Determination of Frost Penetration in LTPP Sections, Final Report

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LTPP

FOREWORD

As a part of the Long Term Pavement Performance (LTPP) Seasonal Monitoring Program, measures of electrical resistance have been used to monitor frost conditions at selected LTPP test sites. The raw data from the pavement instrumentation have been available in the LTPP database for some time. However, to be useful in engineering analyses, the raw data must be interpreted to derive estimates of frost and thaw penetration depths. This report documents analysis conducted to develop and apply procedures for interpretation of the raw data. The "computed parameters" derived through this analysis have been added to the LTPP database.

This report will be of interest to those who wish to use the LTPP seasonal monitoring data, and to other users (or potential users) of similar technology for monitoring frost conditions..

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16. Abstract

To better understand the environmental factors and their effects on pavement performance, the Long Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) was initiated during 1992. Sixty-four LTPP pavement sections were identified to be included in the SMP. These sections are monitored frequently to acquire data on seasonal variation in pavement conditions. As part of this program, work is being performed to identify and monitor the freeze state in the base, subbase, and subgrade at the SMP sections located in the freeze zone in the United States and Canada. This work makes use of temperature sensors and electrical resistivity techniques.

The main goal of the study reported here was to determine frost penetration at the selected SMP sections. As part of the study, an interactive computer program, FROST, was developed to facilitate the interpretation of the electrical resistivity and temperature data. Analysis results include the freeze state at each electrical resistivity sensor and the frost penetration at each site.

As part of the overall LTPP data analysis effort, it is expected that the information on the seasonal variation in the freeze state in the unbound base, subbase, and subgrade will be used to develop improved understanding of the seasonal variation in the load-carrying capacity of pavements and the subsequent effect on pavement performance.

17. Key Words Asphalt pavements, concrete pavements, electrical resistivity measurement, freeze-thaw, frost penetration, LTPP, pavement performance, pavement testing, pavement monitoring, subgrade, subgrade freezing, thaw weakening.	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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CHAPTER 1 - INTRODUCTION

Need for Frost Penetration Data

More than 85 percent of the land in the United States and Canada is subjected to seasonal frost. In some areas, particularly at higher altitudes or latitudes, frost penetration can be up to 2.5 m deep. Problems caused by frost include the seasonal change in the bearing capacity of soils brought by freezing and thawing. A large increase in the elastic modulus of the unbound road materials is expected when the material freezes. A factor of 100 is used to relate the modulus at freezing to the modulus at nonfreezing conditions [1]. When the frost thaws in the spring, the substantial moisture increase in the soil can lead to weakened support for the pavement structure. Another mechanical process associated with frost is the volumetric changes that can take place in frost-susceptible soils. Such volumetric changes could lead to vertical differential movements of the road and subsequent poor performance. The maintenance of highways and airport runways is often complicated by heaving of roadbeds out of vertical alignment and breaking of the pavement surface.

These problems have long been realized. Considerable efforts have been expended to monitor and predict the frost penetration in different seasons, as well as the associated structural changes in pavements. One of the most common methods to "measure" the frost penetration is to measure the temperature profile, as a function of depth, and assume the freezing conditions to exist at temperatures below 0 °C. However, two problems associated with this method make its use less reliable than desired. The first problem is that the freezing point could be depressed by the existence of salts in the soil. The second is the zero isothermal (i.e., temperature is constant at 0 °C) conditions that are known to exist during the spring thaw, making it difficult to identify the frost-line location.

To better understand the environmental factors and their effects on pavement performance, the Long Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) was initiated during 1992. Sixty-four LTPP sections were identified to be included in the SMP. These sections are monitored frequently to acquire data on seasonal variation in pavement conditions. As part of this program, work is being performed to identify and monitor the freeze state in the base, subbase, and subgrade at the SMP sections located in the freeze zone in the United States and Canada. This work makes use of temperature sensors and electrical resistivity technique.

The electrical resistivity technique is based on the fact that the bulk resistivity of a soil increases dramatically when the soil freezes. The technique, referred to as the Electrical Resistivity (ER) method, involves measurement of electrical resistance and electrical resistivity of the soil material using metal wire electrodes. The probes used in the LTPP program were developed by the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL).

Objectives

The objective of the freeze-state study reported here was to produce a good estimate of the freeze state at the selected SMP sections and to create computed quantity tables within the Information Management System (IMS) that provide an estimate of the probable frost locations within the pavement structure, based on the interpretation of resistivity and temperature measurements at the SMP test sections. Table 1 lists the SMP sites where the electrical resistivity probes are installed. This report describes the approach and method used to analyze the data, summarizes the analysis results, and provides some of the important background material related to the collection and analysis of electrical resistivity data.

Overview of Freeze-Related Data Collection in LTPP

The techniques, equipment, and schemes of data collection under the SMP are described in detail in the LTPP Seasonal Monitoring Program: *Instrumentation Installation and Data Collection Guidelines* [2]. For the reader's convenience, a brief description of ER and soil temperature data is presented in this section.

Collection of ER Data

Data from three ER measurements (resistivity, resistance, and voltage) are collected approximately every month, every other year, at the selected SMP sections. The resistivity probes used in the measurement are permanently installed in a 0.25-m hole under the pavement, near the end (or beginning) of the test section. The probe consists of 36 metal wire electrodes spaced approximately 51 mm apart and mounted on a solid polyvinyl chloride (PVC) rod 1.9 m long. Individual lead wires connect the electrodes to a pin connector. A readout device is connected to the pin connector to read voltage and current data. A layout of the SMP instrumentation is shown in figure 1.

The first ER measure is termed *contact resistance*. It is measured using two consecutive electrodes at a time, so it is often referred to as *2-point resistance*. Contact resistance (referred to as *resistance* in the remainder of the report) is obtained by dividing the voltage drop between two electrodes by the electrical current passing through the soil from one electrode to the other, according to Ohm's law. Figure 2 shows the assembly used to obtain resistance data.

The second ER measure is termed *resistivity*. It is measured using four consecutive electrodes at a time, so it is often referred to as *4-point resistivity*. Resistivity is obtained by dividing the voltage drop between the two inner electrodes by the electrical current passing through the soil between the outer two electrodes, and multiplying by a geometric factor. Figure 2 also shows the assembly used to obtain the resistivity. The difference between resistance and resistivity is that resistivity is a material property. It is the resistance of a unit length and cross section of a material.

Table 1. SMP sites with electrical resistivity probes.

Section ID	State Name	Experiment Type[1]	Pavement Type[2]	TDR Install. Date[3]	Monitoring Period	Seasonal Round
041024	Arizona	GPS-1	ACP	08/21/95	11/95 - 08/96	C
081053	Colorado	GPS-1	ACP	07/01/93	10/93 - 09/97	A
091803	Connecticut	GPS-1	ACP	08/19/93	08/93 - 10/97	A
161010	Idaho	GPS-1	ACP	09/30/93	10/93 - 06/97	B
183002	Indiana	GPS-3	JPCP	09/07/95	09/95 - 08/96	A
204054	Kansas	GPS-4	JRCP	08/24/95	08/95 - 08/96	A
231026	Maine	GPS-1	ACP	09/15/93	09/93 - 06/95	A
241634	Maryland	GPS-2	ACP	05/11/95	05/95 - 11/97	A
251002	Massachusetts	GPS-1	ACP	09/01/93	09/93 - 10/97	A
271018	Minnesota	GPS-1	ACP	08/24/93	08/93 - 06/95	A
271028	Minnesota	GPS-1	ACP	09/08/93	09/93 - 09/97	B
276251	Minnesota	GPS-1	ACP	09/14/93	09/93 - 09/97	C
274040	Minnesota	GPS-4	JRCP	09/21/93	09/93 - 09/97	D
308129	Montana	GPS-1	ACP	08/12/92	10/93 - 10/97	A
313018	Nebraska	GPS-3	JPCP	08/10/95	08/95 - 08/96	B
331001	New Hampshire	GPS-1	ACP	10/14/93	10/93 - 10/97	A
364018	New York	GPS-4	JRCP	10/27/93	10/93 - 10/97	A
421606	Pennsylvania	GPS-4	JRCP	08/09/95	08/95 - 10/97	A
460804	South Dakota	SPS-8	ACP	07/14/94	07/94 - 09/97	B
493011	Utah	GPS-3	JPCP	08/03/93	11/93 - 09/97	A
501002	Vermont	GPS-1	ACP	10/06/93	10/93 - 10/97	A
561007	Wyoming	GPS-1	ACP	08/10/93	08/97 - 09/97	A
831801	Manitoba	GPS-1	ACP	10/12/93	10/93 - 09/97	A
833802	Manitoba	GPS-3	JPCP	10/14/93	10/93 - 09/97	B
871622	Ontario	GPS-1	ACP	09/22/93	09/93 - 10/97	A
893015	Quebec	GPS-3	JPCP	09/29/93	09/93 - 11/97	A
906405	Saskatchewan	GPS-1	ACP	10/06/93	10/93 - 09/97	A

[1] GPS = General Pavement Studies, SPS = Specific Pavement Studies.

[2] ACP = Asphalt Concrete Pavement, JPCP = Jointed Plain Concrete Pavement, JRCP = Jointed Reinforced Concrete Pavement.

[3] TDR = Time-Domain Reflectometry Sensors.

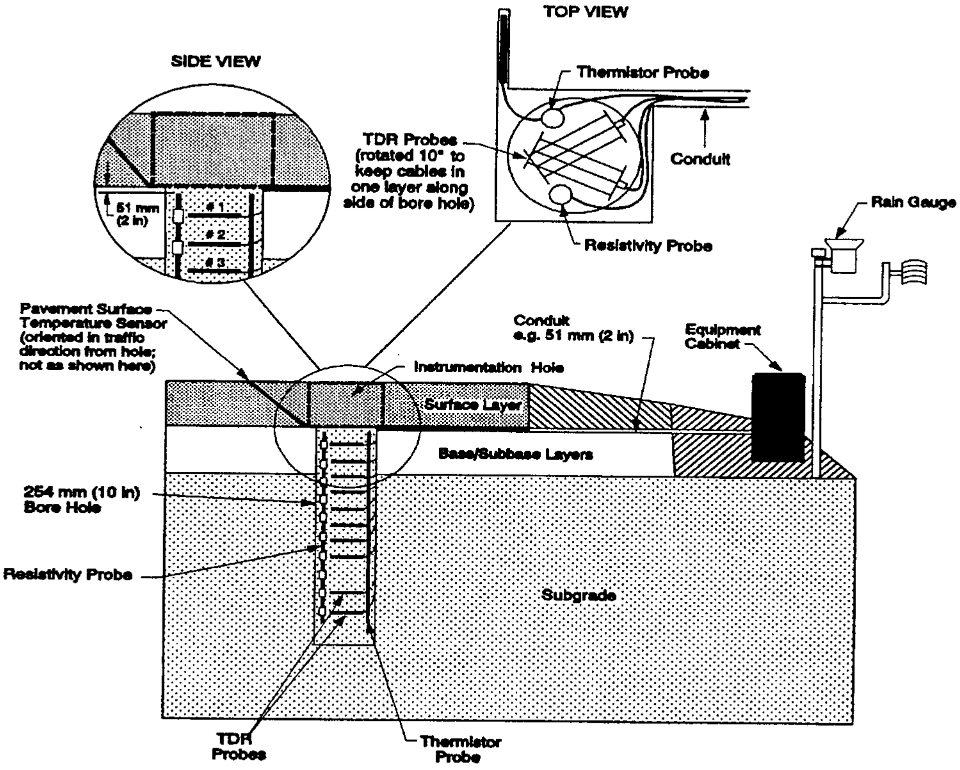
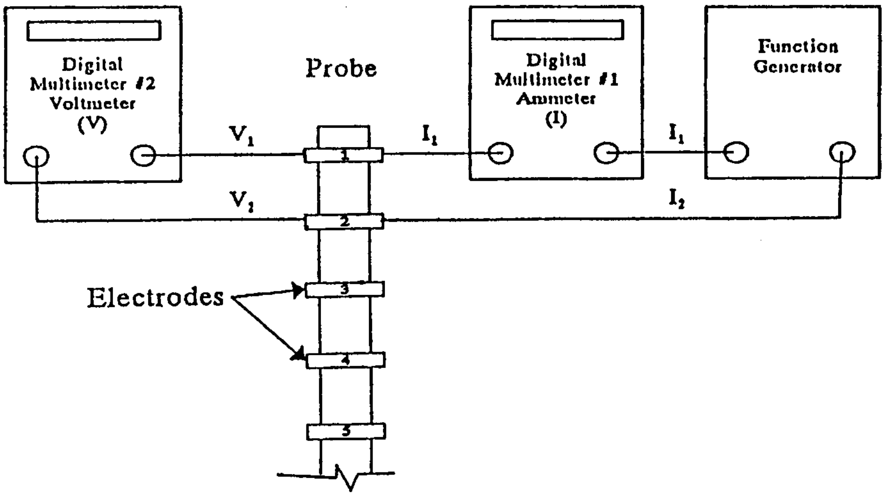
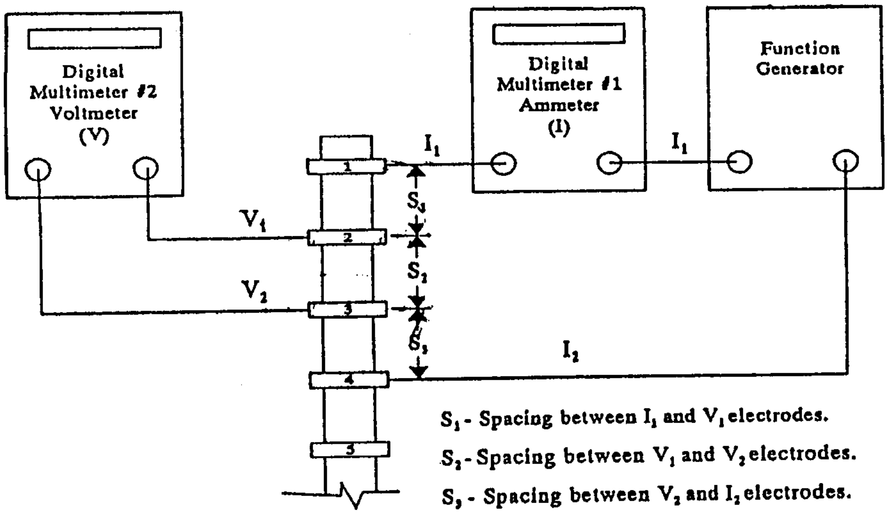


Figure 1. LTPP SMP instrumentation layout [2].



a. Contact (Two-Point) Resistance Measurement.



b. Four-Point Resistivity Measurement.

Figure 2. Electrical resistivity measurements – CRREL probe (adopted from [2]).

The third measure is the automated volt drop measure, in which the volt drop between two electrodes is measured by a readout device. Volt drop is representative of the resistance of the soil between the two electrodes. Volt drop will be referred to as *voltage* in the remainder of this report.

All three ER measures are collected sequentially along the probe depth. Due to the testing arrangement, there are 35 resistance readings, 35 voltage readings, and 33 resistivity readings for each probe, representing resistance, voltage, and resistivity at different depths.

Collection of Soil Temperature Data

In the SMP, the temperature profile is measured at 18 depths, measured by 18 thermistors that are permanently installed in a 0.25-m-diameter hole located near the section end. The first three thermistors are embedded in the surface bound layer, and the rest are embedded in the base, subbase, and subgrade layers. Data from the first five thermistors are recorded hourly. Daily temperature statistics, including maximum, minimum, average temperature, and times of maximum and minimum temperature, are recorded for all thermistors. Temperature data were used jointly with resistivity data to determine the frost depth.

Abbreviation and Terminology

Throughout this report the following terminology will be used:

Abbreviation	**Description**
LTPP	Long Term Pavement Performance program
SMP	Seasonal Monitoring Program
IMS	Information Management System of LTPP
ER	Electrical Resistivity, including resistance, resistivity, and voltage
Resistance	Soil electrical resistance as measured from the 2-point resistance (contact resistance) measurement
Resistivity	Soil electrical resistivity as measured from the 4-point resistivity measurement
Voltage	Voltage drop as determined by the automated volt drop measurement

Organization of the Report

This report consists of six chapters. Chapter 1 introduces the problem of frost, the objective of the research, and the collection of ER and temperature data. Chapter 2 reviews some of the theoretical models developed to predict frost penetration depth, presents some of the theoretical considerations on the sensitivity of ER data to other variables, and presents some of the models developed to quantify such effects. Chapter 3 explores the characteristics of ER and temperature data as they relate to frost penetration analysis. Chapter 4 presents the procedure selected for data interpretation, including the development of the computer program FROST to interpret the ER and temperature data. Chapter 5 reports the results of the analysis and the output format. Chapter 6 presents the study conclusions and recommendations for future data collection and analysis.

Frost penetration plots are given in appendix A for each of the 27 SMP sections with electrical resistivity probes. Sample time-series electrical resistivity plots used in the computer program FROST are given in appendix B. The computed parameter table SMP_FROST_PENETRATION is given in appendix C.

CHAPTER 2 - THEORETICAL CONSIDERATIONS FOR FROST PENETRATION PREDICTION AND MEASUREMENT

Due to the significant impact of frost on environmental, agricultural, and engineering systems, many models have been developed to predict the maximum frost penetration depth and the rate of penetration for specific areas. These models are based on thermodynamic laws of energy and moisture balance. Techniques have also been developed to measure frost penetration. This chapter provides a brief review of frost penetration prediction models and methods of frost depth measurement.

Frost Penetration Prediction Models

A number of theoretical models have been developed to predict frost penetration at a specific location, given climatological data and soil type. These models are discussed in references 3 through 13.

Frost Penetration Measurement Using ER

To better understand the freezing and thawing processes, and to be able to predict their occurrence, more data about the frost depth and rate of formulation at various regions and various climatic and geological conditions are needed. Frost tubes have been used as a direct method to measure frost depth in soils. In addition, soil temperature and soil ER have been used to estimate the depth of frost penetration in soils. Since the LTPP program uses ER probes to measure frost penetration, this section describes some of the theoretical considerations for ER data.

Factors Influencing Soil ER

It is important to realize that the ER of a soil element is the result of the resistivities of the element components: soil particles, water, ice, and air. The ER of the soil particles is large enough to consider them as an insulator. The water resistivity is very low, depending on the salt content of the water. Ice resistivity is much larger than water resistivity. Following are the factors that influence the bulk resistivity of a soil.

Type of Soil

Whether a soil is largely clay or very sandy can change the resistivity very much. In addition, there is a wide variation in the resistivity range within a given soil type, depending on the soil composition. Tables 2 and 3 show the resistivity ranges of different soils from two different sources. The tables show the wide range of variation within and between different soil types. It should be noted that the maximum resistivity of these soils does not correspond to completely dry conditions (the effect of moisture content is demonstrated in table 4).

Table 2. Resistivities of different soils (U.S. Bureau of Standards Technical Report 108).

Soil	Resistivity, ohm-cm		
	Average	Minimum	Maximum
Fills—ashes, cinders, brine wastes	2,370	590	7,000
Clay, shale, gumbo, loam	4,060	340	16,300
Same—with varying proportions of sand and gravel	15,800	1,020	135,000
Gravel, sand, stones, with little clay or loam	94,000	59,000	458,000

Table 3. Resistivities of different soils (Evershed & Vignoles Bulletin 245).

Soil	Resistivity, ohm-cm	
	Minimum	Maximum
Surface soils, loam, etc.	100	5,000
Clay	200	10,000
Sand and gravel	5,000	100,000
Surface limestone	10,000	1,000,000
Limestones	500	400,000
Shales	500	10,000
Sandstone	2,000	200,000
Granites, basalts, etc.	100,000 (average)	
Decomposed gneiss	5,000	50,000
Slates, etc.	1,000	10,000

Moisture Content

Because the resistivity of water is much less than that of soil particles, the bulk resistivity decreases as the moisture content increases. Table 4 shows examples of the effect of moisture content on soil resistivity. The table shows the dramatic decrease in soil resistivity with an increase in moisture content, especially after the first 2.5 percent moisture content by weight. For the two types of soil listed in the table, it is evident that the soil is a good insulator when dry. The introduction of 15 percent moisture content led to a decrease of resistivity by a factor of about 50,000.

Table 4. Effect of moisture content on soil resistivity.*

Moisture Content, % by Weight	Resistivity, ohm-cm	
	Top Soil	**Sandy Loam**
0	1,000 * 10^6	1,000 * 10^6
2.5	250,000	150,000
5	165,000	43,000
10	53,000	22,000
15	21,000	13,000
20	12,000	10,000
30	10,000	8,000

*From "An Investigation of Earthing Resistance," by P.J. Higgs, *I.E.E. Journal*, vol. 68, p. 736, February 1930.

Dissolved Salt Concentration

Pure water has high resistivity that is greatly reduced by adding salts. In natural soils, salts such as sodium chloride, copper sulphate, and sodium carbonate can exist. Since water is the most important component through which current is passed, the soil resistivity is also influenced by the dissolved salt concentration. Table 5 demonstrates the effect of salt content on soil resistivity.

Table 5. Effect of salt content on soil resistivity.*

Added Salt % by Weight of Moisture	Resistivity, ohm-cm
0	10,700
0.1	1,800
1.0	460
5	190
10	130
20	100

*For sandy loam—moisture content, 15 percent by weight, temperature, 17°C (63°F). *Getting Down to Earth—Manual on Earth-Resistance Testing for Practical Man,* 4th edition, Biddle Instrument, April 1981.

Temperature

Little information has been collected regarding the effect of temperature on resistivity. However, two facts have been observed: water present in soil mostly determines the resistivity, and temperature serves as a catalyst that increases the conductivity of the dissolved ions in the water. An increase in temperature markedly decreases water resistivity. Table 6 shows the effect of temperature on soil resistivity. The table demonstrates a large reduction in soil resistivity with temperature increase. It should be noted that there is a large increase in resistivity between ice at 0 °C and water at 0 °C. The resistivity keeps increasing as the temperature decreases below 0 °C.

Table 6. Effect of temperature on soil resistivity.*

Temperature		**Resistivity, ohm-cm**
°C	**°F**	
20	68	7,200
10	50	9,900
0	32 (water)	13,800
0	32 (ice)	30,000
-5	23	79,000
-15	14	330,000

* For sandy loam, 15.2 percent moisture.

From the above discussion, it is evident that the interpretation of ER data of soils is a complex matter. Soil ER varies with temperature, moisture content, salinity, soil type, and freezing conditions; hence, such data must be analyzed carefully.

Mixing Model for Electrical Resistivity

The soil resistivity may be computed using mixing models. Assume that the soil cylinder through which the current is passed consists of four homogenous parts, each with a volume component as follows:

V_S = soil particles
V_{LW} = liquid water
V_{FW} = frozen water

If the electrical current passes through the soil components in a parallel manner, then the bulk (equivalent) resistivity (ρ_e) may be expressed by:

$$\rho_e = \frac{\rho_{LW}\,\rho_{FW}\,\rho_S}{\rho_{LW}\,\rho_{FW}\,V_S + \rho_{LW}\,\rho_S\,V_{FW} + \rho_S\,\rho_{FW}\,V_{LW}} \qquad (1)$$

where
ρ_{FW} = resistivity of the frozen water, typically = 500,000 (ohm-m).
ρ_{LW} = resistivity of the liquid water, typically = 20,000 (ohm-m).
ρ_S = resistivity of the soil solids, typically in millions of ohm-m.

If the soil is not expansive (subject to frost heave or moisture-induced volume changes), then the volumetric changes resulting from freezing can be neglected. In this case, the sum of the frozen and liquid water volumes equals the initial (before freezing) volumetric moisture content (V_W). If air volume is neglected, then the solids volume is the total volume less the initial water content. The above equation can be rewritten in terms of the initial volumetric moisture content as follows:

$$\rho_e = \frac{\rho_{LW}\ \rho_{FW}\ \rho_S}{V_{FW}\ \rho_S\left(\rho_{LW} - \rho_{FW}\right) + V_w\ \rho_{FW}(\ \rho_S - \rho_{LW}) + \rho_{LW}\ \rho_{FW}} \tag{2}$$

where: $V_W \geq V_{FW}$.

As expected, the above equation shows that when the ice content (V_{FW}) is zero, then the ice resistivity term will vanish and the bulk resistivity will only depend on the moisture content and the resistivity of water and solid particles. Also, when the initial water content (V_W) is zero, the first two terms in the denominator will vanish and the bulk resistivity equals the solid particles' resistivity.

When the ice volume (V_{FW}) equals the initial volumetric moisture content (V_W), the liquid water resistivity term will vanish and the bulk resistivity is determined by the ice content and the resistivities of soil particles and ice. Equation 2 also shows that when the ice content increases, the value of the denominator is reduced (since the liquid water resistivity is less than that of the frozen water), and the bulk resistivity is increased.

The change in bulk resistivity per unit change in the volumetric ice content may be obtained analytically by differentiating the bulk resistivity with respect to the volumetric ice content. Alternatively, numerical substitution in the above equation can be used to quantify the change in resistivity due to change in ice content.

Example

Assume the following for a soil:

- Initial volumetric moisture content = 10 percent.
- Ice resistivity = 500,000 ohm-m.
- Water resistivity = 20,000 ohm-m.
- Soil particle resistivity = 3,000,000 ohm-m.

Table 7 shows the expected resistivity as a function of the ice content (changes from 0 to 10 percent) using equation 2. The change in resistivity is shown in the third column. The table shows that the theoretical bulk resistivity increases when ice content increases and that the amount of increase is a function of the amount of remaining unfrozen moisture in the soil. The use of these equations in the analysis of ER data requires the knowledge of moisture content and the electrical resistivity parameters for all soil components. It should be noted that the electrical resistivity of water is greatly influenced by the water salinity. Also, soil particle resistivity is a function of the chemical composition of the particles; hence, some field calibration may be required to use the above models.

The mixing models are a simplification of reality. Many factors can influence the measured resistivity, such as the complexity of the path of the electrical current within the soil mass (not in series or in parallel, but in a combination of both). In addition, factors such as the quality of contact between the electrodes and the soil, and between the soil particles may influence the measured bulk resistivity.

Table 7. Change in bulk resistivity per unit change in the volumetric change in ice content.

Percent Ice Content	**Resistivity (ohm-m) (Equation 2)**	**Change in Resistivity (ohm-m)**
0	188,679	---
1	207,469	18,790
2	230,415	22,946
3	259,067	28,652
4	295,858	36,791
5	344,828	48,970
6	413,223	68,395
7	515,464	102,241
8	684,932	169,468
9	1,020,408	335,476
10	2,000,000	979,592

CHAPTER 3 - PRELIMINARY DATA ANALYSIS

A number of diagnostic studies performed to explore the characteristics of ER and temperature data can be used to identify the freeze state of soils. Diagnostic studies were aimed at identifying erroneous or suspicious data that should not be used in the analysis of the freeze state. This chapter presents the findings of the diagnostic studies that were conducted to identify data concerns.

Characteristics of Temperature Data

A variety of visualization tools were utilized to determine the characteristics of temperature data. These include categorized line plots, summary statistics, and histograms of the time of maximum and minimum temperature. The following are the highlights of the temperature characterization study:

1. Temperature versus time plots at each thermistor take a sinusoidal shape. The amplitude, which represents the seasonal variation in temperature, declines with thermistor depth.

2. Diurnal variation is represented by the separation between the minimum and maximum daily temperature curves. It should be noted that the separation decreases with the thermistor depth, until the maximum and minimum temperatures become almost identical in the lower eight thermistors.

3. The deeper thermistors show smoother time-series curves than the upper ones. This indicates that day-to-day variations are smaller for deeper thermistors.

4. Maximum and minimum daily temperature curves are mostly parallel. This indicates that both maximum and minimum temperatures increase on hot days.

5. Temperature time-series curves at various thermistors are generally parallel. This indicates that when a day is hot, temperature should increase in all thermistors, and vice versa. However, a lag may exist between the upper and lower thermistors.

6. Based on the review of the time-series plots and summary statistics, the general temperature trends were reasonable and as expected. Comparisons between various temperature measures, taken at various times and locations, showed that the majority of temperature data appear reasonable and agree with expected trends. Missing, erroneous, and suspicious data were identified so they could be isolated from the database and their sources investigated.

7. For the purpose of this study, subsequent analysis excluded all suspicious data. It should be noted that only a few thousand records appear to be suspicious.

Compared to the size of the total data set (about 400,000 records), the portion of suspicious data is less than 1 percent.

8. There are about 6,000 records of ER data for which soil temperature is not currently available. Based on observation 3 above, temperature within 2 days from the measurement date can be used as a substitute. More details on this are presented in chapter 4.

The Latent Heat of Fusion Phenomenon

As discussed earlier, temperature by itself is not a reliable indicator of the freeze state of soils. Although a soil temperature above 0 °C may confirm that the soil is not frozen, temperature cannot confirm freezing for the following reasons: First, the freezing point may change due to salt concentration in the soil and in the pore water. Second, if the soil is dry, then there will be no moisture to freeze, regardless of temperature. Third, during spring thaw, temperature may stay constant at 0°C; hence, there could be uncertainty in the freeze state determined if only temperature data are used. It is also known that these conditions could extend deep in the soil, possibly resulting in a large error in determining the frost depth.

To evaluate the usefulness of temperature for identifying freezing conditions, a set of conditions was defined to indicate that the soil is in the process of freezing. These represent the phenomenon of the latent heat of fusion, that is, when the soil is undergoing freezing (or thawing), temperature stays constant about the thawing point until the entire water body is frozen (or thawed). It is assumed that this process takes a long time because the subsurface temperature changes usually occur at a slow rate. The following conditions are assumed to indicate a phase change:

- Temperature is at or below 0 °C.
- Maximum and minimum daily temperatures are the same (constant temperature during that day).
- There is no change in the average daily temperature in at least 2 consecutive days. This condition is added because it was found that the day-to-day temperature changes in the lower thermistors are normally small (less than 1 °C). If only the zero temperature variation in one day is used to identify phase change, then too many phase change points would be identified, many of which would be false.

The above conditions were programmed, and any particular thermistor satisfying these conditions on a given day was identified. Line plots were generated for each section and thermistor, with the average temperature plotted against the time of the year. Points where phase change took place were identified on the plot. Figure 3 is a sample plot showing the possible points of phase change for section 833802. It should be noted that the upper three thermistors were excluded from this analysis because they are embedded in the surface layer.

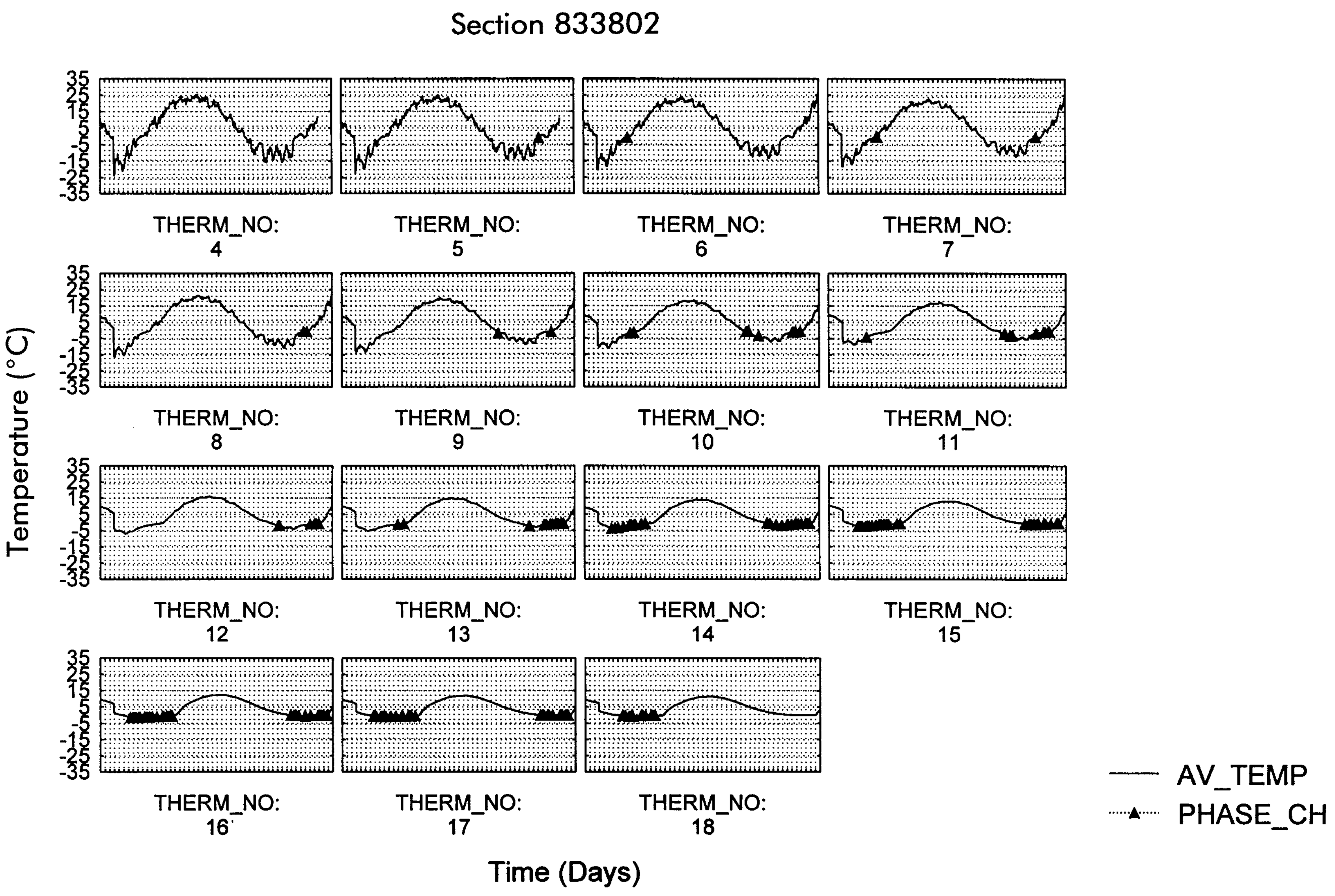


Figure 3. Phase change events using latent heat of fusion.

Based on inspection of such plots, the timing and pattern of phase change points are very reasonable. Test sections with high temperatures, by definition, did not experience phase change. Some sections showed a persistent pattern with two distinct phase change points (possibly indicating freezing in winter and thawing in spring). In other cases, some upper thermistors did not exhibit phase change, while lower ones did. That can be caused by the absence of moisture in the upper layers.

Table 8 summarizes the results of this analysis. The table shows a phase change in 20 of 45 sections. Out of the 25 sections that did not exhibit a phase change, 20 had a minimum temperature above 0 °C. The closeness of thermistors that exhibit a phase change (i.e., freezing thermistors being adjacent) is expected, since ice formation is more likely to be in a form of continuous layers rather than in the form of broken lenses, although the latter also is possible.

Limitations

There are limitations in the use of the latent heat of fusion phenomenon for identifying the freeze state. One limitation is caused by the frequency of temperature measurement. As indicated earlier, in order to define the process of freezing, we analyze the temperature data. If the temperature data do not change for more than 2 days, it is assumed that the phase change may be taking place. If a large drop in temperature caused a quick phase change that lasted only a fraction of a day, then the system cannot detect such an event.

Most upper thermistors did not indicate a freeze state, even when temperature was significantly below 0 °C. It is possible that the temperature change in the upper thermistors is faster than that of the lower ones, and that the phase change events in the upper thermistors (which may have occurred in less than a day) were not detected. Also, if a phase change occurred in fractions of 2 days (i.e., starting some time in one day and ending some time in the next), it will not be detected by the algorithm because the temperature may be variable on both days.

Another limitation is that the day-to-day variations in the lower thermistors are small. As indicated earlier, the day-to-day variations in the average temperature in the lower nine thermistors are less than 1 °C. Hence, a constant temperature does not necessarily mean a phase change. Plots of temperature data showed constant temperature in both cold and hot conditions.

Summary

Based on the review of time-series plots and summary statistics, the general temperature trends were found to be reasonable and as expected. Comparisons between various temperature measures, taken at various times and locations, showed that the majority of temperature data appear reasonable and agree with expected trends. Missing, erroneous, and suspicious data were identified so they could be isolated from the database and their sources investigated.

Table 8. Summary of phase change analysis.

Section	Minimum Temp., °C	Thermistors with phase change	Section	Minimum Temp., °C	Thermistors with phase change
041024	3.9	none	364018	-12.9	5-18
063042	3.9	none	371028	-0.1	none
081053	-11	none	404165	1	none
091803	-5.5	none	421606	-5.8	5-7
131005	3.9	none	469187	-10.4	5-6, 7-10
131031	0.7	none	481060	8.4	none
133019	0.5	none	481068	4.2	none
161010	-9.6	4-9	481077	0	none
183002	16	6-9	481122	6.3	none
204054	-3.4	none	483739	7.4	none
231026	-15.8	5-16	484142	9.5	none
241634	-1.7	none	484143	11.4	none
251002	-9.6	none	491001	-12.3	none
271018	-22.1	9-18	493011	-0.8	none
271028	-25.6	12-18	501002	-17.4	9-14
274040	-23.3	6-18	533813	-0.4	none
276251	-27.9	6, 9, 11, 13-18	561007	-8.8	6-8
281016	0.6	none	831801	-29.1	9-18
281802	2.5	none	833802	-24.9	5-18
308129	-15.1	10-12	871622	-21.6	11-16
313018	-10.3	10	893015	-20.4	9-14
331001	-12.1	9-13	906405	-28.3	7-18
351112	2.3	none			

The use of the latent heat of fusion phenomenon to identify the timing of the soil phase change appears promising. The conditions used to identify a phase change event are negative temperature (below 0 °C) and constant temperature over a period of 2 days. These conditions identified a phase change in 20 of 45 SMP sections, with a plausible profile and reasonable timing for a phase change. However, there is a limitation dictated by the arbitrary assumption of a 2-day time period over which constant temperatures indicate a phase change. In actuality, this period is variable, depending on the rate of temperature change and the thermal properties of the soil. This limitation makes the latent heat of fusion method incomplete. Supporting measures from other sources (such as resistivity, resistance, and voltage data) are needed to complement the latent heat of fusion method.

Characteristics of ER Data

A diagnostic study of ER data was undertaken. The objective of the diagnostic study was to verify the consistency of the data and the reasonableness of resistivity measures. Of particular interest was the relationship between resistivity measures and the definition of the characteristics of ER data as affected by the freeze state of the soil. A brief discussion of the analysis methods and results is presented below.

Consistency of ER Data

To investigate the consistency of the three ER measures (resistivity, resistance, and voltage), overlay plots of these three measures were generated. Each plot showed the variation in voltage, resistivity, and contact resistance at a given depth as a function of time. For each resistivity measure, the within-same-day values were averaged to generate a single value at each experiment depth. The generated plots were examined with two questions in mind: Are the plots of the three measures parallel (i.e., are the measures consistent with each other)? and Are the measures reflective of the season (i.e., showing very high values during the freezing season)?

The correlation coefficients between each pair of resistivity measures were computed. The correlation coefficient quantifies the magnitude of correlation between the two variables; the squared correlation coefficient represents the amount of common variability of the two variables.

The results of these analyses may be summarized as follows:

- Agreement between resistivity measures is reached in 62 percent of the cases; this includes partial and total agreements. Hence, more reliable results will be obtained when using all measures, rather than a single one.

- Agreement between resistivity measures cannot be reached in 38 percent of the cases. Hence, different results can be reached using different resistivity measures.

- In 56 percent of the observations, some or all resistivity measures were successful in identifying freezing conditions. Hence, more reliable results are obtained using all measures rather than a single method.

- In 44 percent of the observations, none of the resistivity measures were successful in identifying freezing conditions. Hence, there seems to be a reliability problem with resistivity data.

Variability Characteristics of ER Data

In this analysis, the variation characteristics of resistivity measures were studied. Three variability components were quantified for each section: same day non-winter, same day winter, and diurnal electrode variabilities.

Same Day Non-Winter Variability

For each section, the magnitude of variation between any two depths in non-winter months (May to November) was computed. The maximum values were retained as an upper limit of the variability. These measures were computed for resistivity, resistance, and voltage values. This variability encompasses electrode-to-electrode variability in the same day due to material change and diurnal variations at each electrode, but it does not include changes due to freezing or thawing since only the non-winter measurements are considered.

Same Day Winter Variability

For each section, the magnitude of variation between any two depths in winter months (December through March) was computed. The maximum values were retained as an upper limit of the variability. These measures were computed for resistivity, resistance, and voltage values. This variability encompasses electrode-to-electrode variability in the same day, diurnal variations at each electrode, and changes due to freezing or thawing, since winter measurements are considered.

Diurnal Electrode Variability

The diurnal electrode variability refers to the variation between the readings taken during the same day at the same electrode. This variability does not include the effect of the change in material type. Because the time between measurements is short (a few hours), no significant change in moisture condition or freeze state is expected to take place during the measurement time. Therefore, this variability provides a measure of the stability of resistivity measures.

The results of the comparative evaluations and statistical analysis performed on the above variabilities revealed the following characteristics:

- There is a large within-day non-winter variability in all resistivity measures. That variability is attributed to non-freezing (or thawing) factors, including the effect of material variability on resistivity. In some sections, this variability approached the extent of the resistivity, resistance, and voltage scale, leaving only a small margin for changes due to actual freezing conditions.

