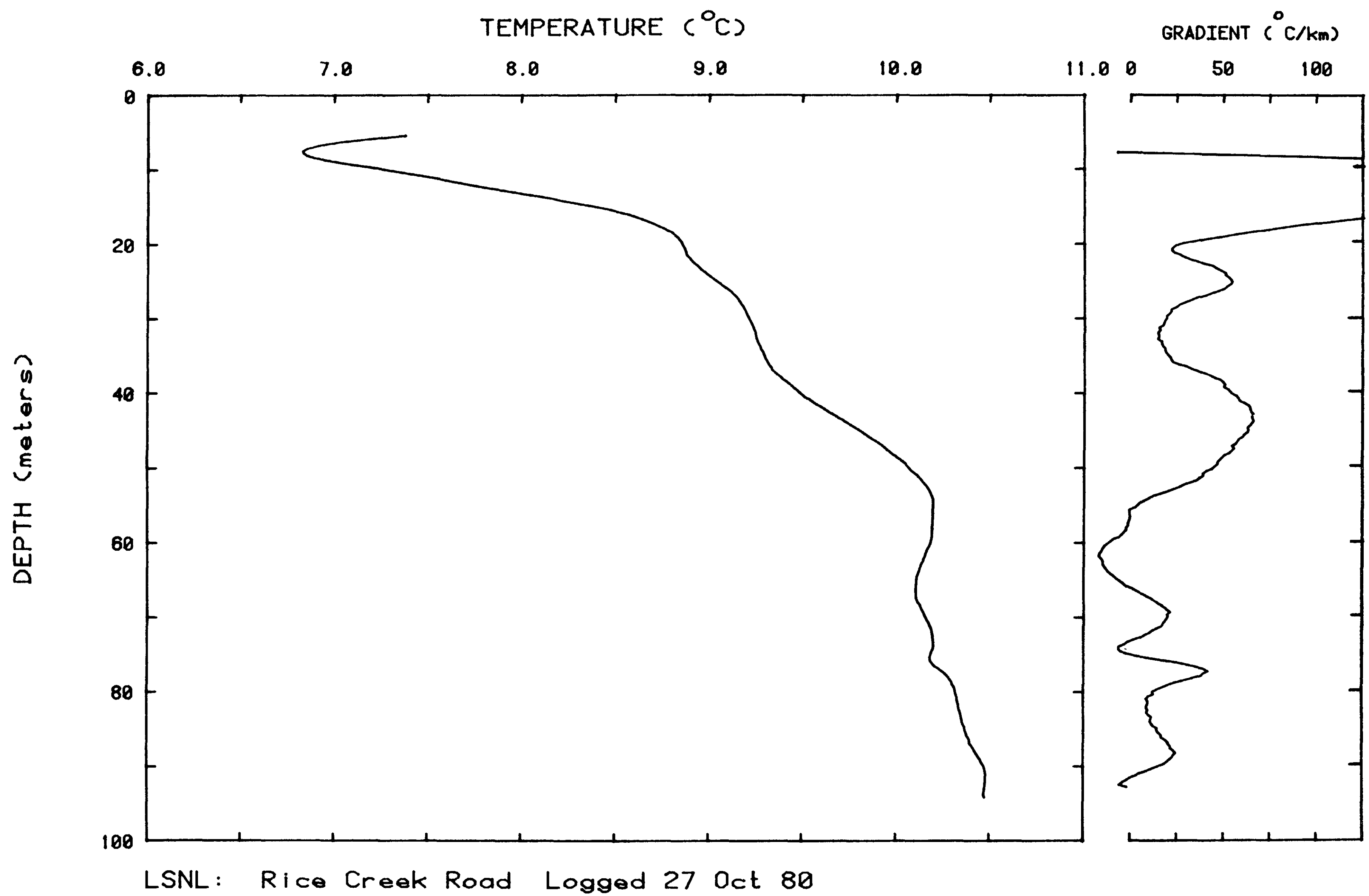
