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Temperatures and Water Potentials in Shallow Unsaturated Alluvium Next to a Burial Site for Low-Level Radioactive Waste, Amargosa Desert, Nye County, Nevada, 1987-96

Water-Resources Investigations Report 99-4261

Prepared in cooperation with the
U.S. NUCLEAR REGULATORY COMMISSION,
Office Of Nuclear Regulatory Research
under Interagency Agreement RES-94-003
Job Control Number W6293

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By Mary L. Tumbusch *and* David E. Prudic

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Carson City, Nevada
2000

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic centimeter (cm^3)	0.06102	cubic inch
cubic meter (m^3)	35.31	cubic foot
gram (g)	0.03527	ounce
hectare (ha)	2.471	acre
kilometer (km)	0.06125	mile
megapascal (MPa)	145	pound per square inch
meter (m)	3.281	foot
microvolt (μV)	1×10^{-6}	volt
milliampere (ma)	1000	ampere
millimeter (mm)	0.03937	inch

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

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ABSTRACT

Temperature and water-potential were determined in unsaturated alluvium using thermocouple psychrometers. The thermocouple psychrometers were placed beneath a vegetated area next to a commercial burial site for low-level radioactive waste in the Amargosa Desert, south of Beatty, Nev. The data were collected as part of a study to determine the direction and rate of water movement in unsaturated alluvium.

Thirty-three access pipes were inserted 3 to 4.6 meters outward from a 1.5 meter diameter monitoring shaft between the depths of 3 meters and 13 meters. As of 1992, thermocouple psychrometers were installed in 25 of 33 access pipes. Prior to installation, the thermocouple psychrometers were calibrated in the laboratory. The calibration data were analyzed using stepwise regression techniques. The coefficient of multiple determination (R^2) for each thermocouple psychrometer was greater than 0.95 and the standard error was less than 0.65 megapascals.

Daily values of temperature and water potential were determined for all data collected at the monitoring shaft between January 1987 and June 1996 and at the nearby instrument borehole between January 1987 and September 1992. Seasonal temperature fluctuations were greatest at shallower depths in the monitoring shaft (about 13-15 degrees Celsius at a depth of 1.2 meters) and decreased with depth (less than 0.5 degrees Celsius at a depth of 13 meters). Similar fluctuations were observed in the instrument borehole between depths of 3 meters and 7.9 meters. Below 7.9 meters, temperatures were consistently higher and had different patterns of fluctuations compared with those at similar depths in the monitoring shaft. Seasonal water-potential fluctuations were observed at depths to 8 meters. Water potentials in the monitoring shaft ranged from -6 to -1 megapascals at a depth of 3 meters and from -3.5 to -3 megapascals at a depth of 13 meters. Water potentials in the instrument borehole ranged from -6 to -4 megapascals between depths of 2.8 meters and 8.9 meters and from -4 to -2 megapascals between depths of 10.1 meters and 11.9 meters.

Although temperatures were measured reliably from most thermocouple psychrometers, water potentials could not be determined from all thermocouple psychrometers because voltages were out of range or decreased linearly to zero with time. Data collected during 1987-96 at the monitoring shaft and instrument borehole illustrate uncertainties in determining whether water potentials determined with thermocouple psychrometers are representative of actual fluctuations or if they are artifacts of instrument drift.

INTRODUCTION

A study was begun in 1982 to better define the direction and rates of water movement through the unsaturated zone in undisturbed sediments next to a commercial burial site for low-level radioactive waste (LLRW), in the Amargosa Desert Hydrographic Area[1] (Fischer, 1992), about 18 km south of Beatty, Nye County, Nev. (fig. 1). A 16-ha parcel of land was set aside for the study through agreements with the Bureau

[1]Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's (Rush, 1968; Cardinalli and others, 1968) for scientific and administrative purposes. The official hydrographic-area names, numbers, and geographic boundaries continue to be used in Geological Survey scientific reports and Division of Water Resources administrative activities.

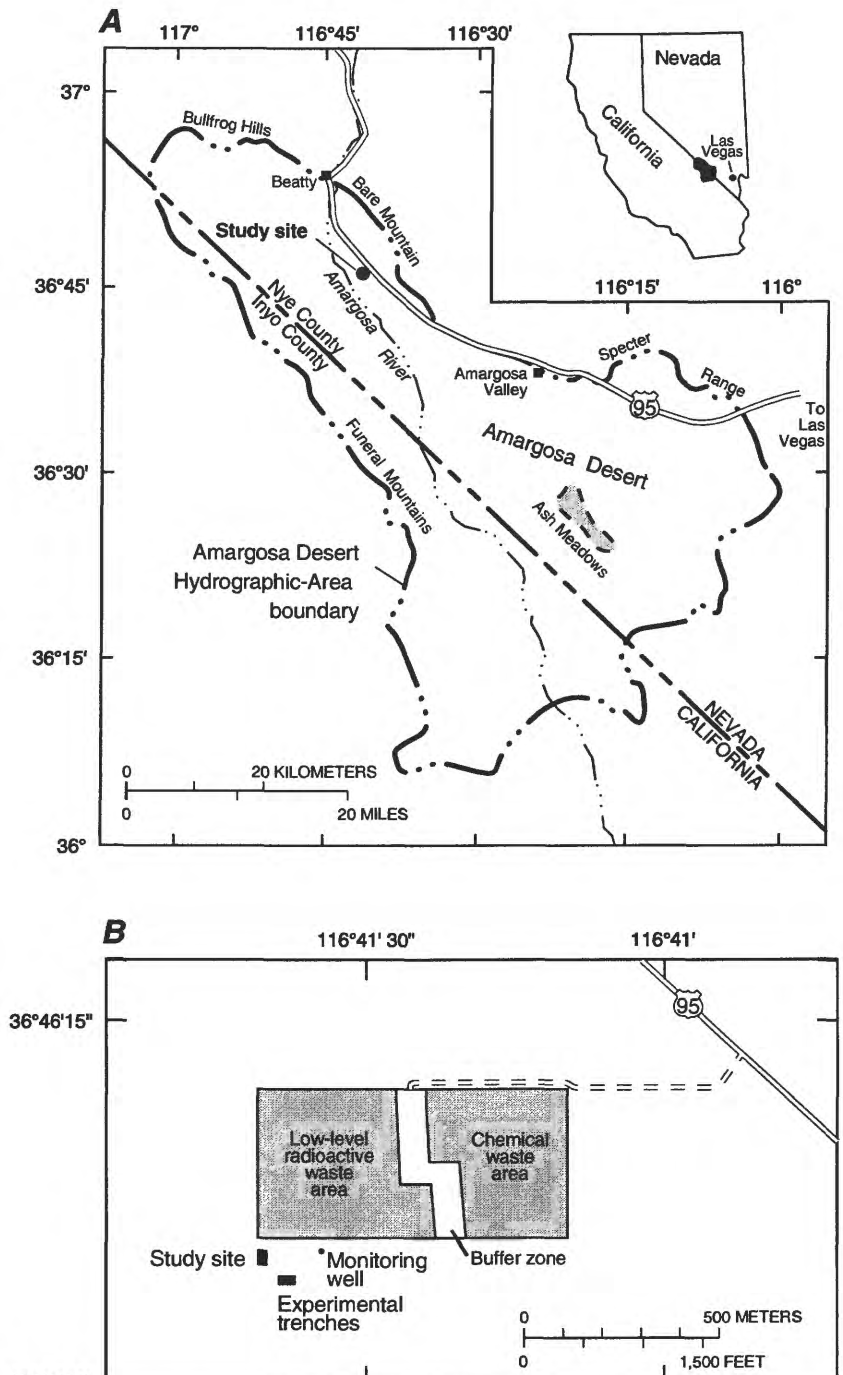

Figure 1. *(A)* Location of study site within the Amargosa Desert Hydrographic Area, and *(B)* location of study site in relation to waste-burial areas (modified from Fischer, 1992, fig. 1). Hydrographic area from Harrill and others (1988).

of Land Management and the Nevada Division of Health. This parcel of land is in the southeast quarter of the northwest quarter of Section 35, Township 13 south, Range 47 east and abuts the southwest corner of the burial site for LLRW.

One of the objectives of the initial study was to develop methods for collecting data to calculate rates, quantities, and directions of water movement through the unsaturated zone. To accomplish this objective, a shaft, 1.5 m in diameter and 13.7 m deep, was emplaced vertically in a hole measuring 2.44 m in diameter in 1983 (Fischer, 1992, p. 15). The monitoring shaft is within a fenced enclosure (fig. 2) about 50 m south of the southwest corner of the burial site for LLRW. Depth to ground water in a nearby monitoring well is 112 m below land surface. The purpose of the monitoring shaft was to install thermocouple psychrometers (TCP's) horizontally outward through access pipes into unsaturated alluvium beneath an undisturbed, vegetated area (fig. 3). A vertical borehole was drilled about 8 m northwest of the monitoring shaft (fig. 2) in 1986 and also instrumented with TCP's. The data collected from these TCP's were compared with data collected from TCP's installed in the monitoring shaft (Fischer, 1992, p. 18).

TCP's are used to measure water (matric and osmotic) potential at the study site because water potentials in the dry unsaturated alluvium are much lower than what can be measured using tensiometers (limited to 0 to -0.08 MPa) or gypsum blocks (limited to -1.5 MPa). In contrast, TCP's measure water potentials from about -0.2 to -8 MPa (Andraski, 1997) and thus are suitable for measuring low water potentials typical of many arid regions where depth to ground water exceeds 100 m (Scanlon and others, 1991, p. 6). However, TCP's are not commonly used because of difficulties in calibration, installation, and data interpretation and because the operational life span is largely unknown (Andraski, 1997). Both temperature and water potential are important for calculating the direction and rate of water movement in the unsaturated zone.

Purpose and Scope

The purposes of this report are to describe and document the calibration and installation procedures of TCP's at the monitoring shaft, and to present and evaluate temperatures and water potentials measured from TCP's. In particular, this report describes changes to the initial calibration and installation procedures of TCP's described by Fischer (1992), and includes a description of a revised method for drilling horizontal holes outward from access ports in the shaft. Finally, temperatures and water potentials measured from TCP's at the monitoring shaft from 1987-96 and at a nearby instrument borehole from 1987-92 are presented. The data collected from TCP's installed using the new calibration and installation procedures are compared with data collected from TCP's using the initial calibration and installation procedures.

Acknowledgments

Partial funding was provided through an Interagency Agreement, Number RES-94-003, Job Control Number W6293, between the U.S. Geological Survey and the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research. Many people contributed to the work described in this report. The authors thank the following individuals: Bill Baker, Larry Mansker, Trey Martin, and Dale Wallace of Mine Development and Engineering Corporation, Bakersfield, Calif., for their expertise in drilling the primary access holes in 1991. William D. Nichols and Harold H. Zehner designed the monitoring shaft and David S. Morgan and Jeffrey M. Fischer designed, drilled, and installed the initial thermocouple psychrometers in the monitoring shaft prior to 1987. Jeffrey M. Fischer designed and installed thermocouple psychrometers in the instrument borehole. Brian J. Andraski developed the stepwise regression for evaluating the calibration of thermocouple psychrometers in the laboratory. James L. Wood and Kevin J. Hill assisted in the collection of data from the monitoring shaft and instrument borehole.

CALIBRATION AND INSTALLATION OF THERMOCOUPLE PSYCHROMETERS

The theory of TCP's in measuring soil-water potential is discussed by Rawlins (1972) and Briscoe (1984) and the field use of TCP's in arid environments has been described by Moore and Caldwell (1972), Nichols (1986), Fischer (1990, 1992), Scanlon and others (1991), and Andraski (1997). TCP's measure relative humidity in sediments, which is then converted to water potential using the Kelvin equation (Weibe and others, 1971; Rawlins, 1972).

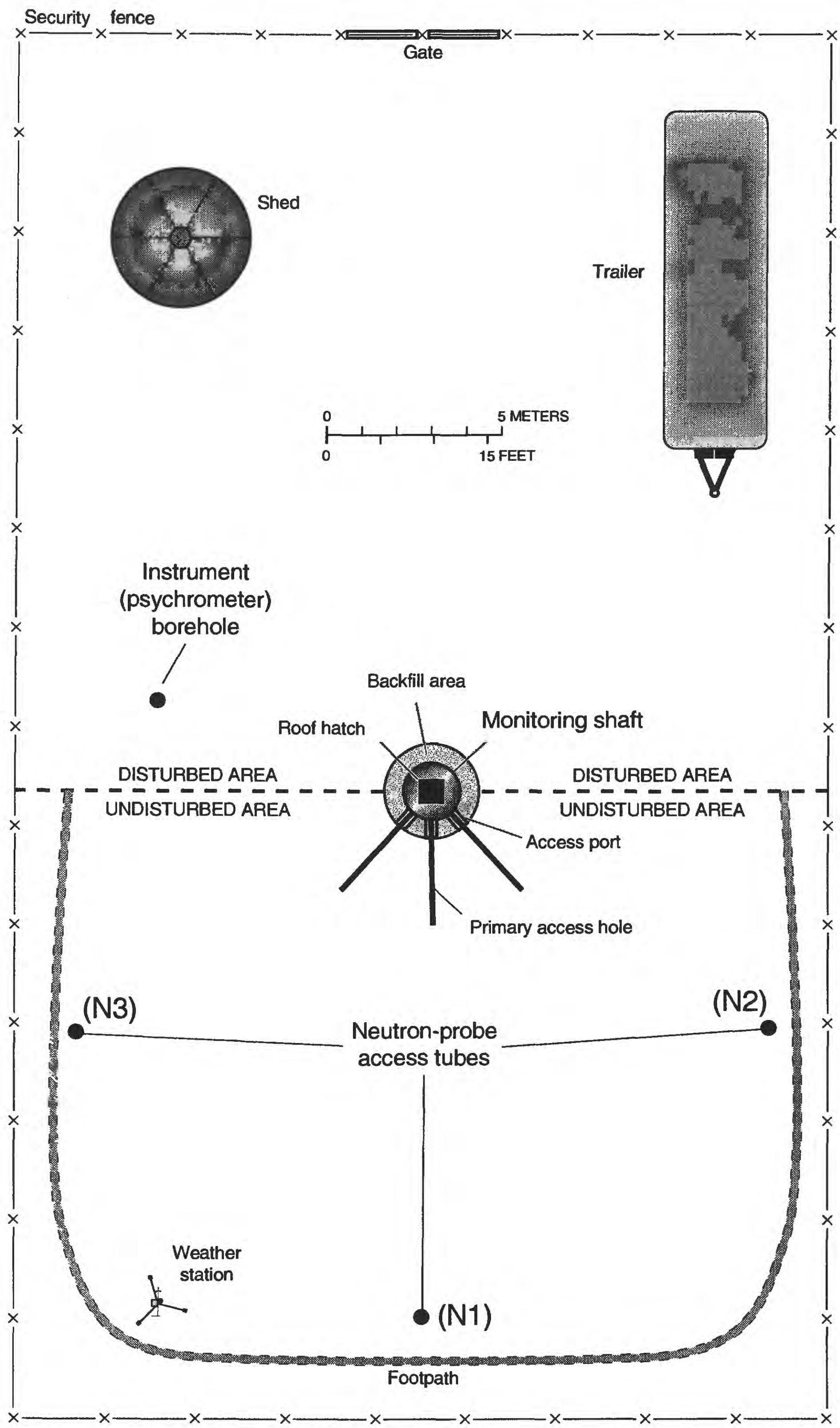

Figure 2. Location of monitoring shaft, instrument (psychrometer) borehole, and neutron-probe access tubes (from Fischer, 1992, fig. 2). Location of study site is shown in figure 1.

Briefly, an electrical current is applied to cool the measuring junction. Water condenses on the cooled junction and begins to evaporate once the applied current ceases. An electric current is created from the evaporating water due to the Peltier effect and is a function of temperature and water potential.

Temperatures and water potentials were measured with single junction design, wire screen-caged Spanner-type TCP's manufactured by J.R.D. Merrill Specialty Equipment Company (Logan, Utah). A Campbell Scientific (Logan, Utah) CR7 datalogger with model A3497 thermocouple psychrometer interface was used to apply the cooling current and to record the output voltage of the measuring junction. The TCP's were outfitted with 18 m of lead wire and type 81-500 Viking connectors, which connect the 1-m long lead wires attached to the datalogger. For calibration and field use, the datalogger was programmed to apply a cooling current of 8 milliamperes to each TCP for 30 seconds. Voltage readings were taken 1 second after the cessation of the cooling current.