- The within-day winter variability is not always larger than that of the non-winter variability. This would indicate that the section in question has not experienced freezing. However, some measures (voltage) showed this condition in sections that are known to experience freezing.

- Approximately one-third of the sections had a ratio of winter to non-winter variability of less than 1 (indicating no freezing took place), one-third had a ratio greater than or equal to 3 (indicating freezing took place), and one-third showed a ratio between 1 and 3 (indicating that it will not be easy to infer whether freezing took place).

- The correlation coefficient between contact resistance and resistivity variability ratio is notably large (0.9), compared to those of other pairs. Hence, contact resistance and resistivity are more likely to be in agreement than any other pair of resistivity measures. Furthermore, the agreement between contact resistance and voltage is better than that between the voltage and resistivity. This supports the earlier observation that contact resistance seems to be in better agreement with other measures.

- On average, the resistivity measures have a larger value when the temperature is below freezing. In some cases, the difference in the average values is large enough to enable reliable interpretation. In other cases, the difference is not large enough to be distinguishable among other variabilities, including diurnal, seasonal, and electrode-to-electrode variability. It is noted that resistivity measures are more meaningful when analyzed in conjunction with temperature data.

- Resistivity measures showed various degrees of time stability. Diurnal electrode variability ranged from single-digit numbers to readings in the hundreds of thousands. Most resistivity and all voltage readings had an average variability of less than 100 (measurement unit). Most contact resistance had an average variability of less than 500 ohm.

- In some cases, the diurnal electrode variability can be very large. There are two possible causes for such a large variability: data collection error and unstable measurements. It is possible that data collection error is the primary cause of such variability.

- Approximately 7 percent of resistivity records were suspicious. Their inclusion in the analysis may cause significant noise and unreliable results. These records were flagged for investigation.

- Each resistivity measure was found to have some advantages over other measures. Contact resistance seemed to be more in agreement with other resistivity measures than are resistivity or voltage. Resistivity data had lower diurnal variability and had more sections with larger winter to non-winter variability ratios than contact resistance. Voltage data seemed to be more stable (low diurnal variation) and had no zero value records.

Potential Data Interpretation Algorithms

The research team worked on developing an automated procedure that combines ER data with soil temperature data to determine the soil freeze state. A number of candidate procedures were investigated for use in interpretation of ER and temperature data in a systematic, structured manner. The following is a brief description of each approach.

The first approach is to average the lowest three ER readings, then multiply that value by a multiplier (e.g., 3, or site dependent). That resulting value is then used as a threshold value. Any higher reading is considered indicative of a frozen state. Values that fall between the average and the threshold are considered in transition, and any value below the average is considered not frozen. This approach may not work if all sensors are frozen. Many of the ER records had such a large difference between the maximum and minimum readings that it was clear that a multiplier of 3 would not yield reasonable values. This suggests that the multiplier is site dependent. The threshold may be calculated using an "arbitrary but consistent" number of standard deviations above the average of the lowest three sensors.

Another approach is to consider the average of the maximum and minimum values as a threshold. Again, this method will not work if all probes are frozen or all probes are not frozen. It could work if there is a large difference in resistance between the maximum and minimum values.

The third approach is to look at the year-round ER values of each probe and establish the ER values corresponding to freezing and thawing conditions for that probe. A threshold value for each probe may be calculated as described above. The advantage of this method is that it compares the readings at the same probe, which cancels the effect of material variation with depth. The problem, however, is that without the year-round values, there will not be a complete assessment of the variation in resistivity readings and, therefore, it would not be possible to establish freezing and thawing values.

The fourth approach is to find the maximum drop in ER (theoretically associated with thawing conditions) and the associated depth. Check the soil temperature at one point above and one point below that point (the temperature thermistor directly above and below that point). If the temperature of at least one of these points is less than or equal to 0 °C, then the above point of resistivity drop corresponds to the frost depth and the search should be stopped. If not, then move on (toward the pavement temperature decrease, excluding data below the first point of maximum resistivity drop), searching for the next maximum drop in resistivity. Repeat the process until a large ER drop corresponding to a negative temperature (frost conditions) is reached, or a positive temperature is encountered throughout the upper resistivity probe (no frost conditions). The problem with this algorithm is its ability to produce false frozen conditions corresponding to small changes in ER values, unless it is "told" what to consider a large enough change in ER.

The fifth approach is based on finding two resistance (or resistivity) threshold values that correspond to unfrozen and frozen soil conditions. These values are section specific. Materials with resistance values below the nonfrozen threshold (NFT) value are considered nonfrozen. Materials with resistance values larger than the freezing threshold (FT) value are considered frozen. Materials with resistance values between NFT and FT are considered to be in a transitional state. The process of finding the site-specific NFT and FT is that of optimization, with the goal of maximizing the agreement between resistance/resistivity and temperature, in classifying the freeze state of soils.

In addition to its capability to handle the site-specific nature of resistance values, the fifth approach worked very well when tested on data from a northern test section (section 893015 in Quebec). Hence, the approach was initially recommended for use. Like all other approaches, the recommended approach assumed an L-shaped curve between temperature and ER; however, diagnostic studies showed that the expected L-shaped curve between temperature and ER data is not vividly present in a good portion of the data, and that ER data may contain too much noise to be interpreted automatically.

Implications for ER Data Interpretation

The results from the above diagnostic studies and experiments with interpretation algorithms suggest the following:

- The expected significant resistivity peak during freezing has been observed in about 33 percent of the data, cannot be verified in 33 percent of the data, and is not apparent in 33 percent of the data. Also, freezing-triggered ER peaks are masked by large non-winter, seasonal, and diurnal variabilities. In addition, more noise is possibly introduced by data collection problems. With the noise inherent in ER data, fully automated interpretation procedures for ER data are not considered reliable at the present time.

- Capitalizing on the strengths of a number of readily available algorithms, a successful ER data interpretation method may be developed. However, unless a better understanding and control of ER data is realized, the method of interpretation may be interactive rather than automated.

- Resistivity measures are not fully redundant, and each measure has some advantage over the others. Therefore, more reliable results can be obtained by using all measures simultaneously. Furthermore, the fact that very large resistivity values were observed in unfrozen conditions (e.g., section 041024 in Arizona) suggests that temperature data should play an important role in the interpretation of ER data. Therefore, the analysis of ER data was planned to be based on resistivity, contact resistance, voltage, temperature, and other supporting data, such as time of the year, location of measurement, and knowledge of established freezing patterns at the given location.

CHAPTER 4 - INTERACTIVE PROCEDURE FOR INTERPRETATION OF ER DATA

An interactive computer program has been developed to process electrical resistivity data to determine the frost penetration in SMP sections. The program, called FROST, determines the freeze state of a soil based on the values of the three ER measures (voltage, contact resistance, resistivity) and soil temperature. Based on time-series plots of all of the ER variables at each depth and temperature data, the user determines (using established guidelines) the threshold ER value above which the soil is considered potentially frozen. If the soil temperature is negative and the ER value is larger than the established threshold, the soil is considered frozen.

The program stores the results in a database format, which can be retrieved and reprocessed later. Other graphing capabilities in the program include frost penetration plots, ER time-series plots by electrode, and ER profile by depth at a given date—all designed to assist the user in interpreting the data.

Procedure Highlights

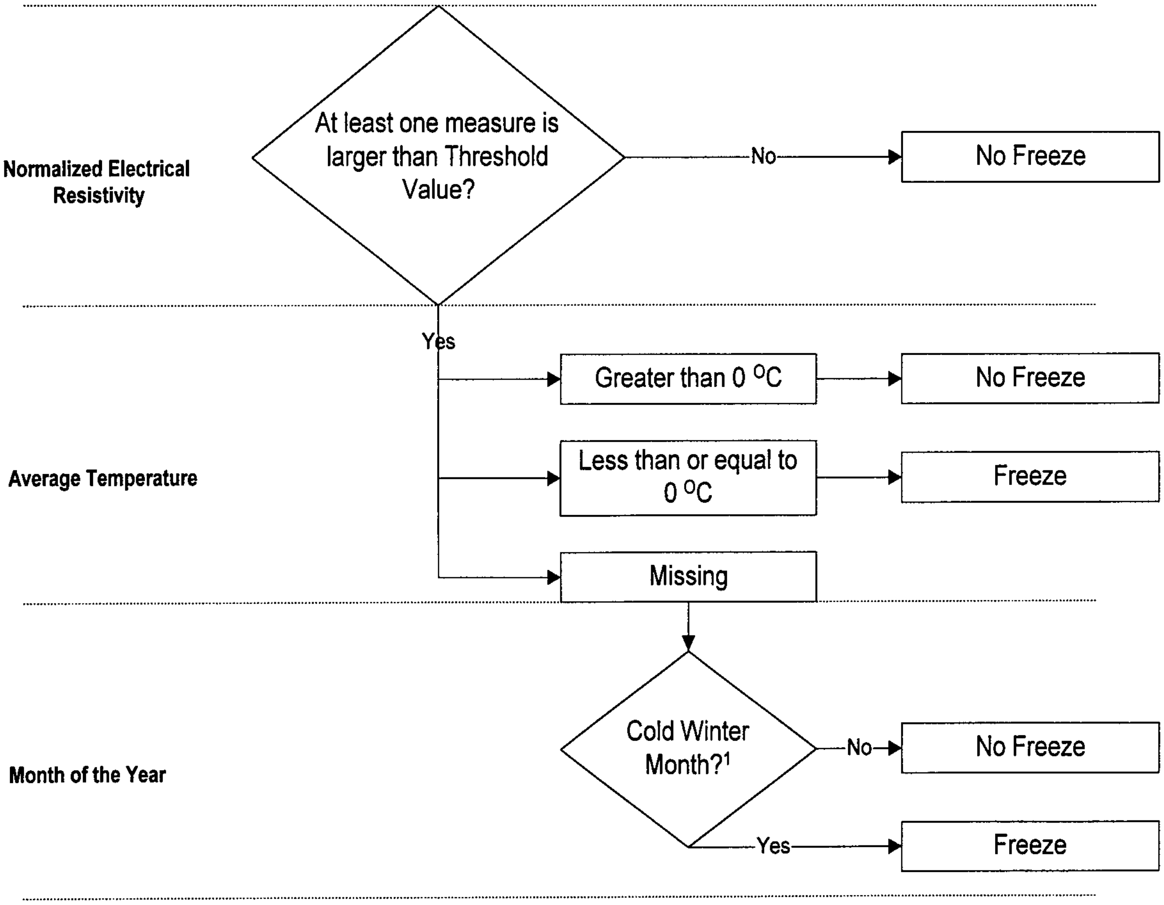
The following are the highlights of the procedure:

- Uses five variables simultaneously in the analysis (three ER measures, soil temperature, and date) to improve reliability.
- Uses normalized ER parameters that are based on relative values at each electrode, thereby reducing the noise due to material variability. Normalized ER measures are numbers between 0.0 and 1.0 representing the magnitude of resistance, resistivity, or voltage relative to their extreme values measured at a specific electrode. For instance, a normalized voltage value of 0.0 indicates that this reading is the lowest voltage value recorded at that electrode. A value of 1.0 corresponds to the highest value ever recorded at that electrode.
- Uses average ER values for a given date to stabilize diurnal variability.
- Software assists the user with warning messages and a variety of graphing views.

The procedure requires user interaction and familiarity with ER data interpretation.

Program Decision Tree

Figure 4 illustrates the decision process used by FROST to determine the freeze state. Table 9 provides the list of months during which negative soil temperatures were observed at the 27 SMP sections being assessed as part of this study. This information given in table 9 is necessary for cases where soil temperature is missing.



[1] Cold winter months were established based on the daily temperature records for each site. Cold winter months are defined as months during which negative (below 0°C) soil temperature values were observed at the top of the base layer.

Figure 4. FROST decision tree.

Table 9. Cold winter months during which freezing is expected

Section	From	To
041024	—	—
081053	Nov	Feb
091803	Jan	Mar
161010	Dec	Feb
183002	Dec	Mar
204054	Dec	Feb
231026	Nov	Apr
241634	Jan	Feb
251002	Jan	Mar
271018	Nov	Apr
271028	Nov	Apr
274040	Nov	Apr
276251	Nov	Apr
308129	Nov	Mar

Section	From	To
313018	Dec	Mar
331001	Nov	Mar
364018	Dec	Mar
421606	Dec	Mar
460804	Nov	Apr
493011	Nov	Mar
501002	Nov	Apr
561007	Nov	Apr
831801	Oct	Apr
833802	Oct	Apr
871622	Nov	Apr
893015	Nov	Apr
906405	Oct	Apr

User Influence

Selection of reasonable values for the ER threshold is important. If the user selects too low a value, the freeze state will be determined based on temperature only. If the user selects too high a value, the freeze state will be "no freeze," regardless of temperature. Guidelines for selecting the ER threshold values are presented later in this chapter.

Analysis Steps

The determination of the freeze state using ER and soil temperature data may be described in terms of three steps: preprocessing, processing, and smoothing. A brief description of each follows.

Preprocessing

FROST uses data from six IMS tables. To facilitate data acquisition and reduce the program run time, a single database table was created to store all data elements required by FROST. The ACCESS™ database table from which FROST reads and to which it writes needs to be in a specific format. The following steps are required to produce the intermediate variables required by FROST:

1. Compute measurement depth (the average depth of the electrodes used in the measurements). It is noted that each voltage and contact resistance measurement is performed using two electrodes and each resistivity measurement is performed using four electrodes.

2. Compute the average resistance, resistivity, and voltage for testing day and measurement depth.

3. Query contact resistance, resistivity, and voltage, for matching section, date, and measurement depth. The query should be designed to return all available records where at least one ER measure is available.

4. For each measurement depth, normalize resistivity, resistance, and voltage with respect to their extreme values. For instance, normalized resistivity may be computed according to the following formula:

   $$R_{N,i} = \frac{R_i - R_{\mathrm{min},\,i}}{R_{\mathrm{max},\,i} - R_{\mathrm{min},\,i}} \tag{3}$$

   where: $R_{N,i}$ = normalized resistivity, at measurement depth *i*.
   R_i = actual resistivity taken at measurement depth *i*.
   $R_{max,i}$ = maximum resistivity value measured at depth *i*.
   $R_{min,i}$ = minimum resistivity value measured at depth *i*.

   The normalized contact resistance and voltage can be obtained in a similar fashion. It should be noted that the actual and normalized ER values are linearly related and the normalization process does not "distort" the ER profiles.

5. Interpolate the average soil temperature at each ER measurement depth. As shown in figure 5, the measurement depths of ER probes do not match those of thermistor probes.

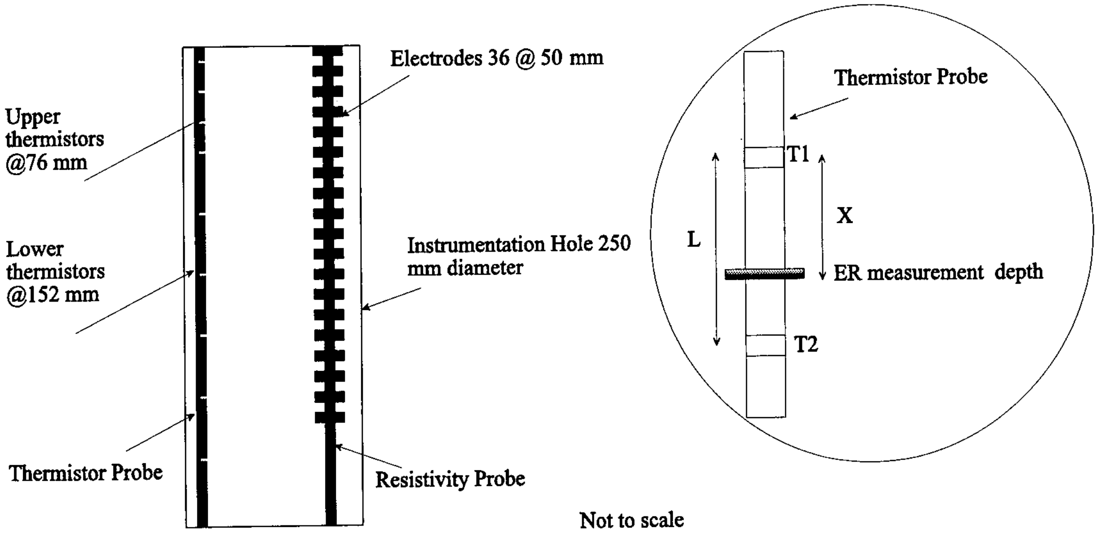


Figure 5. Schematic diagram of the arrangement of thermistor and resistivity probes.

To obtain the temperature at the ER measurement depth (as shown in the schematic), the following linear interpolation formula was used:

$$T_i = T_1 + (T_2 - T_1) * \frac{X}{L} \tag{4}$$

where:

T_i = interpolated temperature.
T_1 = temperature at the upper thermistor.
T_2 = temperature at the lower thermistor.
X = distance from the ER measurement depth to the upper thermistor.
L = distance between the two thermistors.

6. If same-day temperature is missing, then use temperature within 2 days. In 25 percent of the records (6,000 of 24,000), soil temperature data were missing. Missing temperature data can affect the determination of the frost penetration. Since the average absolute difference between the average temperature of any 2 consecutive days was 0.4 °C, temperatures within 2 days of the site visit date were used to fill in the missing temperature data. In so doing, the number of missing temperature records was reduced to about 1,800. The hierarchy used to select available temperature data is shown in table 10.

Table 10. Temperature substitution hierarchy.

First Preference	Same-day temperature
Second Preference	Previous-day temperature
Third Preference	Next-day temperature
Fourth Preference	2-days-previous temperature
Fifth Preference	2-days-later temperature

7. Determine cold winter months for each section based on historical temperatures. As shown in the FROST decision tree (figure 4), cold winter months are used to confirm ER peaks only if temperature data are missing. Table 9 shows the cold temperature months for the selected SMP sections, as determined from temperature data. Cold winter months were defined as those months in which a negative temperature (below 0 °C) was measured at the top unbound pavement layer.

Processing Using FROST

Once the data are prepared and saved in a specific format, FROST is used to determine the freeze state and frost penetration. As mentioned earlier, FROST requires user interaction to determine the soil freeze state. The user must input an ER threshold line that separates freezing from nonfreezing conditions. Guidelines on placing the ER threshold line are presented later. Based on these values, FROST determines the freeze state according to the decision tree shown in figure 4.

Smoothing the Frost Profile

In some cases, FROST determines a frost profile that may consist of thin layers of frozen soil and thawed pockets of soil. Although this may not be uncommon, it is possible that highly irregular frost profiles may be caused by noisy data. In addition, it is recognized that thawing and freezing often occur gradually, possibly forming zones of transitional freeze state. However, current ER data do not seem precise enough to enable reliable identification of such a transitional state. As such, the current method of ER data interpretation uses a "freeze/no-freeze" designation, with the inherent assumption that the transitional freeze state could be upgraded to freeze or downgraded to no-freeze based on the overall frost profile.

Electrical resistivity probes are placed approximately 50 mm apart, depthwise. Therefore, the layer thickness resolution for freeze-state determination is 50 mm. However, from a pavement engineering perspective, a 50-mm-thick layer of thawed soil between two thick frozen layers is very likely to be ignored, given the resolution of current structural analysis techniques. Based on these considerations, smoothing of the frost profile was implemented as follows:

- After using time-series ER plots to define the threshold line at the 35 measurement depths, FROST will display the frost penetration profile. The user should inspect the frost penetration profile and manually change the freeze state at any location on the graph. If the freezing condition at a particular point is in disagreement with surrounding points (e.g., the point shows freezing while the soil above and below show a no-freeze state), then the freeze state of that point could be forced to agree with that of surrounding soil. In addition to the option to manually change the freeze state, FROST includes an option to "smooth" the frost profile obtained at any given date.

- Selecting the automated smoothing option will invoke a procedure that starts from the top down, comparing the freeze state at each point with those of the points above and below it. If the freeze state is different from these two points, the freeze state at the point under consideration will be changed to agree with that of surrounding points. This procedure is executed for all points except the top point. Smoothing the frost penetration profile will only result in changes for layers less than 100 mm thick.

It should be noted that smoothing was performed in only 25 out of approximately 24,000 records, amounting to approximately 0.1 percent of the data.

Guidelines for Defining the ER Threshold Line in FROST

The concept involves drawing a threshold line that separates peak ER values from the rest of the data on the ER time-series plots. An ER peak is a relatively large ER value that occurs in cold temperature and winter months. Peaks are not consistent in their absolute values from one year to another. Therefore, the threshold line must account for all potential peaks for multi-year data. The program places a vertical line through each point having the right condition for freezing according to temperature or season. These points should be inspected carefully, since the user input will affect only these points. All other data points are automatically considered unfrozen, regardless of the user input.

The user should inspect the marked points and ensure that they are all above the threshold line. Marked points that do not show an ER peak (i.e., their ER values are not significantly larger than those of non-winter points) should not be placed above the threshold line, especially if placing such points above the threshold line may result in lowering the line such that non-winter readings will fall above the threshold line (which would violate the definition of the threshold line).

Tips

The analyst should be aware of the following:

- It does not matter how low or high the threshold line is, as long as it separates the peaks from the rest of the data. In many cases, the user has some flexibility in placing the threshold line and can still achieve the same results.

- Points midway between peaks and valleys should be included with peaks, as long as they occur in the winter months. In such cases, temperature will determine the freeze state for such observations.

- It does not matter if one, two, or all three of the ER measures are above the threshold line. If any measure is above the line, it is considered to be a candidate for a freezing condition. In most cases, the peaks of ER values are at different magnitudes. Therefore, the user does not need to place all ER peaks for a given date above the threshold line.

- Points located near the threshold line (especially at a freeze temperature) should be examined for discontinuity. If the freezing condition at that particular point is in disagreement with surrounding points, then the threshold line may be moved to produce more consistent results.

Example

Figure 6 shows an example plot used in the freeze-state determination. The plot represents the time-series of normalized ER measures and temperature for Saskatchewan section 906405, about 0.4 m below the pavement surface. Based on temperature and season, there are four incidents of possible freezing in the winter of 1993/1994, five in the winter of 1994/1995, and two in the winter of 1996/1997. These incidents are marked by a vertical line.

The user first attempts to place all marked points above the line. As indicated earlier, only the upper ER peak needs to be placed above the line. For instance, in the last possible freezing incident marked by the right-most vertical line in the graph, the line passes through three points: voltage (upper curve), resistance, then resistivity (lowest value). Only the upper peak for voltage needs to be placed above the threshold line.

It can be seen that some of the marked points do not show an ER peak and cannot be placed above the threshold line without bringing the line too low. Such points are left below the line, indicating a no-freeze condition.

Figure 7 shows a frost penetration profile at section 271028 in Minnesota. Each point in the graph represents the freeze state at a specific time and location. Dark areas indicate frozen soil, whereas white areas indicate unfrozen conditions. By clicking on any point on the graph, the user can access a number of utilities, including an interactive time-series ER plot (similar to that shown in figure 6), ER versus depth graph for the selected date (similar to that shown in figure 8), manual freeze-state change option, and frost profile smoothing option.

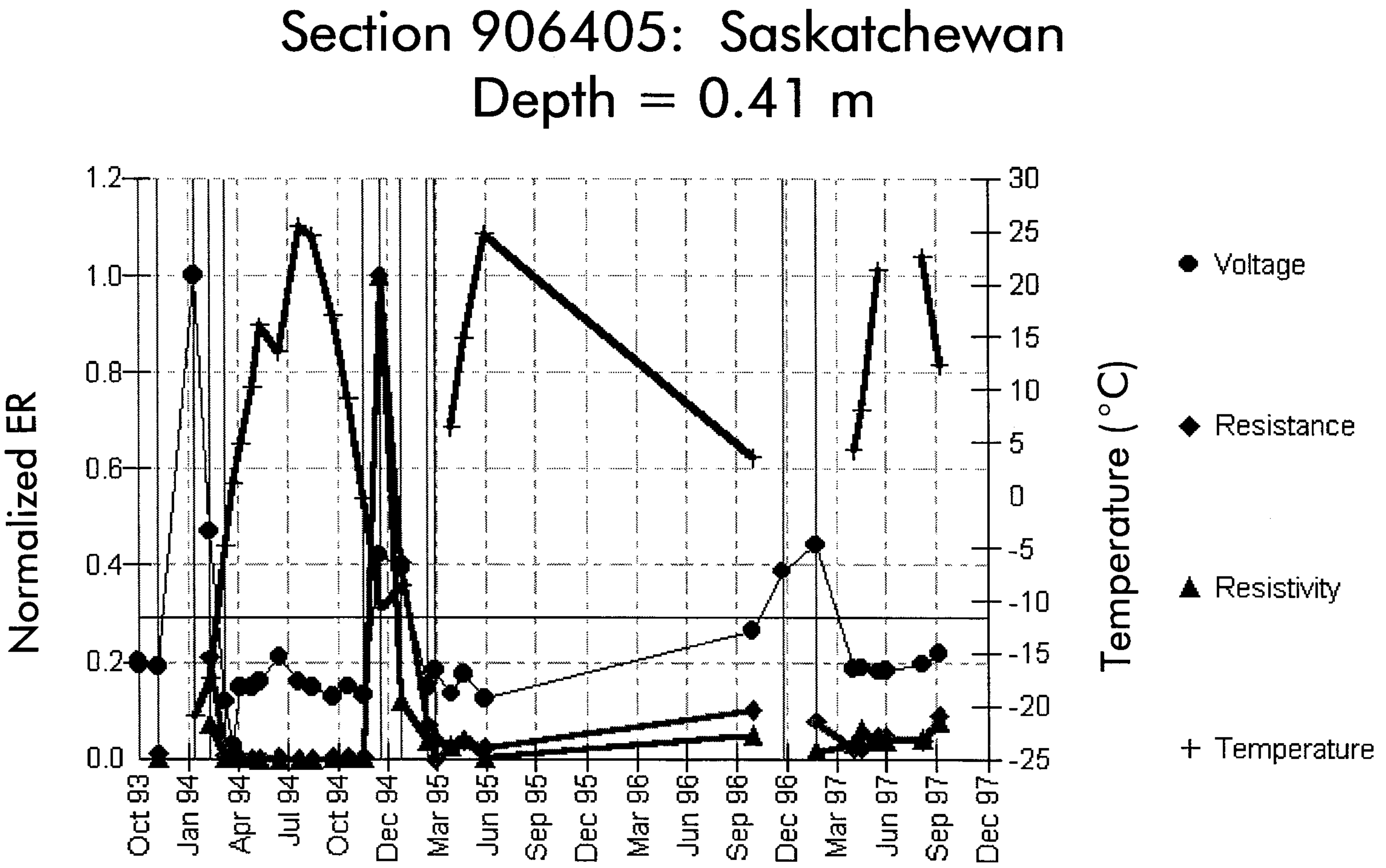


Figure 6. Example ER time-series graph produced by FROST.

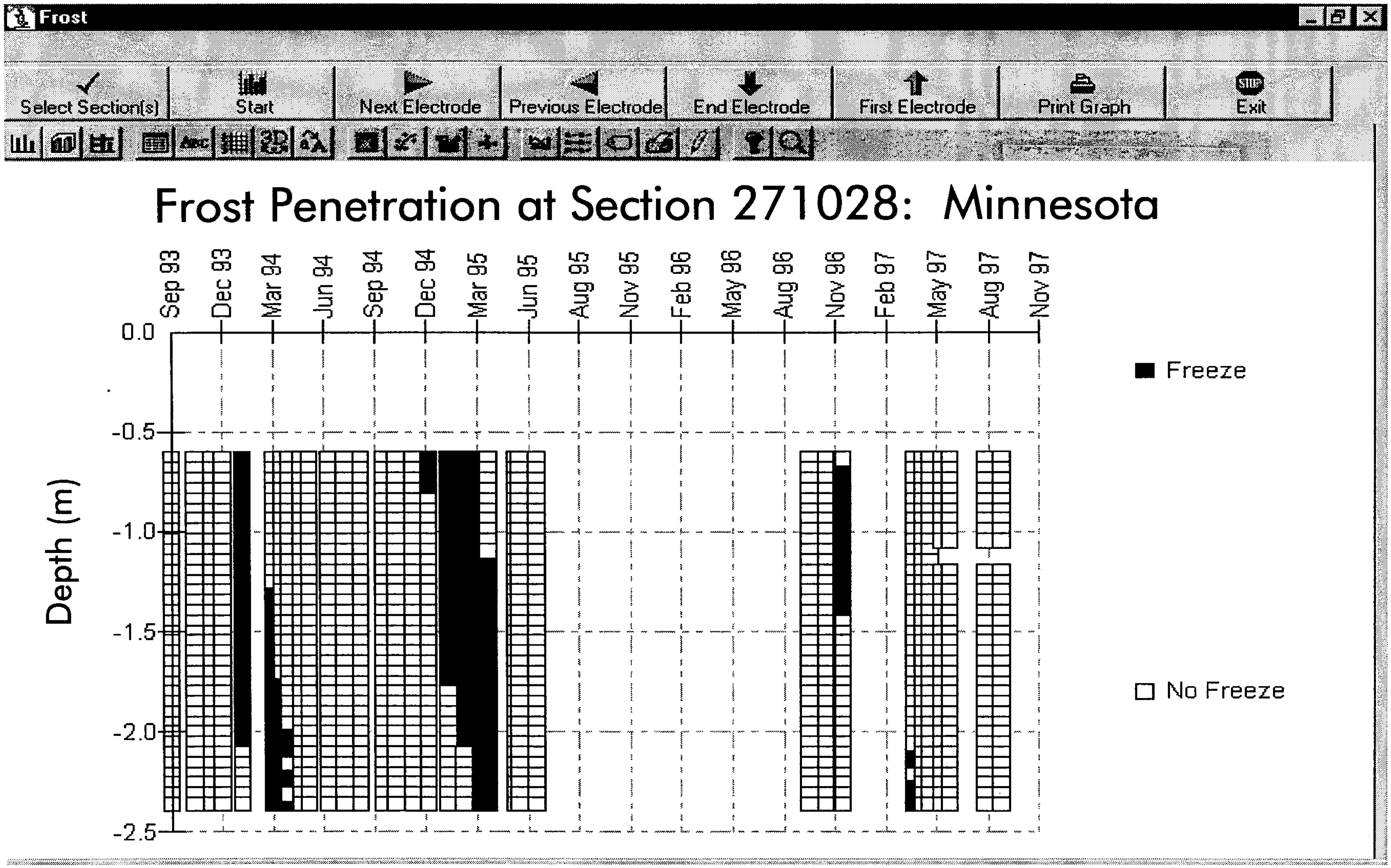


Figure 7. Example frost penetration graph produced by FROST.

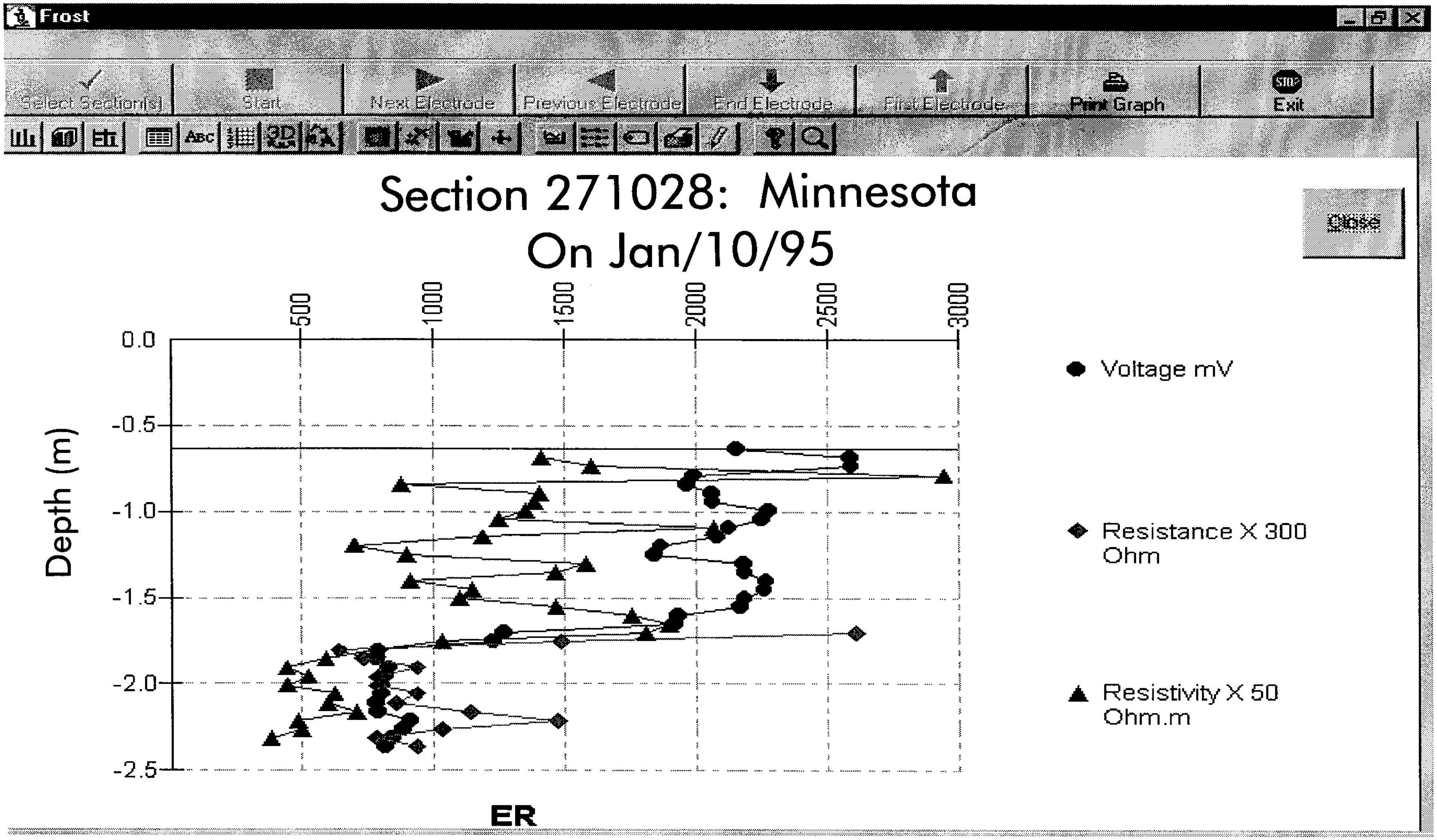


Figure 8. Example ER versus depth plot produced by FROST.

CHAPTER 5 - ANALYSIS RESULTS

The procedure used for ER data interpretation was described in chapter 4. The results of the analysis are presented in this chapter. To assess the reliability of the results, the computed frost penetration was compared to historical average frost penetration in each section, as found in climatic maps. Correlations with time-domain reflectometry (TDR) measurements were also investigated.

Frost Penetration Graphs

For each SMP section, a graph is created to depict the freezing profile during the entire data collection period. Appendix A contains these frost penetration plots for the 27 SMP sections that had valid ER data. Figure 9 is an example frost penetration plot for section 231026 in Maine. The graph shows the formation of frost some time between November 10, 1993, and January 10, 1994 (no readings in December 1993). The frost depth increases until it reaches 1.75 m below the pavement surface on February 28, 1994. It then thaws between March 24, 1994, and April 11, 1994.

Another freezing cycle was observed in the winter of 1994/1995. The frost formed between December 12, 1994, and January 17, 1995. It reached a maximum depth of 1 m on February 14, 1995, then thawed before March 6, 1995. It should be noted that the freeze cycle was shorter and the frost penetration shallower during the winter of 1994/1995 than that during the winter of 1993/1994. Samples of the interpretation plots are provided in appendix B, which shows the time-series ER plots used to define the threshold line at section 231026 in Maine.

Comparison With Historical Data

The computed frost penetration was compared to the historical value at each test location, as published in climatic maps. Figure 10 is a contour map of the average frost penetration depth in the United States, adopted from *Climatic Maps of Geologic Interest* [14]. The comparison between computed and historical frost depth is summarized in table 11. The table shows that for some sections, there is an excellent match, whereas for others, the difference between computed and historical depths is up to 0.8 m. A perfect match is not expected for the following reasons:

1. The estimates provided in the map are reflective of collective conditions that have occurred over a period of years. Observed conditions for any given day, week, month, or even year often differ sharply from those indicated in the map.

2. Within the same region, local conditions may vary due to factors such as soil type, soil moisture content, sunshine, altitude, or demographic activities. Such microchanges are not reflected in the map.

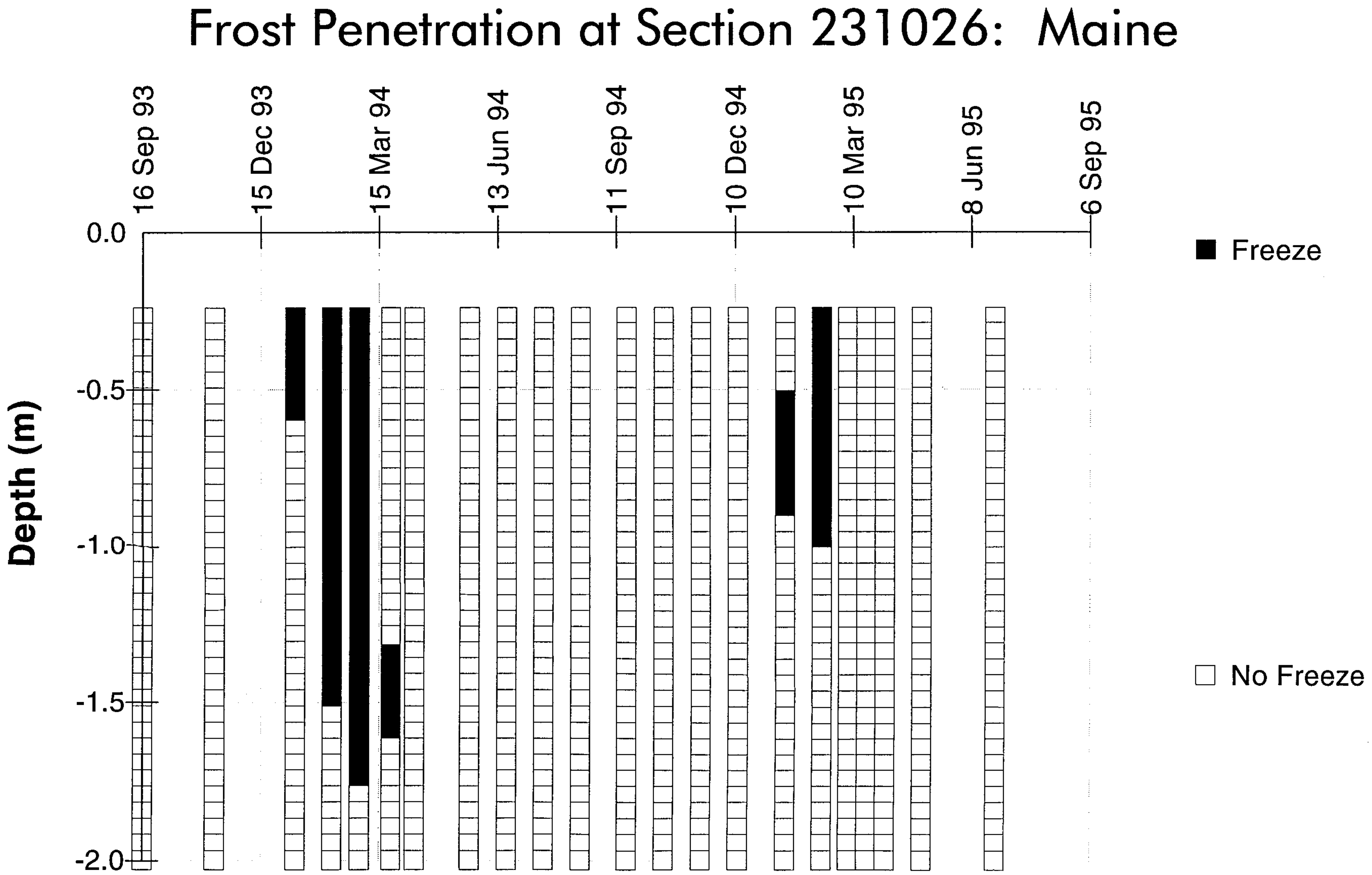
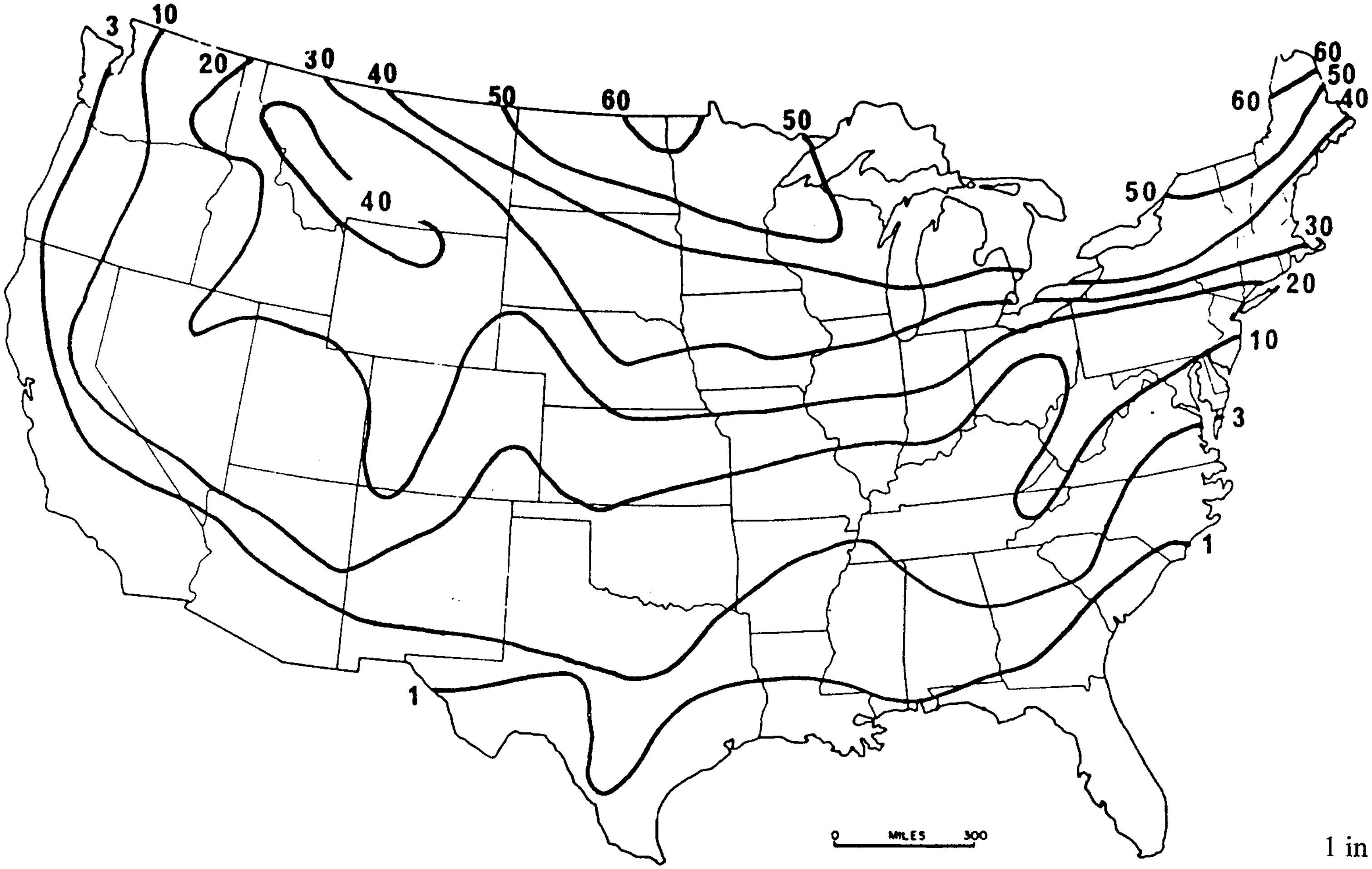


Figure 9. Sample frost penetration plot.