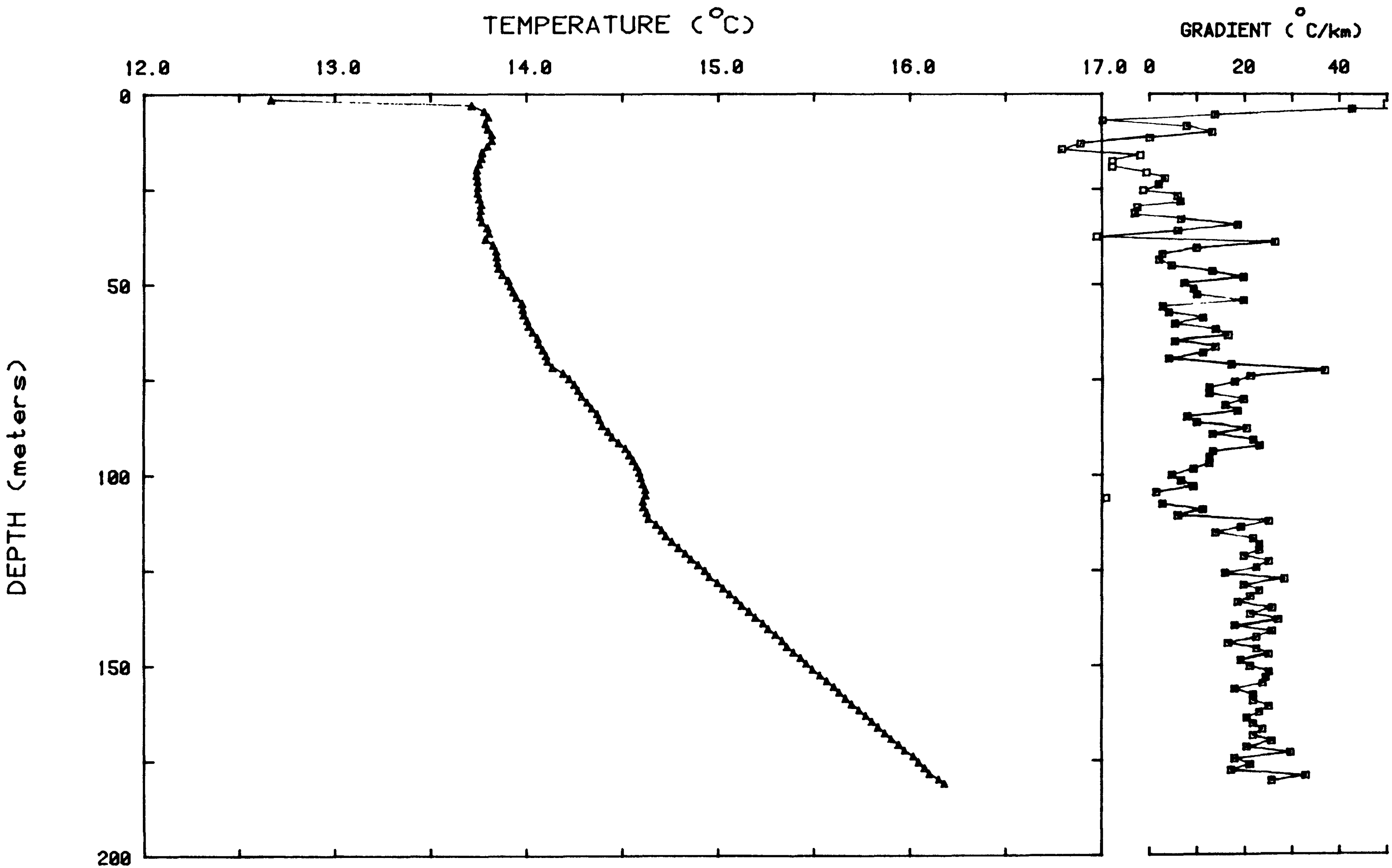