Final output of psychrometer data is reported as temperature (degrees Celsius), zero offset (microvolts), and voltage (microvolts). Zero offset is the temperature difference between the measuring and reference junctions prior to Peltier cooling (zero under isothermal conditions). A zero offset of +60 microvolts (μV) indicates that the measuring junction is approximately 1°C cooler than the reference junction. Voltages measured by the TCP were adjusted by the datalogger for variations in zero offset and were used to correct water potential estimates for temperature gradients within the TCP. TCP's are sensitive to temperature gradients between the measuring junction and reference junction. A 1°C difference can result in a measurement error of ±13 MPa (Rawlins and Campbell, 1986). Temperature and voltage were used to calculate a water potential using regression equations determined through laboratory calibrations.

Laboratory Calibration

Prior to field installation, the TCP's were calibrated in the laboratory. The TCP's were fitted into stainless steel calibration chambers and calibrated with salt solutions of known osmotic potentials. A piece of filter paper saturated with a salt solution was sealed with the TCP's in the chamber. Calibration was performed in a water bath under isothermal conditions because psychrometer output and water potential are temperature-dependent variables. Voltages were then plotted against water potential for several different temperatures to yield a family of curves. Because the relation between voltage and water potential is not linear throughout the entire range, several different salt solutions were used for each of several temperatures (Brown and Bartos, 1982). Salt solutions with molalities ranging from 0 to 1.6 were applied to filter paper lining the chamber. After letting the TCP chamber equilibrate in the water bath for a given temperature and osmolality, and after several readings were made, the temperature, the salt solution, or both were changed. Measurements of temperature, zero offset, and voltage were recorded for the TCP's and stored by the datalogger. This process continued until a calibration curve was completed that included the range of temperatures and water potentials expected in the field.

The 17 TCP's installed in the shaft between 1986 and 1987 were calibrated at temperatures of 15, 22, and 29°C, and over salt solutions with osmotic potentials ranging from -7.8 to -0.4 MPa (Fischer, 1992). Two sets of TCP's were calibrated in 1990 and 1991. The first set used water bath temperatures of 15, 20, 25, and 30°C and salt solutions with osmotic potentials ranging from -7.8 to -0.4 MPa. The second set used water bath temperatures of 10, 20, and 30°C over salt solutions with osmotic potentials ranging from -7.8 to 0 MPa. TCP's were recalibrated when data were questionable due to leakage into the stainless steel chamber. Water-potential measurements were not calculated when the measured zero offset was less than -2 μV or greater than 2 μV because of possible problems with the TCP. TCP's were named according to the year of calibration, then numbered sequentially.

The laboratory calibration data were analyzed using stepwise regression techniques (Meyn and White, 1972). Five independent variables were evaluated in the analysis: voltage (V), temperature (T), voltage times temperature (VT), voltage times voltage (VV), and temperature times temperature (TT). Results of the stepwise regression are listed in table 1 for each TCP installed in the monitoring shaft or instrument borehole. Typically, two independent variables explained the calibration data (V and VT) but several included a third variable (VV). The coefficient of multiple determination (R^2) for each regression equation was greater than 0.95 and the standard error was less than 0.65 MPa for all TCP's (table 1).

Table 1. Summary of laboratory calibration results for thermocouple psychrometers in monitoring shaft and in instrument borehole. Location of shaft and instrument borehole shown in figure 2.

Thermocouple psychrometer[1]	Calibration equation[2]	Coefficient of multiple determination (R^2)	Standard error (megapascals)
86-01	0.243-0.464(V)+0.00851(VT)	0.996	0.198
86-02	0.168-0.428(V)+.00759(VT)	.998	.133
86-03	0.407-0.635(V)+0.0128(VT)	.992	.288
86-04	0.223-0.454(V)+0.00823(VT)	.998	.143
86-05	0.168-0.459(V)+0.00839(VT)	.998	.149
86-06	0.165-0.428(V)+0.0759(VT)	.998	.143
86-07	0.161-0.433(V)+0.00783(VT)	.997	.172
86-08	0.145-0.415(V)+0.0729(VT)	.998	.141
86-09	0.116-0.418(V)+0.00734(VT)	.998	.126
86-10	0.175-0.458(V)+0.00838(VT)	.998	.153
86-11	0.165-0.431(V)+0.00772(VT)	.998	.138
86-12	0.113-0.418(V)+0.00735(VT)	.998	.134
86-13	0.203-0.460(V)+0.00839(VT)	.995	.225
86-14	0.175-0.437(V)+0.00777(VT)	.998	.138
86-15	0.196-0.440(V)+0.00790(VT)	.998	.133
86-16	0.167-0.423(V)+0.00745(VT)	.998	.143
86-17	0.191-0.431(V)+0.00765(VT)	.998	.132
86-18	0.186-0.444(V)+0.00808(VT)	.995	.221
86-20	0.185-0.448(V)+0.00787(VT)	.996	.192
86-21	0.167-0.439(V)+0.00790(VT)	.998	.146
86-22	0.600-0.494(V)+0.00911(VT)	.997	.166
86-23	0.131-0.441(V)+0.00792(VT)	.998	.136
86-24	0.170-0.462(V)+0.00837(VT)	.997	.173
86-25	0.158-0.474(V)+0.00881(VT)	.997	.157
86-29	-0.160-0.393(V)+0.00840(VT)-0.00137(VV)	.997	.155
86-31	-0.125-0.413(V)+0.00910(VT)-0.00149(VV)	.997	.179
86-32	0.00138-0.407(V)+0.00694(VT)	.990	.274
86-35	-0.220-0.390(V)+0.00709(VT)	.996	.184
86-36	-0.242-0.417(V)+0.00822(VT)	.987	.320
86-38	0.245-0.429(V)+0.00761(VT)	.996	.186
86-39	0.00711-0.438(V)+0.00973(VT)-0.00161(VV)	.996	.179
86-40	0.117-0.421(V)+0.00762(VT)	.995	.205
90-01	0.541-0.542(V)+0.0104(VT)	.962	.577
90-02	-0.129-0.438(V)+0.0101(VT)-0.00204(VV)	.993	.234
90-03	-1.390+0.00404(VV)-0.408(V)+0.0990(T)	.951	.647
90-04	-0.0742-0.448(V)+0.00986(VT)-0.00148(VV)	.993	.233
90-05	-0.297-0.450(V)+0.0126(VT)-0.00480(VV)	.983	.359
90-06	-0.502-0.478(V)+0.0144(VT)-0.00540(VV)	.966	.515
90-07	-0.602-0.450(V)+0.0114(VT)-0.00294(VV)	.994	.214
91-01[3]	-0.183-0.474(V)+0.00915(VT)	.986	.303

Table 1. Summary of laboratory calibration results for thermocouple psychrometers in monitoring shaft and in instrument borehole—Continued

Thermocouple psychrometer[1]	Calibration equation[2]	Coefficient of multiple determination (R^2)	Standard error (megapascals)
91-03[3]	-0.201-0.483(V)+0.00951(VT)	0.983	0.330
91-04[3]	-0.141-0.486(V)+0.00963(VT)	.989	.276
91-07[3]	-0.182-0.507(V)+0.0101(VT)	.985	.312
91-09[3]	-0.176-0.461(V)+0.00888(VT)	.988	.279
91-11[3]	-0.267-0.485(V)+0.00975(VT)	.984	.327
91-14[3]	-0.200-0.463(V)+0.00899(VT)	.987	.289
91-15[3]	-0.169-0.469(V)+0.00905(VT)	.985	.310
91-16[3]	-0.249-0.477(V)+0.00949(VT)	.984	.320
91-18[3]	-0.103-0.478(V)+0.00926(VT)	.987	.294
91-19[3]	-0.116-0.453(V)+0.00854(VT)	.990	.261
91-21[3]	-0.109-0.470(V)+0.00894(VT)	.987	.291
91-23[3]	-0.147-0.477(V)+0.00922(VT)	.989	.273
91-24[3]	-0.174-0.465(V)+0.00914(VT)	.986	.308
91-25[3]	-0.190-0.449(V)+0.00855(VT)	.990	.260
91-27[3]	-0.195-0.477(V)+0.00944(VT)	.985	.313
91-28[3]	-0.151-0.444(V)+0.00839(VT)	.988	.275
91-29[3]	-0.242-0.490(V)+0.00970(VT)	.985	.313
91-30[3]	-0.266-0.466(V)+0.00925(VT)	.988	.284

[1] Thermocouple psychrometers are identified according to last two digits of year of calibration, then numbered sequentially.

[2] Equations are result of stepwise regression techniques (Meyn and White, 1972) of calibration data assuming independent variables of voltage *(V)*, temperature *(T)*, voltage times temperature *(VT)*, voltage times voltage *(VV)*, and temperature times temperature *(TT)*.

[3] Thermocouple psychrometers used in laboratory experiments. Several were subsequently installed in monitoring shaft in September 1992.

Field Installation, 1986-87

Details on the field installation of TCP's in the monitoring shaft and nearby instrument borehole (fig. 2) are described by Fischer (1992) and are summarized in the following sections. Location of TCP's in the monitoring shaft and instrument borehole are shown in figure 3. TCP locations in the monitoring shaft are designated as left (L), middle (M), and right (R), followed by a number from 1 to 11, indicating the level in the shaft.

Monitoring Shaft

Access holes were drilled horizontally outward from 17 ports in the monitoring shaft using a blast-hole drill. These holes were drilled to a minimum distance of 3 m from the shaft to minimize the effects of temperature fluctuations caused by the shaft. Drill cuttings were removed with air to avoid introduction of liquid into the access hole. The holes were drilled horizontally outward from the shaft to avoid disturbing the vertical sediment column above the TCP's.

The access holes were cased with nominal 2.5-cm-diameter PVC pipe, which was fitted with a centering plug made of Delrin, an industrial grade plastic (fig. 4*A*). The centering plug was glued into the end of the access pipe before installation into the access hole. Once the PVC access pipe was installed in the access hole, polyurethane foam was used to seal the pipe in place and to act as a thermal and vapor barrier. The access pipes were designed to allow the installation of TCP's such that they could be replaced or recalibrated.

TCP's were threaded through 9.5-mm-diameter tubing composed of semi-rigid polyethylene. Silicon sealant was injected into both ends of the tubing.

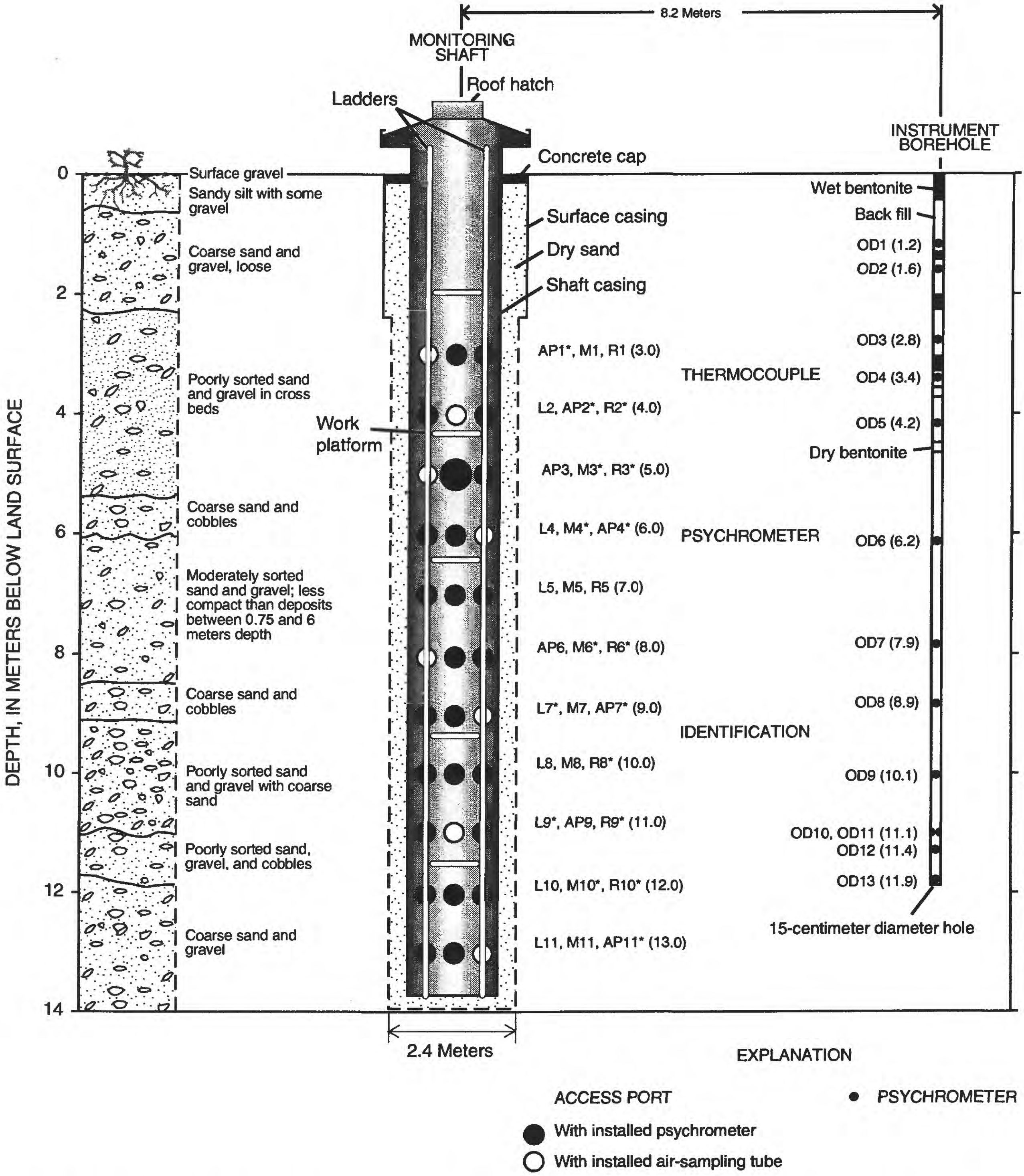

Figure 3. Monitoring shaft and instrument borehole showing locations of thermocouple psychrometers. Distance between monitoring shaft and instrument borehole is not to scale. Location of monitoring shaft and instrument borehole shown in figure 2. Thermocouple psychrometers installed in monitoring shaft and designated with L (left), M (middle), and R (right), followed by a number from 1 to 11 that indicates level in shaft. Eight access ports designated as AP (air ports) are installed with air-sampling tubes. Asterisk follows identification of access ports drilled during July 1991. Thermocouple psychrometers installed in instrument borehole are designated OD1 through OD13. Depth of each psychrometer, in meters below land surface, is given in parentheses (modified from Fischer, 1992, fig. 9).

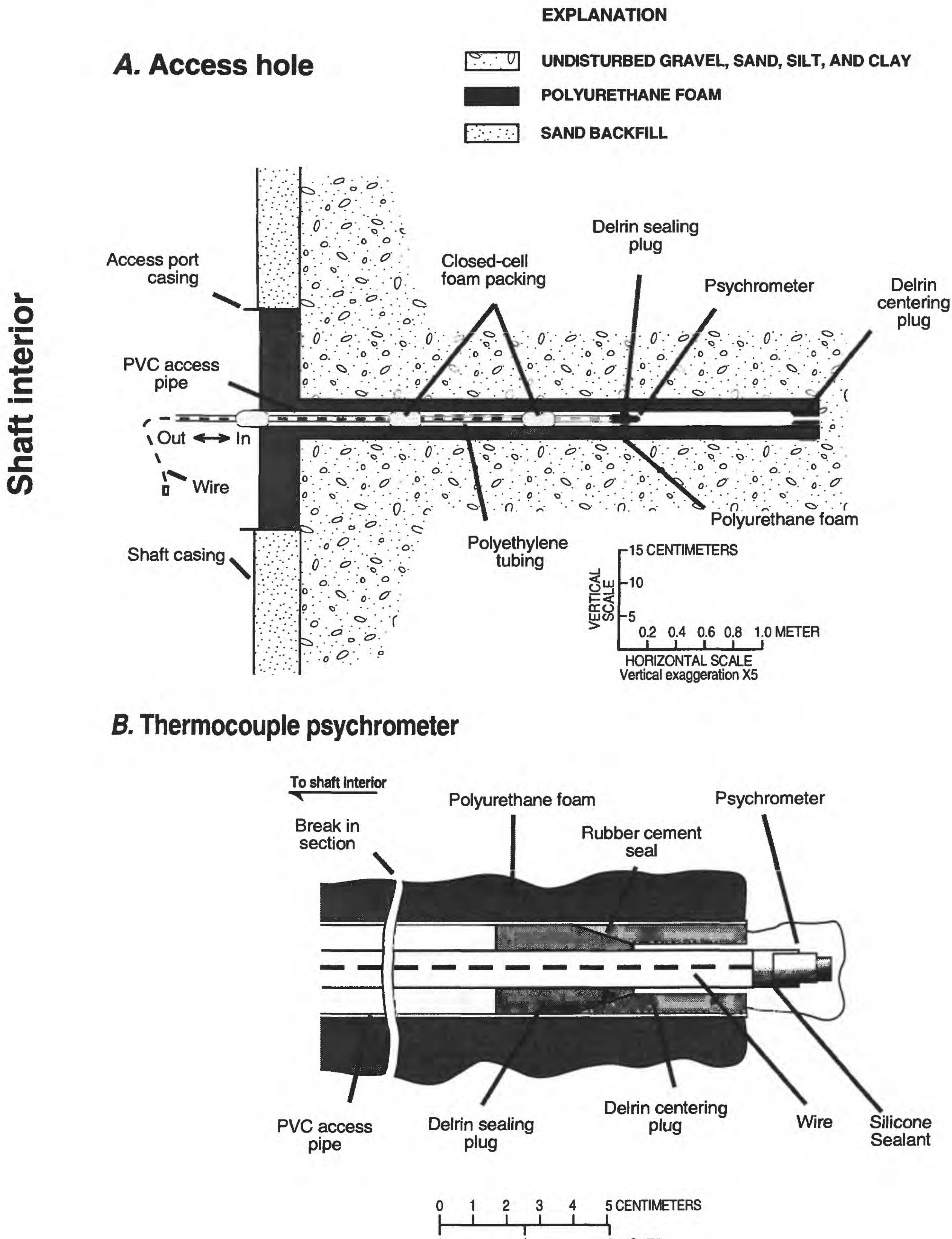

Figure 4. Original installation methods in monitoring shaft for *(A)* access holes and *(B)* thermocouple psychrometers (modified from Fischer, 1992, fig. 10). Abbreviations: PVC, polyvinylchloride; cm, centimeter.