1 in = 25.4 mm
1 mi = 1.61 km

Figure 10. Average depth of frost penetration (inches) in the United States [14].

Table 11. Comparison between computed and average estimated frost penetration.

Section ID	State	Historic Average Frost Penetration (in)	Historic Average Frost Penetration (m)	Maximum Computed Frost Penetration (m)	Comments
041024	Arizona	1	0.0254	0	warm weather
081053	Colorado	20	0.508	0	warm weather
091803	Connecticut	25	0.635	0	mostly warm weather
161010	Idaho	25	0.635	0.75	
183002	Indiana	25	0.635	0	no sufficient winter readings
204054	Kansas	15	0.381	0	
231026	Maine	35	0.889	1.75	
241634	Maryland	7	0.1778	0	
251002	Massachusetts	30	0.762	0.75	
271018	Minnesota	45	1.143	2.2	
271028	Minnesota	45	1.143	2.3	
274040	Minnesota	45	1.143	2.0	
276251	Minnesota	45	1.143	2.25	
308129	Montana	40	1.016	1.05	
313018	Nebraska	25	0.635	1.2	
331001	New Hampshire	35	0.889	0	
364018	New York	45	1.143	2.0	
421606	Pennsylvania	15	0.381	0	
469187	South Dakota	35	0.889	1.2	
493011	Utah	15	0.381	0	
501002	Vermont	45	1.143	0.8	
561007	Wyoming	40	1.016	0	no winter readings
831801	Manitoba	55	1.397	1.5	
833802	Manitoba	55	1.397	1.5	
871622	Ontario	55	1.397	1.25	
893015	Quebec	60	1.524	1.55	
906405	Saskatchewan	50	1.27	2.05	

3. Although the map data provide estimates for natural (uncovered) land, the computed frost penetration was for conditions under pavements, which may very well affect the frost penetration. In addition, snow removal activities carried out by many northern State highway agencies use de-icing salts on the pavement, which eventually penetrate the soil and affect frost penetration.

In conclusion, the comparison with historical data showed reasonable agreement in most cases. In other cases, large discrepancies were found; however, such discrepancies were not surprising, given the approximate nature of the historical estimates and the length of the measurement intervals (approximately 1 month long).

Comparison With TDR Data

The Time-Domain Reflectometry (TDR) technique is being used in the SMP program to measure the dielectric constant of soils, which can be used to compute the in-situ moisture content. The moisture content computed using TDR data does not reflect the frozen water (ice content). Hence, when a soil freezes, its TDR-computed moisture content drops, since its unfrozen moisture content decreases. TDR data [15] were used to confirm the freezing events as determined by FROST.

In almost all sections, the existence of frost corresponded to a drop in unfrozen moisture content. Figure 11a shows a plot of frost penetration, and figure 11b is a plot of volumetric moisture content at section 274040 in Minnesota (adapted from reference 15). Comparing the two graphs, it is clear that in three winters (1993/1994, 1994/1995, and 1996/1997) frost penetration coincided with a sharp drop in unfrozen volumetric moisture content.

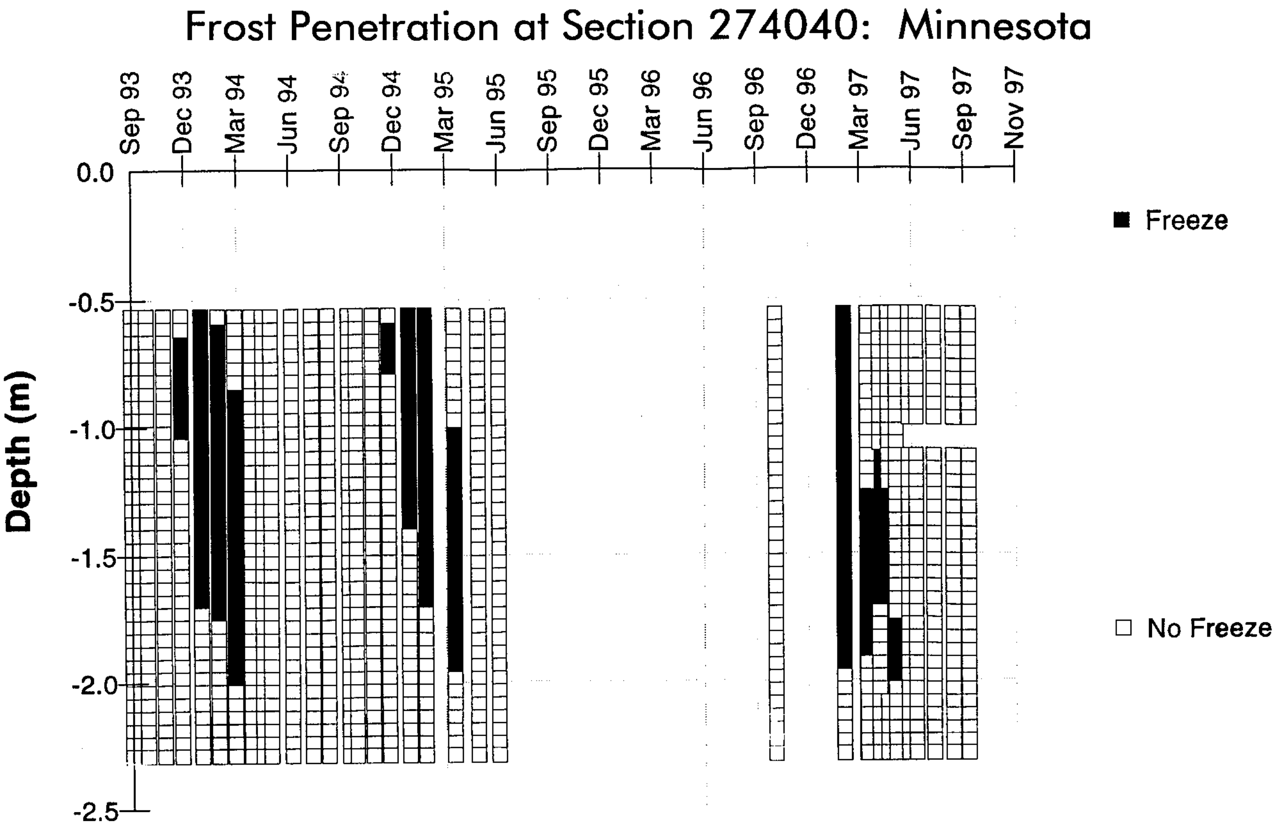
Similarly, figures 12a and 12b show the seasonal variation of frost penetration and unfrozen volumetric moisture content in section 041024 in Arizona. As shown, frost was determined and no sharp drops were observed in the unfrozen moisture content. The above comparisons show that although the two measurements implement different techniques, there was a good correspondence between TDR data and the freeze state as determined by FROST.

Reliability of Results

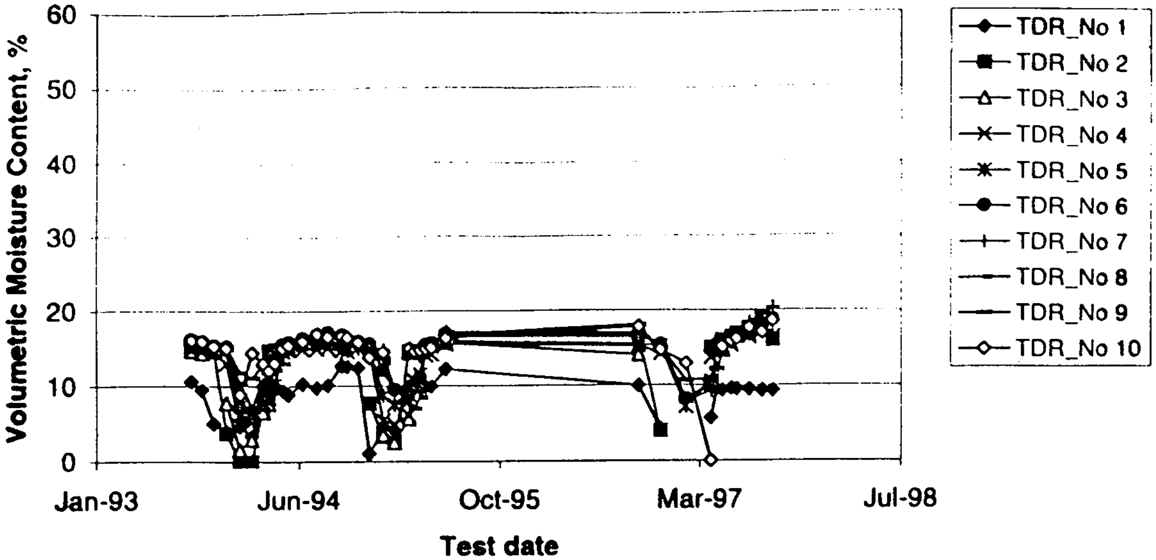
In theory, the overall system reliability (R^*) of a serial system that implements a number of components, each with item reliability R_i, may be computed by the following formula [16]:

$$R^* = \prod_{i=1}^{n} R_i \qquad (5)$$

In serial systems, the components feed from one to another, and any failure in one item will affect all other items. Hence, the reliability of the system is less than the smallest reliability of all items, and the system will fail if any component fails. If the components are connected in a parallel fashion, then the system reliability may be computed by:

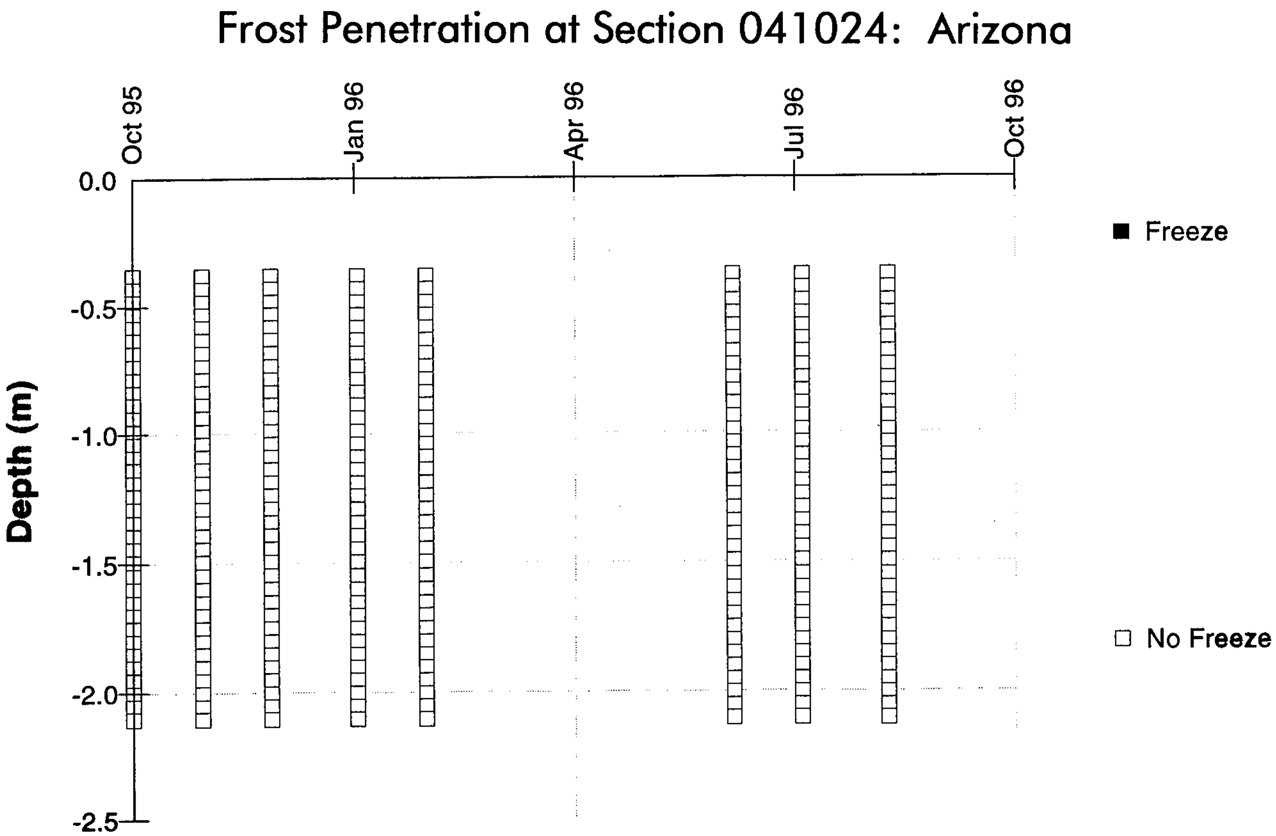


a. Frost Penetration

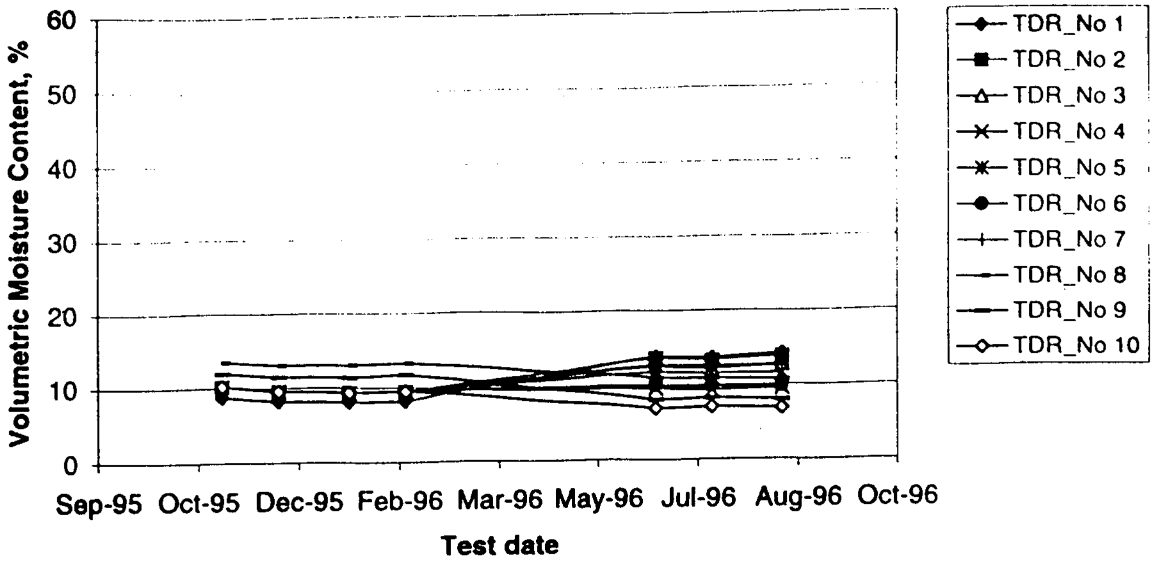


b. Volumetric Moisture Content

Figure 11. Comparison between the seasonal variation of frost and moisture content, section 274040.



a. Frost Penetration



b. Volumetric Moisture Content

Figure 12. Comparison between the seasonal variation of frost and moisture content, section 041024.

$$R^{*} = 1 - \left(\prod_{i=1}^{n} (1 - R_i) \right) \tag{6}$$

The procedure implemented in the determination of the soil freeze state uses a number of measures to arrive at a decision. Each measure can be used independently to determine the freeze state of the soil. For instance, soil temperature has long been used to determine freeze state. Local inhabitants of an area can estimate the frost penetration, given the time of the year, based on historical observations. Since each measure in the procedure (component of the system) can independently produce the final output, then the system reliability is that of a parallel system. Figure 13 is a schematic showing the system arrangement from the reliability analysis point of view.

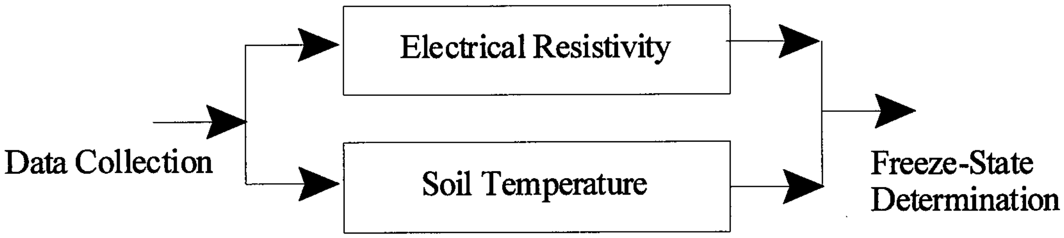


Figure 13. System arrangement for reliability analysis.

It is assumed that there are two measures connected in parallel: the ER measurements (including voltage, resistivity, and contact resistance) and soil temperature. Although the time of the year (date) was also used in the decision process, it was only used when temperature data were not available, amounting to only 7 percent of the observations.

Based on the diagnostic study of ER data presented in chapter 3, the reliability of ER measures is roughly estimated at 60 percent. Soil temperature is very reliable in determining the freeze state when the temperature is above freezing (unfrozen conditions). When the temperature is at or below freezing, the reliability is reduced because of factors such as depressed freezing temperature due to salinity, availability of moisture to freeze, and the isotherm conditions discussed earlier. The reliability of soil temperature to determine the freeze state may be roughly estimated as follows:

- Assumed reliability for determining the freeze state, when temperature is above freezing, is 90 percent.
- Percentage of records with temperature above freezing = 79 percent.
- Assumed reliability for determining the freeze state when temperature is at or below freezing is 50 percent.

- Percentage of records with temperature at or below freezing = 21 percent.
- Then the estimated average reliability is the weighted average of the two conditions, where the weights are based on the number of records. This amounts to an average reliability of 82 percent.

Substituting in equation 6 an ER reliability of 0.6 and a temperature reliability of 0.82, the overall reliability of the freeze-state determination is 93 percent. It should be noted that the reliability analysis presented here is based on estimates of component reliability. The latter encompasses factors such as measurement accuracy.

Interpretation Results

Two sets of results were obtained from program FROST. The first set of results identifies the freeze-state at all electrical resistivity sensor locations. The second set of results identifies the frost depth for each site per test visit to the site. These results are available in the LTPP IMS as part of the SMP_FREEZE_STATE and SMP_FROST_PENETRATION tables. The table SMP_FROST_PENETRATION is included as appendix C.

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the findings of this study and presents recommendations for future ER and related data collection and analysis practices. Although the recommendations are specific to the LTPP data collection and analysis practice, they should be of use to any user of electrical resistivity data.

Conclusions

The diagnostic study of soil temperature data revealed the following:

- The general temperature trends were reasonable and as expected. Comparisons between various temperature measures, taken at various times and locations, showed that the majority of temperature data appear reasonable and agree with expected trends. Missing, erroneous, and suspicious data were identified so they could be isolated from the database and their sources investigated.

- The use of the latent heat of fusion phenomenon to identify the timing of the soil phase change appears promising. The conditions used to identify a phase change event are negative temperature (below 0 °C) and constant temperature over a period of 2 days. These conditions identified a phase change in 20 of 45 SMP sections, with a plausible profile and reasonable timing for a phase change. However, there is a limitation dictated by the arbitrary assumption that the period of time over which constant temperature would indicate a phase change is 2 days. In actuality, this period is variable, depending on the rate of temperature change and the thermal properties of the soil. This limitation makes the latent heat of fusion method incomplete for identifying the timing of the soil phase change. Supporting measures from other sources (such as resistivity, resistance, and voltage data) are needed to complement the latent heat of fusion method.

The diagnostic study of ER data revealed the following:

- The three ER measurements (voltage, resistivity, and resistance) were consistent with each other in about 60 percent of the cases (including partial and total agreements). In the remaining 40 percent of the cases, it is conceivable that different results can be obtained using different resistivity measures.

- Each resistivity measure was found to have some advantages over other measures. Contact resistance seemed to be more in agreement with other resistivity measures than were resistivity or voltage. Resistivity data had lower diurnal variability and had more sections with larger winter to non-winter variability ratios than contact resistance. Voltage data seemed to be more stable (low diurnal variation) and had no zero value records.

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- Since resistivity measures are not fully redundant and each has some advantage over the others, more reliable results can be obtained by using all measures simultaneously.

- Some or all resistivity measures were successful in identifying freezing conditions in about 60 percent of the observations. In the remaining 40 percent of the observations, none of the resistivity measures was successful in identifying freezing conditions. The freezing-triggered ER peaks are masked by large non-winter, seasonal, and diurnal variabilities. In addition, more noise may be introduced by data collection problems. With the noise inherent in ER data, fully automated interpretation procedures are not considered reliable at the present time.

- The fact that very large resistivity values were observed in unfrozen conditions suggests that temperature data must play an important role in the interpretation of ER data. Therefore, the analysis of ER should be based on resistivity, resistance, voltage, temperature, and other supporting data, such as time of the year, location of measurement, and knowledge of established freezing patterns in any given location.

The quest for an optimum and practical method of ER data analysis yielded the following:

- An interactive computer program has been developed to process ER data to determine the frost penetration in SMP sections. The program, called FROST, determines the freeze state of a soil based on the values of three ER measures (voltage, contact resistance, resistivity) and soil temperature. Based on time-series plots of all ER variables at each depth and temperature data, the user determines the threshold ER value above which the soil is potentially frozen. If the soil temperature is negative (below 0 °C) and the ER value is larger than the established threshold, the soil is considered frozen.

- The procedure implemented in FROST has the following advantages.

    - Uses five variables simultaneously (three ER measures, soil temperature, and date) to improve reliability.
    - Uses normalized ER parameters based on relative values at each electrode, thereby reducing the noise due to material variability.
    - Uses average ER values for a given date to stabilize diurnal variability.
    - Software assists the user with warning messages and a variety of graphical reports.

- FROST has been used to process ER data and produce the tables of computed parameters (freeze state and frost penetration) for inclusion in the LTPP IMS database. The frost penetration profiles were compared with historic values and were found to be in reasonable agreement with expectations. Furthermore, an excellent correlation between freezing events, as determined by FROST, and a sharp decrease in the unfrozen moisture content (as measured by TDR) was found for most sites where such data were available.

Recommendations

Based on the findings of this research effort, the following are recommended to improve future collection and analysis of ER data:

- Although the theory behind the ER technique is sound, the noise inherent in ER data made the task of data analysis laborious. It appears that the ER probes are sensitive to exogenous variables, some of which are not easily controlled. One example is the quality of contact between the electrodes and the soil, which may change with time. Other factors that contribute to the noise in the data include durability of the ER probes and data collection errors. It appears that the quality of ER data can be improved by the following means:

    - Development of more durable and robust hardware to avoid current problems.
    - Use of an automated data collection system to avoid human errors.
    - Adoption of a more rigorous instrumentation and data collection protocol.
    - Conduct of laboratory testing to further understand the characteristics of ER data.

- Other immediate steps can also be taken to improve the ER data resolution. These include:

    - More frequent ER data collection to help screen out outliers. Currently, in SMP sections, ER data are collected approximately once a month (with multiple readings on the testing day). The long time lapse between the readings makes it difficult to conclude whether the large change in resistivity is caused by equipment malfunction or by a change in the soil state.
    - Inspecting ER data as they are collected and comparing them to previous readings to identify erroneous data. Atkins [19] recommends the following:

        > *After the readings have been recorded, they should be graphed or otherwise analyzed to ensure that the measurements are reasonable and that they agree with any other available data (such as temperature probes for example). This data reduction process should not be left for too long a period of time after the data has been taken. For example, it is not a good idea to process and review the data just once a month since after a thirty day period it will be too late to discover the cause of any extraneous*

readings!! The best approach is to graph or otherwise analyze the data the same day it is recorded. If it is not possible to process the data the same day that it is taken, then at the very least, a weekly analysis of the data is highly recommended!!

- It is recommended that other techniques be explored to supplement, complement, or be substituted for the ER technique. For instance, the Mn/Road program relies on Watermark™ plugs for frost penetration determination. The Watermark™ plugs, which are based on measurement of the soil suction, were reported to have a reliable, identifiable, sharp increase in suction when the soil freezes. Once the frost penetration is determined in the locations of the Watermark™ plugs, ER data are then used cautiously to fill in the gaps in two-dimensional graphs.

- For the short- and mid-term analysis of ER data, the interactive procedure implemented in FROST (described in chapter 4) is recommended. In the long term, enhancements to the procedure may evolve to a fully automated method when better understanding and control of ER data are achieved.

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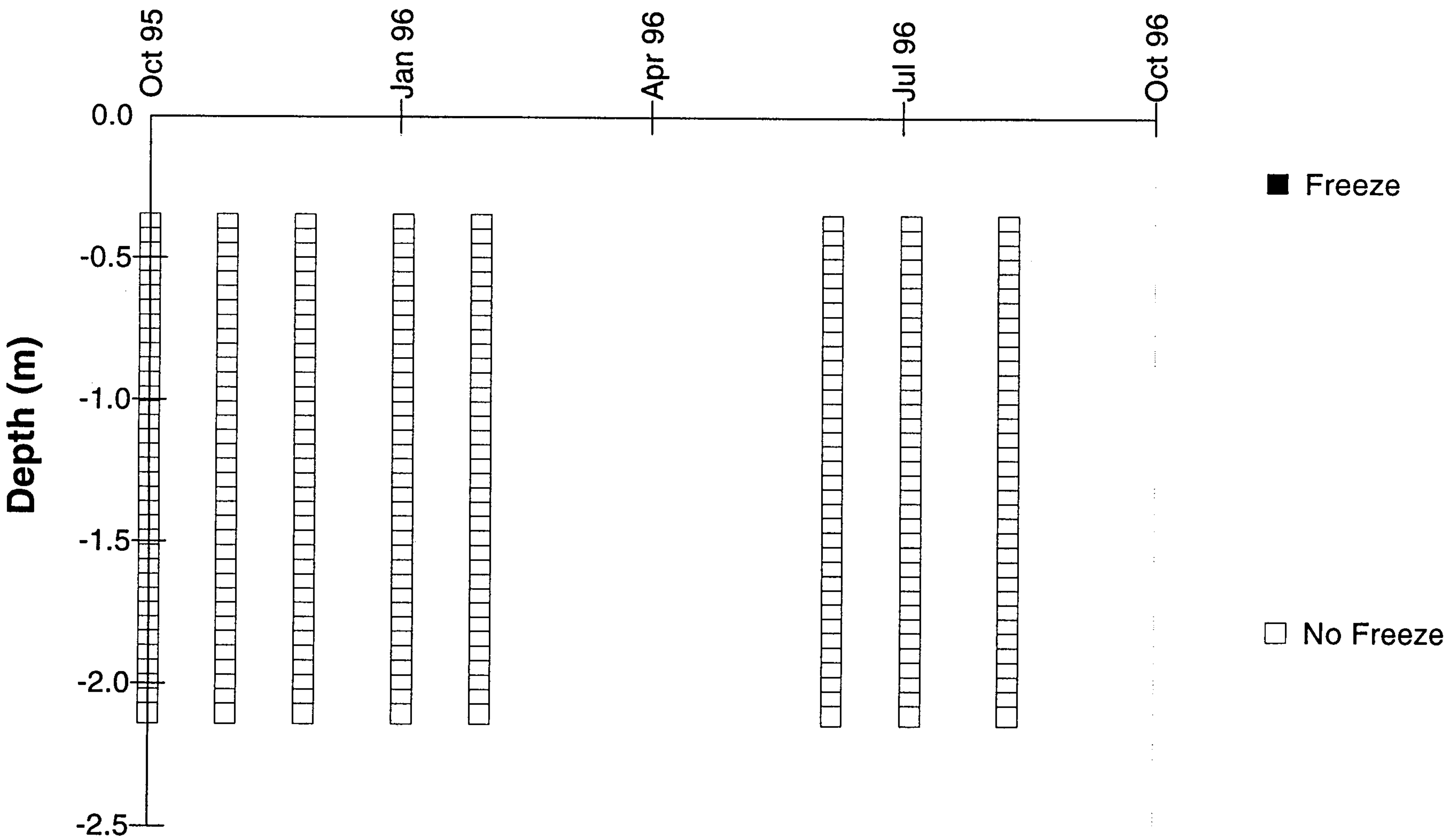
APPENDIX A - FROST PENETRATION PLOTS

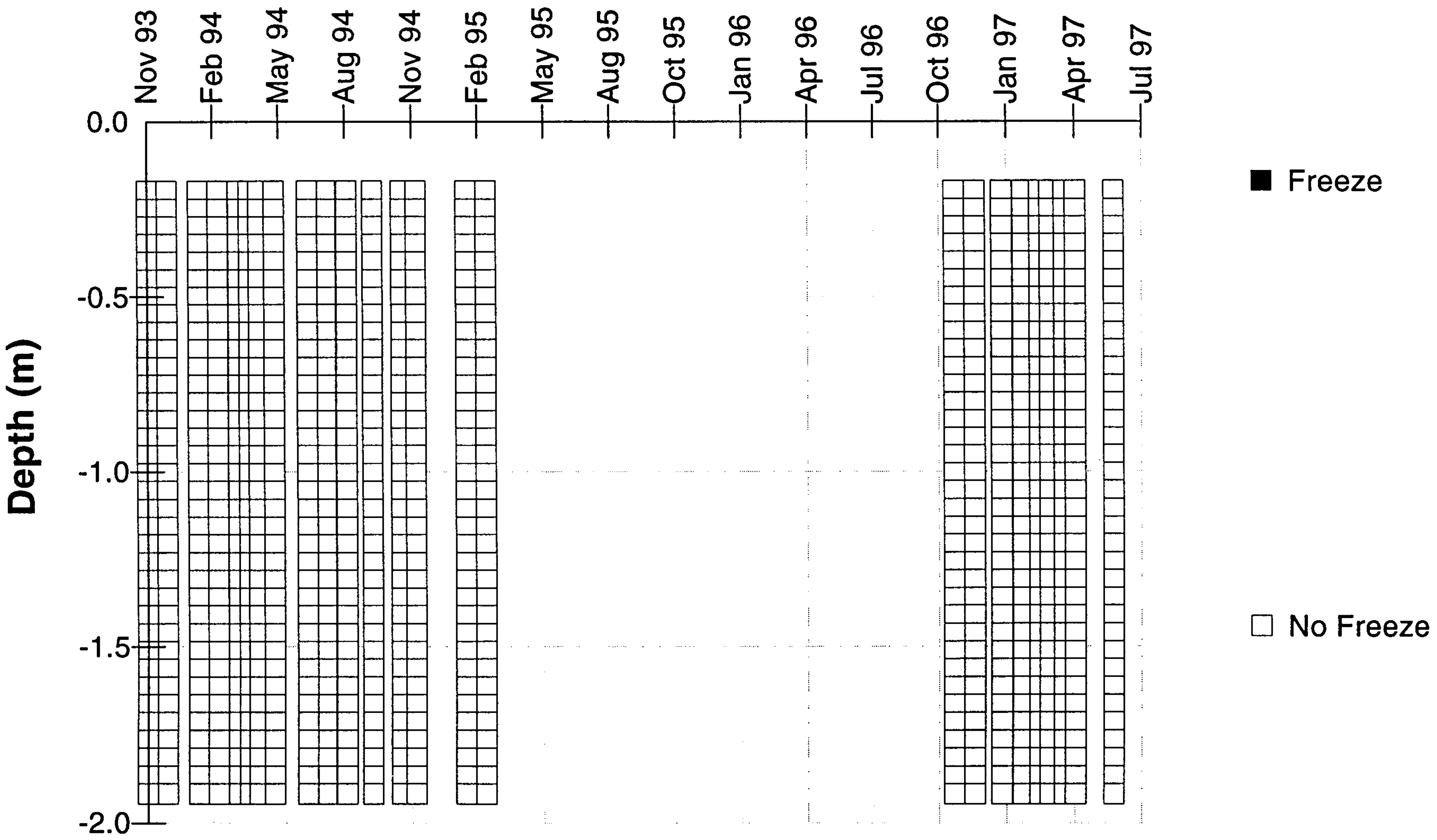
Frost penetration plots are provided for the following sections:

Number	Section ID	State Name
1	041024	Arizona
2	081053	Colorado
3	091803	Connecticut
4	161010	Idaho
5	183002	Indiana
6	204054	Kansas
7	231026	Maine
8	241634	Maryland
9	251002	Massachusetts
10	271018	Minnesota
11	271028	Minnesota
12	276251	Minnesota
13	274040	Minnesota
14	308129	Montana
15	313018	Nebraska
16	331001	New Hampshire
17	364018	New York
18	421606	Pennsylvania
19	460804	South Dakota
20	493011	Utah
21	501002	Vermont
22	561007	Wyoming
23	831801	Manitoba
24	833802	Manitoba
25	871622	Ontario
26	893015	Quebec
27	906405	Saskatchewan

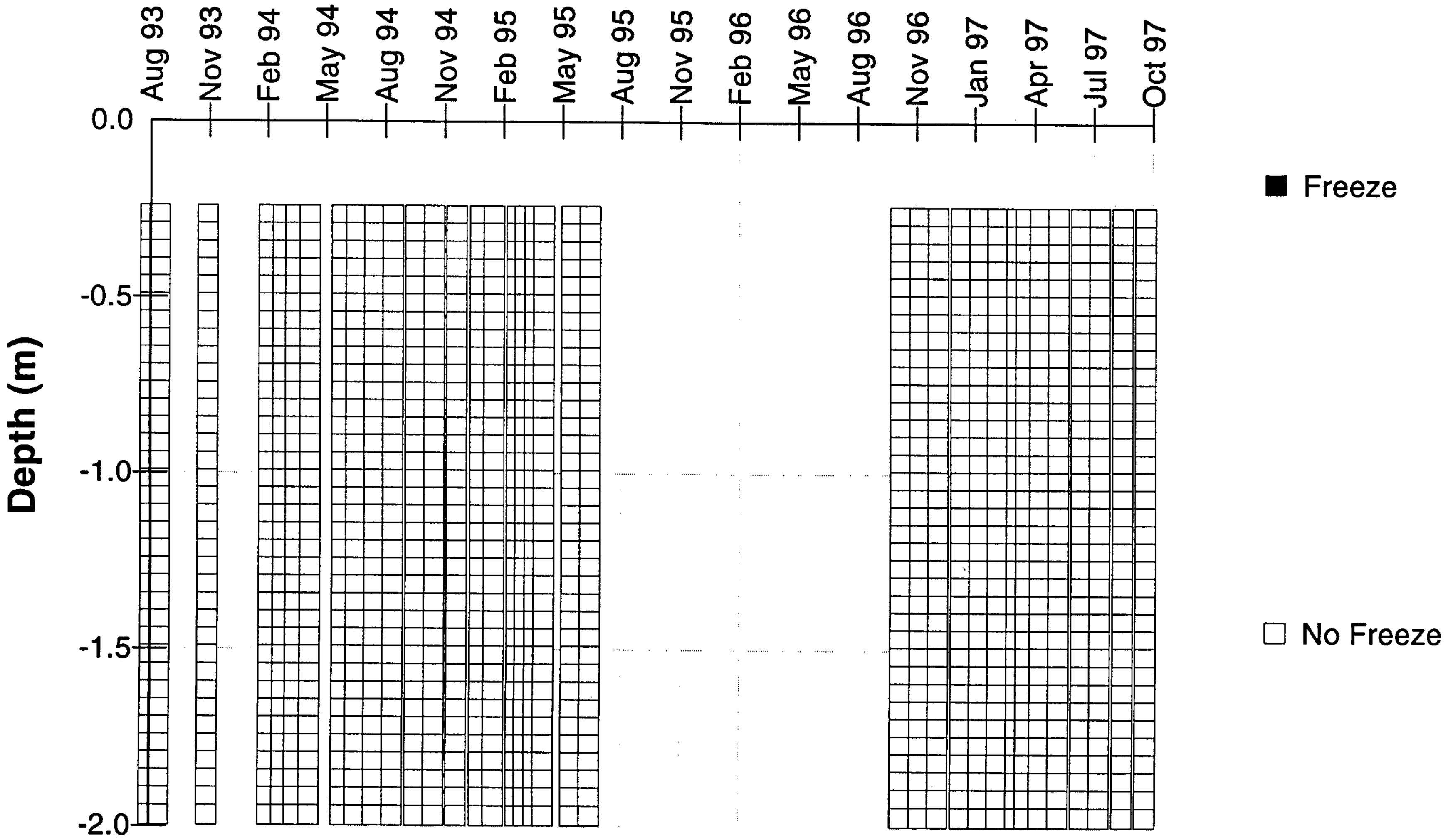
Frost Penetration at Section 041024: Arizona