Figure 15. Temperature and gradients for borehole LSNL.



LSNM: Deer Creek Logged 05 Apr 80

Figure 16. Temperature and gradients for borehole LSNM.

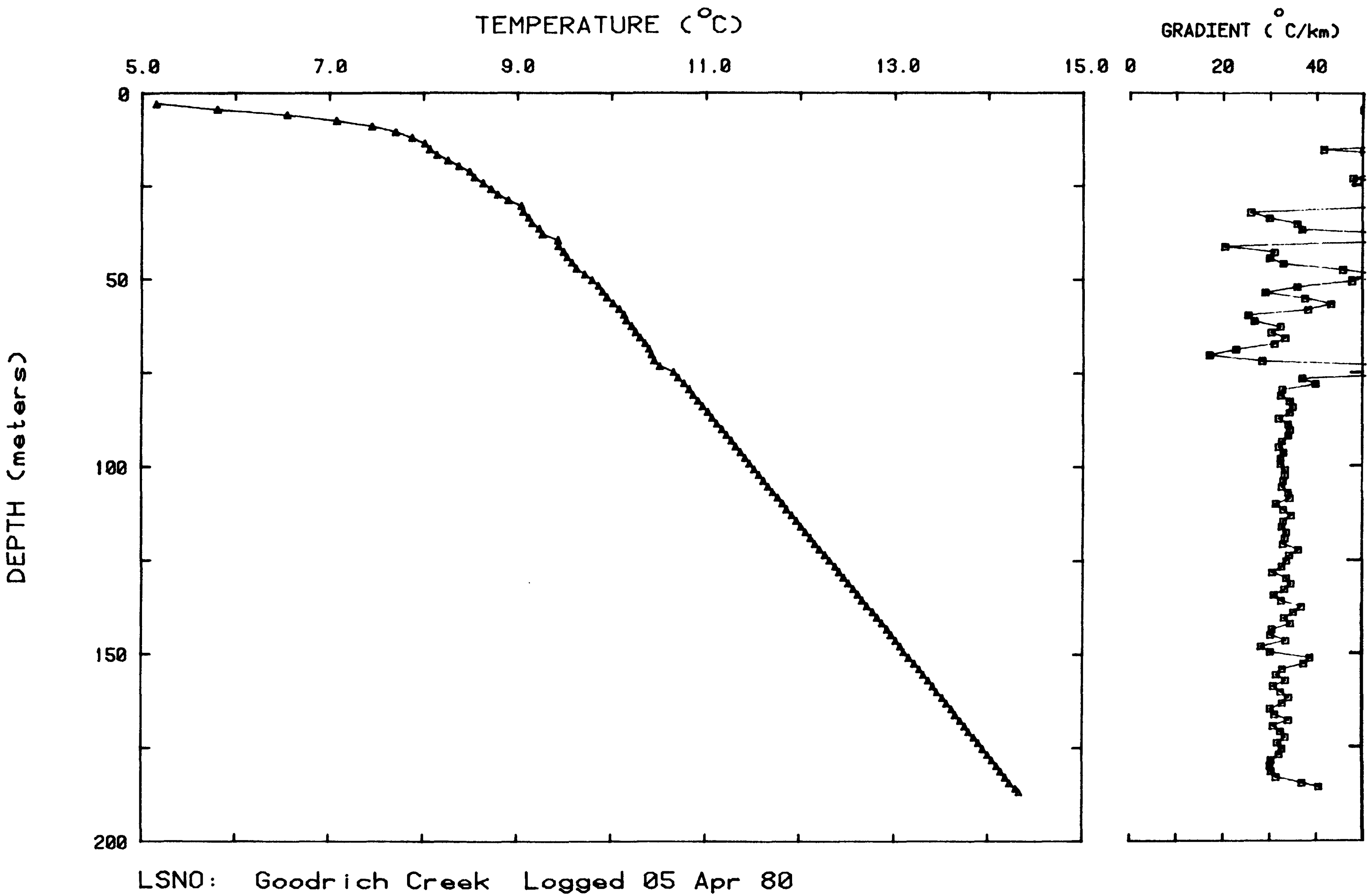


Figure 17. Temperature and gradients for borehole LSNO.