A cone shaped sealing plug, made of Delrin, was fitted over the semi-rigid tubing and was designed to fit precisely into the centering plug at the end of the PVC access pipe (fig. 4*B*). Closed foam packing was wrapped around the outside of the semi-rigid tubing approximately every 90 cm and acted as a thermal barrier between the TCP and shaft (fig. 4*A*).

The TCP's were installed by pushing the semi-rigid tubing into the PVC access pipe until the sealing plug fitted into the centering plug. Initially, rubber o-rings were used to seal between the two plugs; eventually the o-rings were replaced with adhesive glue. The TCP's extended slightly beyond the end of the PVC access pipe into a small diameter hole in the sediments. This hole had been hand drilled using a concrete drill bit welded to threaded rod.

Instrument Borehole

Several TCP's were installed in a vertical borehole drilled in July 1986 (fig. 3, table 2) to compare temperatures and water potentials with TCP's installed in the monitoring shaft (Fischer, 1992, p. 18). The borehole was drilled to a depth of 12 m using the ODEX air-hammer drilling method. TCP's were placed in the cased instrument borehole at approximately 1-m intervals between depths of 1 m and 12 m. TCP's installed in the instrument borehole are designated OD1 through OD13, with OD1 being the shallowest and OD13 being the deepest. The hole was backfilled with cuttings as the casing was withdrawn. Except for TCP's above the depth of 6 m, no seals were placed between TCP's because the addition of liquids would interfere with water potentials in the borehole. TCP's installed at depths of 1 to 4 m had small quantities of wetted bentonite placed between them to prevent preferential movement of wetting fronts down the borehole.

Field Installation, January 1991

In January 1991, new TCP's were installed into PVC access pipes after removing seven TCP's that were not functioning properly. TCP's were removed from locations M1, R1, L2, L4, R5, L8, and M11 (table 2, fig. 3). TCP's were installed using the same method for TCP's installed in 1986-87. During installation, the semi-rigid tubing proved too flexible to determine when the sealing plug was inserted into the centering plug; the TCP's were often damaged because the small diameter hole that was drilled past the PVC pipe and into the sediments often collapsed; and glue used in sealing the plugs did not always provide an adequate vapor seal. Additionally, silicon sealant injected into the ends of the semi-rigid tubing could not be removed from the TCP wires without damage to the wires preventing recalibration of the TCP's in the original chambers. Subsequently, modifications were made to improve the ease of installation and recalibration of the TCP's.

Field Installation, July 1991-92

Drilling New Access Holes

In July 1991, access holes were drilled horizontally outward from the remaining 16 access ports in the shaft. Additionally, the access port at L1 was redrilled because the centering plug at the end of the 2.5-cm diameter PVC access pipe was removed along with a TCP in 1987. Approximately 5-cm diameter access holes were drilled 3.7-4.6 m using an air-hammer percussion drill. This method was superior to the blast hole drill because it reduced drilling time and decreased hole collapse. Similar to the original design, once the hole had been drilled, a centering plug made of Delrin was glued about 1 cm from one end of the 2.5-cm-diameter PVC access pipe. The end of the access pipe was covered with a Teflon screen to prevent sediment from entering the pipe (fig. 5). The screen was held in place with a 5-cm diameter PVC plate glued to the end of the pipe. A center hole in the plate exposed the Teflon screen to the sediments and also was used to center the PVC access pipe in the hole. Polyurethane foam was used to fill the space between the access pipe and the drilled access hole. The foam was used as a thermal seal (fig. 5).

Modifications to Installation Procedures

The modified method was needed to simplify the installation and to allow the TCP's to be recalibrated using the same procedures as used during initial calibration. The method of installation was redesigned so that no adhesive glues were used near the TCP and all materials could be disassembled and reused. The semi-rigid tubing was replaced with nominal 1.3-cm diameter rigid PVC pipe. A new sealing plug, made of Delrin, was designed to fit into the centering plug near the end of the 2.5-cm-diameter PVC access pipe. The sealing plug was fabricated with a 2.5-cm long nipple having

Table 2. List of thermocouple psychrometers in monitoring shaft and in instrument borehole, 1986-96. Location of shaft and instrument borehole shown in figure 2.

[Status: As of June 30, 1986. Functioning, temperatures and water potentials were collected; not functioning, thermocouple psychrometer was recording out of range data; and temperature only, thermocouple psychrometer was measuring temperatures but zero offsets and (or) water potentials were out of range. Air tubes were installed at eight locations on September 9, 1992. Abbreviation: --, not removed but not in use.]

Location identification[1]	Depth (meters below land surface)	Thermocouple psychrometer			
		Identifier	Date installed	Date removed	Status
		Shaft			
L1	3	86-35	02-03-1987	06-28-1991	Air tube
M1	3	86-01	05-21-1986	01-11-1991	
		90-01	01-16-1991	Not removed	Functioning
R1	3	86-02	05-21-1986	01-15-1991	
		90-02	01-16-1991	Not removed	Functioning
L2	4	86-10	11-12-1986	06-18-1987	
		86-32	07-29-1987	01-15-1991	
		90-03	01-16-1991	Not removed	Functioning
M2	4	None	--	--	Air tube
R2	4	91-01	09-09-1992	Not removed	Functioning
L3	5	86-38	02-03-1987	09-09-1992	Air tube
M3	5	91-03	09-09-1992	Not removed	Functioning
R3	5	91-04	09-09-1992	Not removed	Temperature only
L4	6	86-36	02-03-1987	01-15-1991	
		90-06	01-16-1991	Not removed	Functioning
M4	6	91-14	09-09-1992	Not removed	Temperature only
R4	6	None	--	--	Air tube
L5	7	86-29	02-03-1987	Not removed	Functioning
M5	7	86-06	12-18-1986	Not removed	Functioning
R5	7	86-03	12-18-1986	01-15-1991	
		90-07	01-16-1991	Not removed	Functioning
L6	8	86-40	02-03-1987	09-09-1992	Air tube
M6	8	91-15	09-09-1992	Not removed	Temperature only
R6	8	91-16	09-09-1992	Not removed	Functioning
L7	9	91-21	09-09-1992	Not removed	Temperature only
M7	9	86-08	12-18-1986	Not removed	Not functioning
R7	9	None	--	--	Air tube
L8	10	86-31	02-06-1987	01-15-1991	
		90-05	01-16-1991	Not removed	Not functioning
M8	10	86-39	02-03-1987	Not removed	Functioning
R8	10	91-23	09-09-1992	Not removed	Functioning
L9	11	91-24	09-09-1992	Not removed	Functioning
M9	11	86-04	06-18-1987	09-09-1992	Air tube
R9	11	91-25	09-09-1992	Not removed	Not functioning

Table 2. List of thermocouple psychrometers in monitoring shaft and in instrument borehole, 1986-96—Continued

Location Identification[1]	Depth (meters below land surface)	Thermocouple psychrometer			
		Identifier	Date Installed	Date removed	Status
		Shaft—Continued			
L10	12	86-05	05-21-1986	Not removed	Functioning
M10	12	91-29	09-09-1992	Not removed	Functioning
R10	12	91-30	09-09-1992	Not removed	Functioning
L11	13	86-07	12-18-1986	Not removed	Functioning
M11	13	86-09	12-18-1986	01-15-1991	
		90-04	01-16-1991	Not removed	Functioning
R11	13	None	--	--	Air tube
		Instrument Borehole[2]			
OD1	1.2	86-14	06-13-1986	--	Inactive
OD2	1.6	86-12	06-13-1986	--	Inactive
OD3	2.8	86-13	06-13-1986	--	Inactive
OD4	3.4	86-18	06-13-1986	--	Inactive
OD5	4.2	86-11	06-13-1986	--	Inactive
OD6	6.2	86-20	06-13-1986	--	Inactive
OD7	7.9	86-15	06-13-1986	--	Inactive
OD8	8.9	86-21	06-13-1986	--	Inactive
OD9	10.1	86-22	06-13-1986	--	Inactive
OD10	11.1	86-16	06-13-1986	--	Inactive
OD11	11.1	86-17	06-13-1986	--	Inactive
OD12	11.4	86-23	06-13-1986	--	Inactive
OD13	11.9	86-24	06-13-1986	--	Inactive

[1] Thermocouple psychrometers installed in monitoring shaft are designated with L (left), M (middle), and R (right), followed by a number from 1 to 11 that indicates level in shaft. Thermocouple psychrometers installed in instrument borehole are designated OD1 through OD13.

[2] Thermocouple psychrometers in instrument borehole were disconnected from data logger on September 17, 1992. Thermocouple psychrometers still in instrument borehole.

an outside diameter (OD) of 1.5 cm. A 30-cm length of nominal 1.3-cm PVC pipe was inserted over this nipple and glued. The other end of the sealing plug was fabricated with a 2-cm long nipple having an OD of 1.1 cm. When installed, this nipple protrudes into the opening of the centering plug (fig. 5*B*).

A calibrated TCP was threaded through the 30-cm length of 1.3-cm-diameter PVC pipe until it extended past the nipple of the sealing plug. A small piece of kneaded rubber was pressed into the nipple around the TCP wire, extending inside the nipple several millimeters (fig. 5*B*). Once the rubber was in place, the TCP was pressed carefully into the kneaded rubber until snug. The end of the TCP is designed such that it nearly extends to the Teflon screen (fig. 5*B*), thereby reducing the possibility of damage from a collapsed hole in the sediments. The size of the air pocket around the TCP is about the same as that in the calibration chambers. The inside of the sealing plug and the 30-cm length of 1.3-cm-diameter PVC pipe was then filled with silica flour and the outer end plugged with a rubber stopper partly sliced and bored to allow for the TCP wire. The rubber stopper acts as a barrier to vapor flow and the kneaded rubber and silica flour provide an insulating barrier between the tubing and exposed TCP.

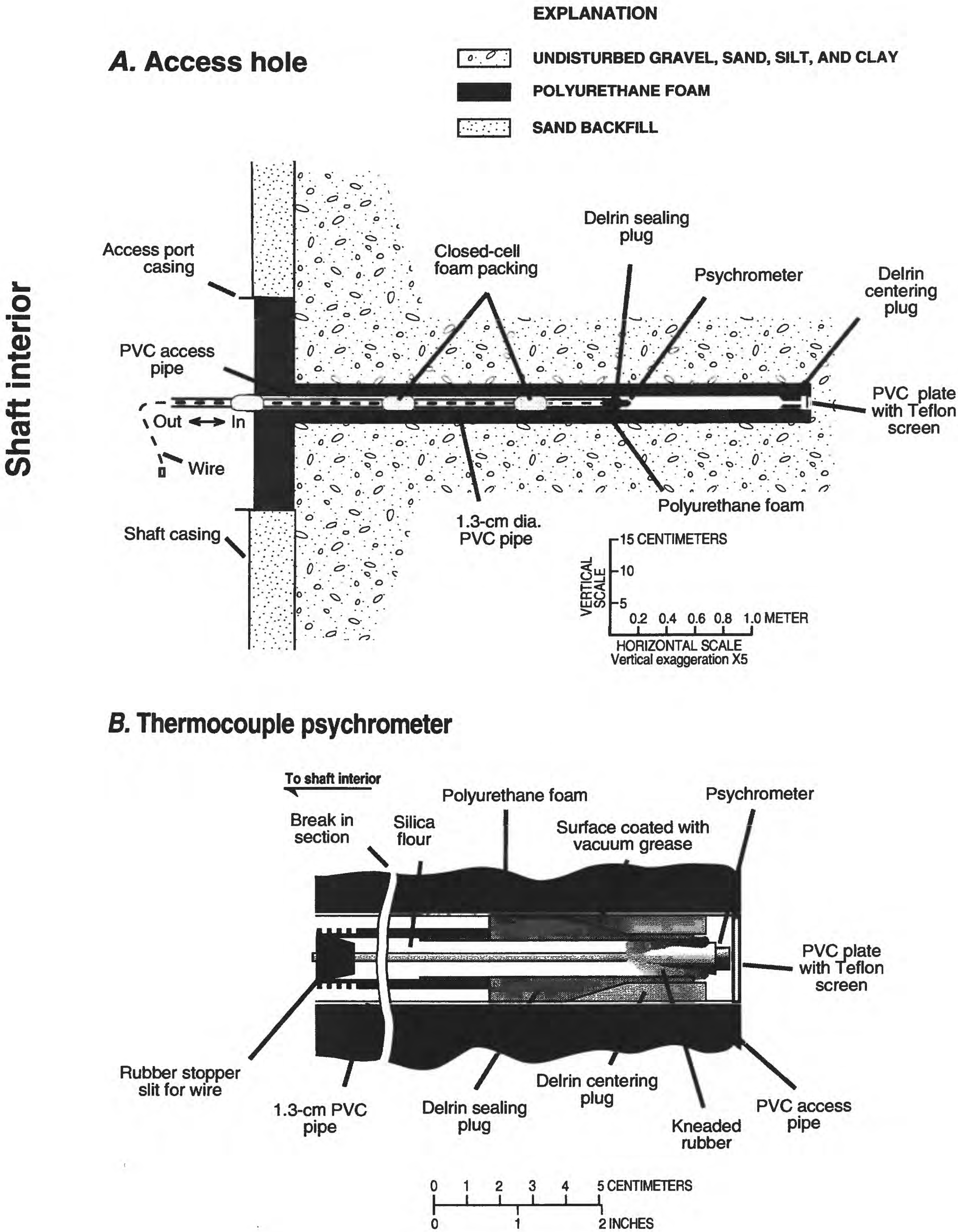

Figure 5. Modified installation methods in monitoring shaft for *(A)* access holes and *(B)* thermocouple psychrometers. Abbreviations: PVC, polyvinylchloride; cm, centimeter.

Laboratory Experiment

Prior to field installation, a laboratory experiment was designed to test the modified method for installing the TCP's. Three boxes with dimensions of 61 cm long by 50.8 cm wide and 15.2 cm deep were constructed and filled with a uniform 60-mesh sand. Different quantities of water were added to the sand in each box with ratios of 1, 2, and 4 grams of water per 100 grams of sand. Each sandbox was completely sealed and had six access ports. TCP's used in the experiment were calibrated in 1991. Two ports were randomly chosen to install TCP's directly in contact with the sand; two were chosen to install TCP's using the original design of the 2.5-cm diameter PVC access pipes in which the centering plug was at the end of the pipe, and two were chosen to install TCP's with the modified method in which the centering plug was recessed approximately 1 cm from the end of the pipe. TCP's were installed into the access pipes using the modified method and the results were compared with those from TCP's installed directly in the sand. Also, two random samples of sand (approximately 1.5 cm^3) were taken from each sandbox at the beginning of the experiments and four samples were taken from each box at the end of the experiments. Water potentials of the sand samples were measured using a water-activity meter (Gee and others, 1992).