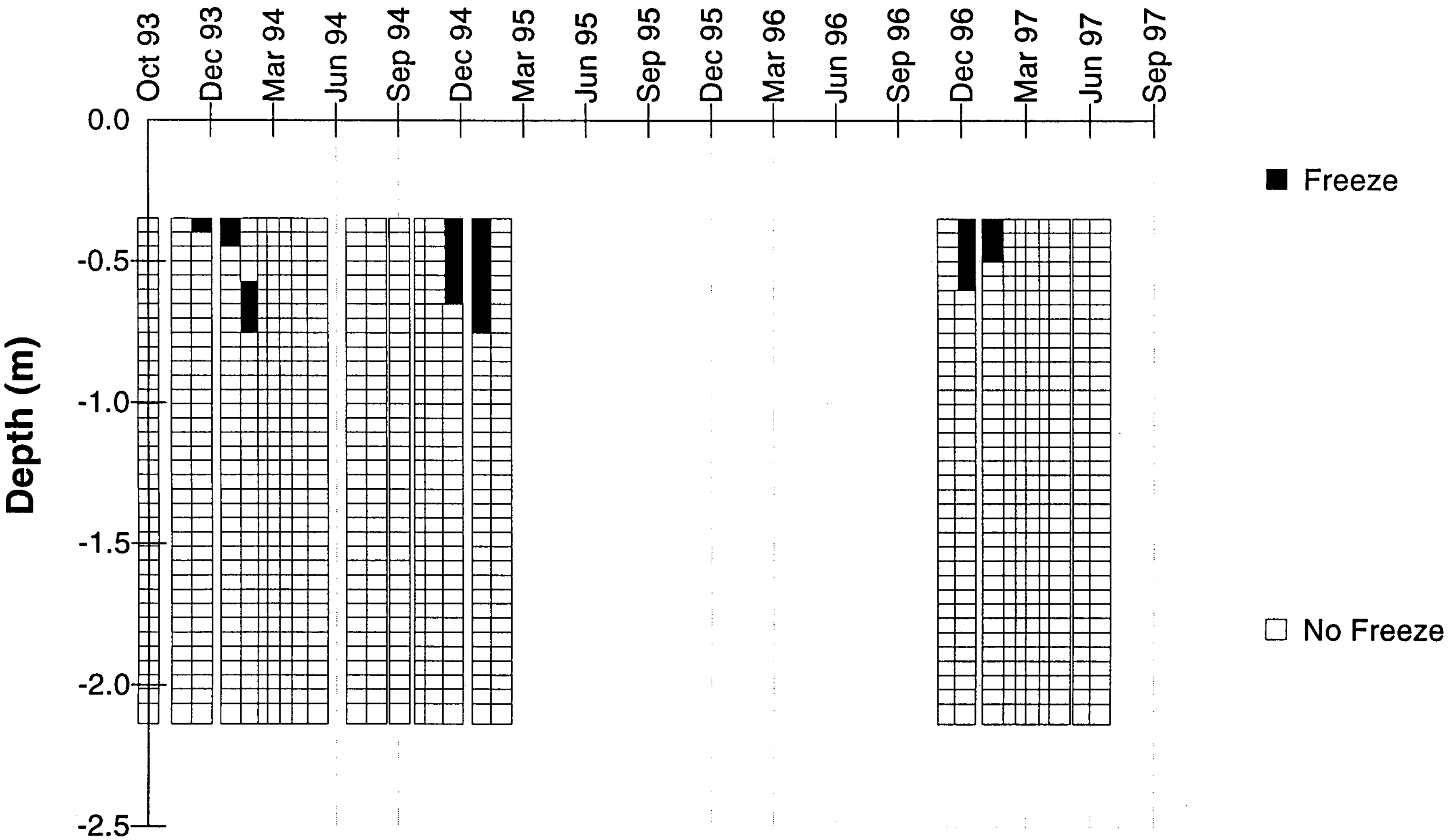
Frost Penetration at Section 081053: Colorado



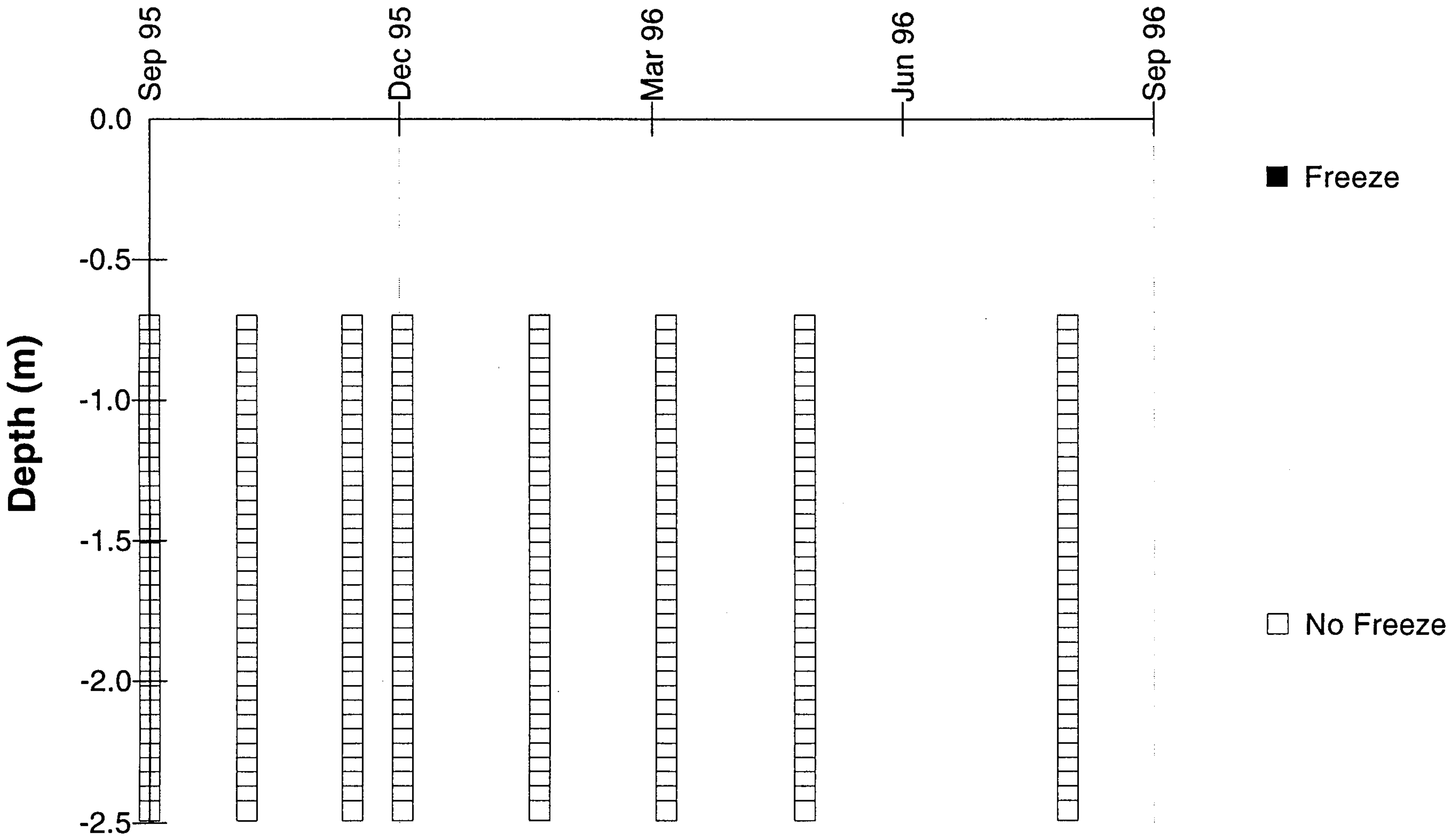
Frost Penetration at Section 091803: Connecticut



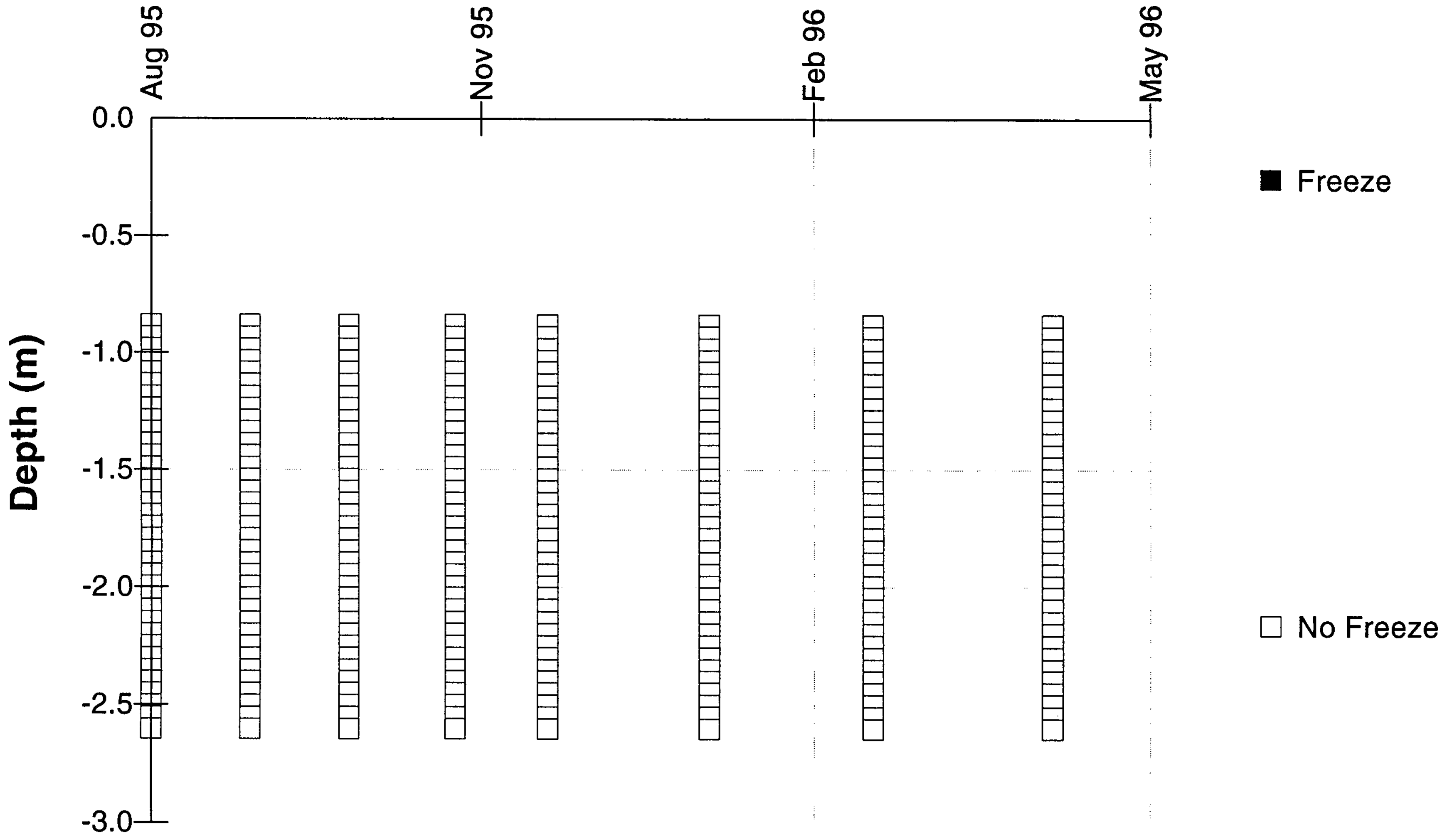
Frost Penetration at Section 161010: Idaho



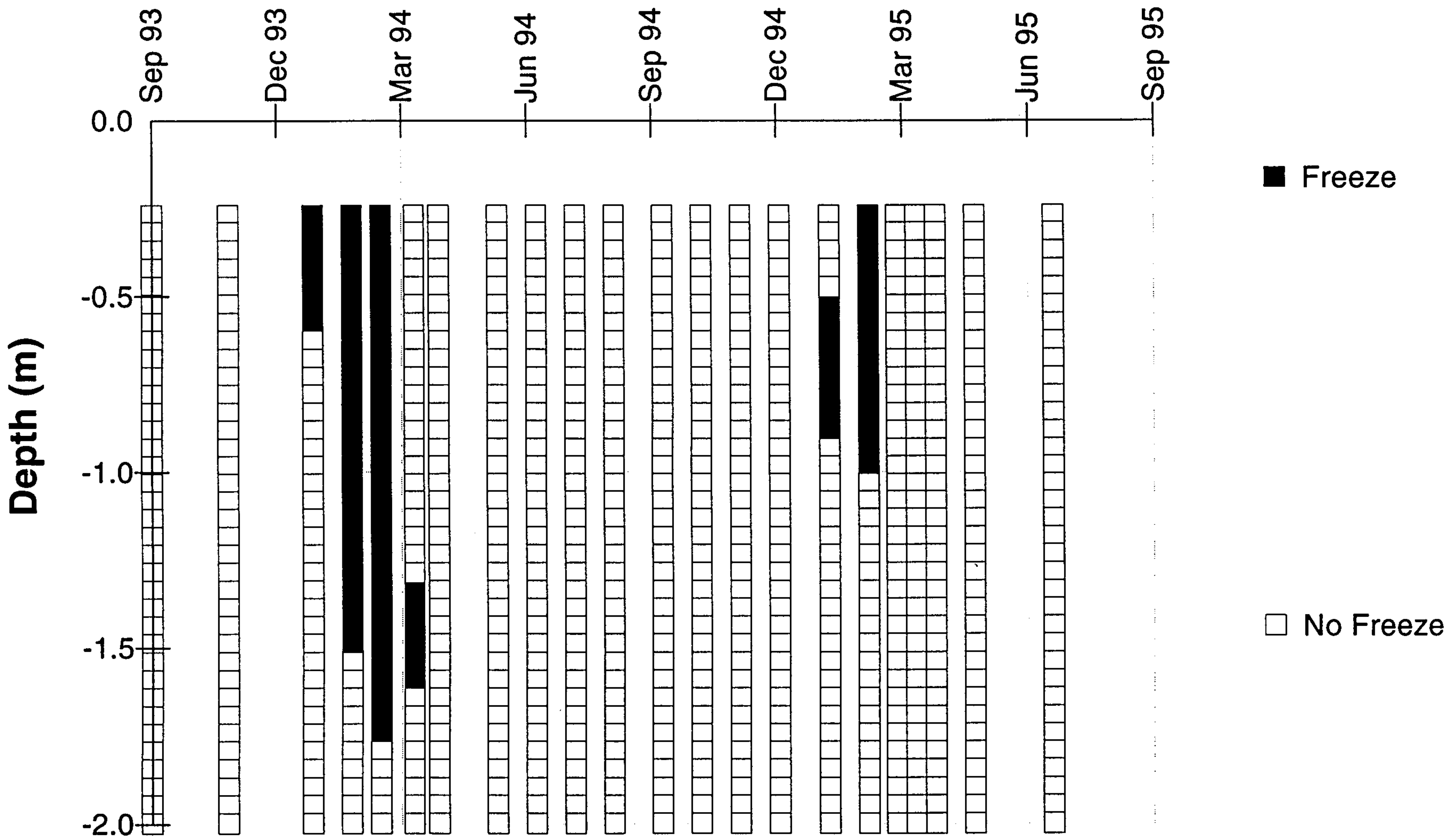
Frost Penetration at Section 183002: Indiana



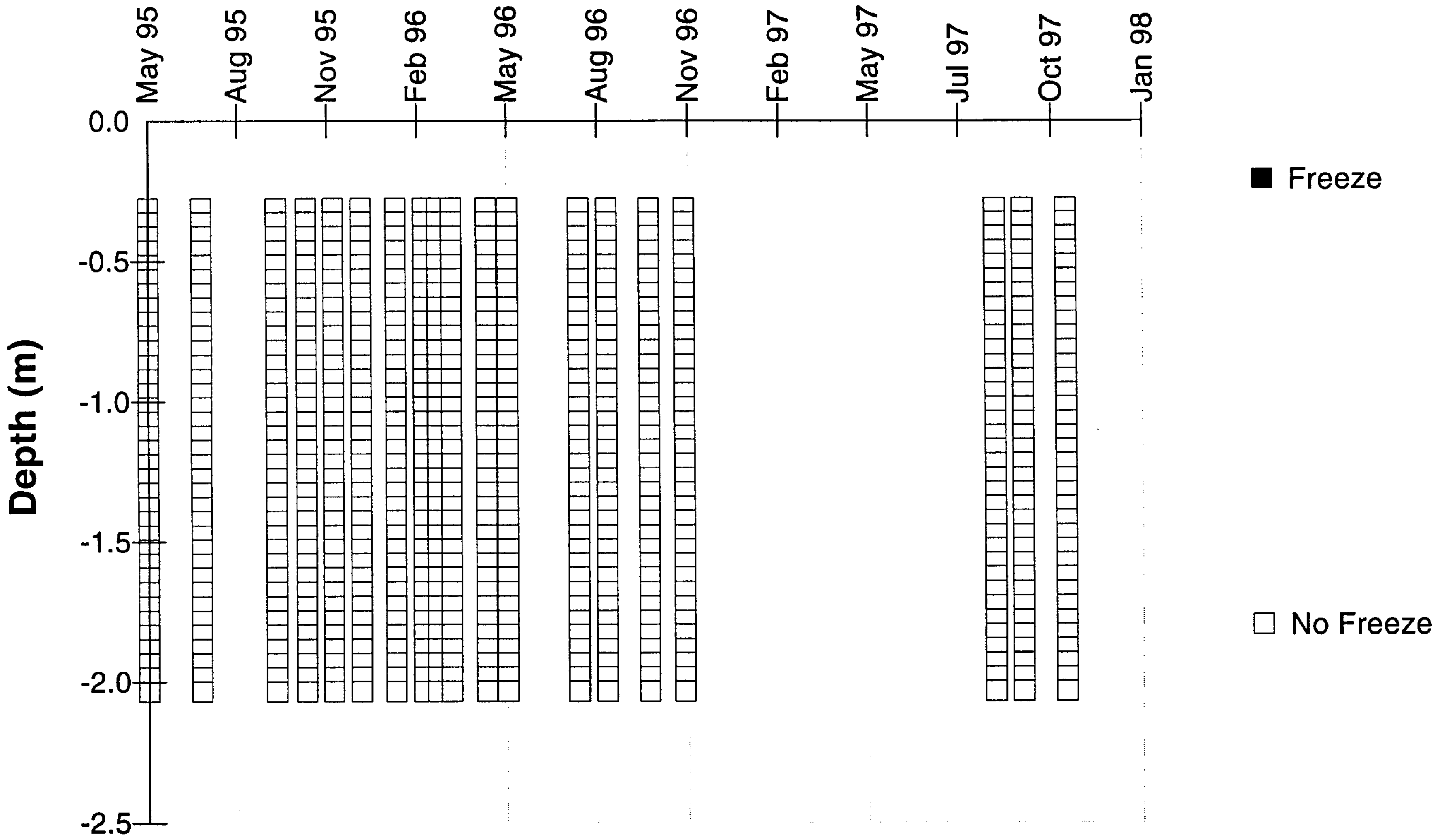
Frost Penetration at Section 204054: Kansas



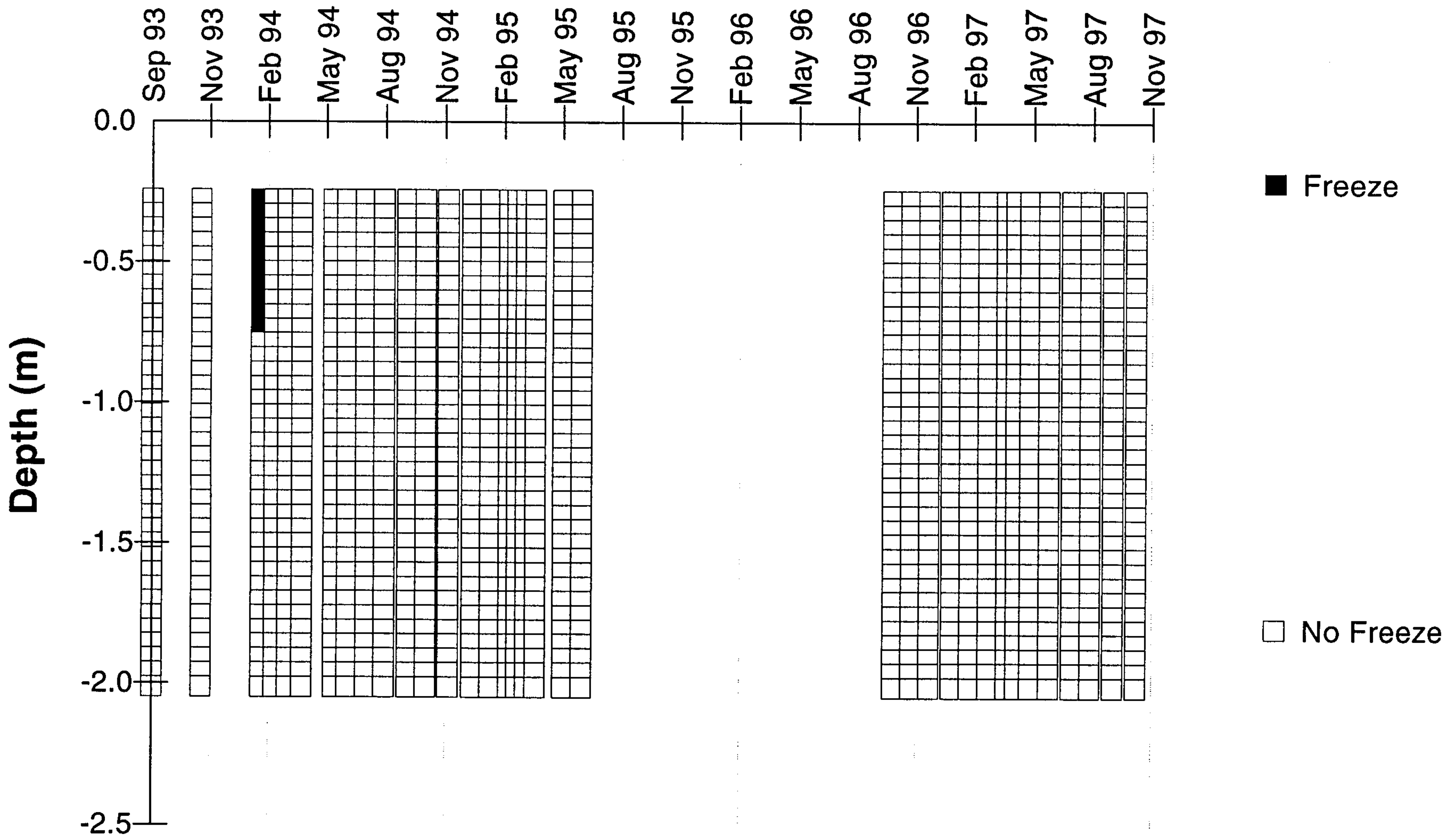
Frost Penetration at Section 231026: Maine



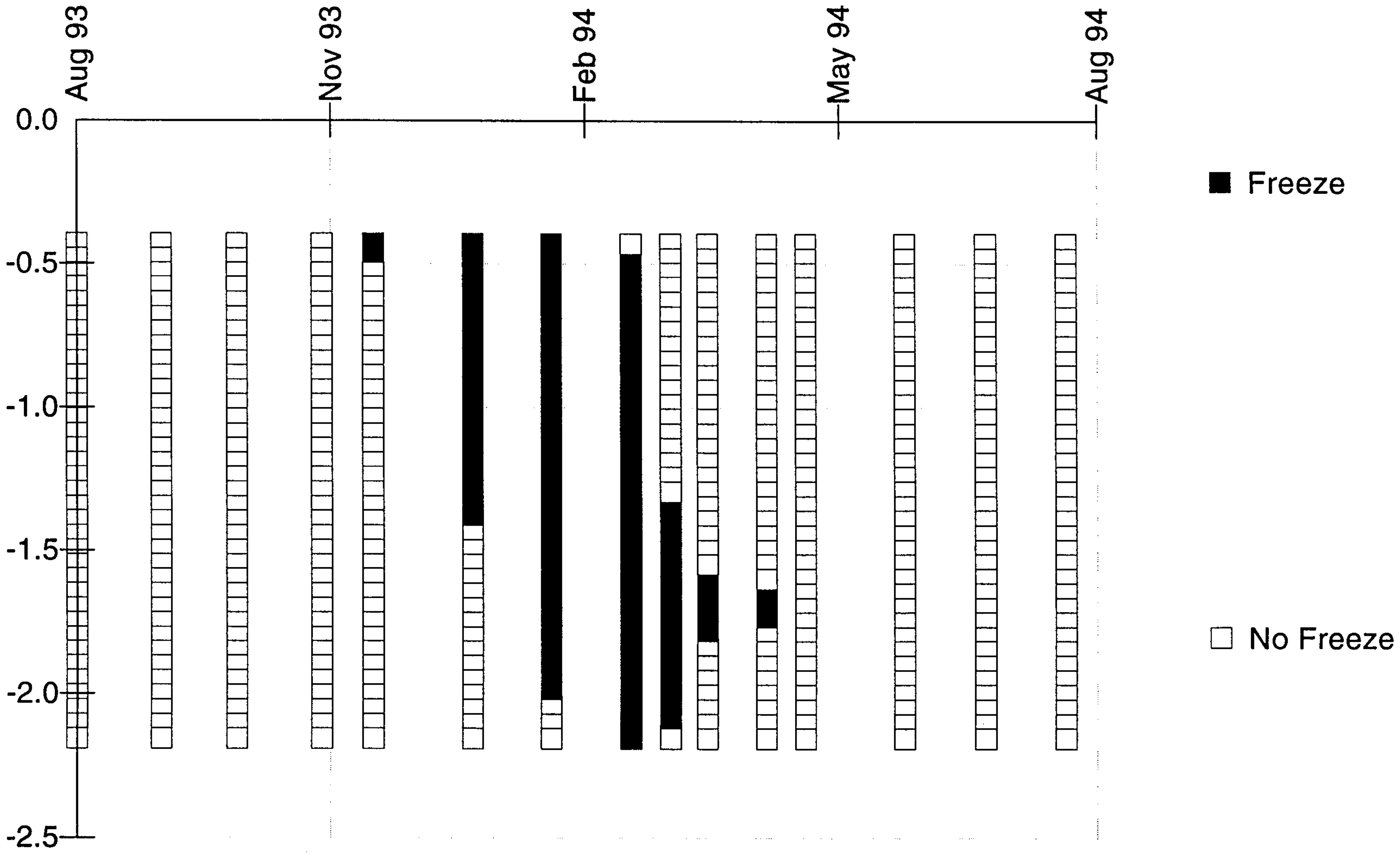
Frost Penetration at Section 241634: Maryland



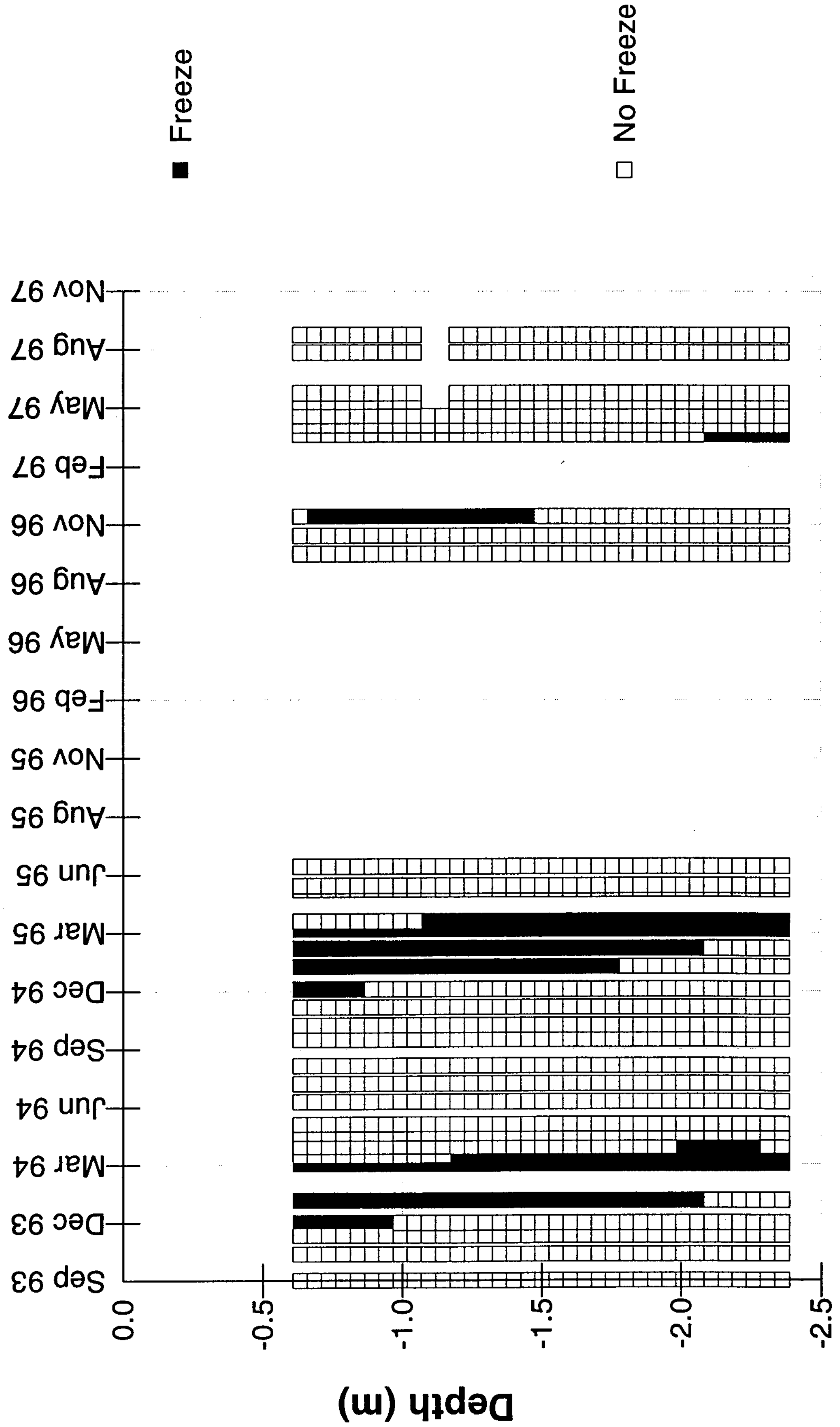
Frost Penetration at Section 251002: Massachusetts



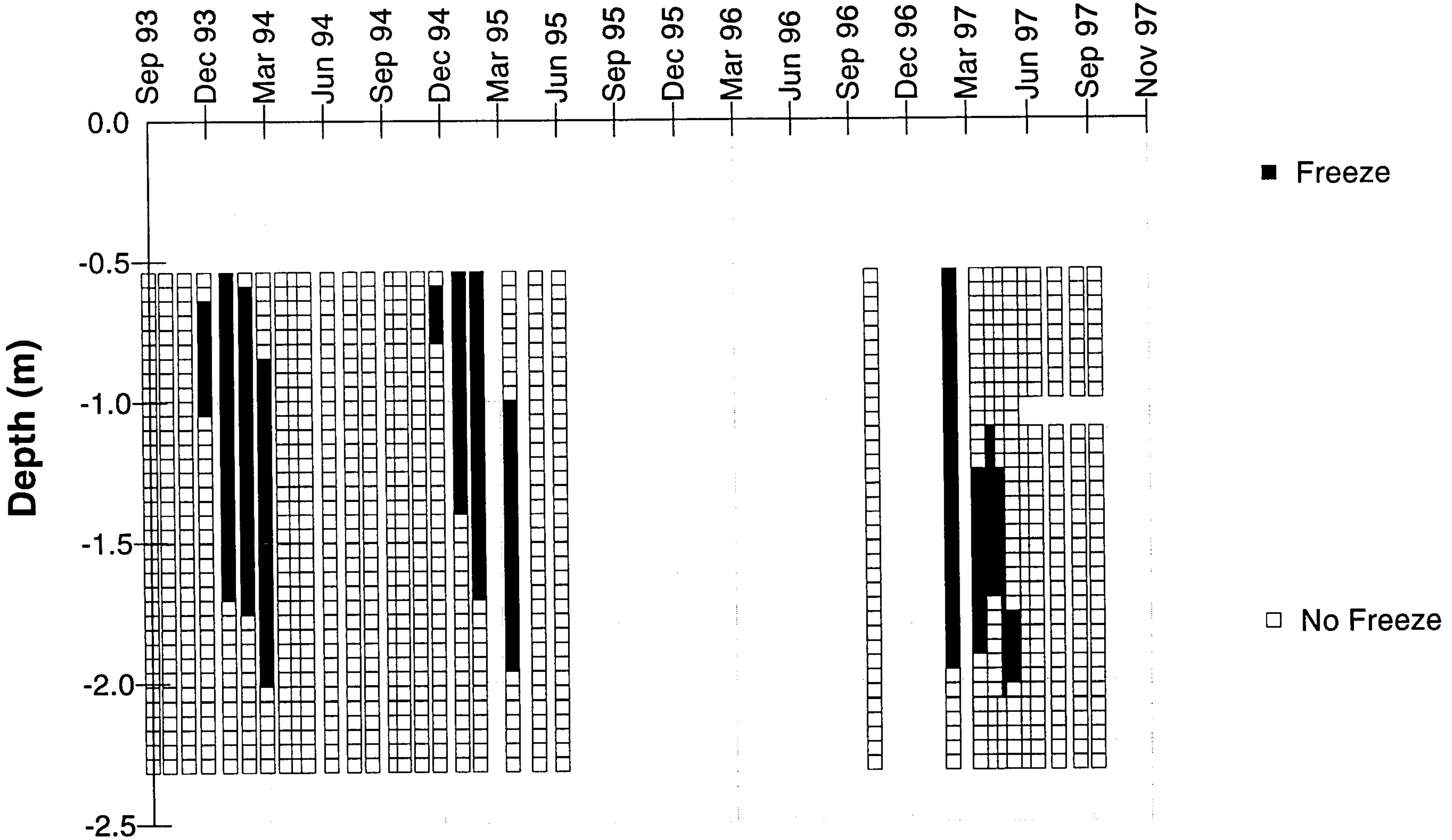
Frost Penetration at Section 271018: Minnesota



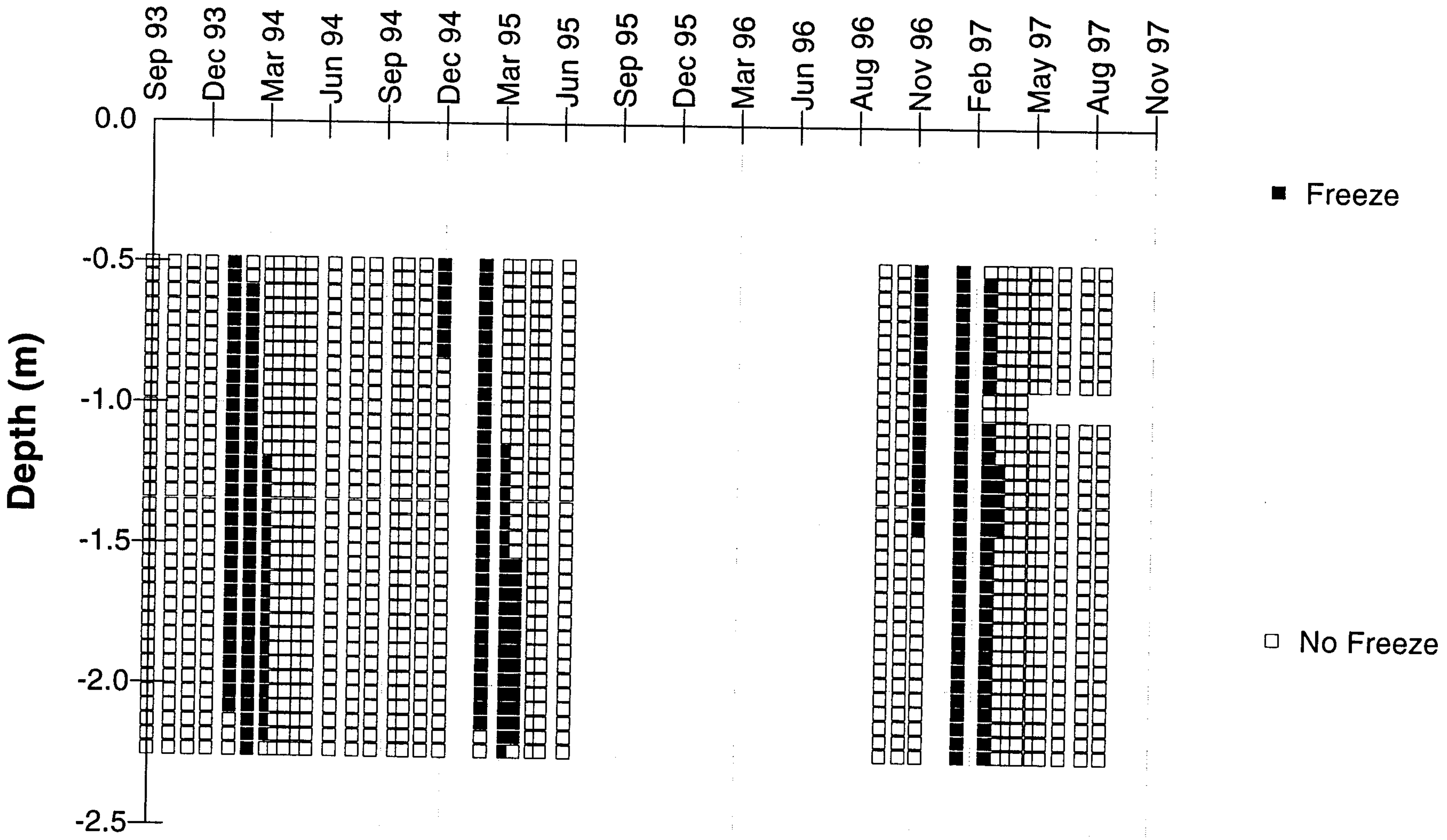
Frost Penetration at Section 271028: Minnesota

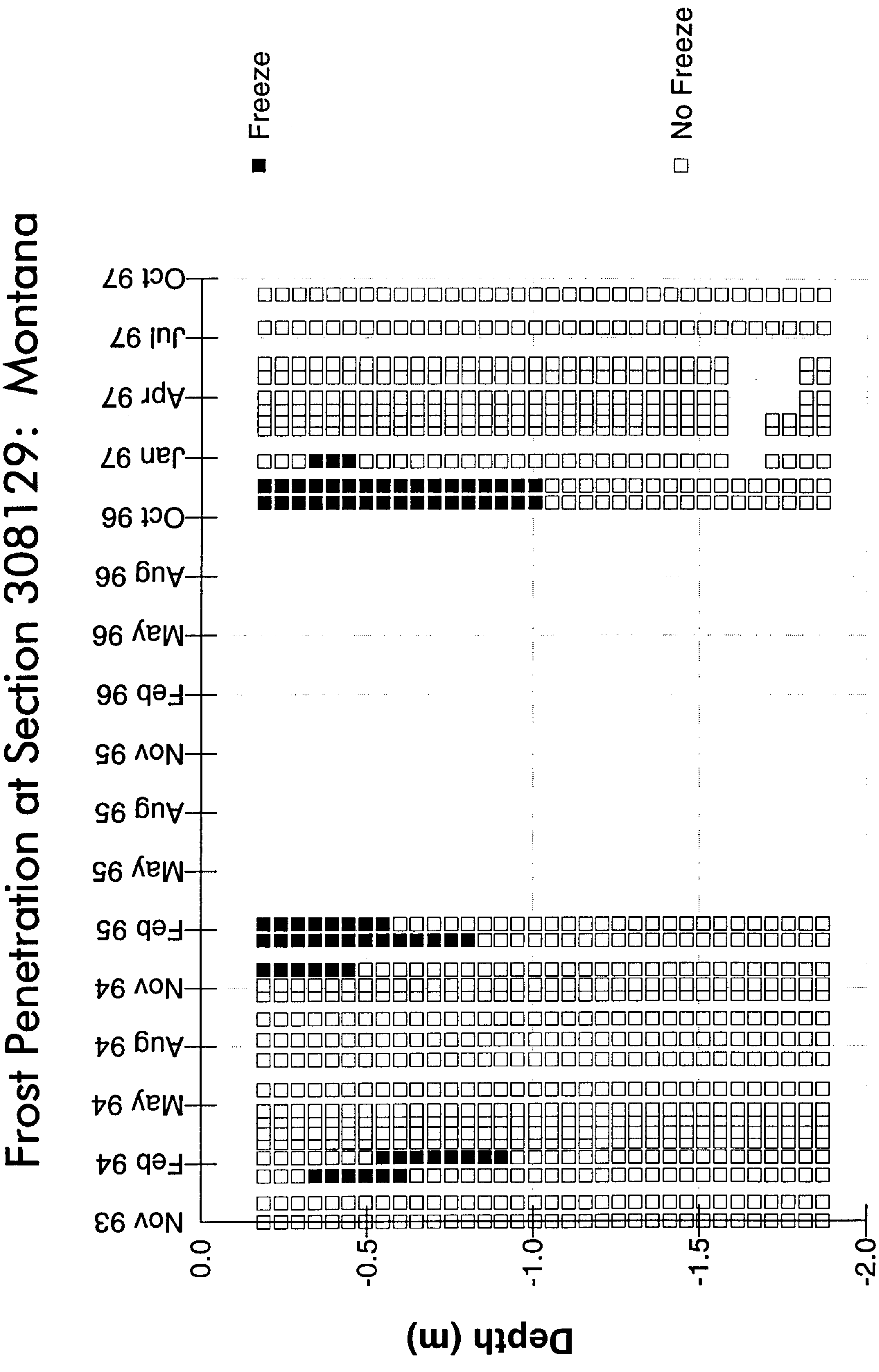


Frost Penetration at Section 274040: Minnesota



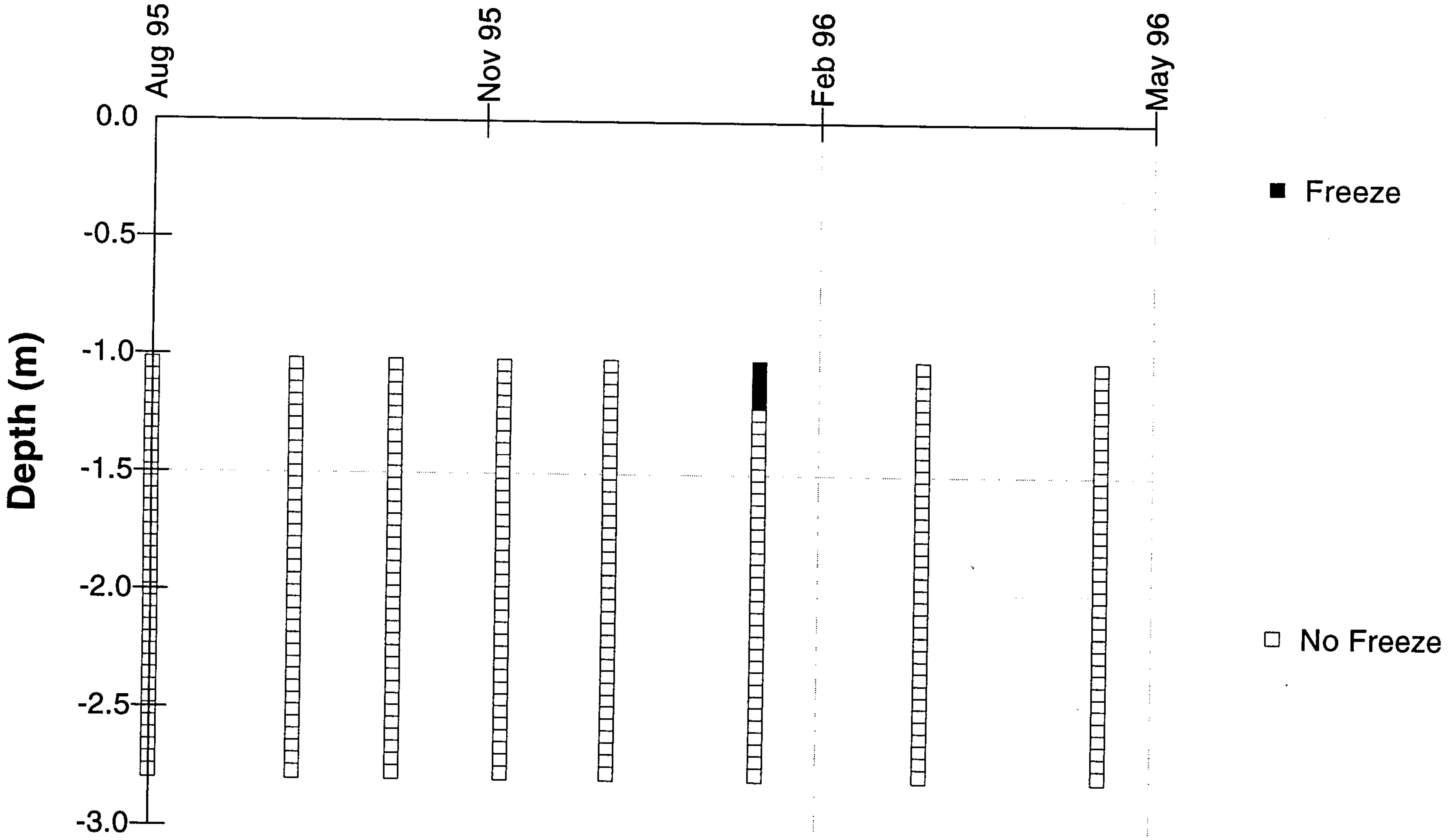
Frost Penetration at Section 276251: Minnesota



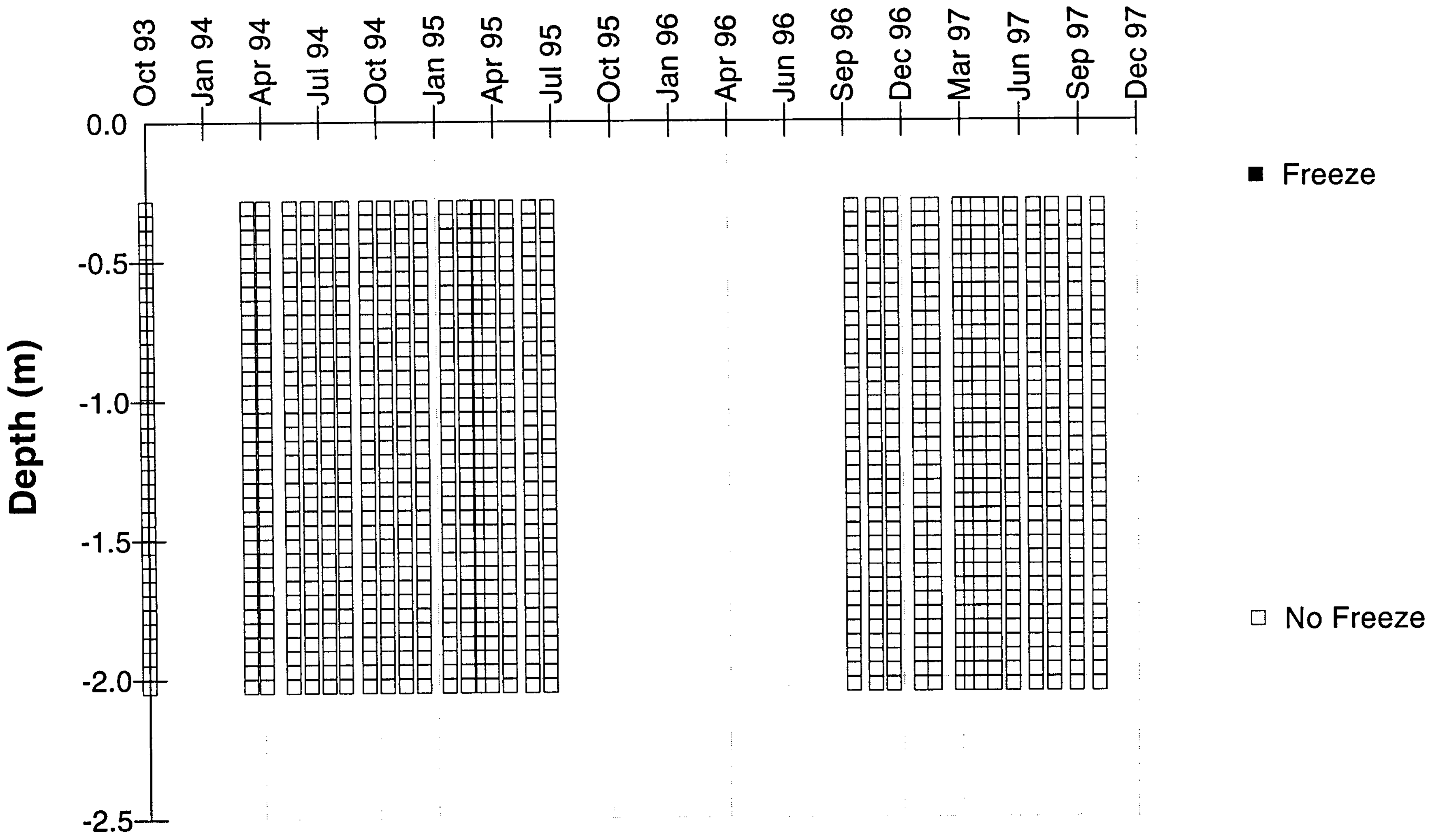


Frost Penetration at Section 308129: Montana

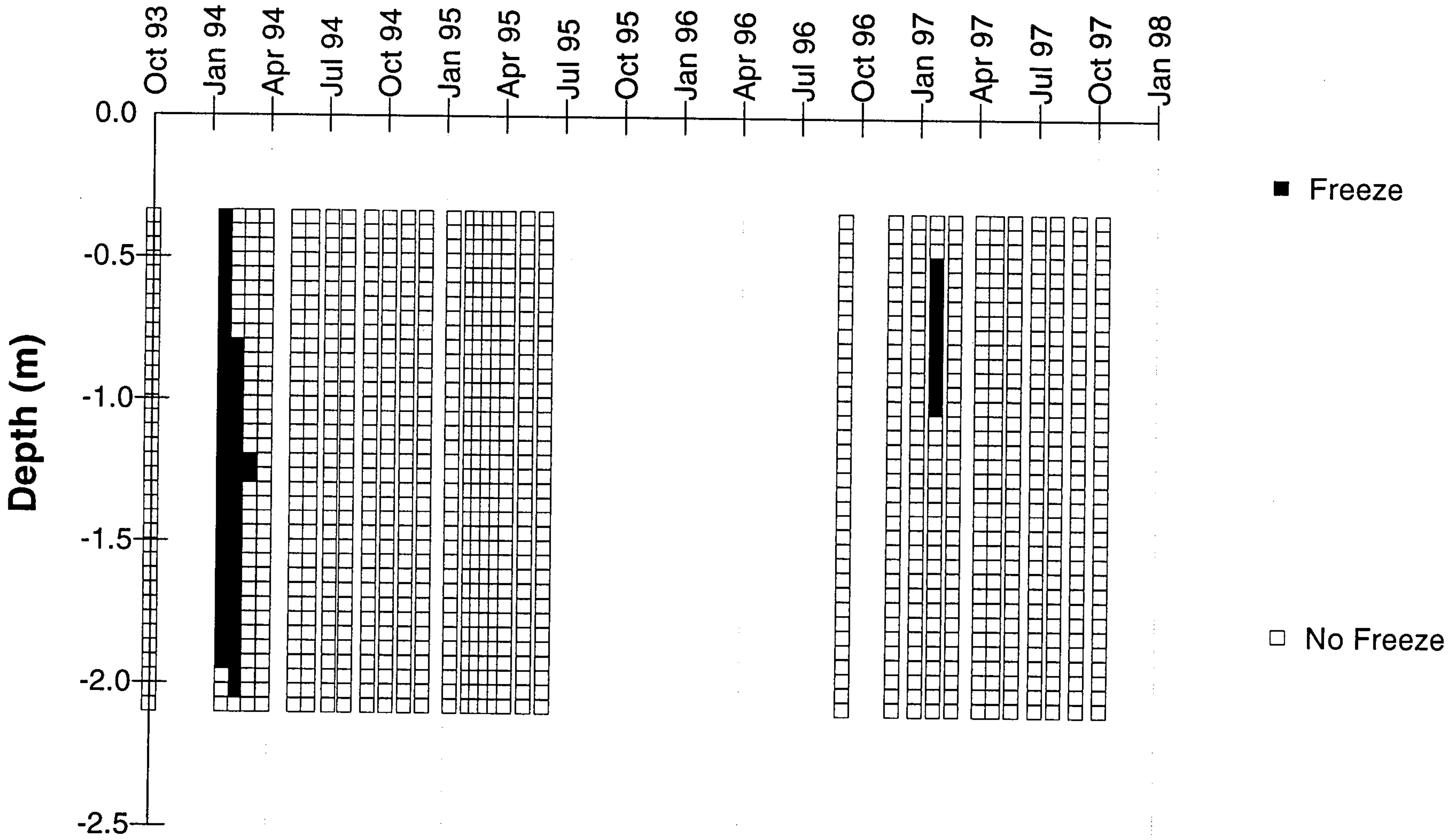
Frost Penetration at Section 313018: Nebraska



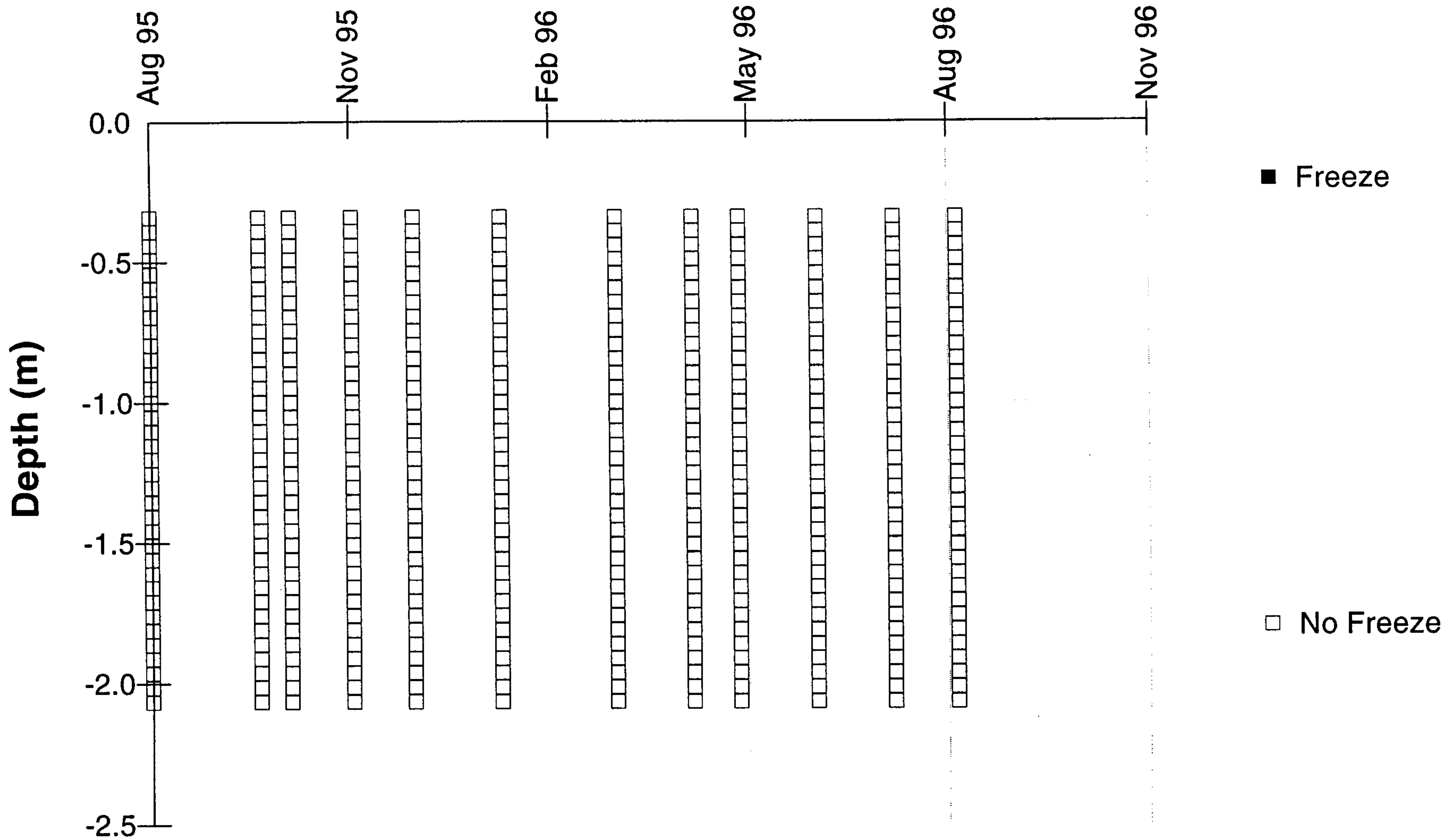
Frost Penetration at Section 331001: New Hampshire



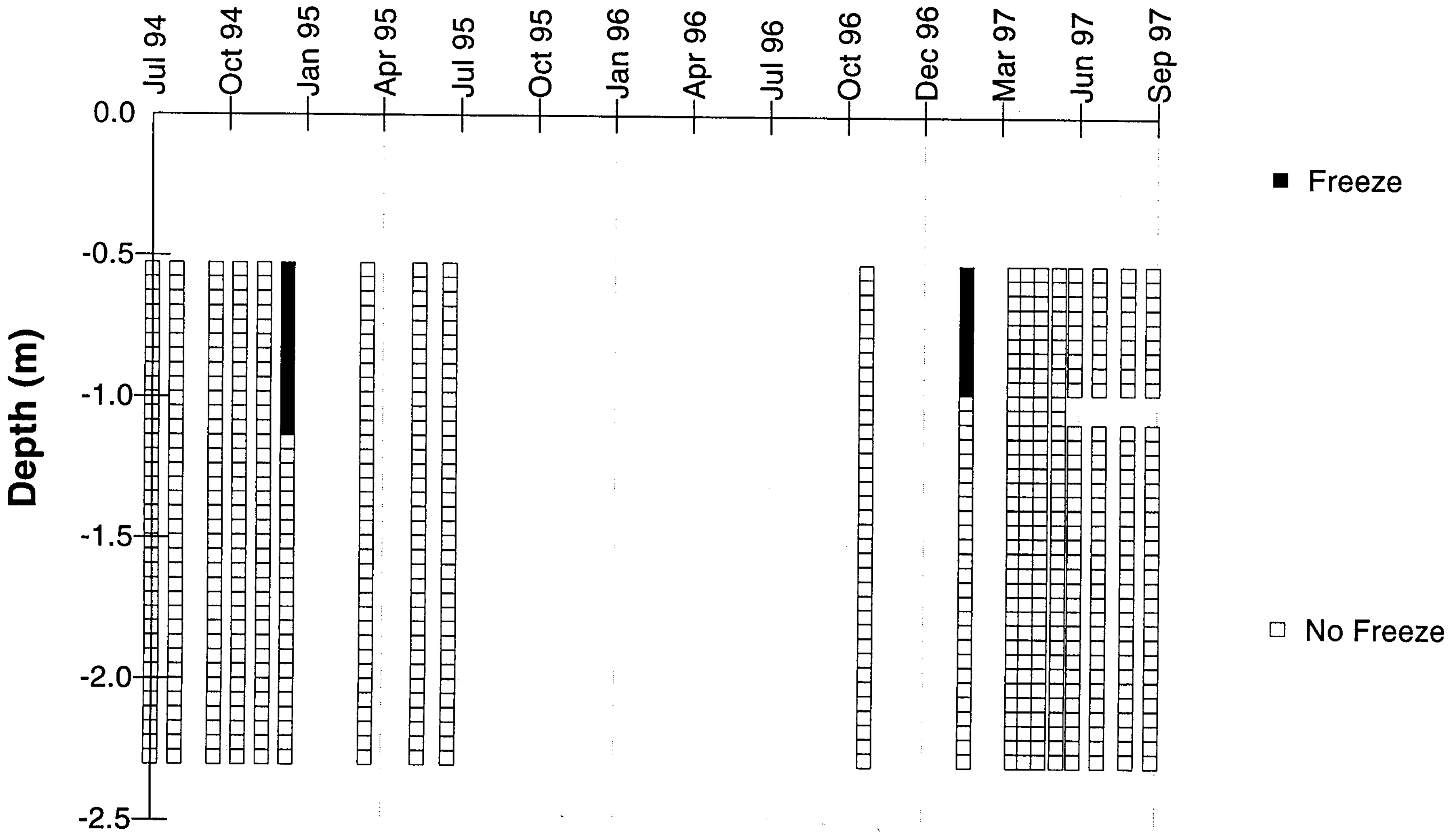
Frost Penetration at Section 364018: New York



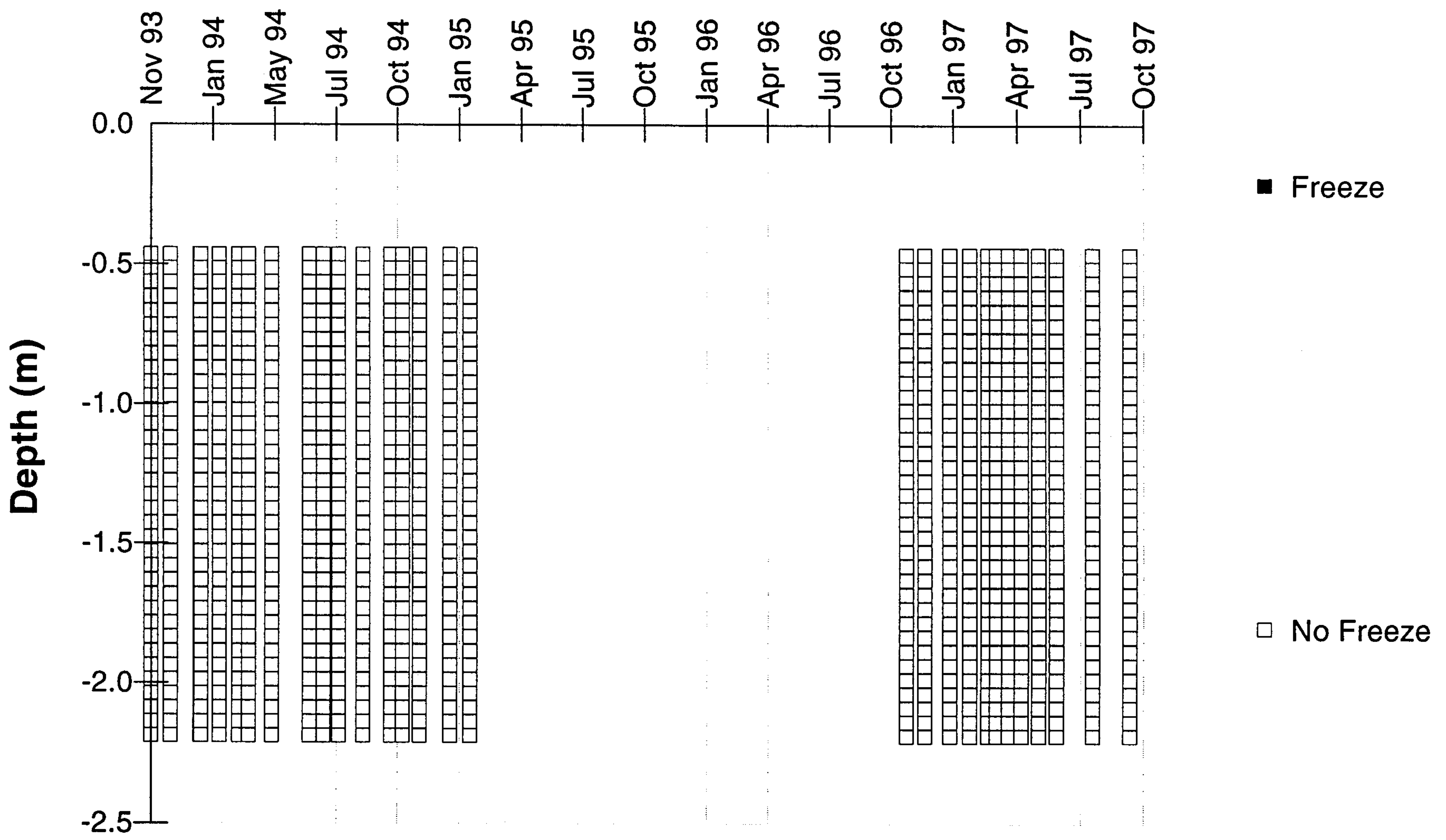
Frost Penetration at Section 421606: Pennsylvania



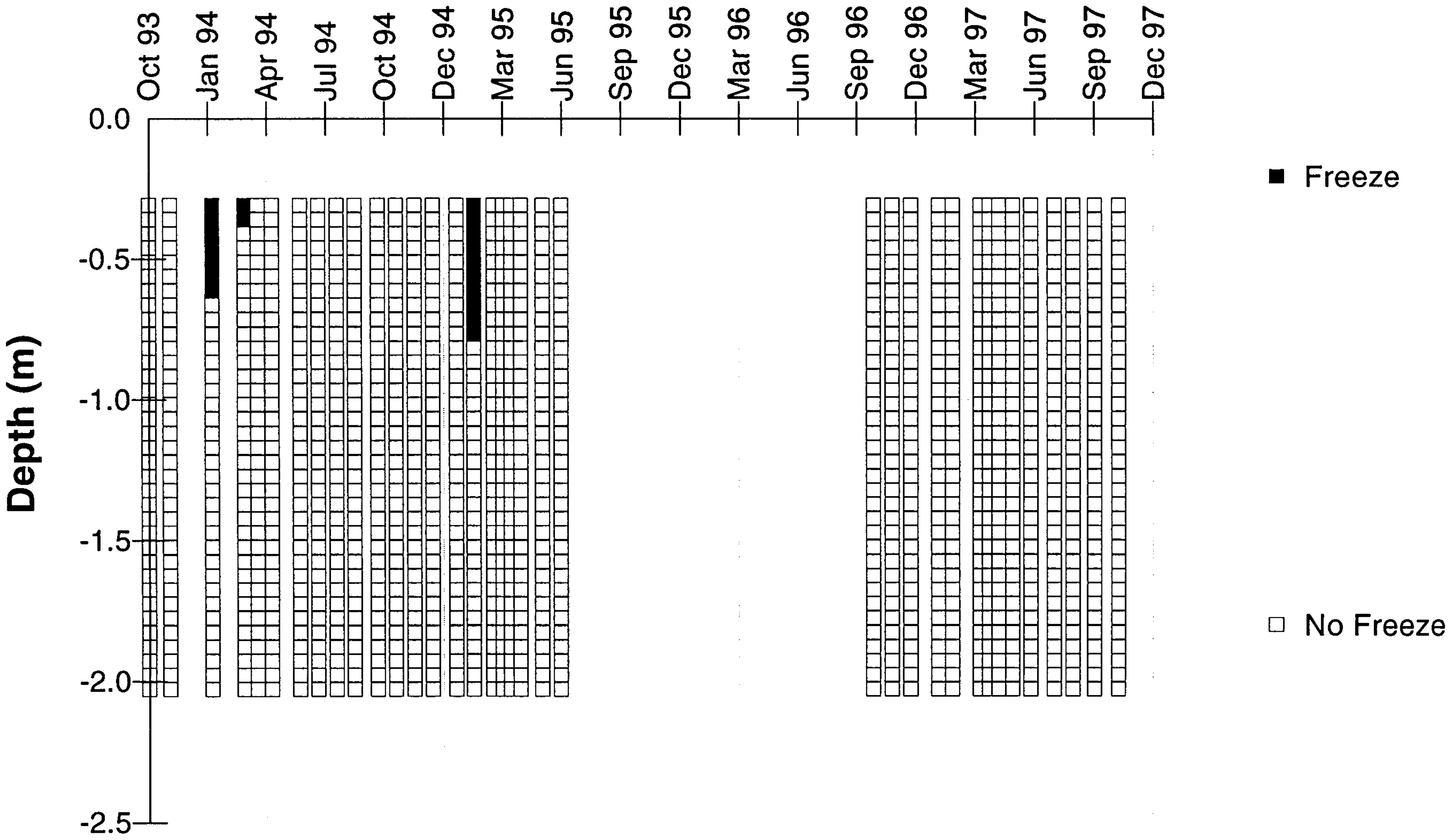
Frost Penetration at Section 460804: South Dakota



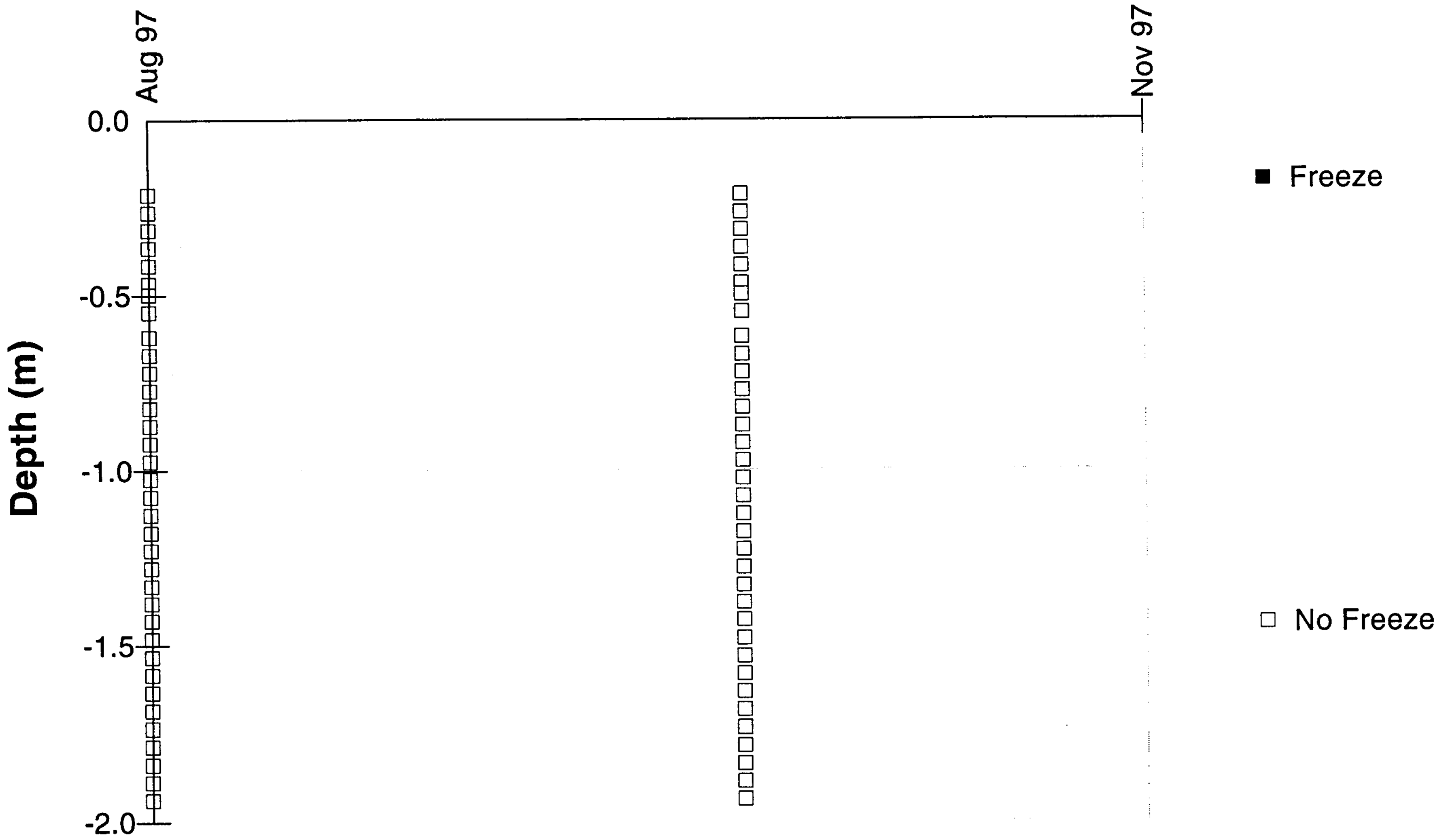
Frost Penetration at Section 493011: Utah



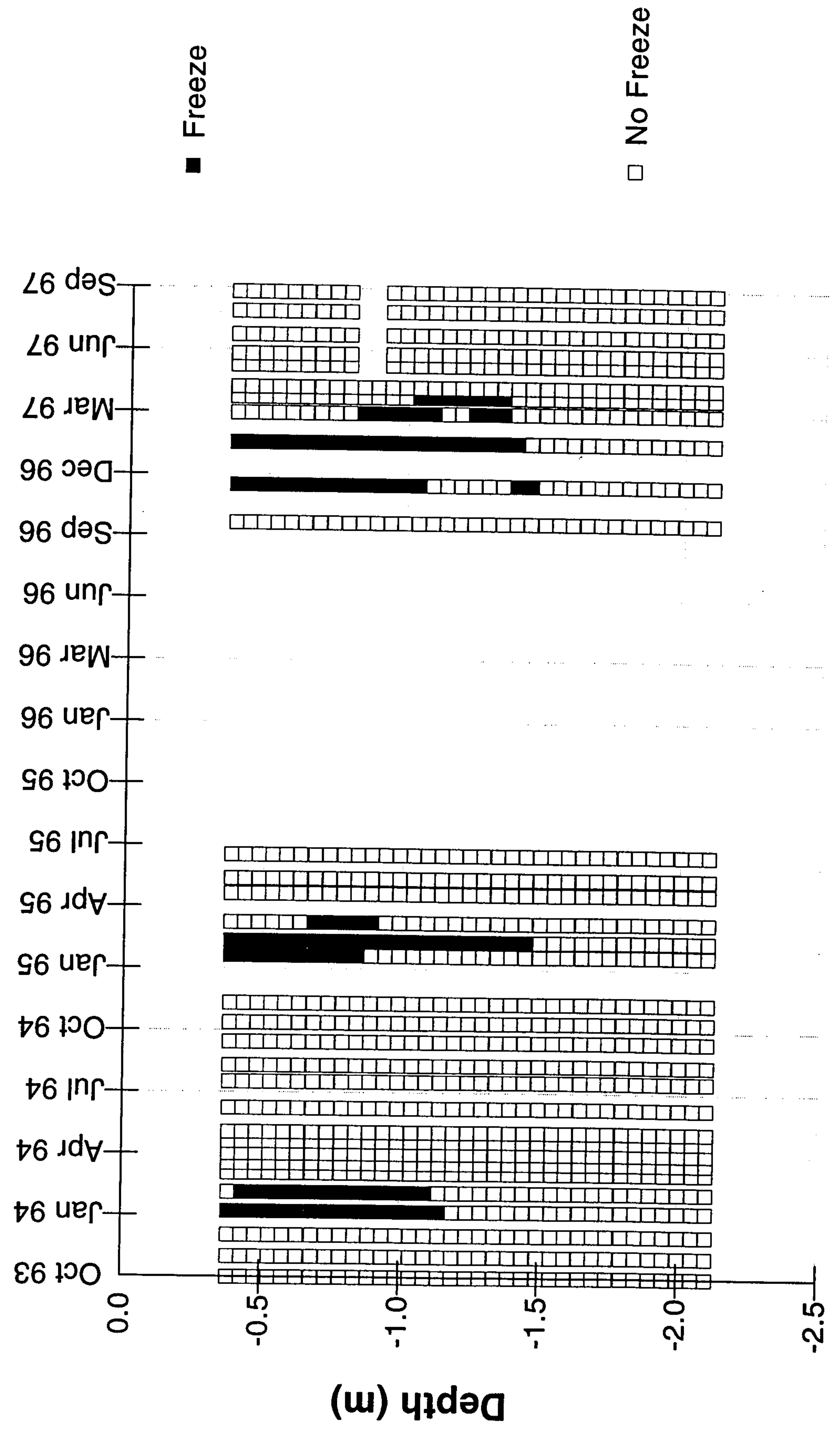
Frost Penetration at Section 501002: Vermont



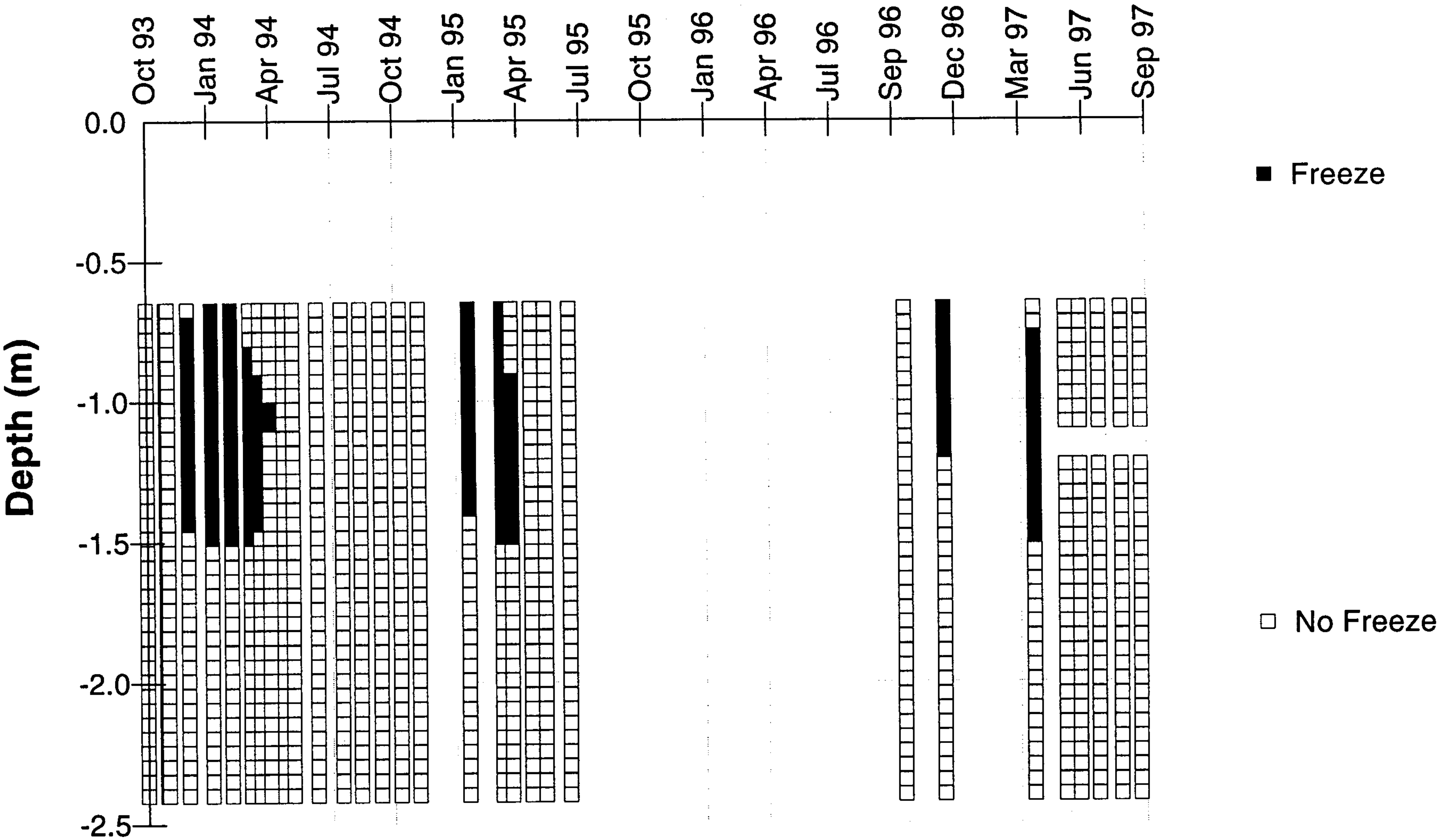
Frost Penetration at Section 561007: Wyoming



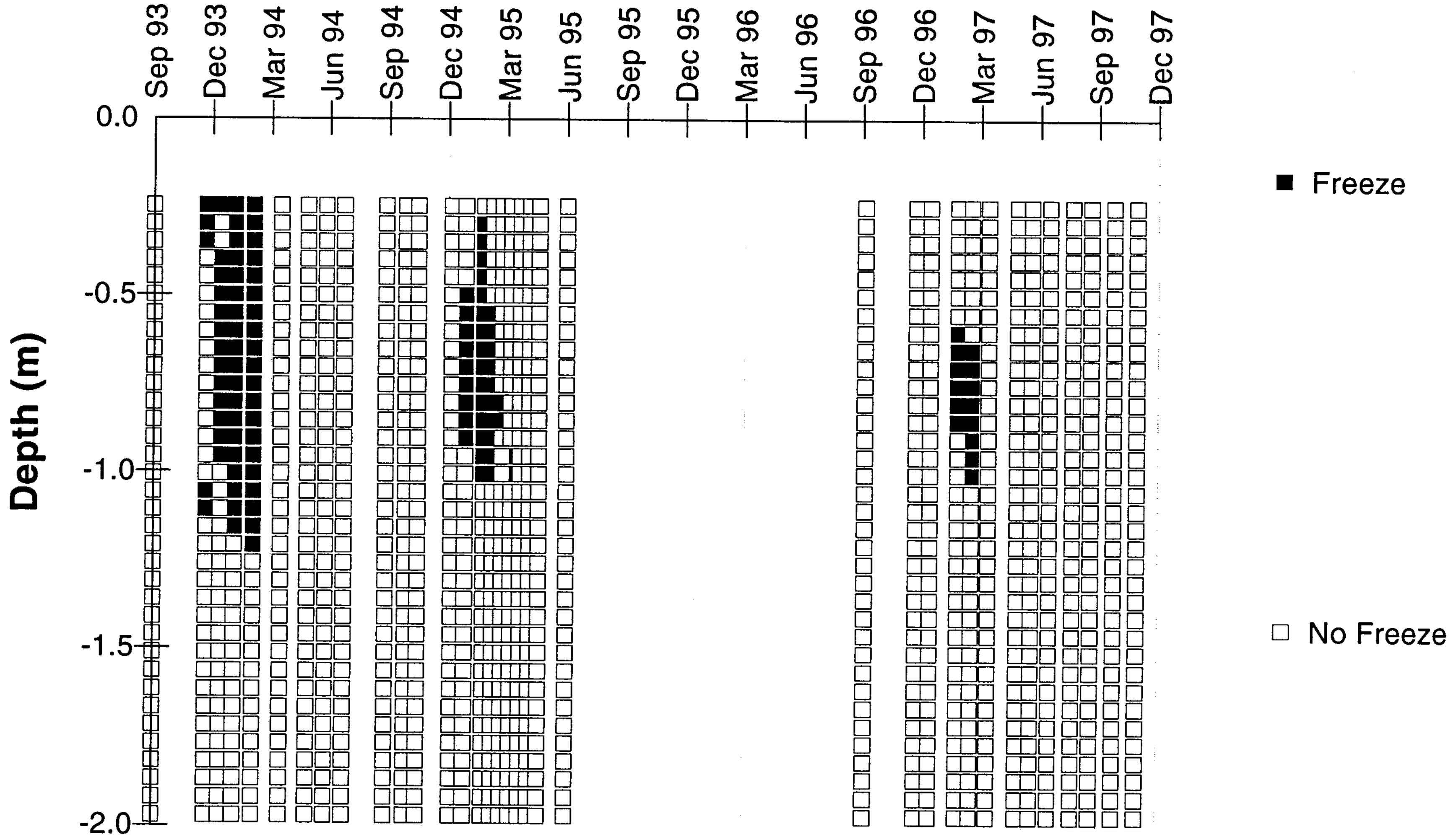
Frost Penetration at Section 831801: Manitoba