Temperatures measured from each TCP in the three boxes are shown in figure 6. Temperatures of the sand show a diurnal variation that is considerably less than the diurnal variations in air temperature (fig. 6*A*). Temperature differences between the two TCP's installed directly in the sand were the same as differences between the four TCP's installed in the access pipes (mean differences were ± 0.06 °C between all TCP's and standard deviations were less than ± 0.1°C). Maximum differences between TCP's in the sand and in the access pipes were less than ± 0.3°C. This indicates that both installation methods (centering plugs recessed and not recessed) are accurately measuring temperatures in the sand and are not being affected by leakage along the access tube.

Water potentials determined from each TCP in the three boxes are shown in figure 7. At the beginning of each experiment water potentials from TCP's installed in the access pipes consistently were less than the water potentials determined from TCP's placed directly in the sand and then increased slowly during the experiment. Water potentials show greater diurnal variations for TCP's installed in access pipes with the centering plug recessed; however, the general trends of TCP's installed in access pipes with the centering plug not recessed are similar. During the experiment, one TCP (91-07; fig. 7*A*) failed after July 31 and another (91-01; fig. 7*A*) did not function for a time because of a faulty connection after the boxes were moved to a new building.

At the end of the experiment, water potential differed among TCP's within each sandbox with the greater difference observed in the box having the least amount of water added to the sand (fig. 7*A*). Much of the difference may result from water potentials in the sandboxes not being uniform throughout. Differences in water potentials, measured with the water activity meter, were observed from a few samples taken from each box at the beginning and end of each experiment and are shown in figure 7. Water potentials determined from TCP's installed using the modified method ranged from +2 to -1 MPa compared with the reference TCP's installed directly in the sand. Thus, the difference in water potentials observed between TCP's in each box may be more of a result of difference in actual water potential in the sand. The installation of TCP's directly in the sand indicated less diurnal variations and faster equilibrium of water potentials. TCP's installed in the access pipes take longer to equilibrate and generally show greater diurnal variations. The advantage of placing TCP's into access pipes and not extending them into the sediments is that they are not damaged while the TCP is being installed.

Field Installation

During field installation, the TCP wire with Viking connector was slipped through a 91-cm length of nominal 1.3-cm diameter PVC pipe and was coupled to the pipe attached to the sealing plug (fig. 5*A*). The pipe and sealing plug were then inserted into the larger PVC access pipe and additional lengths added until the sealing plug was inserted into the centering plug. Closed-cell polyurethane foam packing was wrapped on the outside of the pipe every 60 cm. Once the 1.3-cm diameter PVC pipe protruded past the larger PVC access pipe, a rubber stopper partly sliced and bored was slipped over the wire and pressed into the smaller PVC pipe. A small quantity of silicone sealant was applied to the outside of the stopper. A piece of closed-foam packing was inserted between the two pipes and covered with silicone sealant. Tape was used to secure the smaller PVC pipe until the sealant cured.

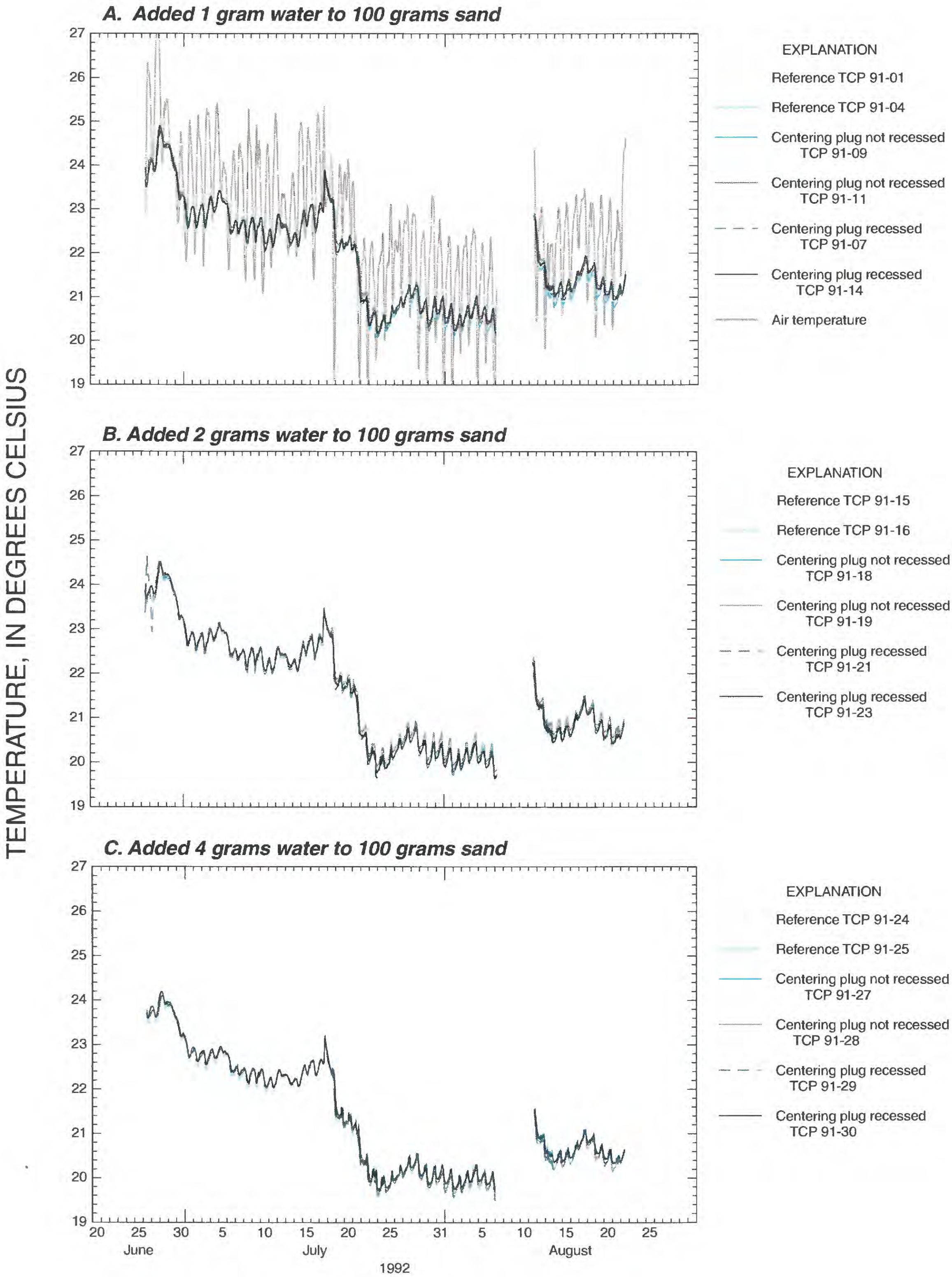

Figure 6. Hourly temperatures from thermocouple psychrometers placed in uniform sand of differing water content with thermocouple psychrometers installed using modified method with centering plugs at end of access pipe and recessed 1-centimeter from end of access pipe. *(A)* 1 gram water added to 100 grams sand, *(B)* 2 grams water added to 100 grams sand, and *(C)* 4 grams water added to 100 grams sand.

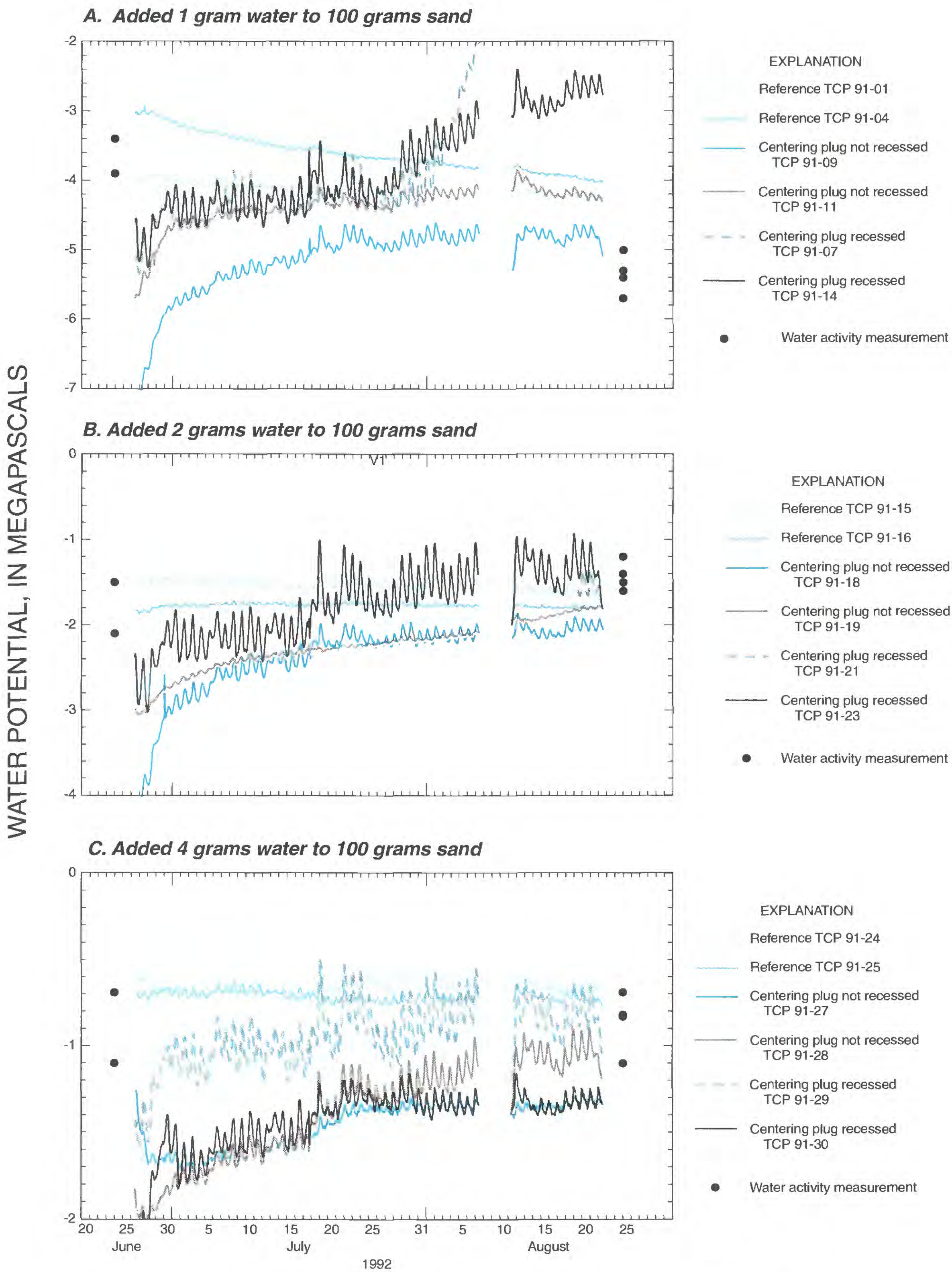

Figure 7. Hourly water potentials determined from thermocouple psychrometers placed in uniform sand of differing water content with thermocouple psychrometers installed using modified method with centering plugs at end of access pipe and recessed 1-centimeter from end of access pipe. *(A)* 1 gram water added to 100 grams sand, *(B)* 2 grams water added to 100 grams sand, and *(C)* 4 grams water added to 100 grams sand.

DESCRIPTION AND EVALUATION OF TCP DATA, 1987-96

Prior to September 1992, temperature, zero offset, and voltage values were recorded to a datalogger at least every 4 hours. The data stored in the datalogger were retrieved using a microcomputer equipped with telecommunications from 1987 to 1990 and then through a personal computer until September 1992. Starting in September 1992, the frequency of measurements in the monitoring shaft were decreased to 12-hour intervals (noon and midnight) and measurements in the instrument borehole were discontinued. The less frequent measurements are sufficient to analyze long-term trends (annual), while reducing the volume of data being stored and retrieved, and decreasing the frequency of TCP excitation. The data were retrieved from a datalogger at least every 3 months during site visits then transferred to personal computers for analysis.

Daily values of temperature and water potential were determined for all data collected at the monitoring shaft and instrument borehole from 1987 to 1996. Average daily temperature and water potential for each TCP was determined using only the noon and midnight values even if data were collected more frequently. The average daily temperature and water potential for 1987 may differ from those reported by Fischer (1992, table 4) because of the different frequencies used to determine the average daily values and because water potentials were calculated using a four-point interpolation of the nearest calibration points (Fischer, 1992, p. 13).

Not all TCP's installed in the monitoring shaft or in the instrument borehole could be used to determine water potentials because (1) TCP's failed at the sensing junction causing erratic voltages or voltages drifting to zero, and (2) problems with wiring or installation caused temperatures, zero offsets, or voltage readings to be out of range. Temperatures were considered out of range when they were less than 0°C or exceeded 45°C (minimum and maximum air temperatures). Zero offsets were considered out of range when the absolute value exceeded 2 μv. Voltages were considered out of range when they exceeded 100 μv or were less than -10 μv. Finally, only water potentials between -8 and 0 MPa are reported. Water potentials outside this range are beyond the calibration limits of the TCP's.

Daily temperatures and water potentials from TCP's in the monitoring shaft and instrument borehole are shown in figures 8 and 9, respectively. Annual average temperatures and water potentials also were determined for each TCP in the monitoring shaft and instrument borehole and are summarized in table 3.

Temperature

Temperatures measured from TCP's are divided into two groups—installed prior to 1992 or installed in 1992. For the first group, temperature trends at different depths in the monitoring shaft are discussed in relation to those in the instrument borehole and to TCP's replaced in 1991. For the second group, temperature trends at different depths in the monitoring shaft are discussed in relation to trends observed from TCP's installed prior to 1992.

TCP's Installed Prior to 1992

Temperature trends in the unsaturated sediments were observed in the monitoring shaft and instrument borehole. Average daily temperatures at the monitoring shaft and instrument borehole show seasonal fluctuations to depths of at least 13 m (fig. 8). Temperature fluctuations are greatest at shallower depths (about 13 to 15°C at a depth of 1.2 m in the instrument borehole, fig. 8*A*) and decrease with depth (less than 0.5°C at a depth of 13 m, fig. 8*L*). Temperature fluctuations at shallow depths follow a pattern similar to the seasonal trend in air temperature (Fischer, 1992, p. 28).

The consistency of temperature measurements from several TCP's installed at the same depth in the monitoring shaft suggest that TCP's give reliable temperature measurements. Temperatures from TCP's installed in 1991 showed the same trends as previously installed TCP's. Temperatures from TCP's at a depth of 3 m in the monitoring shaft show nearly the same temperatures and trends (fig. 8*B*). At a depth of 4 m, TCP's in the monitoring shaft (L2 and R2) show slightly greater fluctuations than TCP's at a depth of 4.2 m (OD5) in the instrument borehole (fig. 8*C*). The lesser fluctuation and slight lag in the peak of OD5 may be the result of it being slightly deeper than L2 and R2. However, temperatures measured by TCP's in the instrument borehole below a depth of 6 m are consistently different than temperatures measured by TCP's at similar depths in the monitoring shaft.