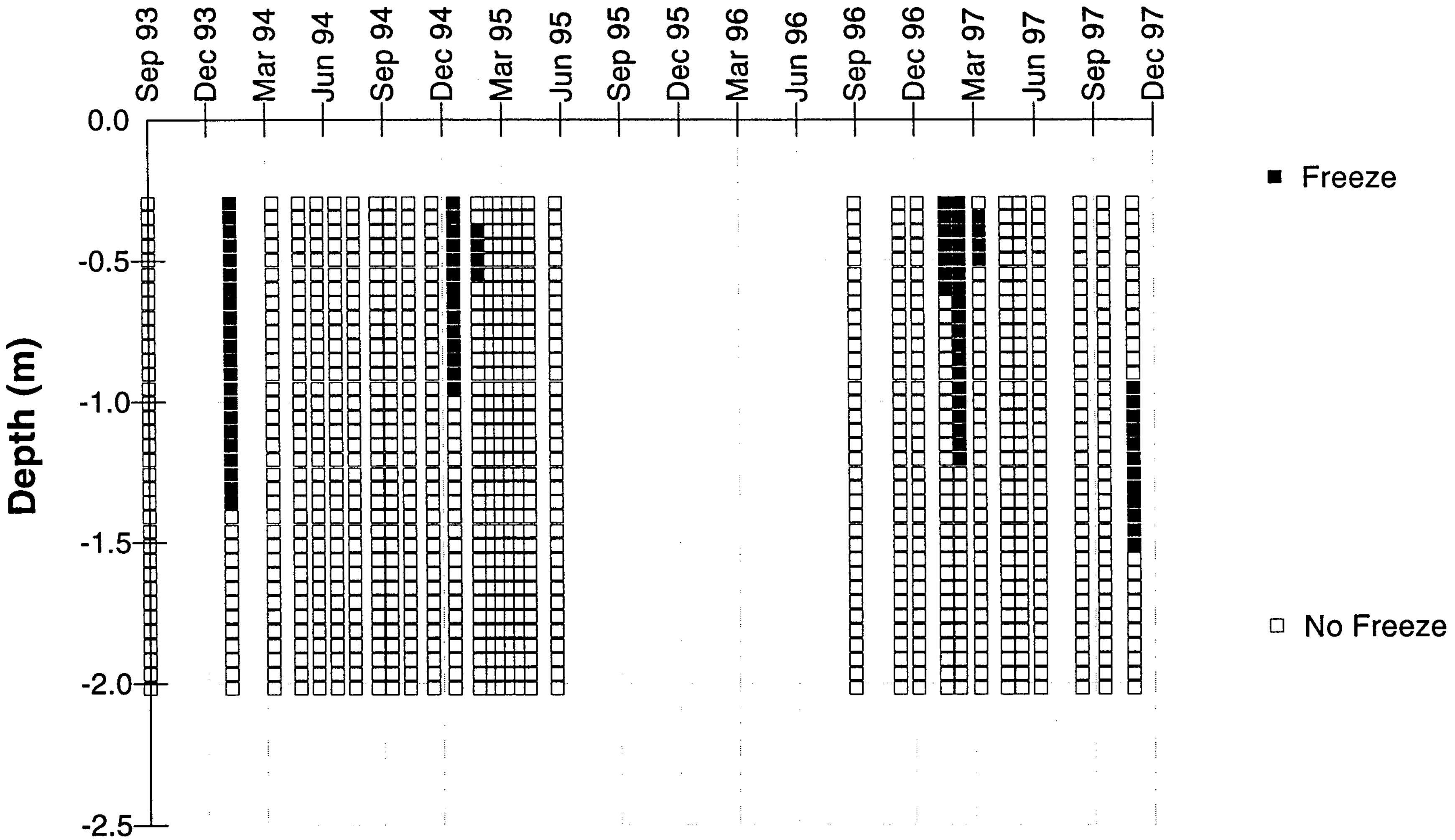
Frost Penetration at Section 833802: Manitoba



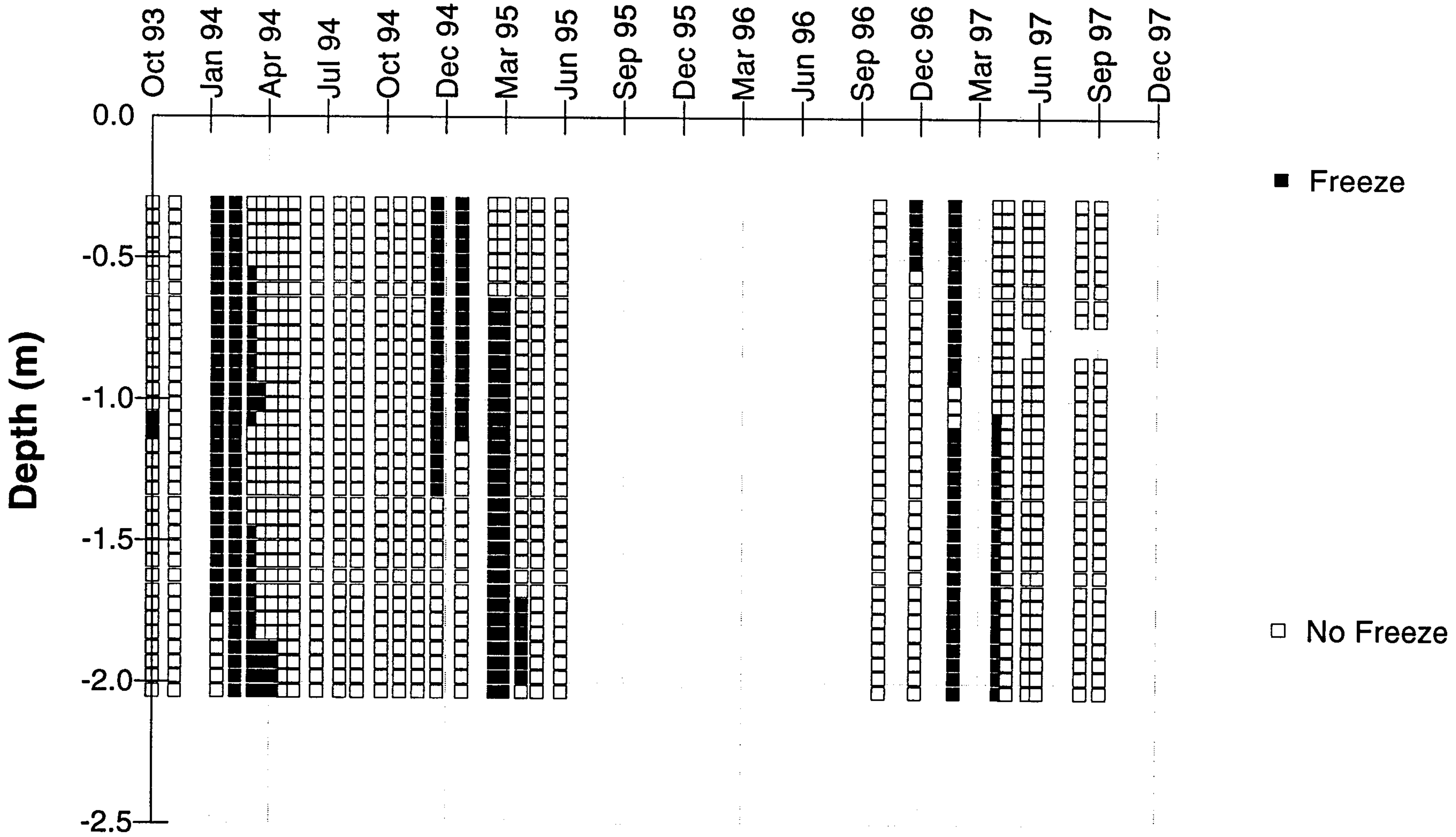
Frost Penetration at Section 871622: Ontario



Frost Penetration at Section 893015: Quebec



Frost Penetration at Section 906405: Saskatchewan



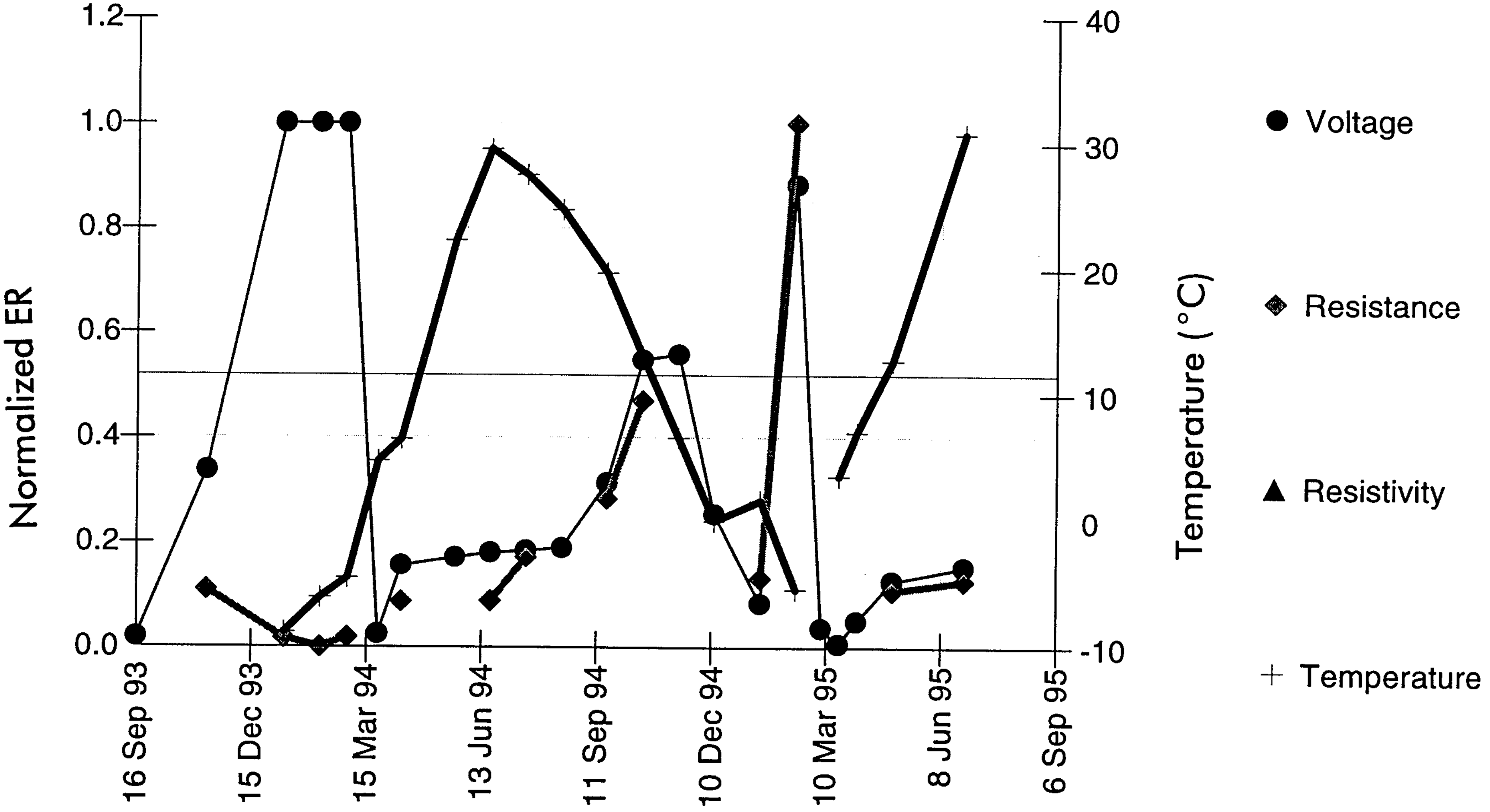
APPENDIX B – SAMPLE TIME-SERIES ER PLOTS USED IN PROGRAM FROST

Time-series plots are provided for section 231026 in Maine for the following depths:

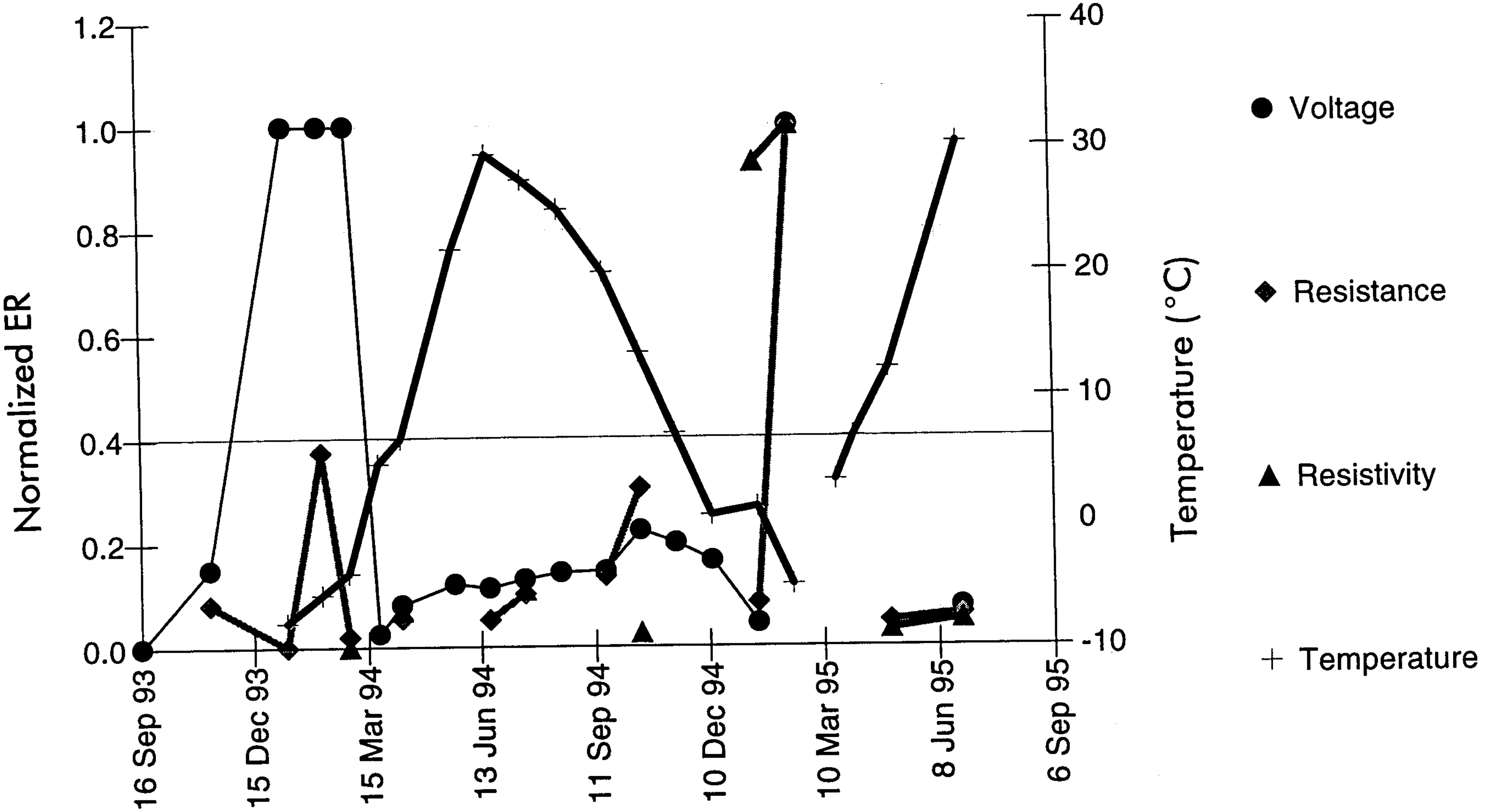
Number	Depth, m
1	0.27
2	0.32
3	0.37
4	0.42
5	0.47
6	0.52
7	0.58
8	0.63
9	0.68
10	0.73
11	0.78
12	0.83
13	0.88
14	0.93
15	0.98
16	1.03
17	1.08
18	1.13
19	1.18
20	1.24
21	1.29
22	1.34
23	1.39
24	1.44
25	1.49
26	1.54
27	1.59

Number	Depth, m
28	1.64
29	1.69
30	1.74
31	1.79
32	1.85
33	1.90
34	1.95
35	2.00

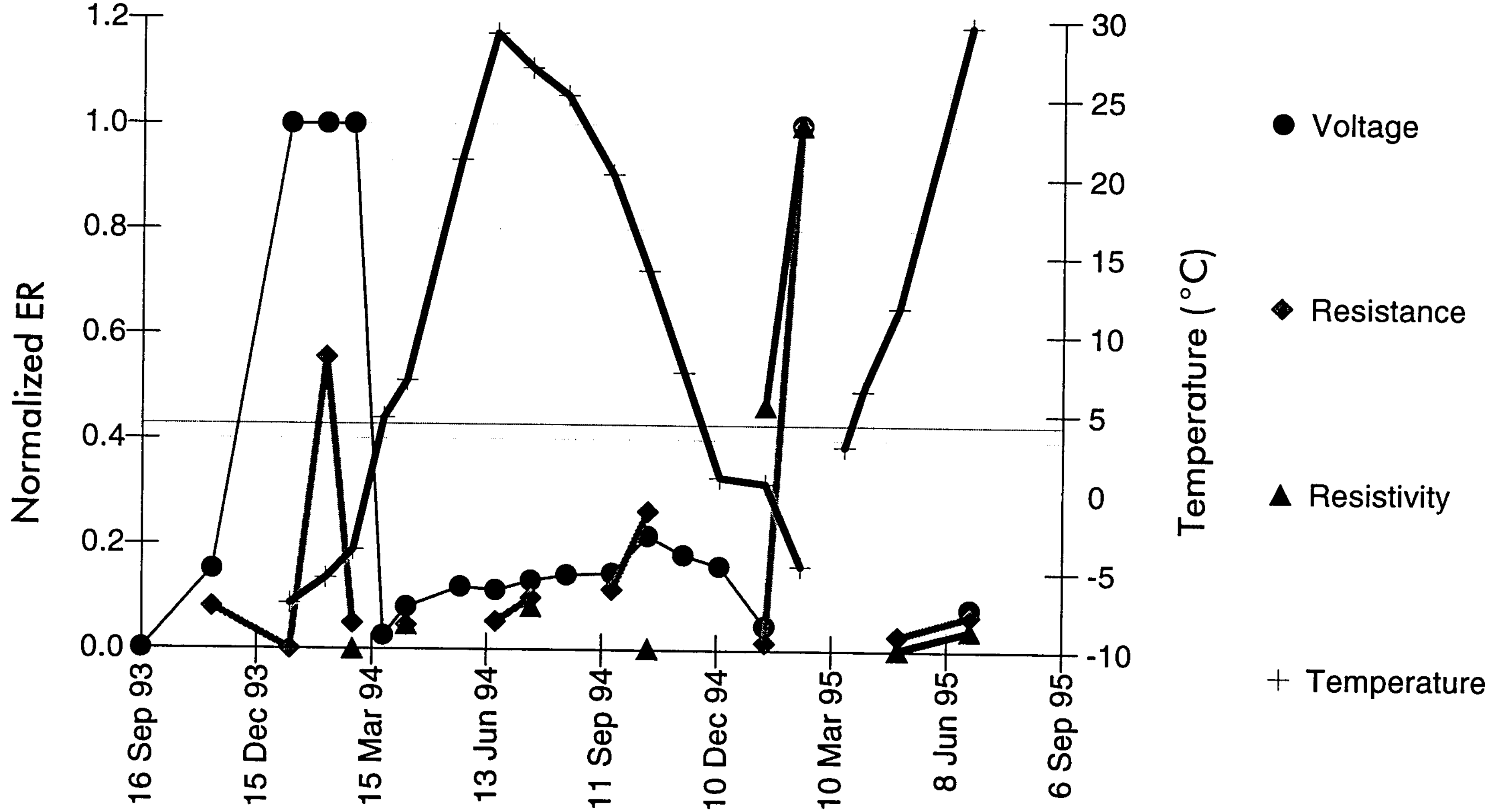
Section 231026: Maine
Depth = 0.27 m



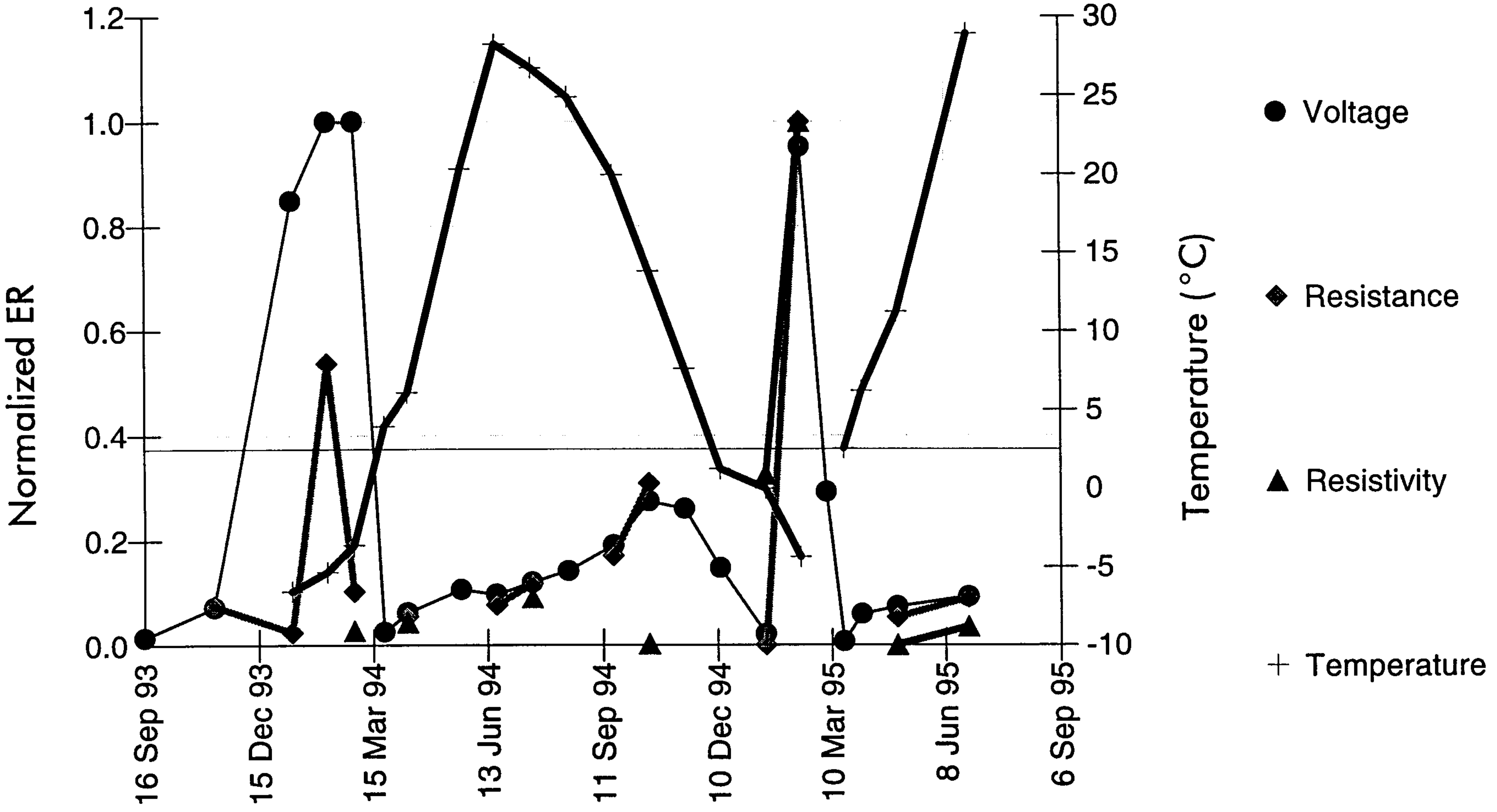
Section 231026: Maine
Depth = 0.32 m



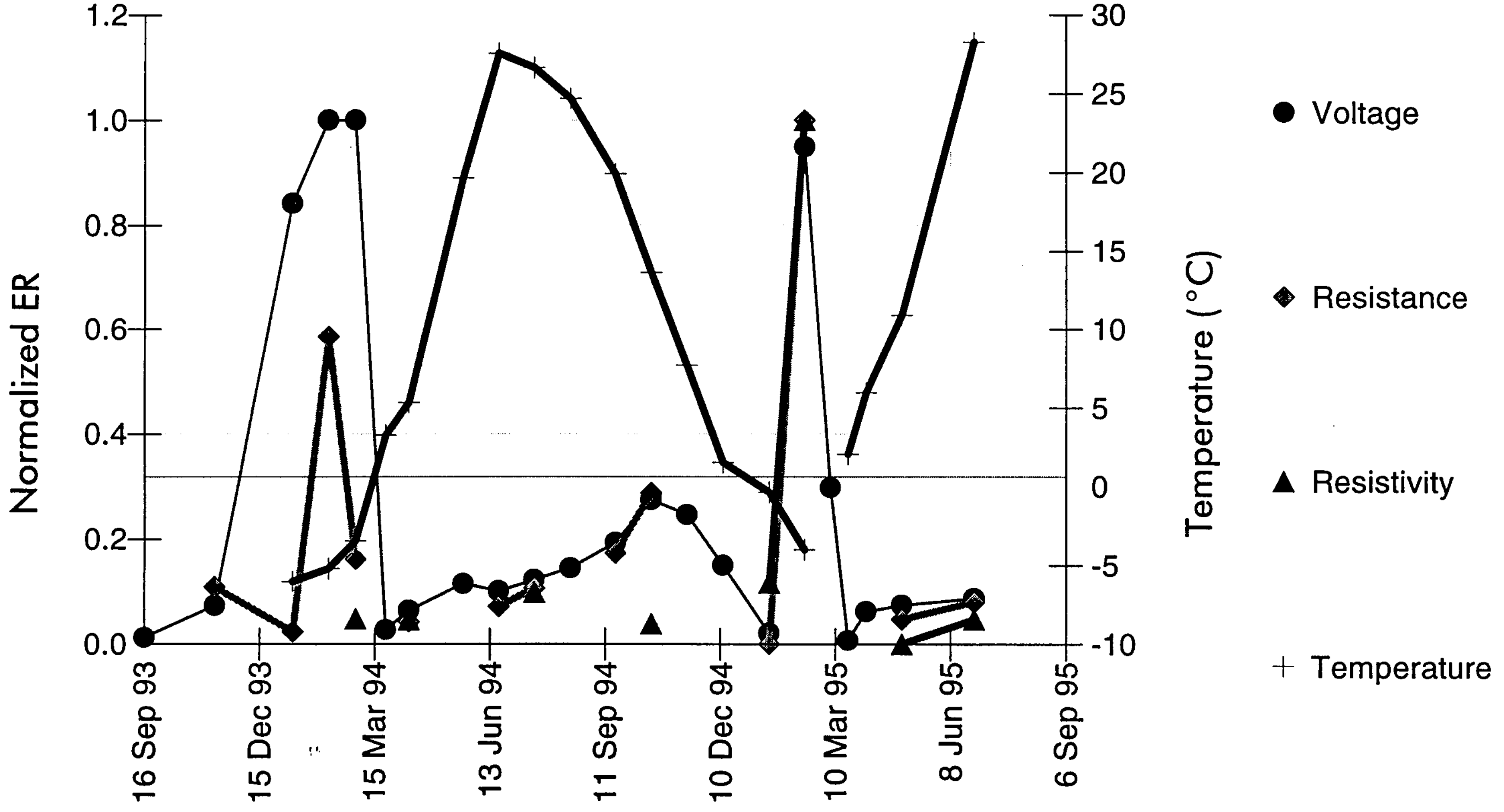
Section 231026: Maine
Depth = 0.37 m



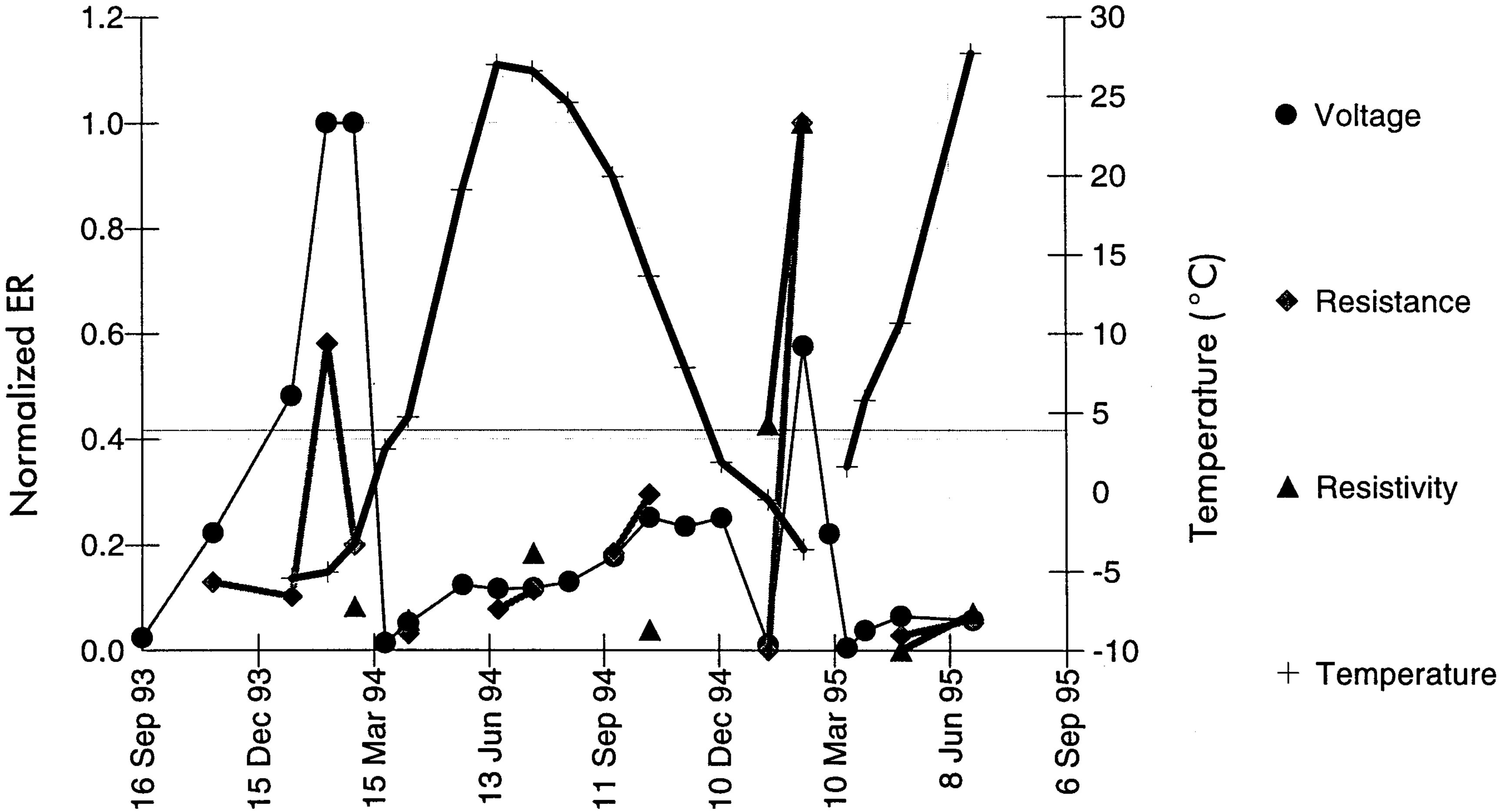
Section 231026: Maine
Depth = 0.42 m

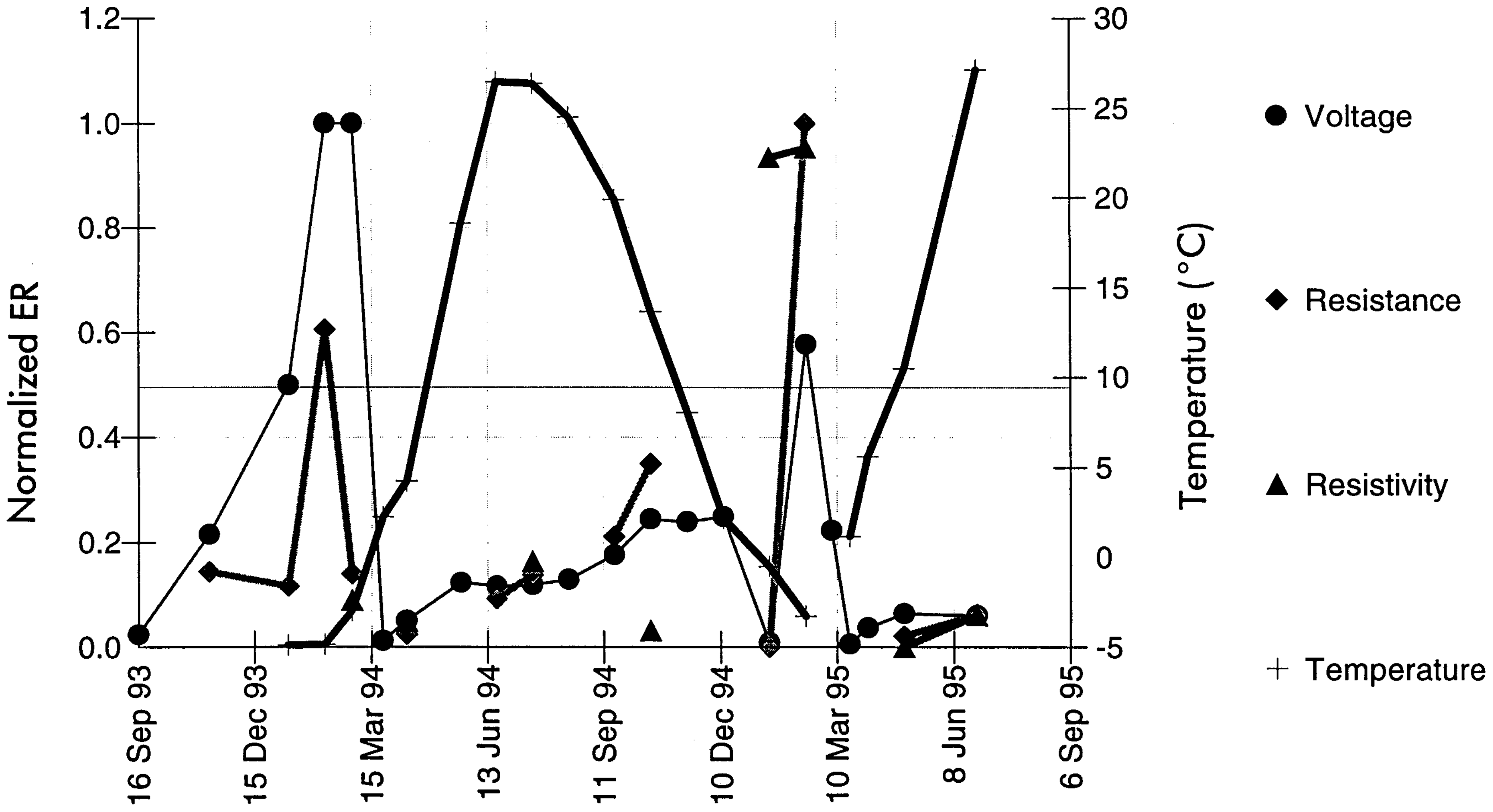


Section 231026: Maine
Depth = 0.47 m



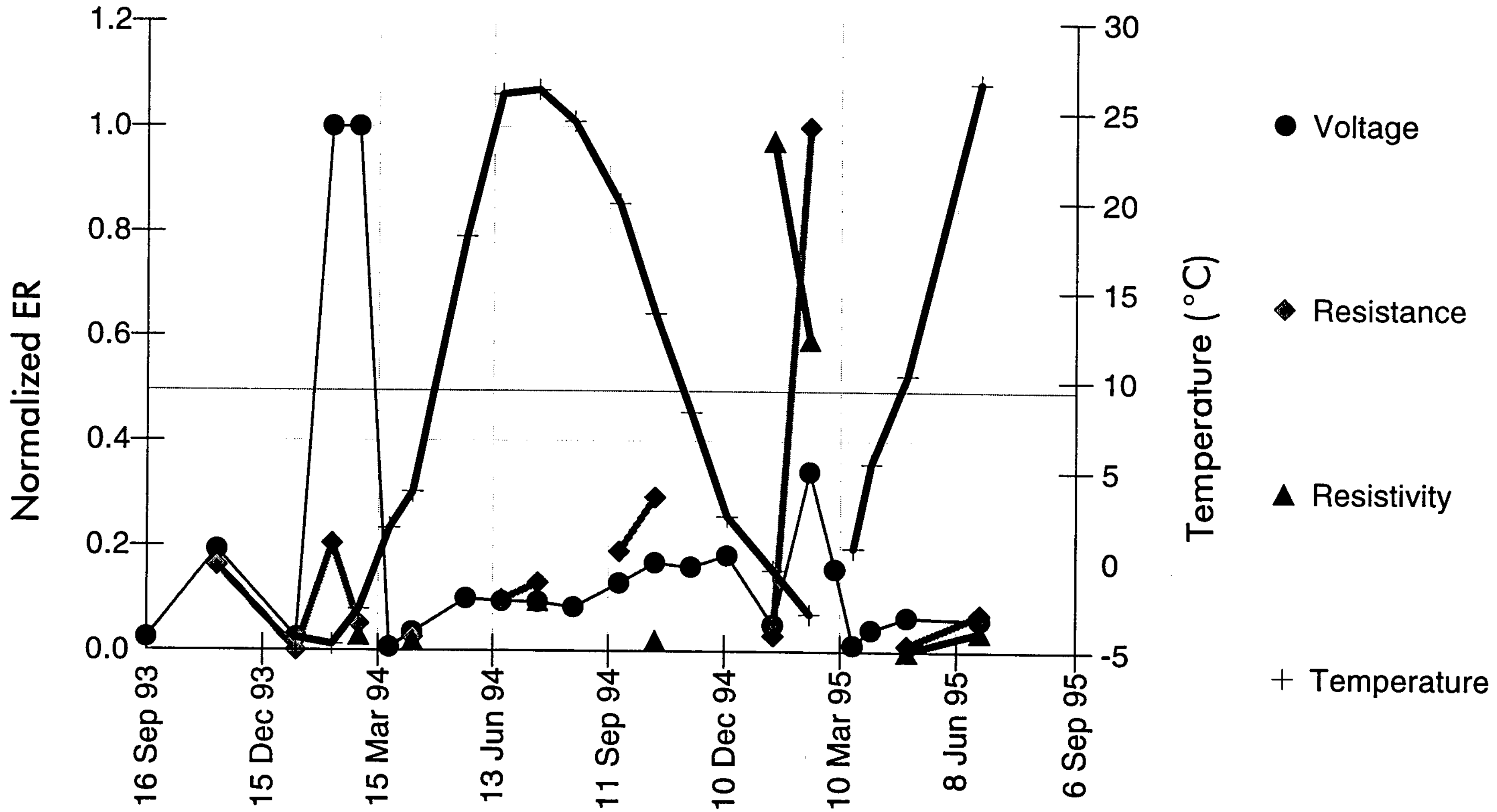
Section 231026: Maine
Depth = 0.52 m



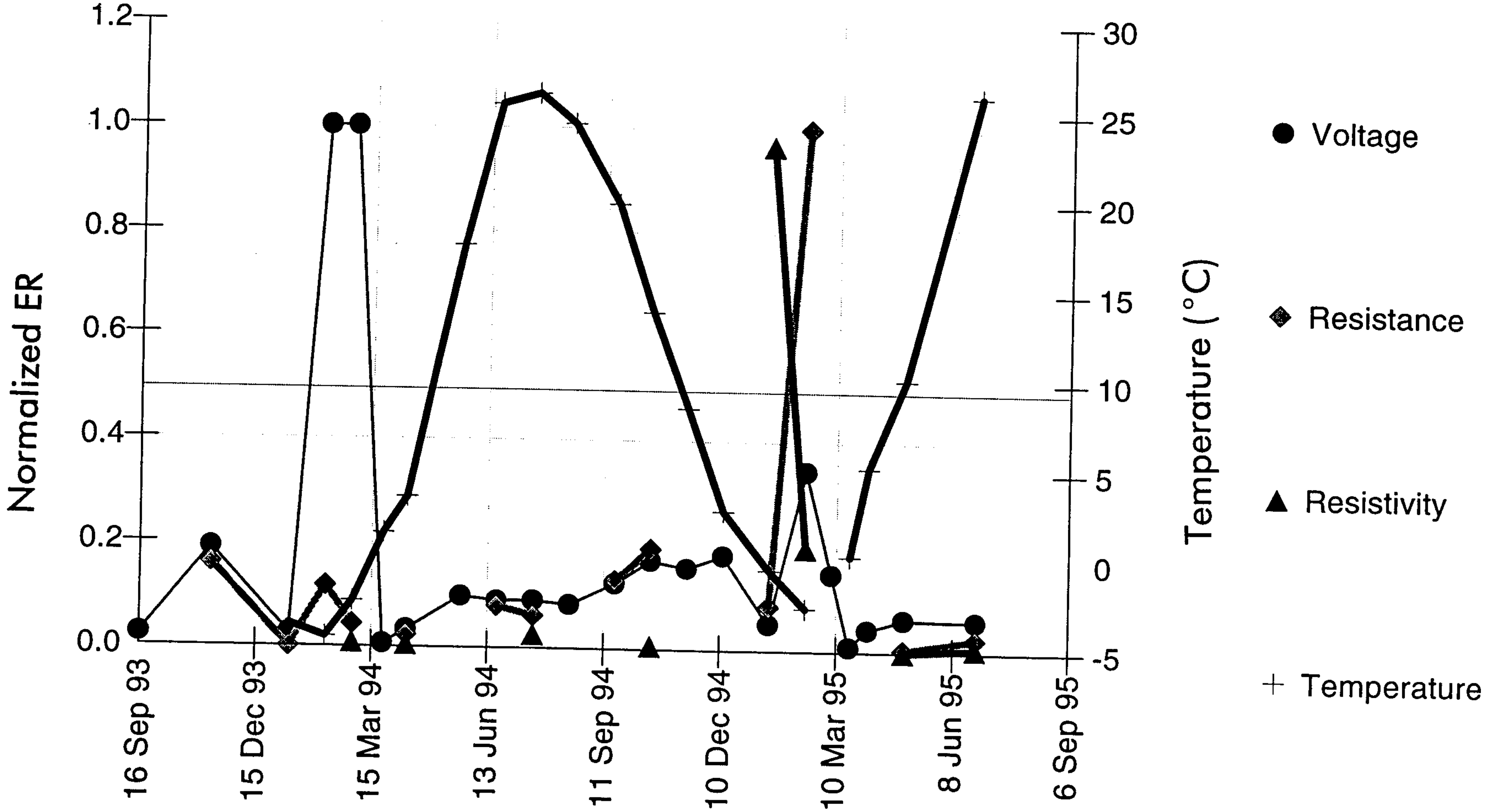


Section 231026: Maine
Depth = 0.58 m

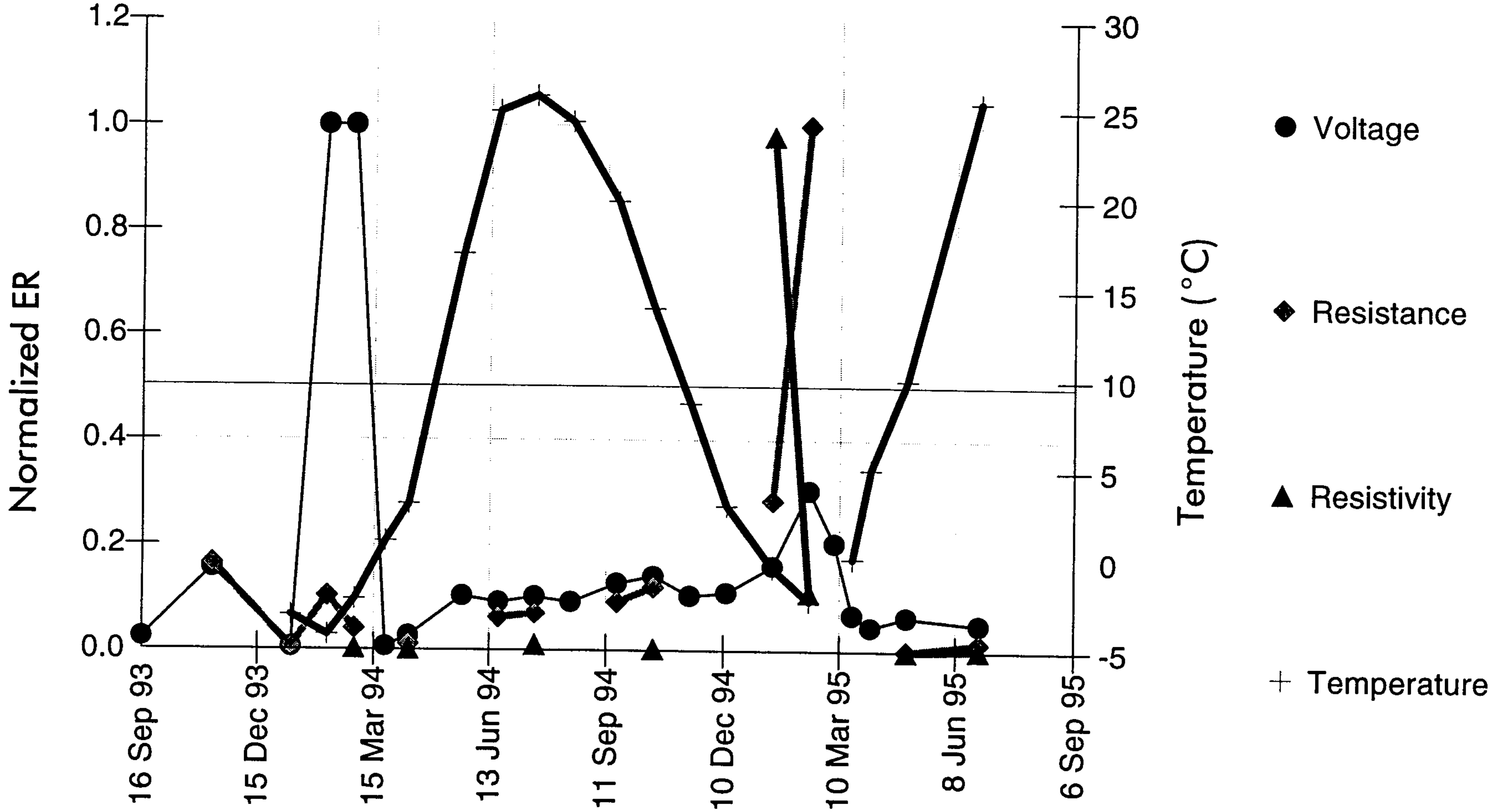
Section 231026: Maine
Depth = 0.63 m



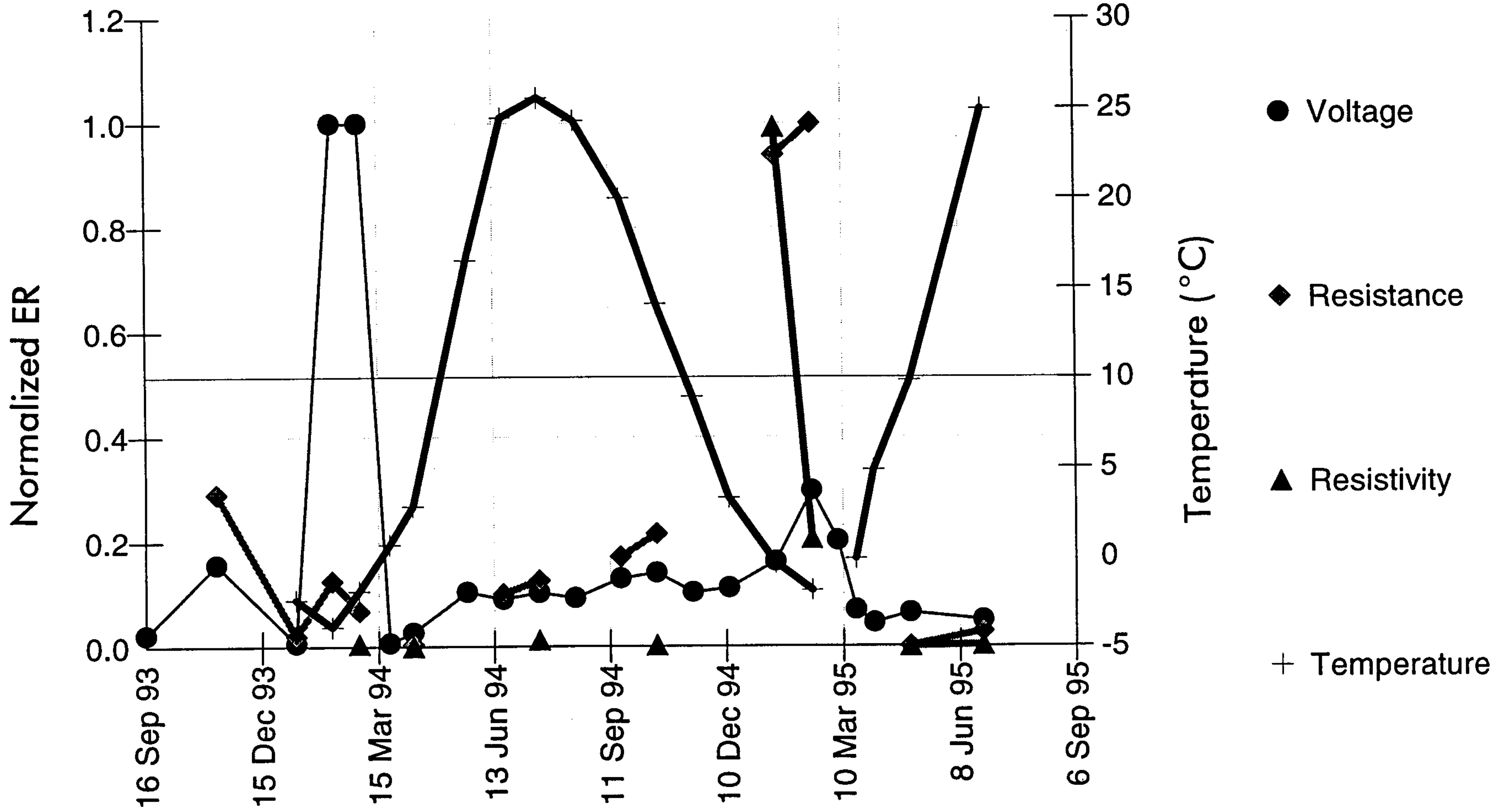
Section 231026: Maine
Depth = 0.68 m



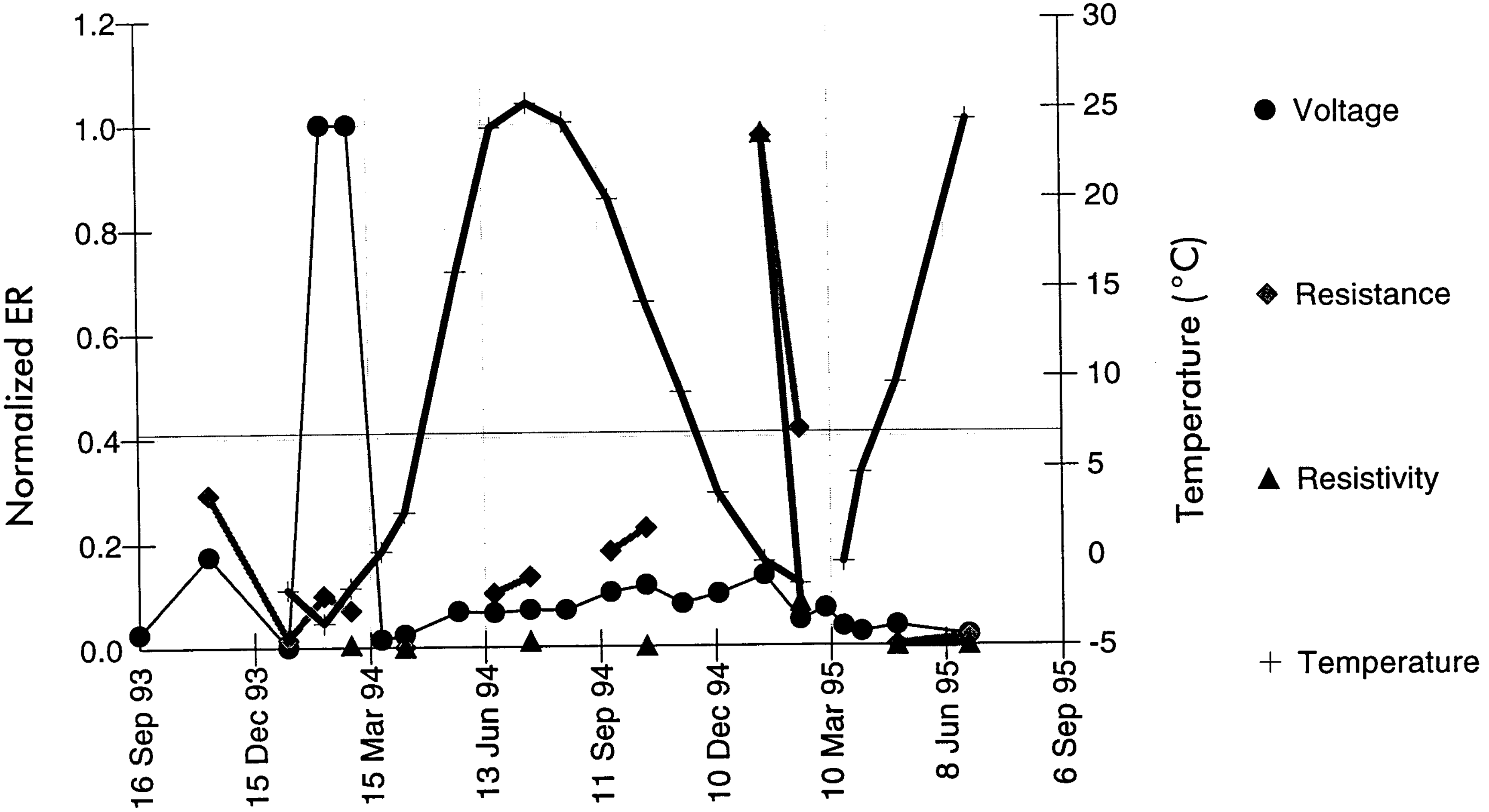
Section 231026: Maine
Depth = 0.73 m



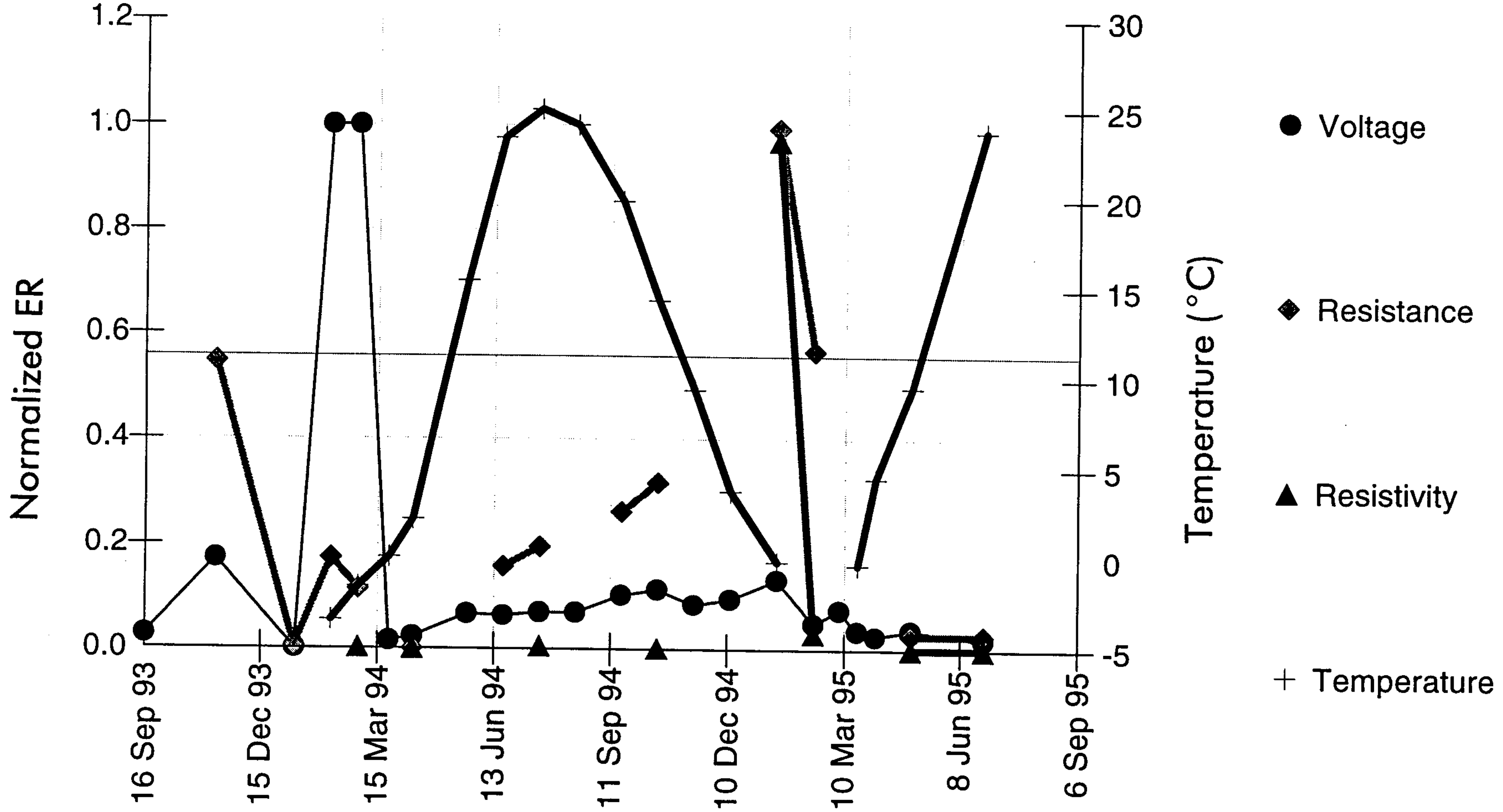
Section 231026: Maine
Depth = 0.78 m



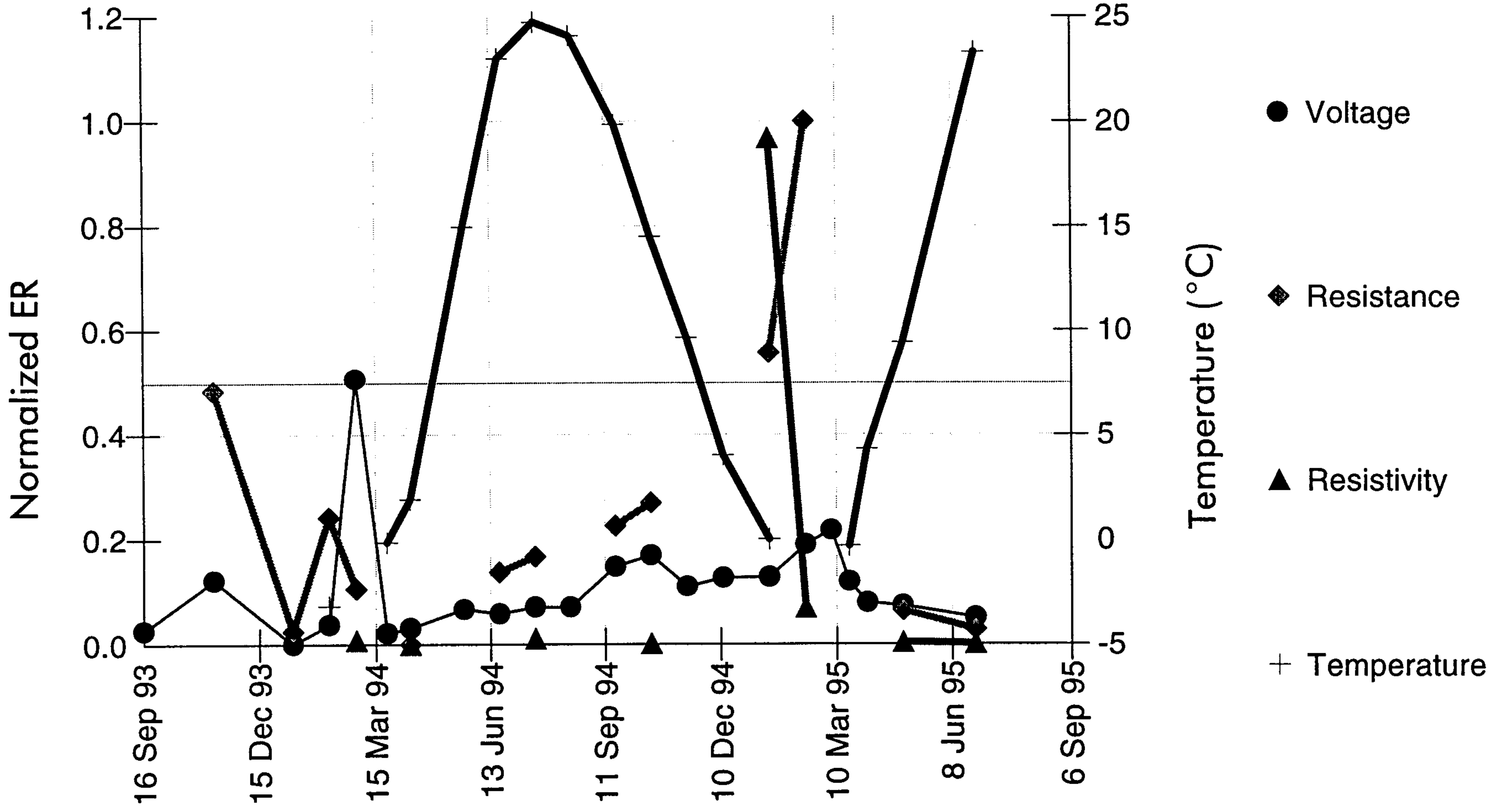
Section 231026: Maine
Depth = 0.83 m



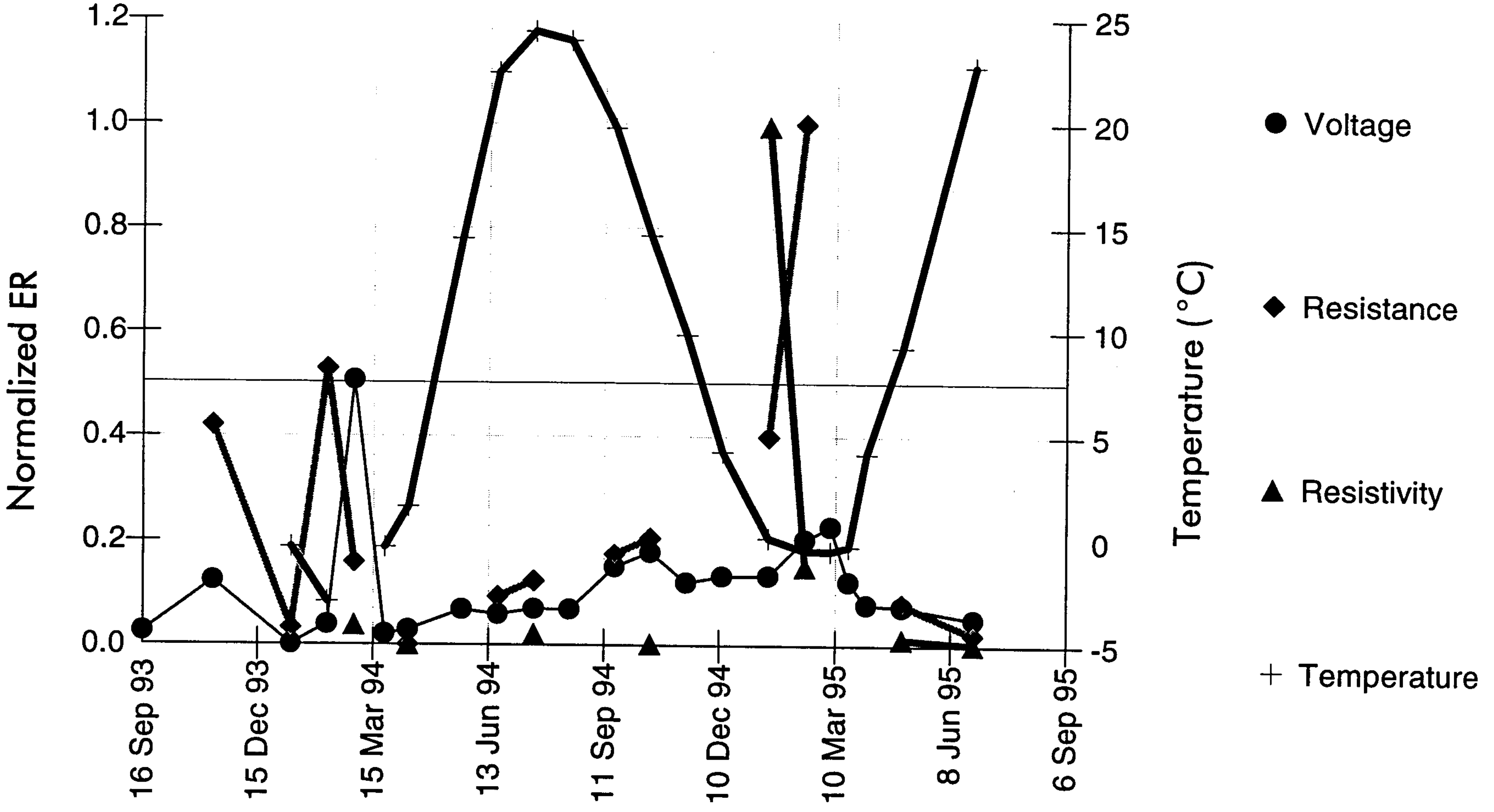
Section 231026: Maine
Depth = 0.88 m

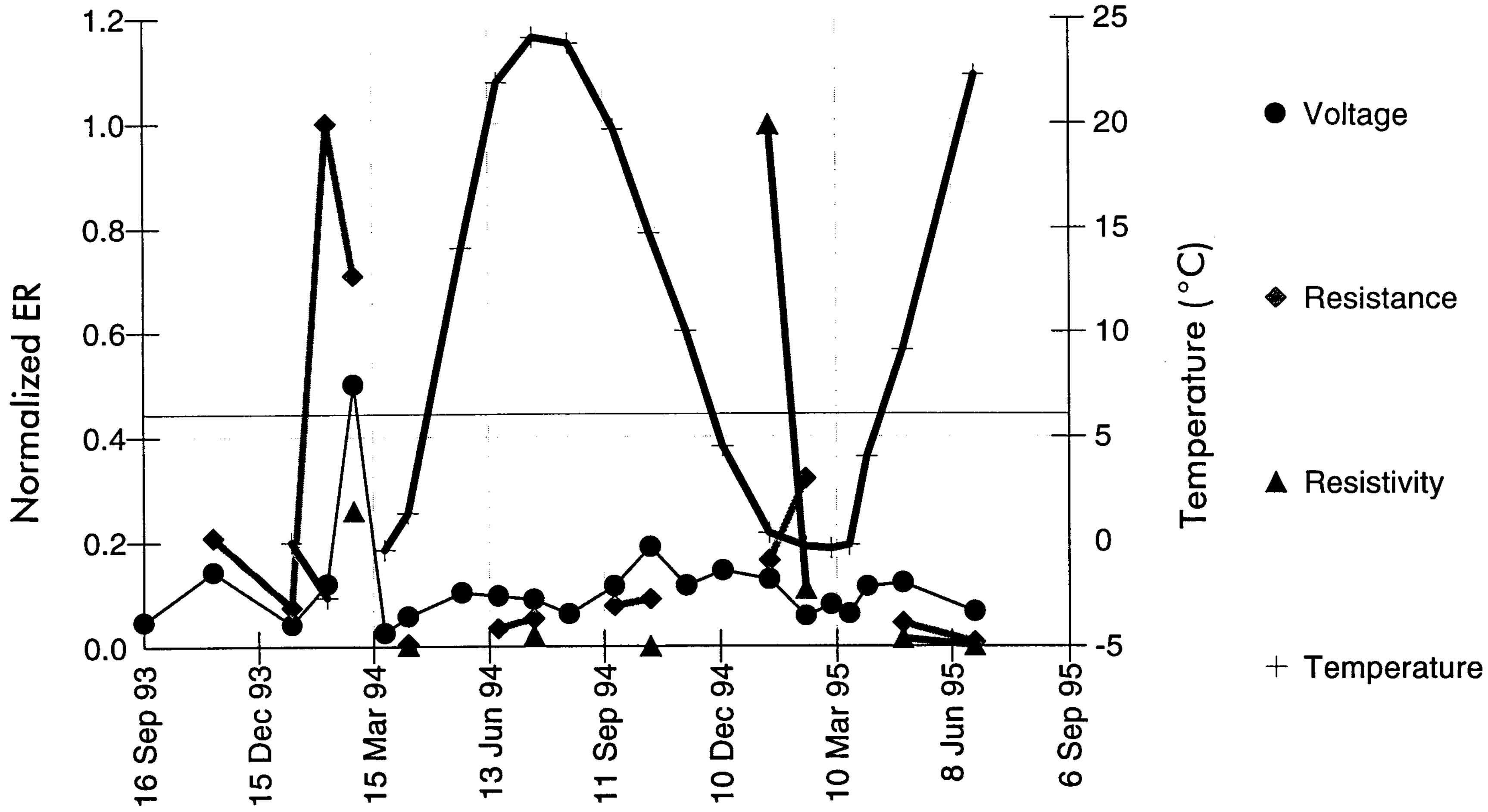


Section 231026: Maine
Depth = 0.93 m

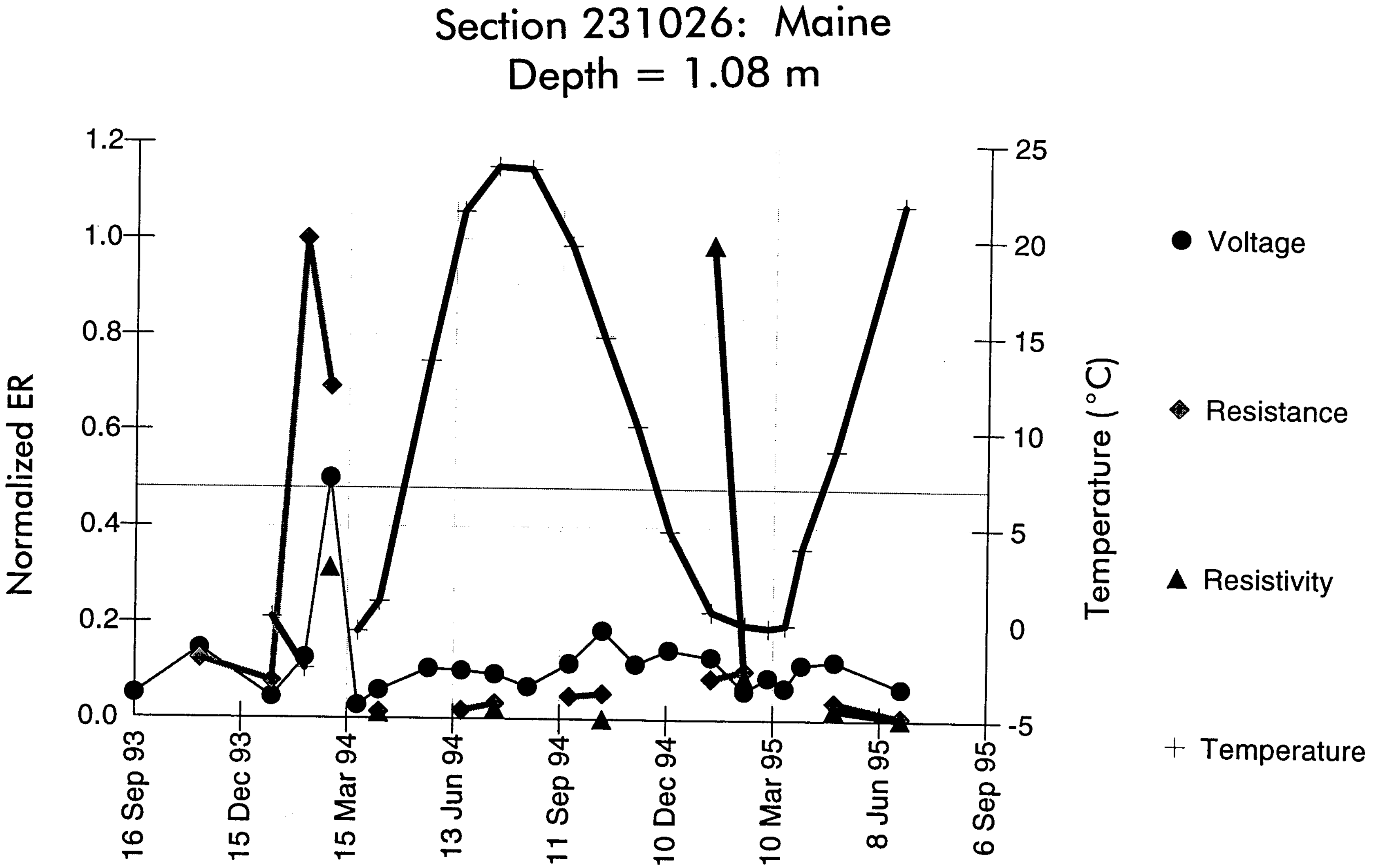


Section 231026: Maine
Depth = 0.98 m

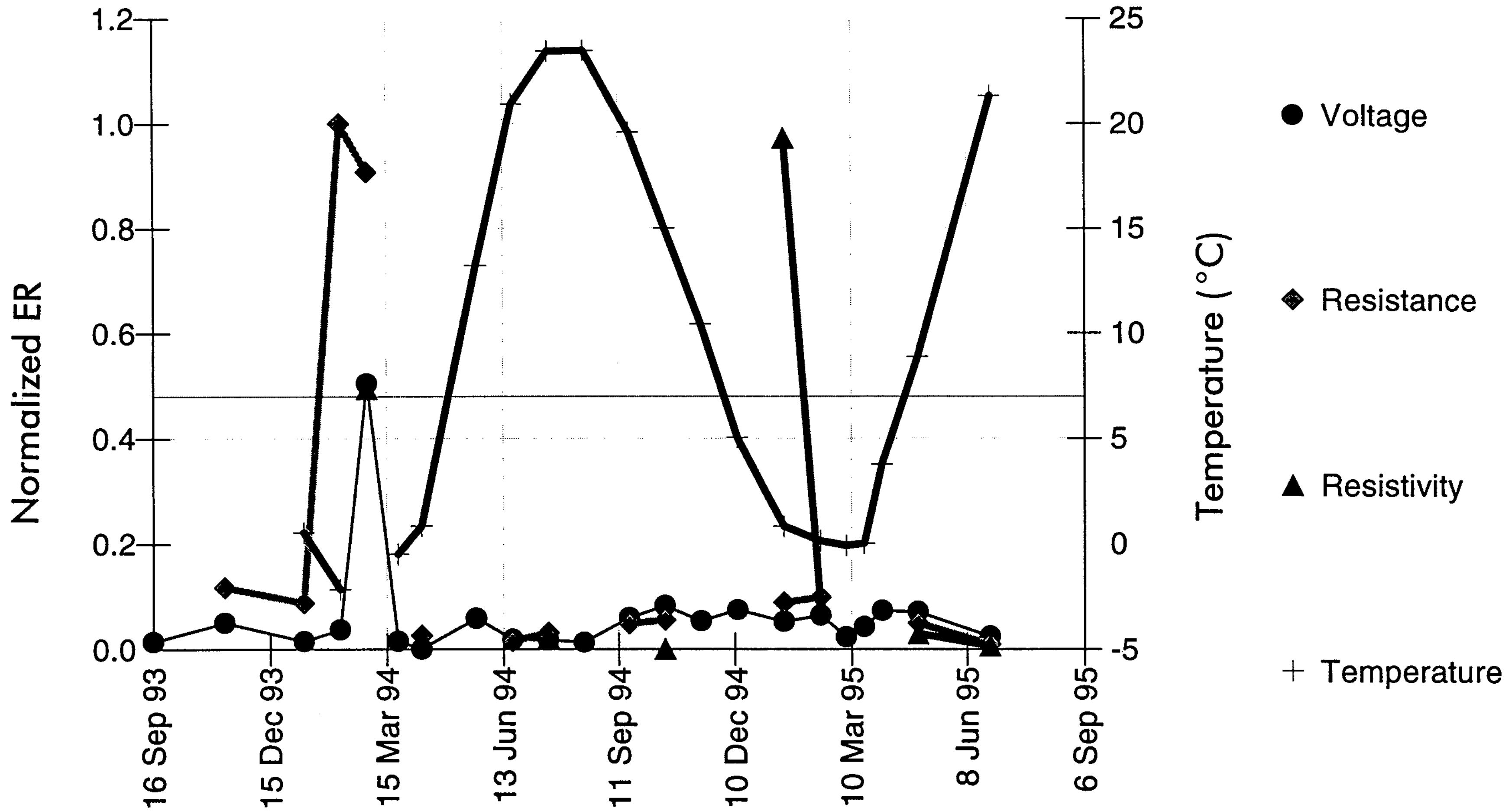




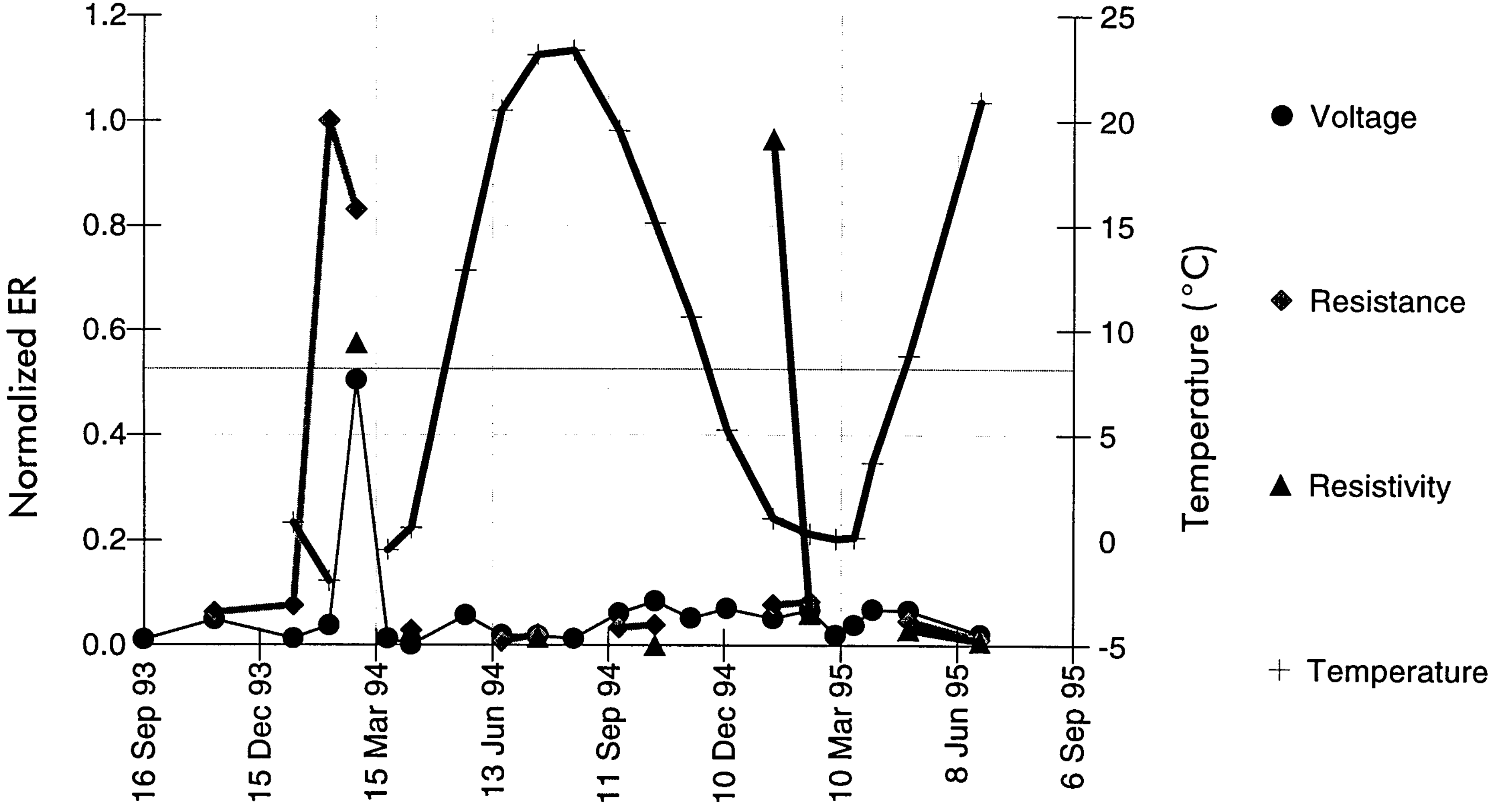
Section 231026: Maine
Depth = 1.03 m


Section 231026: Maine
Depth = 1.08 m
Normalized ER
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Temperature (°C)
25
20
15
10
5
0
-5
16 Sep 93
15 Dec 93
15 Mar 94
13 Jun 94
11 Sep 94
10 Dec 94
10 Mar 95
8 Jun 95
6 Sep 95
● Voltage
◆ Resistance
▲ Resistivity
+ Temperature