Temperatures from TCP's between the depths of 7.9 m and 11.9 m in the instrument borehole have nearly the same seasonal fluctuation of about 0.5°C (figs. 8*G-K*). However, the timing of seasonal

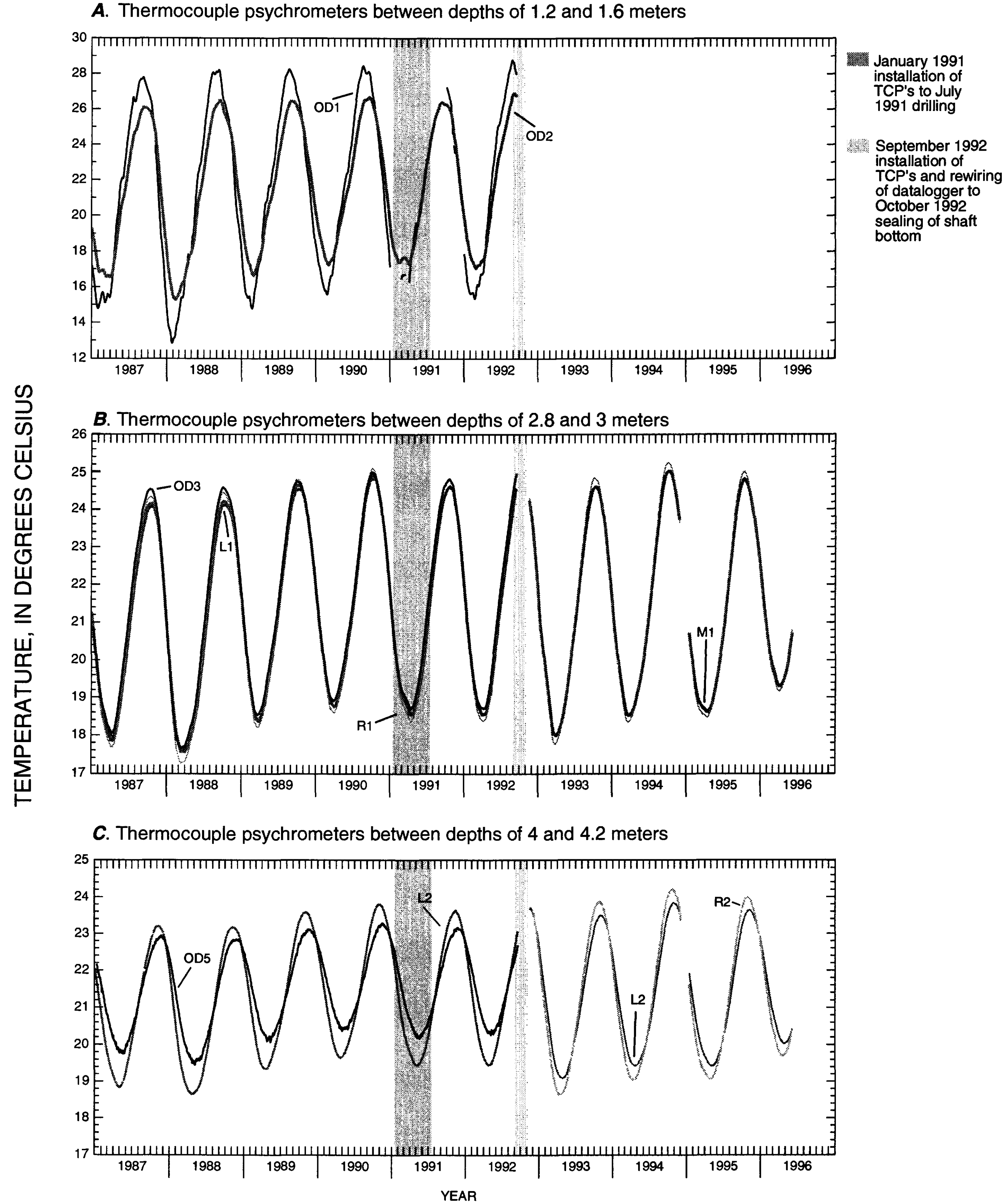

Figure 8. Temperatures measured by thermocouple psychrometers in monitoring shaft and in instrument borehole between the depths of 1.2 and 13 meters. Locations of psychrometers shown in figure 3. Abbreviation: TCP, thermocouple psychrometer.

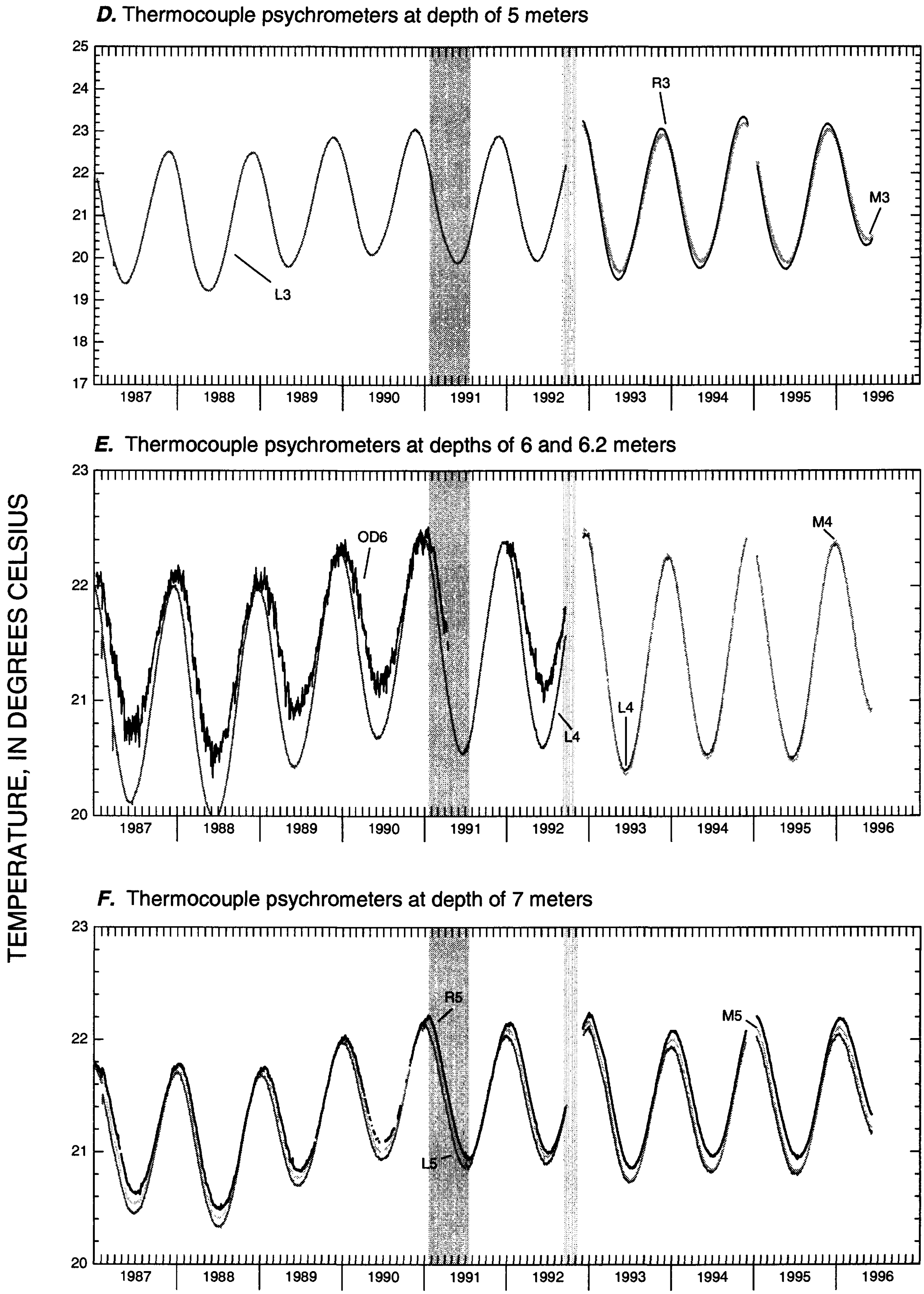

Figure 8. Continued.

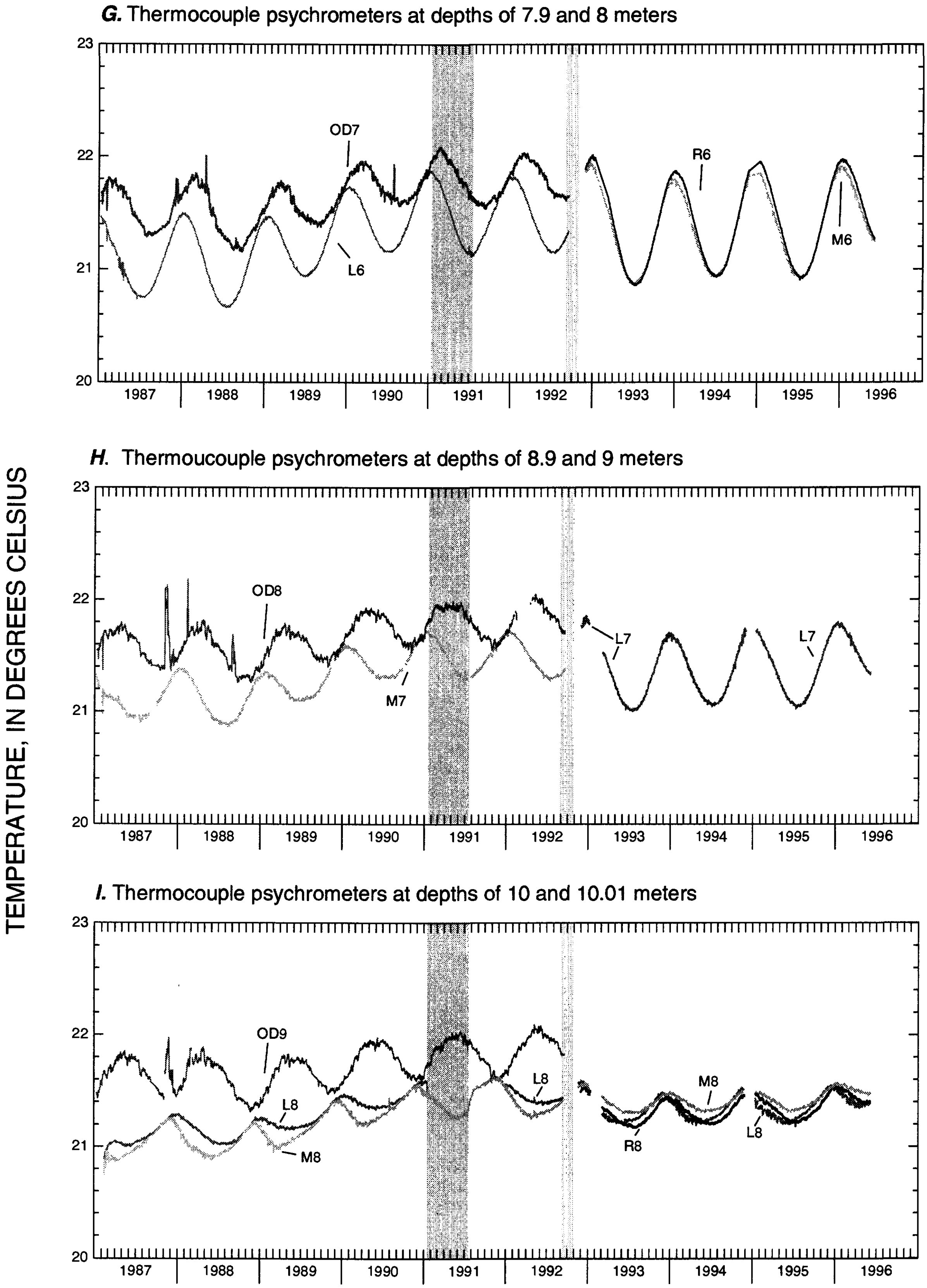

Figure 8. Continued.

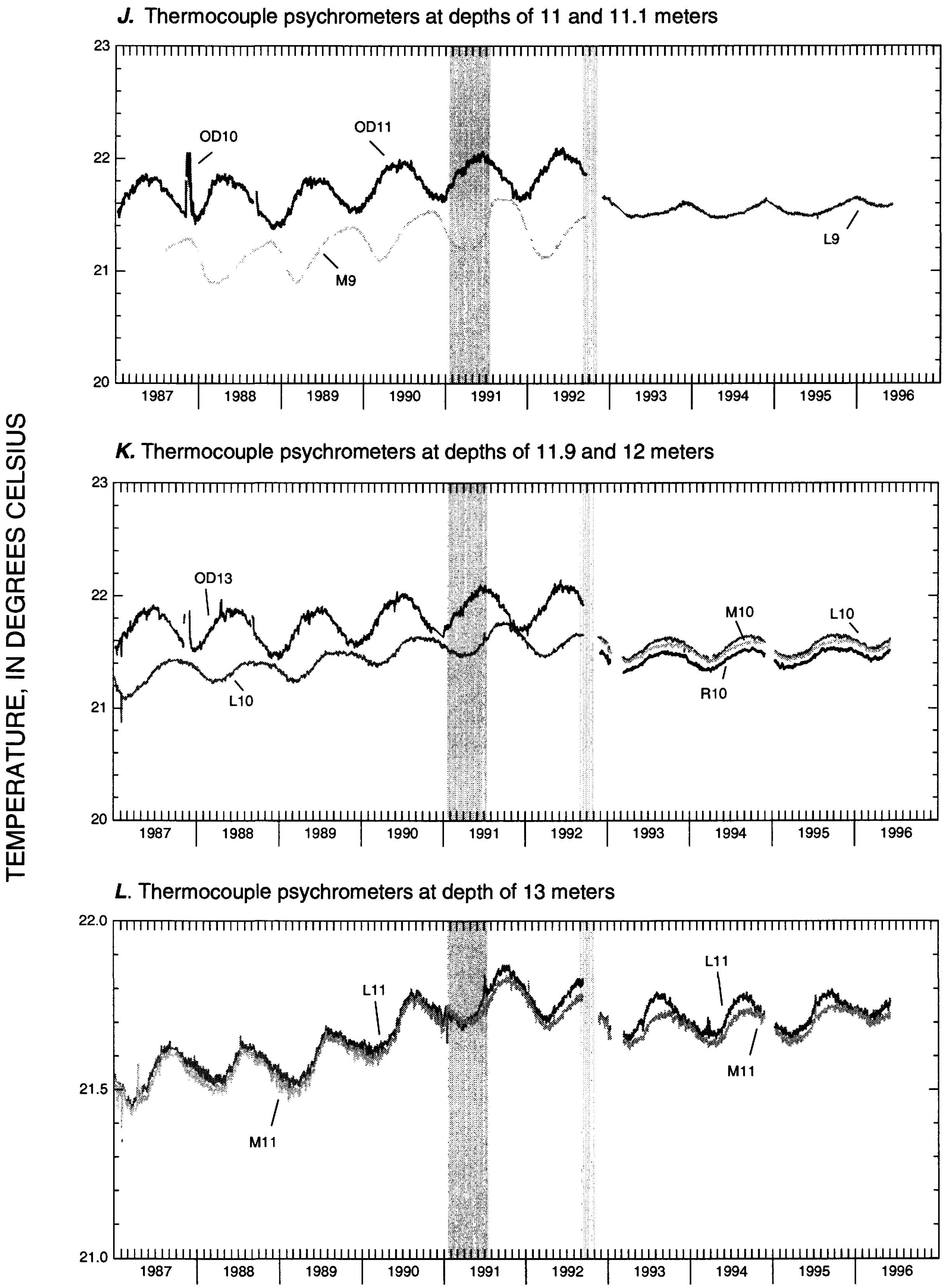

Figure 8. Continued.

Table 3. Annual mean temperature and water potential from thermocouple psychrometers in monitoring shaft and in instrument borehole. Location of shaft and instrument borehole shown in figure 2.

[--, indicates less than 200 days of data.]

Location identification[1]	Depth (meters below land surface)	Year	Temperature (degrees Celsius)		Days used in calculation[2]	Water potential (megapascals)		Days used in calculation[3]
			Annual mean	Standard deviation		Annual Mean	Standard deviation	
				Shaft				
L1[4]	3	1987	20.8	2.10	340	--	--	--
		1988	20.8	2.38	364	--	--	--
		1989	21.5	2.15	362	--	--	--
		1990	21.4	2.10	307	--	--	--
M1	3	1987	20.7	2.36	330	-2.2	0.43	330
		1988	20.8	2.44	364	-2.3	1.11	364
		1989	21.6	2.20	365	-3.5	.40	365
		1990	21.8	2.13	364	-3.0	.10	364
		1991	21.4	2.18	363	-6.3	.80	363
		1992	21.0	1.93	300	-4.6	.97	300
		1993	21.6	2.32	309	-3.5	.17	309
		1994	21.5	2.35	330	-3.4	.12	330
		1995	21.5	2.28	352	-3.8	.16	352
R1	3	1987	20.7	2.65	340	-3.7	.58	340
		1988	20.8	2.62	364	-0.8	.48	364
		1989	21.6	2.30	365	-0.7	.20	365
		1990	21.8	2.23	364	-2.7	1.28	364
		1991	21.4	2.30	364	-4.7	.79	364
		1992	21.1	2.07	303	-4.4	.34	303
		1993	21.7	2.44	309	-4.4	.19	309
		1994	21.6	2.50	330	-4.5	.17	330
		1995	21.5	2.41	352	-4.1	.34	352
L2	4	1987	20.7	2.86	303	-5.0	.28	303
		1988	20.8	1.66	364	-1.7	1.50	364
		1989	21.4	1.50	365	--	--	--
		1990	21.7	1.46	364	--	--	--
		1991	21.4	1.48	364	-6.0	1.02	364
		1992	21.2	1.33	303	-6.0	.13	303
		1993	21.4	1.66	309	-5.8	.08	309
		1994	21.4	1.55	330	-5.8	.08	330
		1995	21.4	1.53	352	-5.8	.09	352
R2	4	1993	21.4	1.93	309	-5.3	.18	309
		1994	21.4	1.85	330	-5.2	.07	330
		1995	21.3	1.81	352	-5.2	.15	352
L3[4]	5	1987	20.9	1.11	337	-4.6	.37	289
		1988	20.8	1.18	364	-4.2	.23	364
		1989	21.3	1.08	365	-4.1	.07	365
		1990	21.5	1.04	364	-4.3	.05	364
		1991	21.3	1.06	365	-4.0	.26	365

Table 3. Annual mean temperature and water potential from thermocouple psychrometers in monitoring shaft and in instrument borehole—Continued

Location identification[1]	Depth (meters below land surface)	Year	Temperature (degrees Celsius)		Days used in calculation[2]	Water potential (megapascals)		Days used in calculation[3]
			Annual mean	Standard deviation		Annual Mean	Standard deviation	
M3	5	1993	21.3	1.23	309	-5.3	0.10	309
		1994	21.3	1.11	330	-5.3	.11	330
		1995	21.3	1.11	352	-5.0	.10	352
R3	5	1993	21.3	1.36	309	-2.9	.75	309
		1994	21.3	1.23	330	-1.4	.58	330
		1995	21.3	1.23	352	--	--	--
L4	6	1987	21.0	.68	340	-4.4	.54	302
		1988	20.9	.71	364	-3.8	.24	364
		1989	21.3	.64	365	-3.8	.10	365
		1990	21.5	.62	364	-4.2	.18	364
		1991	21.4	.65	364	-5.3	.67	340
		1992	21.4	.53	303	-5.0	.25	303
		1993	21.2	.68	309	-5.0	.21	309
		1994	21.3	.61	330	-4.6	.27	330
		1995	21.3	.64	352	-5.0	.18	351
M4	6	1993	21.2	.70	309	--	--	--
		1994	21.3	.63	330	--	--	--
		1995	21.3	.65	352	--	--	--
L5	7	1987	21.0	1.23	340	-4.3	.43	326
		1988	21.0	.48	364	-4.3	.18	364
		1989	21.2	.41	365	-4.3	.22	365
		1990	21.5	.40	364	-3.7	.08	364
		1991	21.5	.42	365	-2.7	.30	365
		1992	21.5	.43	303	-2.3	.11	303
		1993	21.3	.43	309	-2.9	.87	309
		1994	21.3	.39	330	-3.2	.13	330
		1995	21.4	.42	352	-2.8	.21	352
M5	7	1987	21.0	1.08	340	-4.6	.13	340
		1988	21.0	.47	364	-4.2	.22	364
		1989	21.3	.40	365	-3.2	.23	365
		1990	21.5	.39	364	-2.6	.10	364
		1991	21.5	.42	365	-2.3	.18	365
		1992	21.5	.43	303	-1.9	.18	303
		1993	21.3	.44	309	-2.0	.09	309
		1994	21.4	.40	330	-2.3	.11	330
		1995	21.4	.43	352	-2.1	.10	352
R5	7	1987	21.2	.41	338	-2.6	2.07	340
		1988	21.1	.45	364	--	--	--
		1989	21.4	.38	358	--	--	--
		1991	21.5	.43	364	-4.0	.92	364
		1992	21.6	.45	303	-4.0	.15	303

Table 3. Annual mean temperature and water potential from thermocouple psychrometers in monitoring shaft and in instrument borehole—Continued

Location identification[1]	Depth (meters below land surface)	Year	Temperature (degrees Celsius)		Days used in calculation[2]	Water potential (megapascals)		Days used in calculation[3]
			Annual mean	Standard deviation		Annual Mean	Standard deviation	
		1993	21.4	0.42	309	-4.2	0.19	309
		1994	21.5	.39	330	-4.3	.14	330
		1995	21.5	.42	352	-4.2	.10	352
L6[4]	8	1987	21.1	.25	340	-4.3	1.07	340
		1988	21.0	.29	364	-3.9	.09	364
		1989	21.2	.23	365	-3.8	.10	365
		1990	21.4	.22	364	-3.9	.05	364
		1991	21.5	.25	365	-3.7	.10	365
		1992	21.4	.24	261	-3.4	.14	261
M6	8	1993	21.3	.32	309	-4.5	2.58	201
		1994	21.3	.29	330	-4.7	2.55	202
		1995	21.3	.32	352	-4.2	2.95	235
R6	8	1993	21.3	.35	309	-5.3	.06	309
		1994	21.4	.33	330	-5.4	.07	330
		1995	21.4	.35	352	-5.4	.06	352
L7	9	1993	21.3	.24	309	-4.9	1.28	253
		1994	21.3	.22	330	-5.4	.97	239
		1995	21.4	.24	352	-5.5	.95	269
M7	9	1987	21.1	.13	329	-4.6	.06	339
		1988	21.1	.17	364	-4.1	.33	364
		1989	21.2	.13	365	-4.0	.14	365
		1990	21.4	.12	364	-4.3	.07	364
L8	10	1988	21.1	.08	366	-3.8	.06	366
		1989	21.2	.09	365	-3.6	.06	365
		1990	21.4	1.12	364	-3.7	.20	364
		1991	21.4	.12	364	--	--	--
		1992	21.4	.07	303	--	--	--
		1993	21.3	.09	309	--	--	--
		1994	21.3	.09	330	--	--	--
		1995	21.3	.10	351	--	--	--
M8	10	1988	21.0	.10	366	--	--	--
		1989	21.2	.14	364	--	--	--
		1990	21.4	.11	364	--	--	--
		1991	21.4	.12	365	--	--	--
		1992	21.4	.09	303	--	--	--
		1993	21.4	.06	309	-3.7	.03	309
		1994	21.4	.05	330	-3.7	.05	330
		1995	21.4	.06	351	-3.7	.05	351

Table 3. Annual mean temperature and water potential from thermocouple psychrometers in monitoring shaft and in instrument borehole—Continued

Location identification[1]	Depth (meters below land surface)	Year	Temperature (degrees Celsius)		Days used in calculation[2]	Water potential (megapascals)		Days used in calculation[3]
			Annual mean	Standard deviation		Annual Mean	Standard deviation	
R8	10	1993	21.3	0.10	309	-3.8	0.15	309
		1994	21.3	.08	330	-3.8	.13	330
		1995	21.3	.09	351	-4.1	.10	351
L9	11	1993	21.5	.05	309	-3.9	.25	309
		1994	21.5	.05	330	-3.3	.16	330
		1995	21.5	.22	352	-3.0	.13	352
M9[4]	11	1988	21.1	.12	364	-4.2	.06	364
		1989	21.2	.17	365	-4.2	.06	365
		1990	21.3	.15	358	-4.3	.11	358
		1991	21.4	.18	365	-4.1	.06	365
R9	11	1993	21.3	.23	309	--	--	--
		1994	21.3	.25	330	--	--	--
		1995	21.3	.22	352	--	--	--
L10	12	1987	21.3	.12	340	-3.9	.02	340
		1988	21.3	.06	364	-3.8	.03	364
		1989	21.4	.09	365	-3.8	.04	365
		1990	21.5	.09	364	-3.7	.03	364
		1991	21.6	.10	365	-3.6	.04	365
		1992	21.6	.07	303	-3.5	.05	303
		1993	21.6	.06	304	-3.3	.05	304
		1995	21.6	.07	352	-3.3	.06	352
M10	12	1993	21.5	.06	309	-3.8	.12	309
		1994	21.5	.06	330	-3.8	.14	330
		1995	21.5	.06	352	-3.7	.10	352
R10	12	1993	21.4	.04	309	-3.5	.10	309
		1994	21.4	.07	330	-3.4	.03	330
		1995	21.4	.07	352	-3.6	.04	352
L11	13	1987	21.5	.06	340	-3.4	.03	340
		1988	21.6	.03	364	-3.4	.02	364
		1989	21.6	.06	365	-3.3	.01	365
		1990	21.7	.06	364	-3.4	.01	364
		1991	21.8	.05	365	-3.4	.01	365
		1992	21.8	.03	303	-3.4	.01	303
		1993	21.7	.05	309	-3.4	.01	309
		1994	21.7	.04	330	-3.5	.01	330
		1995	21.7	.05	352	-3.5	.01	352

Table 3. Annual mean temperature and water potential from thermocouple psychrometers in monitoring shaft and in instrument borehole—Continued

Location identification[1]	Depth (meters below land surface)	Year	Temperature (degrees Celsius)		Days used in calculation[2]	Water potential (megapascals)		Days used in calculation[3]
			Annual mean	Standard deviation		Annual Mean	Standard deviation	
M11	13	1987	21.5	0.05	340	-2.9	0.31	328
		1988	21.6	.04	364	-2.7	.06	364
		1989	21.6	.06	365	-2.6	.05	365
		1990	21.7	.07	364	-2.6	.05	364
		1991	21.8	.04	364	-3.2	.20	364
		1992	21.7	.03	303	-3.2	.06	303
		1993	21.7	.00	309	-3.2	.13	309
		1994	21.7	.03	330	-3.3	.19	330
		1995	21.7	.00	352	-3.2	.18	352
Instrument Borehole								
OD1	1.2	1987	20.8	4.59	340	-3.9	1.40	340
		1988	21.2	5.15	364	-2.8	2.23	364
		1989	22.0	4.41	365	-5.0	.54	365
		1990	22.0	4.29	364	-5.6	.30	364
OD2	1.6	1987	20.9	3.38	340	-4.0	1.36	340
		1988	21.1	3.91	364	-2.8	2.07	364
		1989	21.8	3.31	365	-5.1	.47	365
		1990	22.0	3.21	364	-5.7	.19	364
		1991	21.7	3.37	365	-4.8	.91	365
OD3	2.8	1987	21.1	2.22	340	-4.7	.13	340
		1988	21.1	2.54	364	-4.6	.29	364
		1989	21.7	2.17	365	-5.4	.35	365
		1990	21.9	2.10	364	-6.1	.35	364
		1991	21.6	2.19	365	-5.6	.35	365
OD4	3.4	1987	21.3	1.65	340	-4.6	.10	340
		1988	21.2	1.82	364	-4.6	.17	364
		1989	21.7	1.58	365	-5.0	.21	365
		1990	21.9	1.52	364	-5.3	.18	364
		1991	21.7	1.58	365	-5.2	.17	365
OD5	4.2	1987	21.3	1.10	340	-4.9	.18	340
		1988	21.1	1.20	364	-4.8	.19	364
		1989	21.6	1.04	365	-4.7	.11	365
		1990	21.8	1.00	364	-5.0	.12	364
		1991	21.6	1.03	365	-5.1	.24	365
OD6	6.2	1987	21.4	.49	340	-4.2	.15	340
		1988	21.3	.56	364	-4.1	.13	364
		1989	21.6	.47	365	-4.4	.09	365
		1990	21.8	.44	364	-4.8	.16	364

Table 3. Annual mean temperature and water potential from thermocouple psychrometers in monitoring shaft and in instrument borehole—Continued

Location identification[1]	Depth (meters below land surface)	Year	Temperature (degrees Celsius) Annual mean	Temperature (degrees Celsius) Standard deviation	Days used in calculation[2]	Water potential (megapascals) Annual Mean	Water potential (megapascals) Standard deviation	Days used in calculation[3]
OD7	7.9	1987	21.6	0.17	315	-4.5	0.16	315
		1988	21.5	.22	364	-3.3	1.25	364
		1989	21.6	.12	365	-.2	0	365
		1990	21.8	.12	364	-.4	1.55	364
		1991	21.8	.17	365	-4.5	.06	365
OD8	8.9	1987	21.6	.14	335	-4.6	.13	322
		1988	21.5	.17	357	-4.4	.11	346
		1989	21.6	.10	365	-4.3	.02	365
		1990	21.8	.11	363	-4.2	.02	363
		1991	21.8	.13	365	-4.2	.02	365
OD9	10.1	1987	21.6	.13	338	-3.2	.80	316
		1988	21.6	.17	356	-2.8	.40	355
		1989	21.6	.13	365	-2.6	.03	365
		1990	21.8	.13	363	-2.4	.04	363
		1991	21.8	.13	365	--	--	--
OD10	11.1	1987	21.7	.13	339	-4.0	.11	291
		1988	21.6	.15	336	-4.1	.43	336
		1989	21.7	.12	365	-3.8	.02	365
		1990	21.8	.12	364	-3.8	.02	364
		1991	21.9	.12	365	-3.8	.02	365
OD11	11.1	1987	21.6	.14	340	-3.8	.44	316
		1988	21.6	.16	347	-2.7	.19	347
		1989	21.7	.13	365	-3.0	.03	365
		1990	21.8	.13	364	-3.0	.02	364
		1991	21.8	.13	365	-3.1	.05	365
OD12	11.4	1987	21.7	.18	340	-4.1	.10	340
		1988	21.8	.24	364	--	--	--
		1989	21.7	.13	365	--	--	--
		1990	21.8	.14	364	--	--	--
		1991	21.9	.13	365	--	--	--
OD13	11.9	1987	21.7	.12	318	-3.8	.07	317
		1988	21.7	.14	357	-3.7	.10	350
		1989	21.7	.12	365	-3.7	.02	365
		1990	21.8	.13	317	-3.7	.02	317
		1991	21.9	.13	365	--	--	--

[1] Thermocouple psychrometers installed in monitoring shaft are designated with L (left), M (middle), and R (right), followed by number from 1 to 11 that indicates level in shaft. Thermocouple psychrometers installed in instrument borehole are designated OD1 through OD13.

[2]Calculation of annual mean temperature is based on 300 or more days.

[3]Calculation of annual mean water potential is based on 200 or more days.

[4]Air tube installed September 9, 1992.

maximums differ with depth. Maximum daily temperatures generally occurred in February and March at a depth of 8 m and in June at a depth of 12 m. In contrast, temperatures from TCP's between the depths of 8 m and 12 m in the monitoring shaft were lower than those at similar depths in the instrument borehole. Seasonal temperature fluctuations for TCP's in the monitoring shaft decreased from about 0.7°C at a depth of 8 m to about 0.3°C at a depth of 12 m. Additionally, maximum daily temperatures occurred in January at a depth of 8 m (fig. 8*G*) and in October at a depth of 12 m (fig. 8*K*). The cause for the difference in measured temperatures between the depths of 8 m and 12 m in the monitoring shaft and instrument borehole is unknown. A continued decrease in seasonal fluctuations with depth is expected so the lack of a decrease in the instrument borehole between the depths of 8 m and 12 m indicates some other factor affects temperature fluctuations. The TCP wires from the instrument borehole extend from the borehole to the monitoring shaft where they are attached to the datalogger. The wires are placed within a PVC pipe buried less than 30 cm below land surface. Perhaps heating and cooling of the wire affected the temperature measurements from the instrument borehole. Another possibility is that the seasonal temperature fluctuations between the depths of 8 m and 12 m are caused by a zone of coarse sediments having a low water content, which allows for greater penetration of heat as compared with the sediments at the monitoring shaft.

TCP's Installed in 1992

Seasonal temperature fluctuations for TCP's installed in September 1992 using the modified installation method show similar patterns to depths of 9 m as TCP's installed prior to 1991. Below a depth of 9 m, seasonal temperature fluctuations from 1993-95 were less than those for 1987-92 for all TCP's (including those installed prior to 1992). This may be explained by the sealing of the bottom of the monitoring shaft. The bottom of the shaft, which was previously exposed to sediments, was sealed with layers of plastic, silica flour, bentonite, and fine sand in October 1992. Prior to October 1992, air could move into and out of the bottom of the shaft into the sediments and may have affected temperatures in the deeper TCP's. Sealing the bottom of the shaft also may explain the more constant temperatures observed in the deeper TCP's (see L8, M8, L9, L10, L11, and M11 for 1992-96 in figs. 8*I*-8*L*).

Water Potential

Water potentials determined from TCP measurements are divided into two groups—installed prior to 1992 or installed in 1992. For the first group, water potential trends at different depths in the monitoring shaft are discussed in relation to those in the instrument borehole and to TCP's that were replaced in 1991. For the second group, water potential trends at different depths in the monitoring shaft are discussed in relation to trends observed from TCP's installed prior to 1992.

TCP's Installed Prior to 1992

Of the original 17 TCP's installed in 1986-87, all but one (TCP at L1) were used for at least part of the period (fig. 9 and table 3). Seven TCP's were replaced in January 1991 with new TCP's (table 2).

Water potentials at a depth of 1.2 m and 1.6 m in the instrument borehole showed a rapid increase in November 1987 followed by a rapid decrease in June and July 1988 (fig. 9*A*). The increase is attributed to preferential flow down the instrument borehole (Andraski, 1997, p. 1910) because the increase preceded an increase in water potentials in near surface TCP's (depths of 0.4 m and 0.6 m). Water potentials at a depth of 3 m in the shaft (M1 and R1) differed greatly from water potentials at depths of 2.8 m and 3.4 m in the instrument borehole (fig. 9*B*). Water potentials at M1 and R1 increased rapidly in 1988 to about -1 MPa, whereas water potentials at OD3 and OD4 remained nearly constant at about -5 MPa. Water potentials decreased rapidly following the summer of 1988 at M1 to about -4 MPa then slowly increased in 1989 and 1990. Water potentials were nearly constant in R1 until 1990 then decreased rapidly to -4 MPa. In contrast, water potentials decreased slowly in OD3 and were nearly constant in OD4. Water potentials at L1 were initially between -6 MPa and -5 MPa during January and February 1987, decreased from March to June and oscillated between -6 MPa and 0 MPa thereafter indicating a TCP that was malfunctioning. Consequently, no water potentials were reported for L1. If the TCP's are measuring water potentials correctly, then M1 and R1 suggest increased water content at a depth of 3 m in 1988 followed by decreasing moisture in 1989-90, whereas OD3 and OD4 suggest nearly constant water content in 1987-88. The increased water potentials in R1 and M1 followed above-normal precipitation in fall of 1987 and spring of 1988, which was followed by a dry period from 1989-90 (Andraski, 1997, fig. 3).

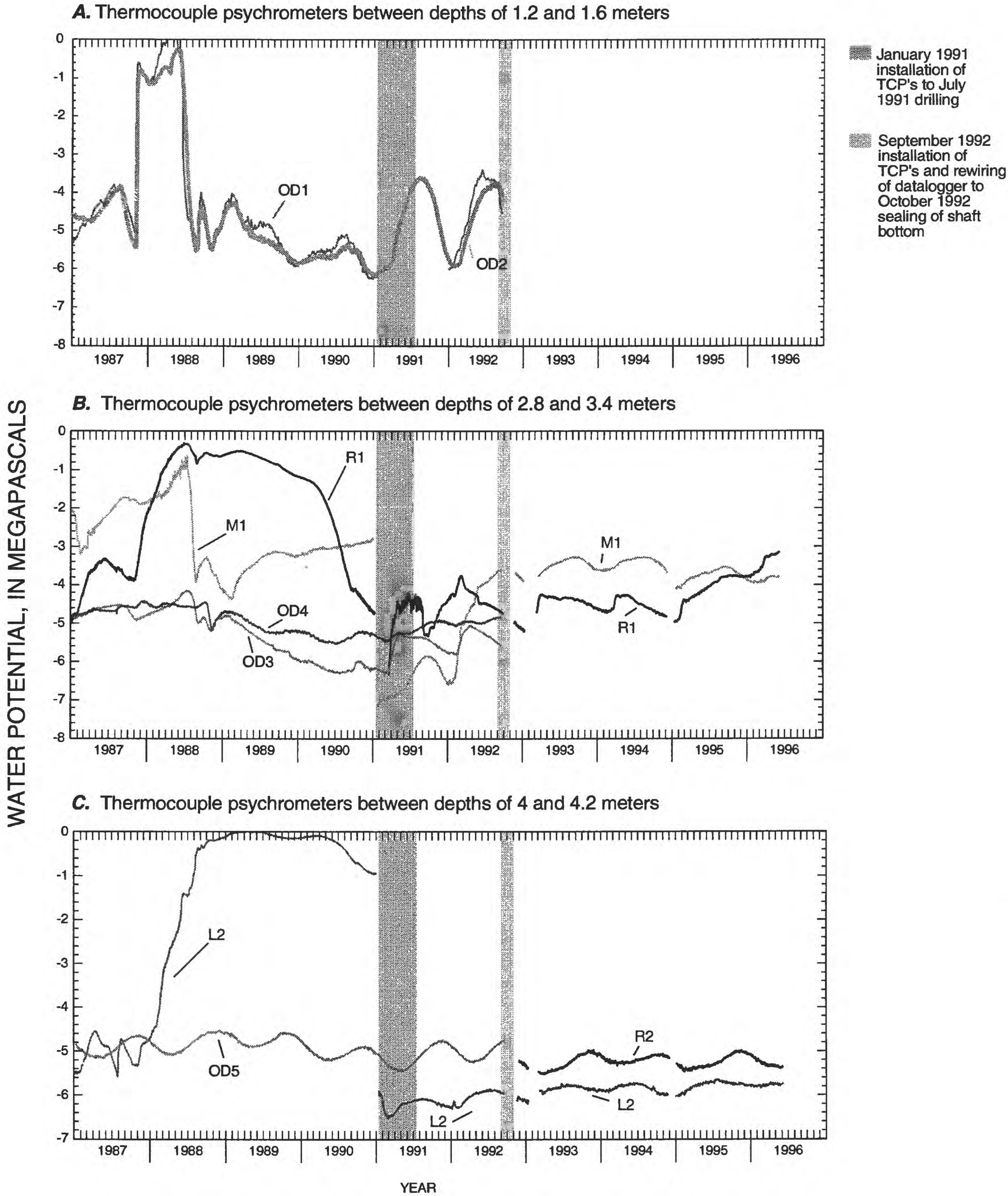

Figure 9. Water potentials determined by thermocouple psychrometers in monitoring shaft and in instrument borehole between the depths of 1.2 and 13 meters. Location of psychrometers shown in figure 3. Abbreviation, TCP, thermocouple psychrometer.

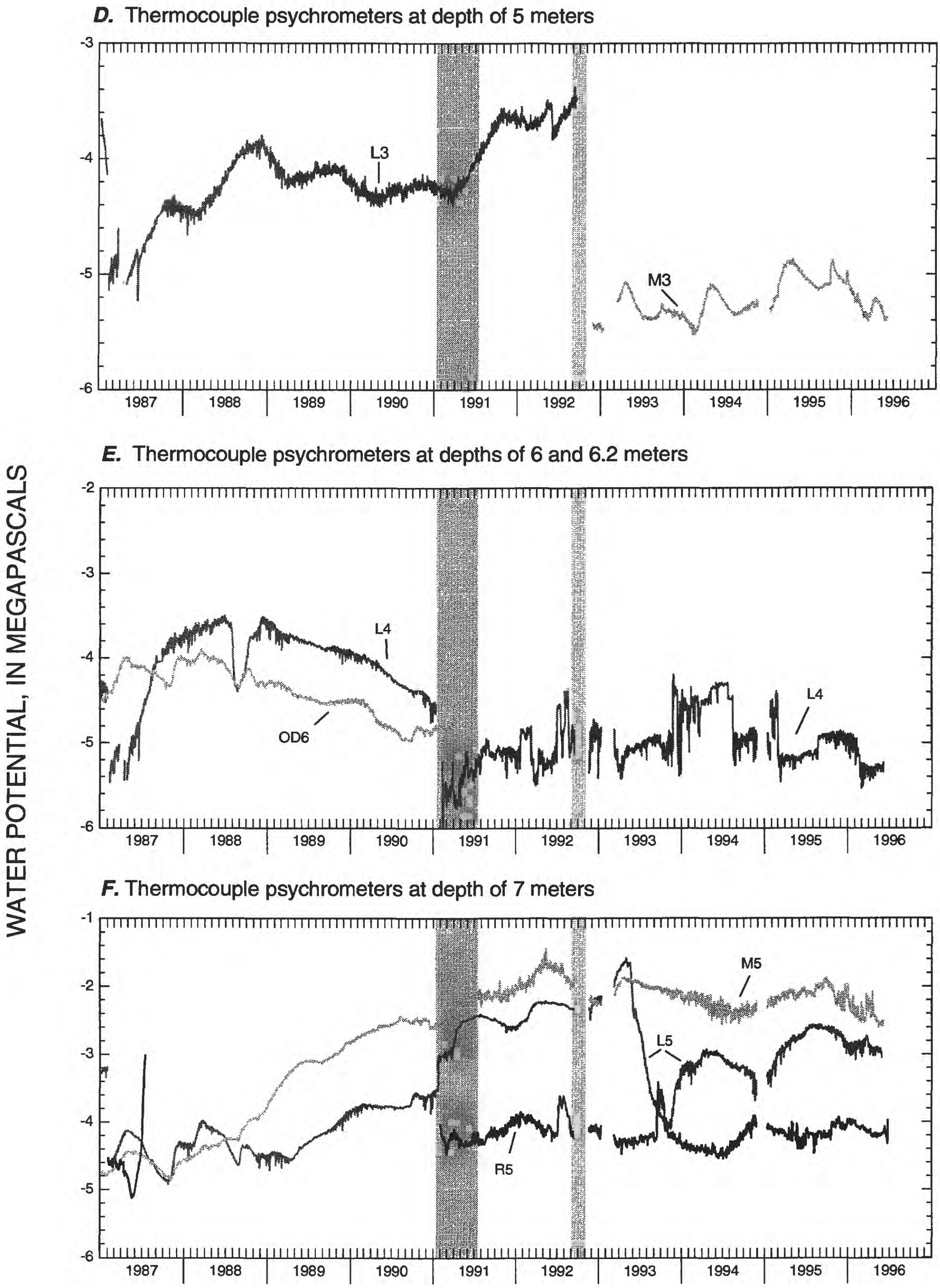

Figure 9. Continued.

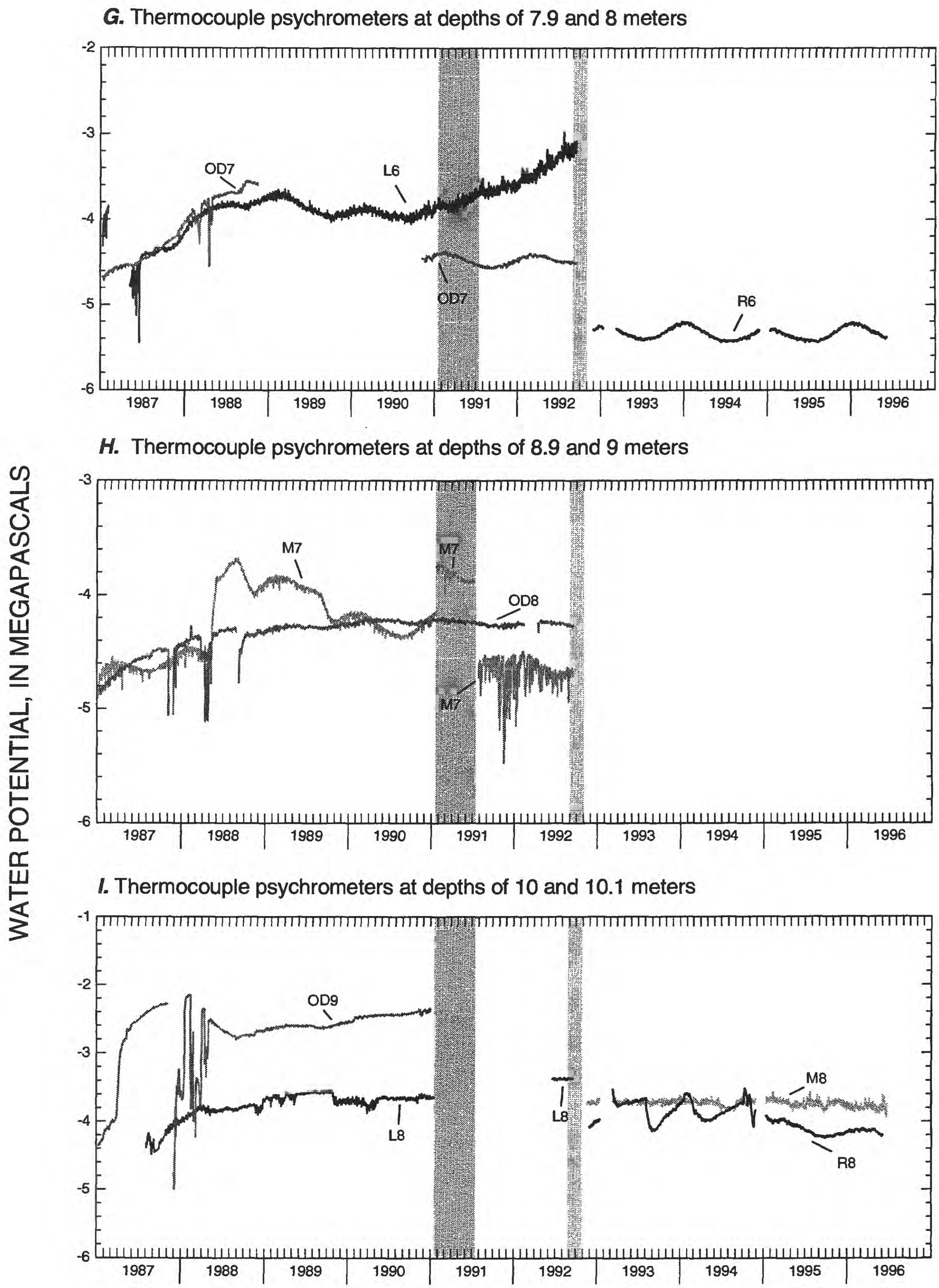

Figure 9. Continued.

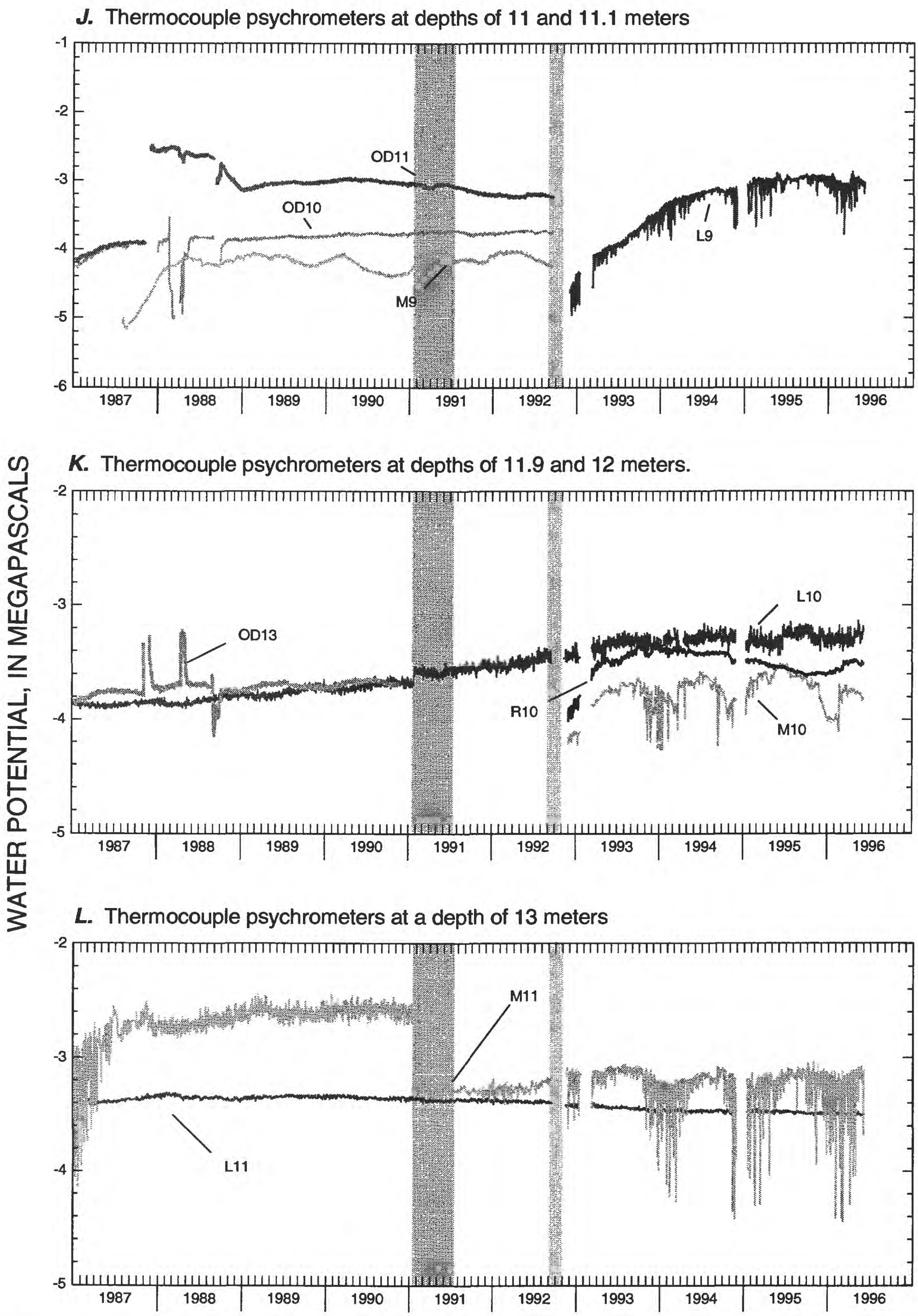

Figure 9. Continued.

Assuming that the sediments next to the TCP's at the monitoring shaft have the same physical properties as those at the nearby experimental trench site (see fig. 1), the water retention data for the depth interval from 2 to 5 m (layers 3, 4, and 5; Andraski, 1996, p. 62) suggest an increase in water potential from -5 to -1 MPa would result in an increase of volumetric water content from about 0.05 to 0.07 m^3/m^3. Such an increase should be measurable; however, water contents remained constant below a depth of 1 m at all three neutron access tubes next to the monitoring shaft from 1987 to 1992 (fig. 2). Although water contents have remained constant in time, the water content in the unsaturated sediments increases from about 0.04 to 0.08 m^3/m^3 between the depths of 1.5 m and 3 m (Andraski, 1997). Thus, a small shift in water content at a depth of 3 m in the sediments surrounding the TCP's could produce relatively large changes in water potential and could explain the variability in water potentials at M1 and R1 between 1987 and 1992 (fig. 9*B*). The lower water potentials in the instrument borehole at OD3 and OD4 may reflect slightly lower water content in the borehole.

Following replacement of M1 and R1 with new TCP's in January 1991, water potentials were initially much lower (fig. 9*B*), perhaps as a result of temporarily drying the sediments at the end of the access pipe while removing and installing the TCP's. After initial water potential increases at both M1 and R1, water potentials ranged from about -5 to -3 MPa during 1992-96.

The rapid increase in water potential shown for L2 (fig. 9*C*) at a depth of 4 m in the shaft during 1988 suggests a deterioration of the TCP because 1987 water potentials were similar to those at the instrument borehole (OD5). The rapid rise is likely a function of low voltages measured by the TCP. The TCP at L2 was replaced in January 1991 and water potentials determined from the new TCP were much lower. Since 1991, water potentials at L2 have remained nearly constant at about -6 MPa (table 3).

Water potentials at a depth of 5 m (L3) in the monitoring shaft increased from -5 MPa in 1987 to -3.4 MPa in 1992, with sharp increases of about -0.6 MPa in 1987, 1988, and 1991 (fig. 9*D*). The sharp increase in water potential in 1991 corresponds to the drilling of new access holes outward from several locations in the monitoring shaft, including the adjacent access hole M3. The TCP at L3 was replaced with an air sampling tube in September 1992.

Water potentials at a depth of 6 m (L4) in the monitoring shaft from 1987-90 generally are greater than water potentials at a depth of 6.2 m (OD6) in the instrument borehole (fig. 9*E*). Water potentials ranged from -5 MPa in 1987 to about -3.5 MPa in 1988 before decreasing to about -4.5 MPa in 1990. Mean water potentials for each year are listed in table 3. Water potentials in OD6 did not show an increase in 1987 and 1988 but did decrease similar to L4 in 1989 and 1990. The TCP at L4 was replaced in 1991 and water potentials in the new TCP were about 1 MPa lower than the previous TCP and averaged about -5 MPa (table 3). Water potentials from the new TCP at L4 show greater variability (fig. 9*E*). The reason for the greater variability is unknown but suggests some type of malfunction with the TCP or with the connection to the datalogger. Consequently, water potentials determined from this TCP (L4), although within the operation criteria used to determine water potentials, may not accurately represent water potentials in the sediments.

Water potentials at a depth of 7 m (L5 and M5) in the shaft showed similar trends in 1987 and 1988 (fig. 9*F*) and averaged about -4.3 MPa (table 3). Water potentials increased during 1988-92 at both locations and were between -2.4 and -2 MPa at the end of 1992. Subsequently, water potentials decreased rapidly at L5 and slowly at M5 during 1993, such that at the end of 1993, the water potential at L5 was about 2 MPa less than that at M5. By June 1996, water potentials were nearly the same (between -2.6 and -3.0 MPa) at both locations. The TCP at R5 stopped functioning during 1987 and was replaced in January 1991. Water potentials from the new TCP were considerably lower than those determined from TCP's at M5 and L5 (fig. 9*F*) and remained nearly constant (at about -4 MPa) from the time it was installed until June 1996 (table 3). Although the differences in water potential seem large, the differences reflect small changes in water content in the sediments (about 0.01 m^3/m^3) and thus could represent complex patterns of liquid water and water vapor movement horizontally and vertically in the unsaturated sediments.

Water potentials at a depth of 8 m (L6) in the monitoring shaft increased during 1987-88, were nearly constant during 1989-90, and slowly increased during 1991-92 (fig. 9*G*). The water potentials were similar to those at a depth of 7.9 m in the instrument borehole (OD7) during 1987-89 then deviated as water potentials at OD7 decreased (table 3). The lower water potentials at OD7 may reflect slightly lower water contents of backfill in the instrument borehole, whereas the increase at L6 during 1991-92 may reflect downward movement of water from the depth of 7 m. No record is available beyond 1992 for L6 as the TCP was replaced with an air sampling tube in September 1992.

Water potentials at a depth of 9 m (M7) in the shaft fluctuated more than water potentials at a depth of 8.9 m (OD8) in the instrument borehole (fig. 9*H*). However, average annual water potentials for both TCP's ranged from -5 to -4 MPa (table 3). Water potentials increased suddenly (about -4.2 to -3.7 MPa) in January 1991 when TCP's were being replaced. The increase is unexplainable as the TCP was not replaced. Water potentials then decreased suddenly (from -3.9 to about -4.6 MPa) in July 1991 following the drilling of new access holes. This decrease may have been caused by slight drying of the sediments from injected air while drilling the new access holes. Finally, the TCP at M7 stopped functioning after it was rewired to the datalogger in September 1992. The channel used to rewire the TCP had been previously used for a TCP at M8, which began functioning after it was rewired to another channel. This indicates the channel that is presently connected to TCP at M7 is inoperative.

Water potentials at a depth of 10 m (L8) in the shaft were nearly constant from 1988-90 (fig. 9*I*) then the TCP was replaced in January 1991 (table 2). The water potentials at L8 (about -4 MPa) were generally lower than those at a depth of 10.1 m (OD9) in the instrument borehole (between -3 and -2 MPa from 1988-90). Water potentials at OD9 oscillated through most of 1988 and in January 1991, it stopped functioning as voltage drifted to zero. Following replacement of the TCP at L8 in January 1991, water potentials were erratic until May 1992 when water potentials stabilized at about -3.3 MPa. The TCP was rewired to the datalogger in September 1992 and afterward water potentials could not be determined because voltages became erratic. However, the TCP at M8 (which was installed in 1987, table 2) began functioning after it was rewired in September 1992 and water potentials were about -3.8 MPa; similar to those from L8 prior to 1991 (fig. 9*I* and table 3).

Water potentials at a depth of 11 m (M9) in the shaft were nearly constant from 1988-92 (fig. 9*J*) at about -4.2 MPa (table 3). The water potentials in M9 were slightly lower than those at a depth of 11.1 m (OD10 and OD11) in the instrument borehole. Water potentials at OD10 averaged about -4 MPa, whereas those at OD11 averaged about -3 MPa (table 3). The TCP at M9 was replaced by an air sampling tube in September 1992 (table 2).

Water potentials at a depth of 12 m (L10) in the shaft increased slightly from about -3.9 MPa to about -3.3 MPa (table 3) between 1987 and 1995. They were nearly identical to water potentials at a depth of 11.9 m (OD13) in the instrument borehole between 1987 and 1990 (fig. 9*K*). The TCP at OD13 failed in 1991 and water potentials could no longer be determined.

Water potentials at a depth of 13 m (L11 and M11) near the bottom of the shaft were nearly constant during 1987-90 (fig. 9*L*) with M11 having a slightly higher water potential (about -2.7 MPa) compared with L11 (about -3.3 MPa). Water potentials at L11 remained nearly constant after sealing the bottom of the shaft in October 1992. A new TCP was installed in M11 in January 1991 and subsequent water potentials at M11 are closer to those at L11 except that they tend to show greater fluctuations. Water potentials at M11 always have shown greater fluctuations and may be caused by poor installation of the 2.5-cm access pipe horizontally outward from the monitoring shaft.

TCP's installed in 1992

TCP's were installed in the monitoring shaft during September 1992. At this time, all TCP's were rewired to the datalogger using connectors that were 1 m in length. Data collection began in November 1992. TCPs from levels R3, M4, M6, L7, and R9 installed in September 1992 were not used to determine water potentials because of unreasonable readings or because voltages decreased to zero over a few months.

Water potentials measured from TCP's installed in September 1992 show similar trends as TCP's installed previously (fig. 9). For example, water potentials at a depth of 4 m (L2 and R2) were within 1 MPa during 1993-96, and were less than 1 MPa different than OD5 at a depth of 4.2 m (fig. 9*C*). Also, water potentials at a depth of 10 m (R8 and M8; fig. 9*I*) were within 0.5 MPa during 1993-96 and were within 0.5 MPa of water potentials at L8 during 1988-90.

Water potentials at M3 and R6 ranged from -5.4 to -5.0 MPa during 1993-95 (table 3), whereas water potentials at L3 and L6 slowly increased from 1990 to 1992 and were about -3.4 MPa in September 1992 (figs. 9*D* and 9*G*). One possible explanation is that the TCP's are measuring different water-potential trends in the unsaturated sediments that are caused by natural heterogeneities. Other possibilities are that TCP's at L3 and L6 were slowly drifting towards a zero voltage and may not be reflecting any changes in water potentials or the TCP's at M3 and R6 were not properly installed and water potentials reflect a mixing of drier air in the shaft with that in the unsaturated sediments.

Water potentials at L9 showed considerable variability (fig. 9*J*); however, water potentials were within the range measured at M9 and OD10 and OD 11, so the TCP at L9 may have been affected by air flow through the access pipe. Mean annual water potentials ranged from -3.9 MPa to -3.0 MPa during 1993-95 (table 3).

Water potentials at a depth of 12 m (L10, M10, and R10) were generally between -4.0 and -3.4 MPa, which were similar, on average, to water potentials at OD13 (fig. 9*K*). Mean annual water potentials for 1993-95 from TCP's at M10, R10, and L10 ranged from -3.9 to -3.3 MPa (table 3). Water potentials at this depth showed less seasonal variability and had generally higher water potentials than at shallower depths. The greater variability in water potentials at M10 suggests that it, too, may be affected by air flow through the access pipe.

On the basis of comparing TCP's installed in 1992 with TCP's installed prior to 1992, the modified method for installing TCP's in the monitoring shaft produced similar results to TCP's installed with the original method while allowing easier installation, less potential for damaging the TCP's during installation, and easier removal of TCP's for recalibration. Water potentials from TCP's installed in the instrument borehole compared well with TCP's installed at similar depths in the monitoring shaft. Thus, water potentials in the unsaturated sediments can be obtained from TCP's installed in a backfilled borehole. The disadvantage of installing TCP's in a backfilled borehole is that the TCP's cannot be retrieved nor replaced.

All data illustrate uncertainties in measuring water potentials with TCP's because it is sometimes difficult to evaluate if TCP measurements are accurately determining water potentials in the unsaturated sediments or if the measurements are showing differences in actual water potentials caused by heterogeneities in the sediments. TCP measurements in the monitoring shaft do show, however, less variation and higher water potentials at the deepest depths in the monitoring shaft as compared with measurements at shallower depths and suggest that seasonal effects at land surface extend several meters into the unsaturated sediments.

SUMMARY AND CONCLUSIONS

During 1986-87, thermocouple psychrometers (TCP's) were installed horizontally outward 3 to 4.6 m from 17 access ports in a 1.5-m diameter monitoring shaft. The TCP's were installed at depths of 3 to 13 m. The TCP's are used to determine temperature and water potentials beneath an undisturbed, vegetated area south of the southwest corner of a commercial burial site for low-level radioactive wastes. The burial site is about 18 km south of Beatty, Nev., in the Amargosa Desert. Temperature and water potential data were collected as part of a study to determine the direction and rate of water movement through the unsaturated zone. A procedure was developed that allows the TCP to be replaced from access pipes in the shaft. The intent was to remove TCP's that were not functioning and replace them with newly calibrated TCP's. A modified method of TCP installation was developed in 1992 to simplify the procedure, to develop a better way to minimize damage to TCP's during installation, and to allow TCP's to be recalibrated in the original calibration chambers.

Prior to field installation, TCP's were calibrated in the laboratory. To ensure accuracy, all TCP's installed prior to 1991 were calibrated for the range of -7.8 to -0.4 MPa and TCP's installed in 1992 were calibrated for the range of -7.8 to 0 MPa. The laboratory calibration data were analyzed using stepwise regression techniques. Typically, two independent variables explained the calibration data—voltage and voltage times temperature; however, several included a third variable of voltage times voltage. The coefficient of multiple determination (R^2) for each regression equation was greater than 0.95 and the standard error was less than 0.65 MPa.

During July 1991, new access holes were drilled horizontally outward from 16 access ports in the shaft. The drilling of the access holes and installation of TCP's into access pipes was modified from the original method used in 1986 and 1987. The centering plug was recessed 1 cm from the end of the 2.5-cm-diameter PVC access pipe. The pipe was placed in the hole and the hole was backfilled with polyurethane foam. A new sealing plug was designed such that the end of the TCP does not extend past the end of the opening in the access pipe, thereby reducing the possibility of damage from a collapsed hole in the sediments.

A laboratory experiment was designed to test the modified method for installing TCP's in the monitoring shaft. Three boxes were constructed and filled with a uniform 60-mesh sand having three different water contents. Each sandbox was completely sealed and had six access ports. Results from TCP's installed into access pipes using the modified method were compared with those from TCP's installed directly in the sand and with water-activity meter measurements of the sand at the beginning and end of the experiments. Mean differences were less than $\pm$ 0.06°C between all TCP's and the standard deviations were less than $\pm$ 0.1°C. At the beginning of each experiment, water potentials from TCP's installed in access pipes consistently were less than the water potentials determined from TCP's placed directly in the sand. Water potentials from TCP's installed in access pipes increased slowly during the experiment, and showed greater diurnal variations. At the end of the experiment, water potentials differed among TCP's within each sandbox with greater variation observed in the box having the lowest water content. Much of the difference in water potentials observed between TCP's in each box may be the result of water content not being uniform throughout each box.

Daily values of temperature and water potential were determined for all data collected at the monitoring shaft and instrument borehole. The consistency of temperature measurements from several TCP's installed at the same depth in the monitoring shaft suggest that TCP's give reliable temperature measurements. Temperature trends in the unsaturated sediments were observed in the monitoring shaft and instrument borehole. Average daily temperatures at the monitoring shaft and instrument borehole show seasonal fluctuations to depths of at least 13 m. Temperature fluctuations are greatest at shallower depths (about 13-15°C at a depth of 1.2 m) and decrease with depth (less than 0.5°C at a depth of 13 m). Temperature fluctuations at shallow depths follow a pattern similar to the seasonal trend in air temperature.

TCP's installed at the monitoring shaft using the modified method showed similar seasonal temperature trends as TCP's installed using the original method. However, temperatures were more constant and seasonal temperature fluctuations were less in all TCP's below a depth of 9 m from 1993-95 compared with seasonal fluctuations from 1987-92. The change in these TCP's may be caused by sealing the bottom of the shaft in October 1992, which reduced air circulation into the deeper sediments at the bottom of the monitoring shaft.

Water potentials determined from TCP's installed in September 1992 show trends similar to those installed previously. Water potentials from TCP's installed in the instrument borehole compare well with TCP's installed at similar depths in the monitoring shaft. Thus, water potentials in the unsaturated sediments can be obtained from TCP's installed in a backfilled borehole. The disadvantage of installing TCP's in a backfilled borehole is that the TCP's cannot be retrieved nor replaced. TCP measurements in the monitoring shaft show less variation and higher water potentials at the deepest depths in the shaft as compared with measurements at shallower depths. Seasonal water potential fluctuations can be observed to depths of 8 m. Water potentials generally ranged from -6 to -1 MPa at a depth of 3 m and -3.5 to -3 MPa at a depth of 13 m.

Not all TCP's installed in the monitoring shaft or in the instrument borehole could be used to determine water potentials because a TCP failed at the sensing junction or problems with wiring or installation resulted in temperature, offset, or voltage readings being out of range. Additionally, the data illustrate uncertainties in measuring water potentials with TCP's because of the difficulty in evaluating if TCP measurements are accurately determining water potentials or if the measurements are showing differences in actual water potentials caused by heterogeneities in the sediments.

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