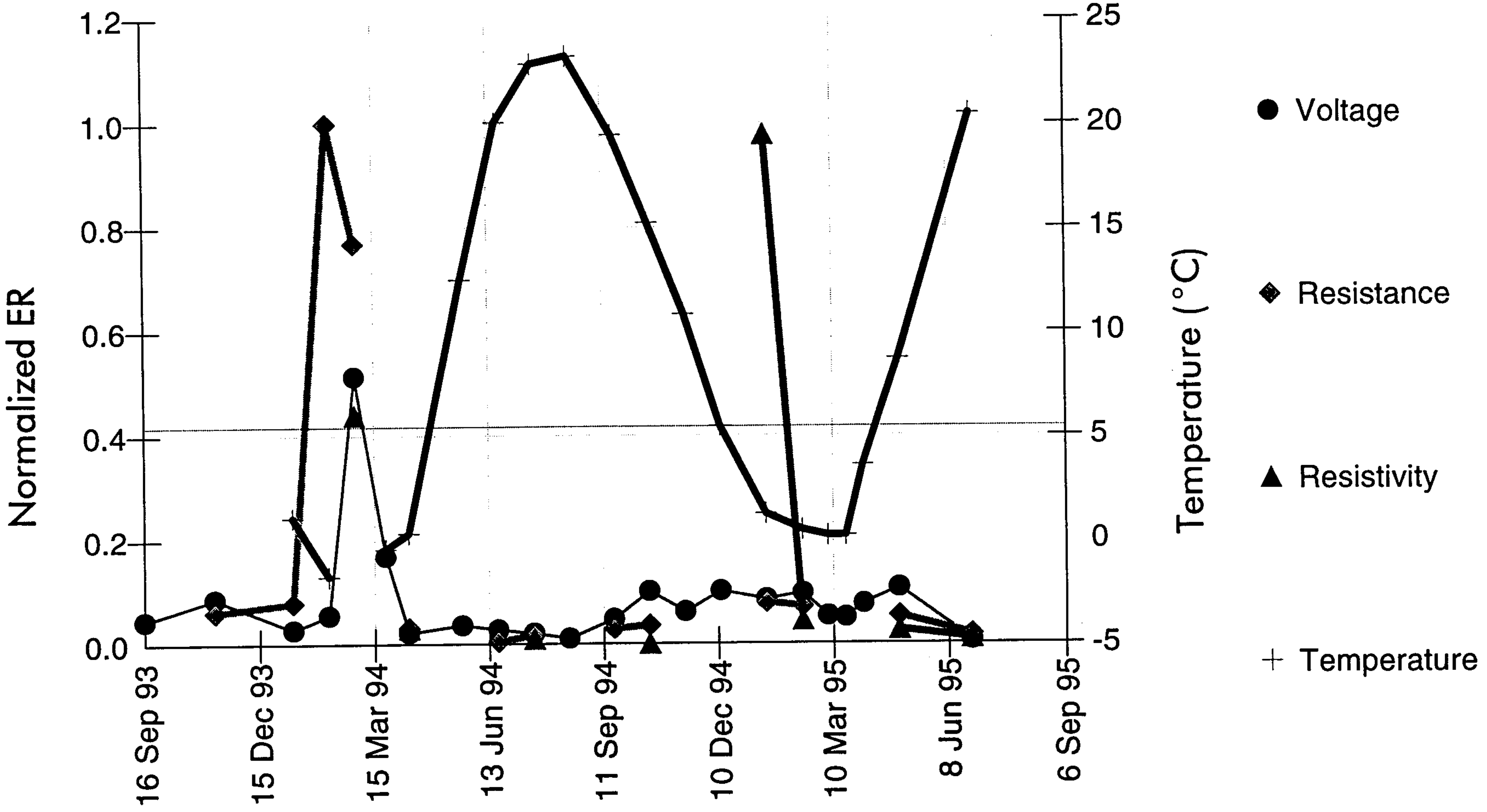
Section 231026: Maine
Depth = 1.13 m

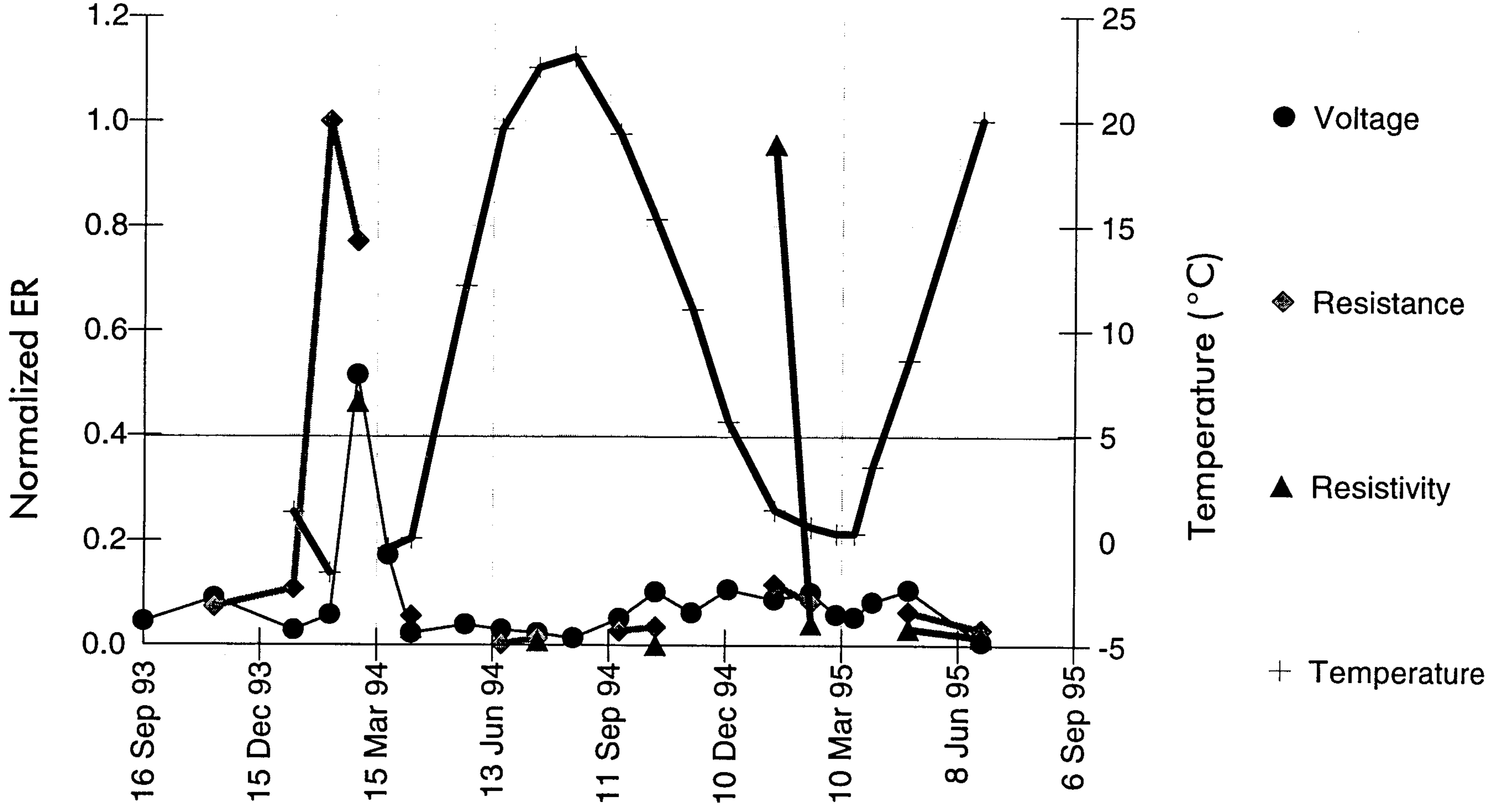


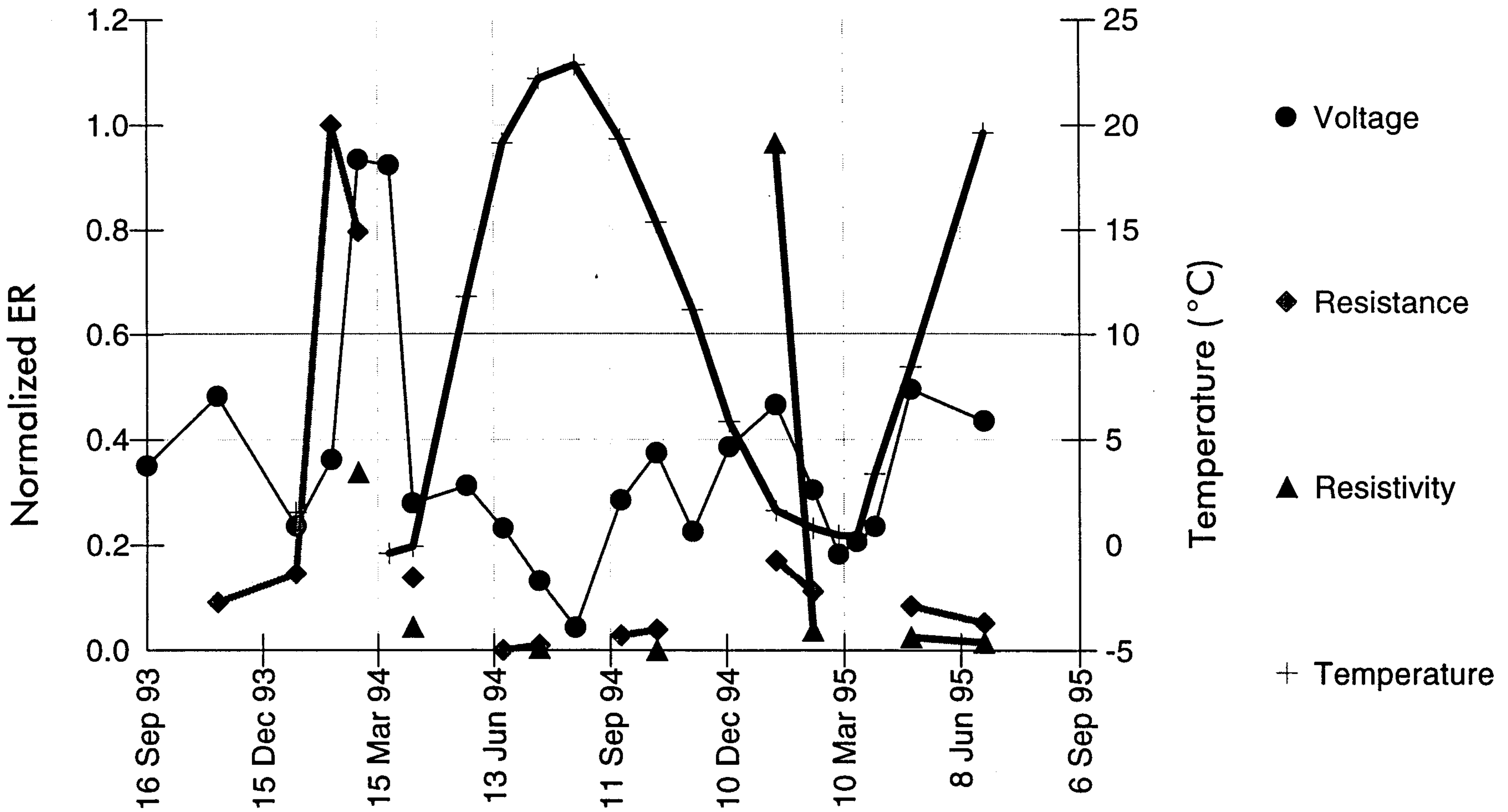
Section 231026: Maine
Depth = 1.18 m



Section 231026: Maine
Depth = 1.24 m

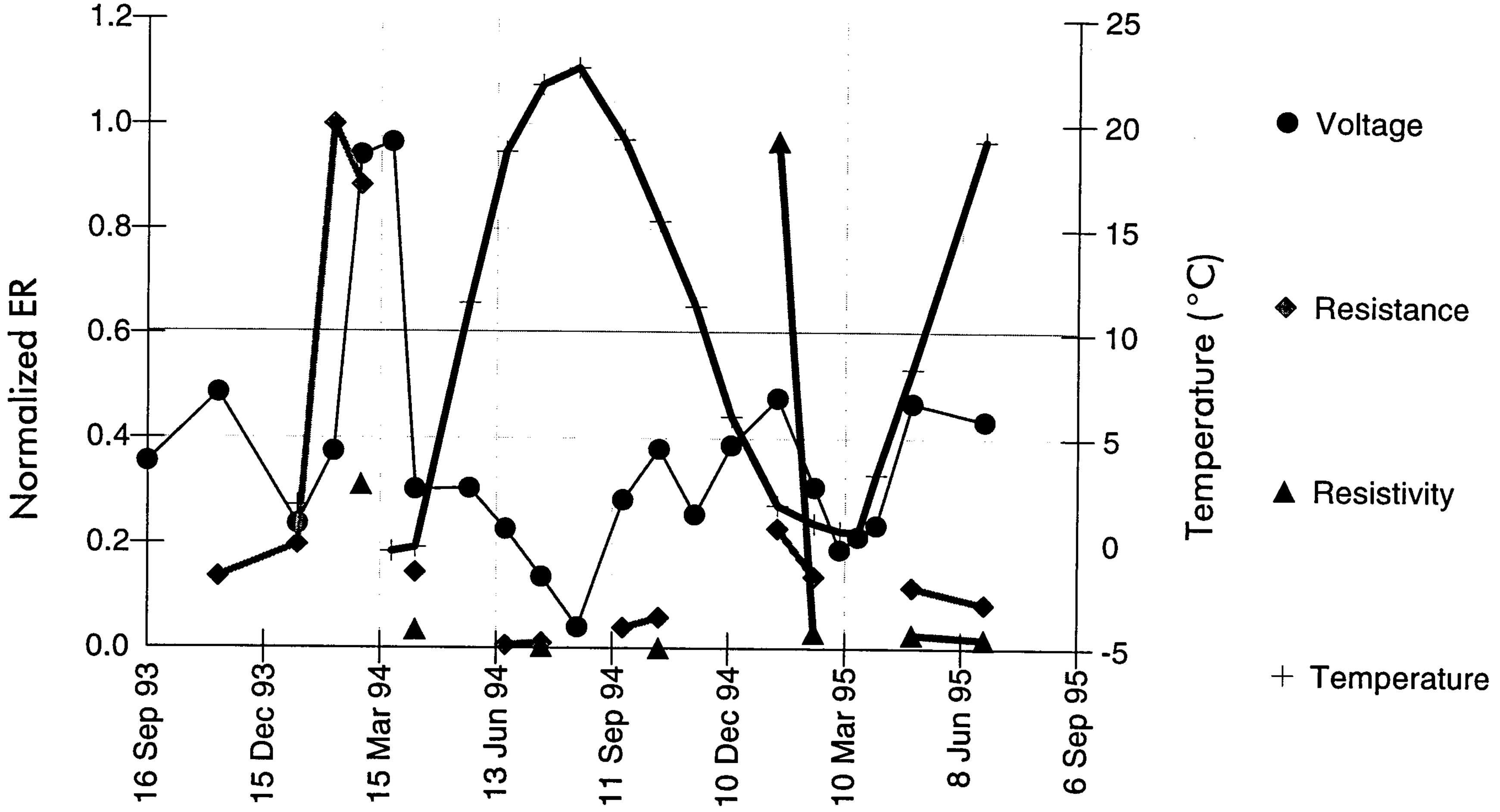


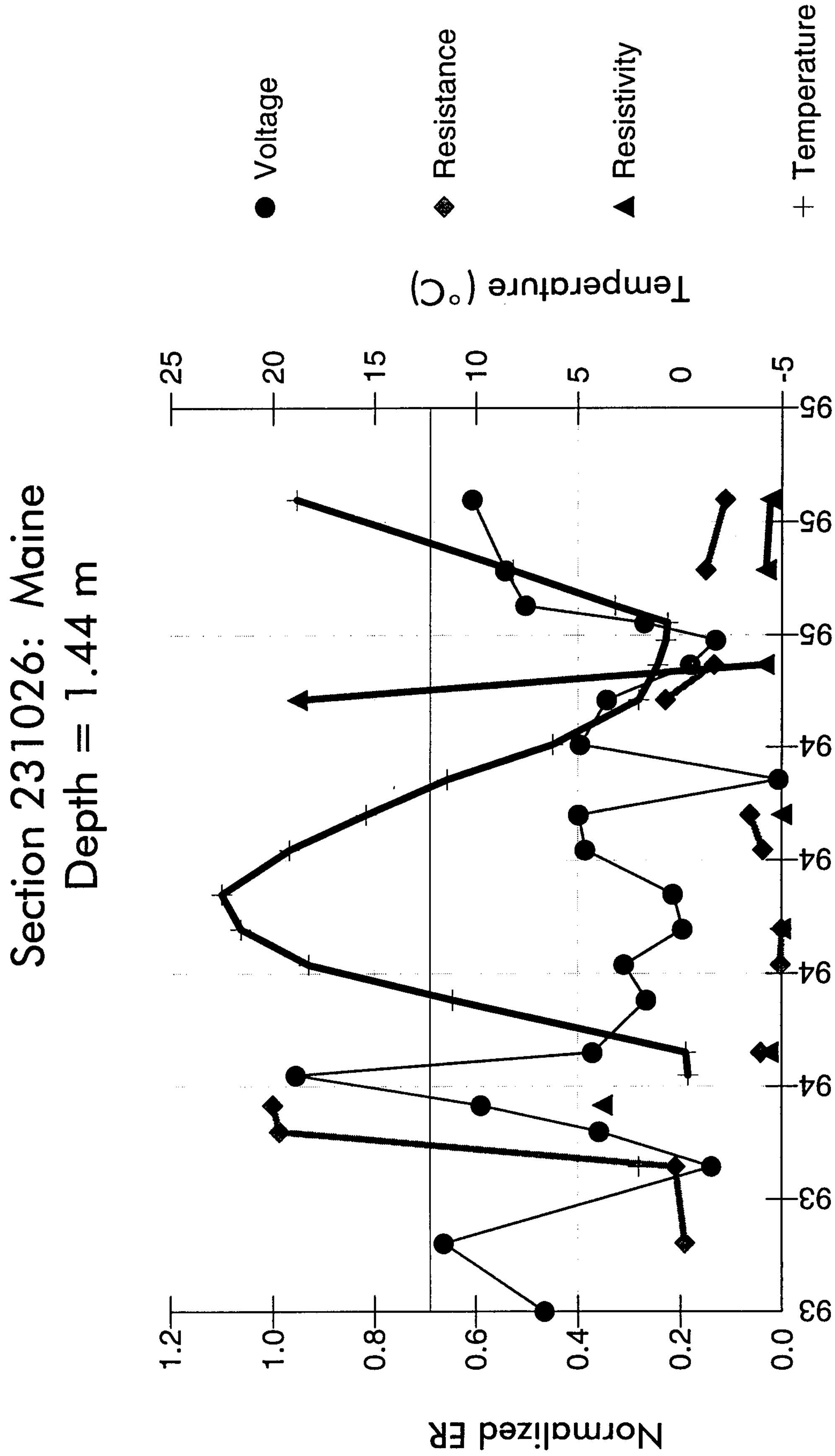

Section 231026: Maine
Depth = 1.29 m



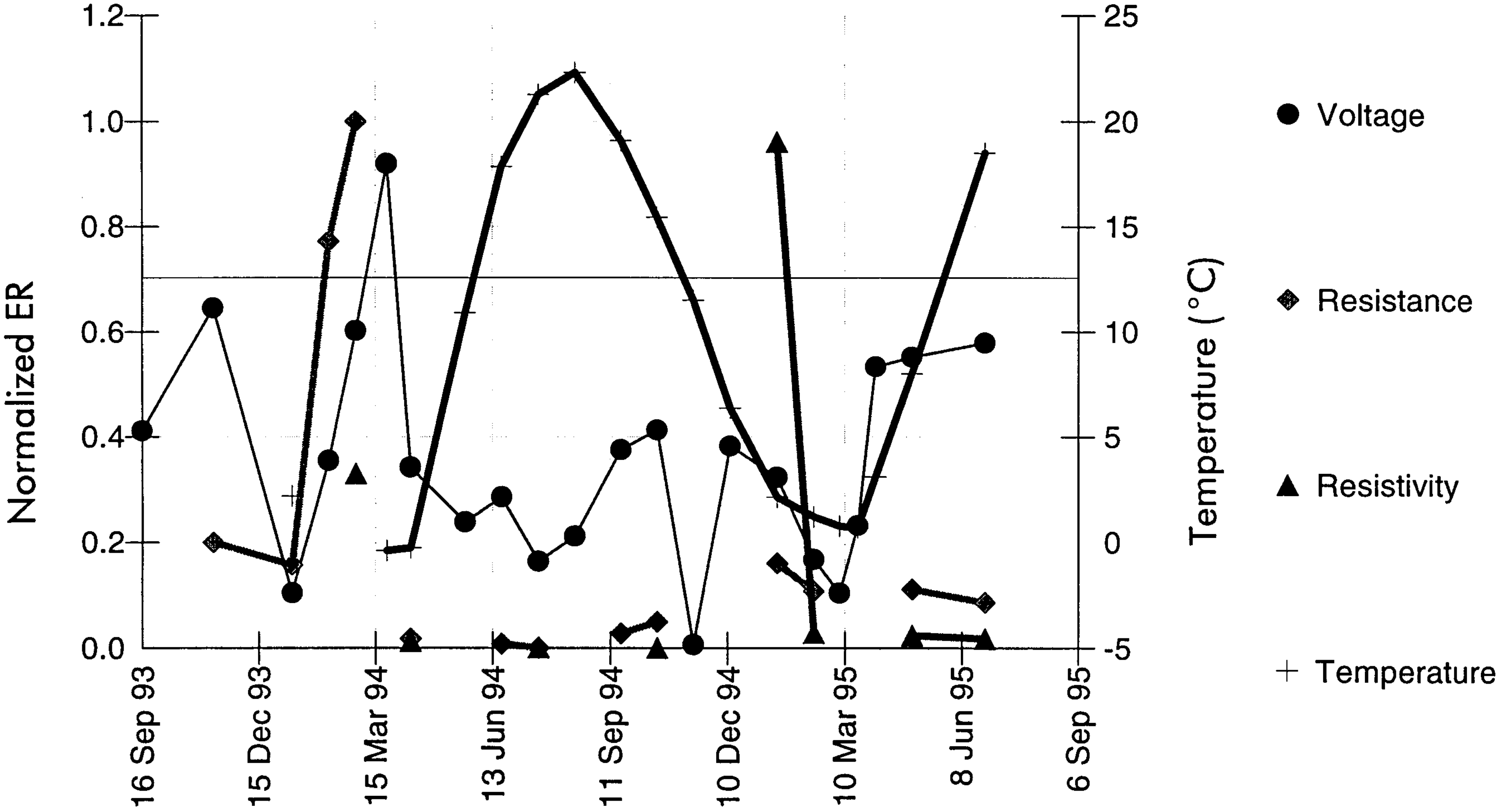
Section 231026: Maine
Depth = 1.34 m

Section 231026: Maine
Depth = 1.39 m

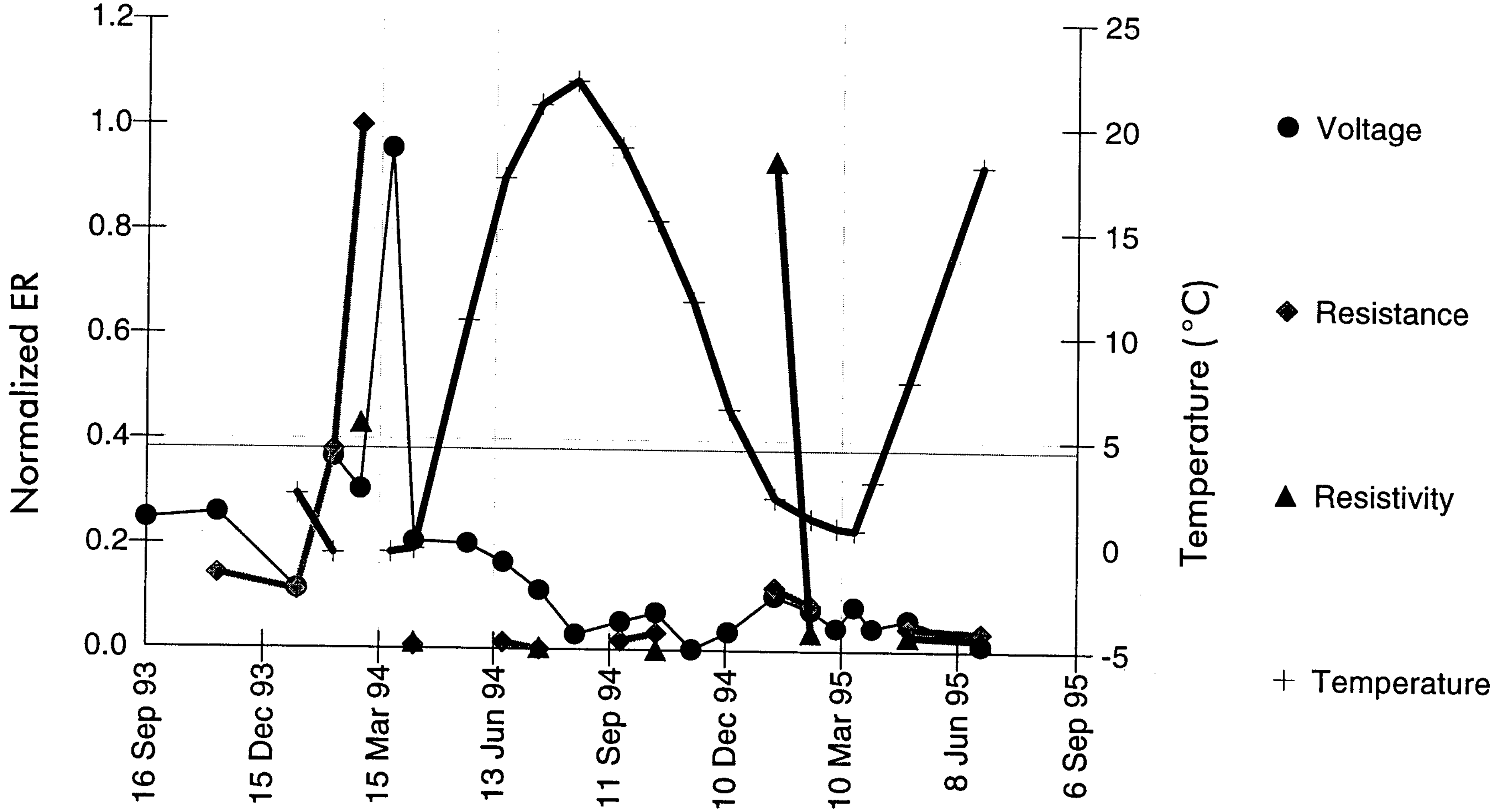



Section 231026: Maine
Depth = 1.44 m

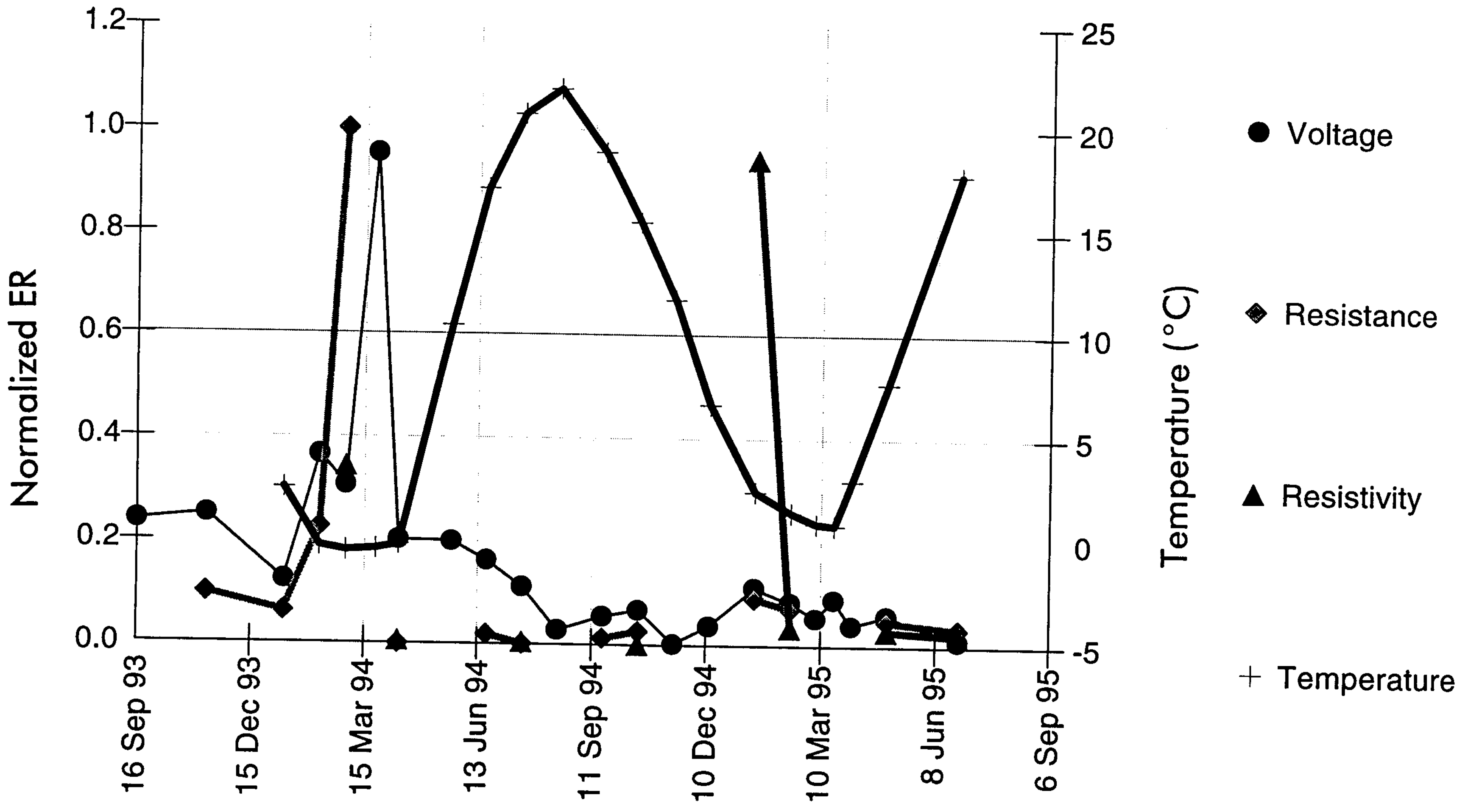
Section 231026: Maine
Depth = 1.49 m



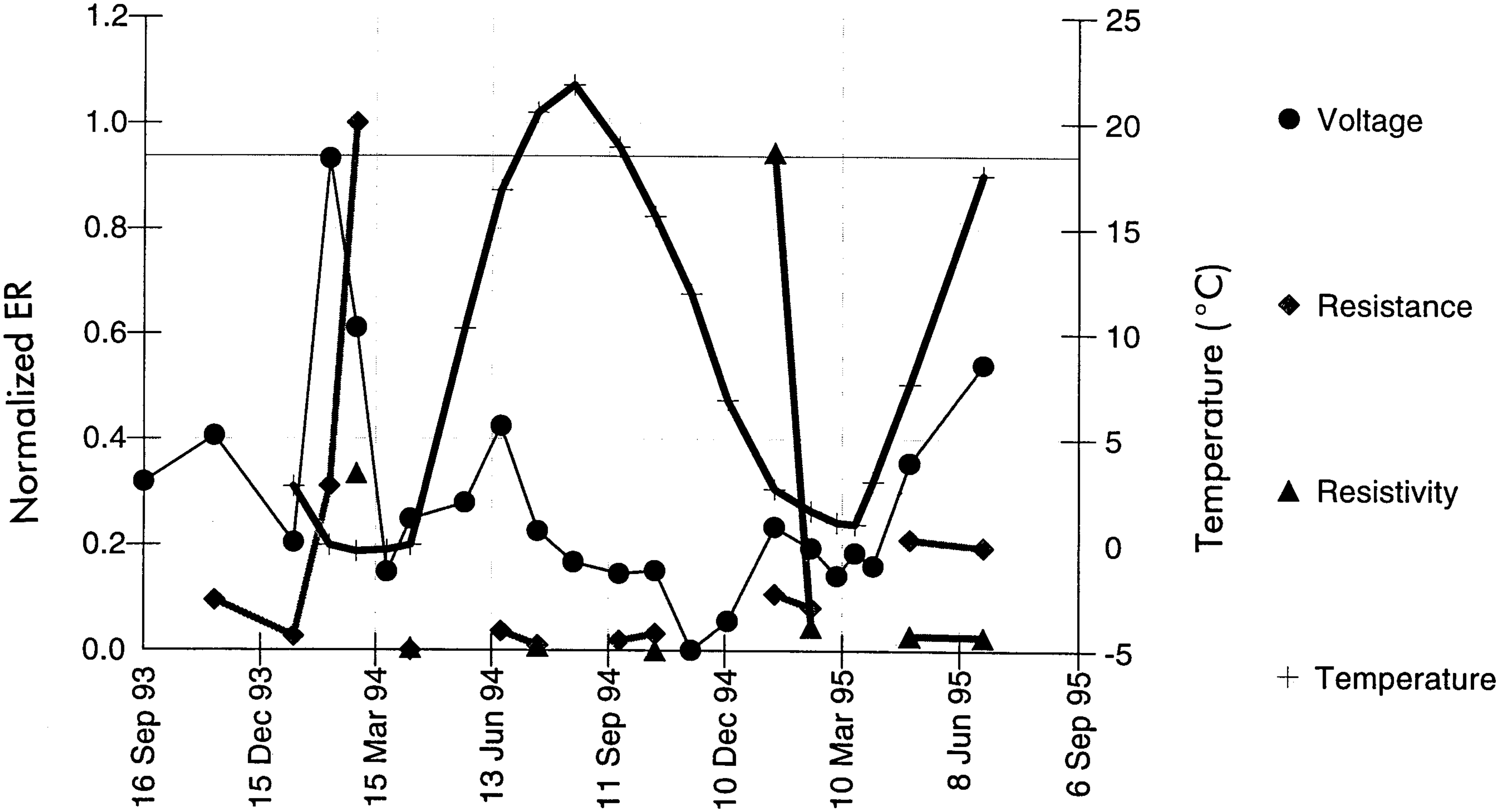
Section 231026: Maine
Depth = 1.54 m



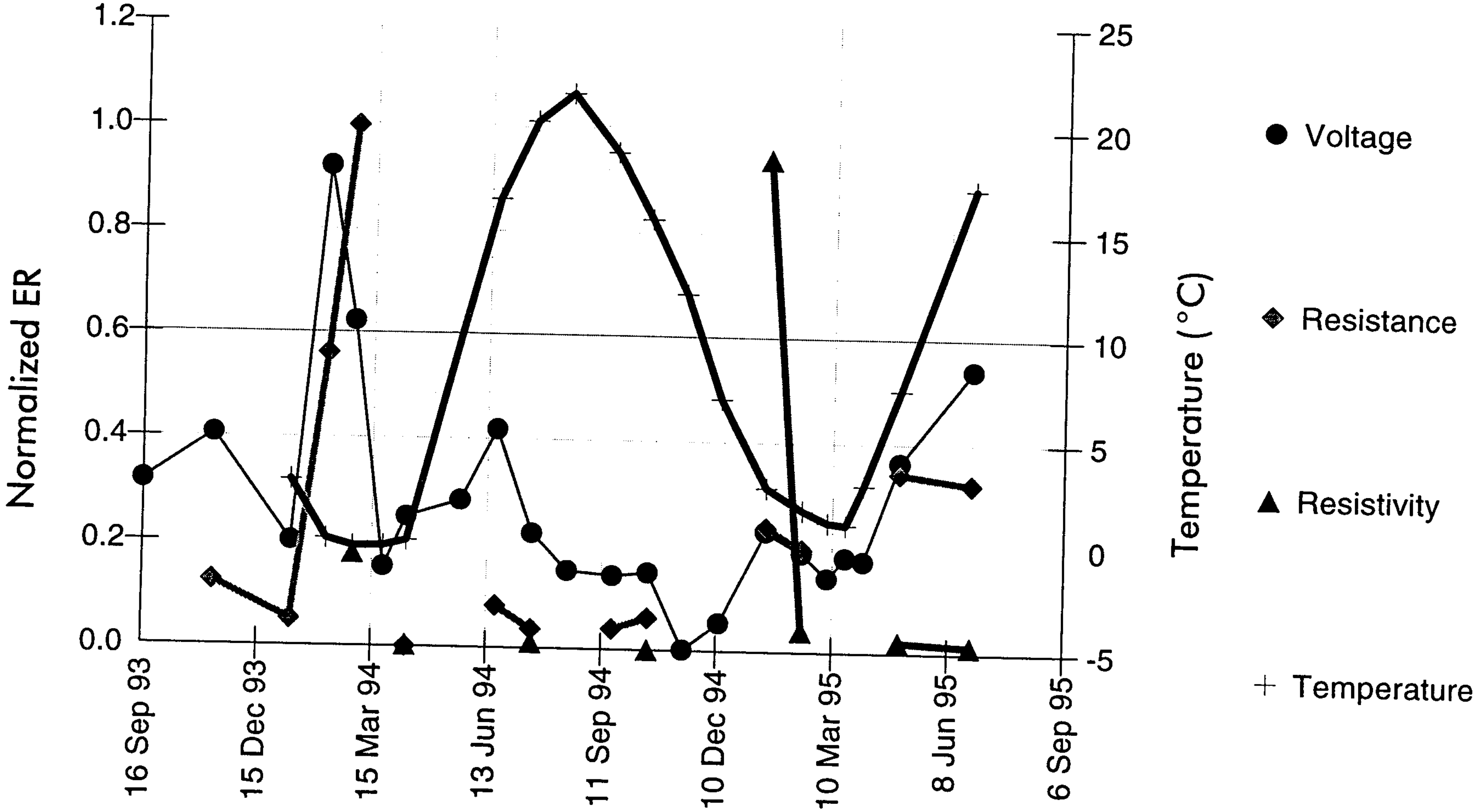
Section 231026: Maine
Depth = 1.59 m



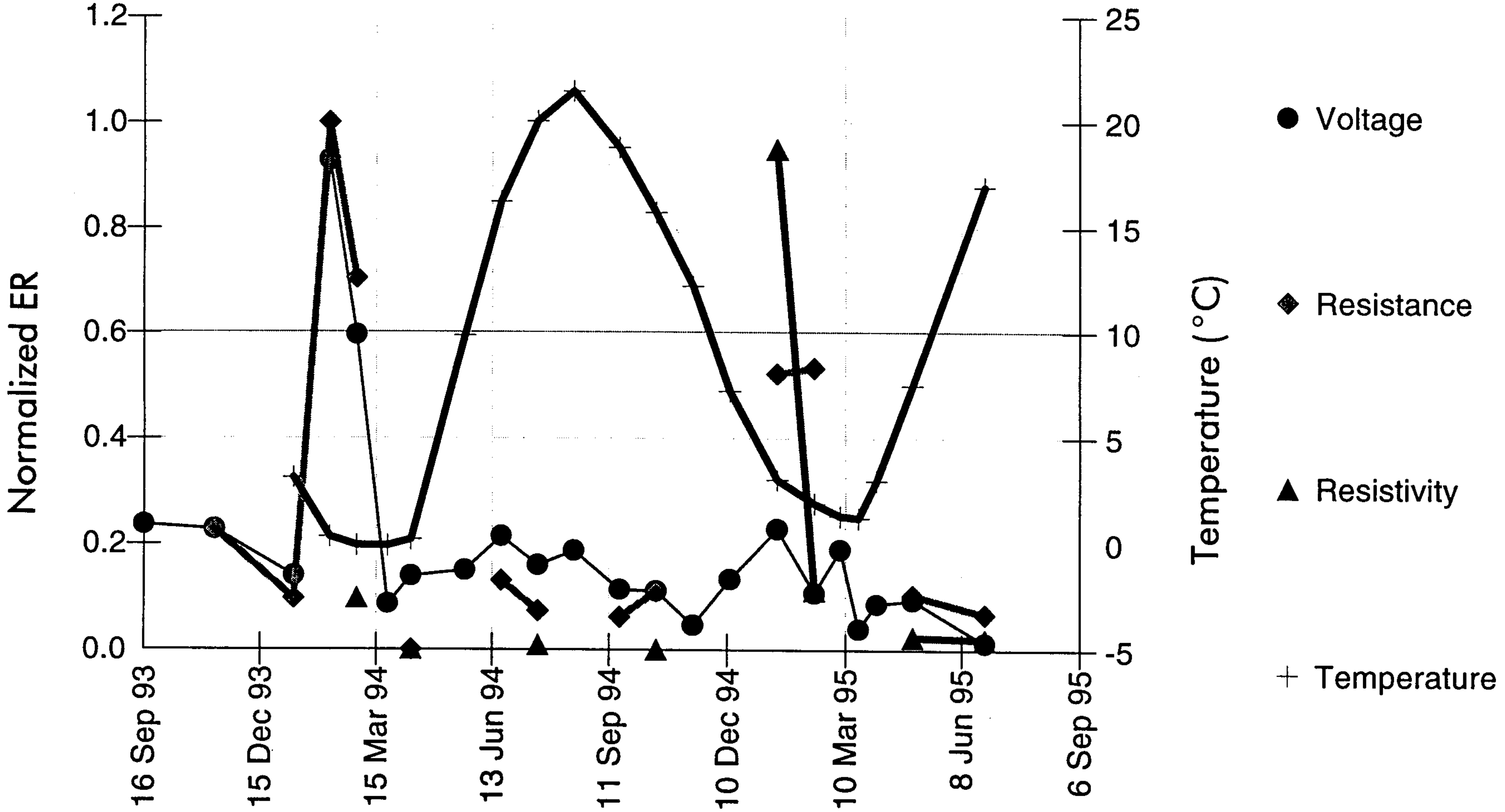
Section 231026: Maine
Depth = 1.64 m



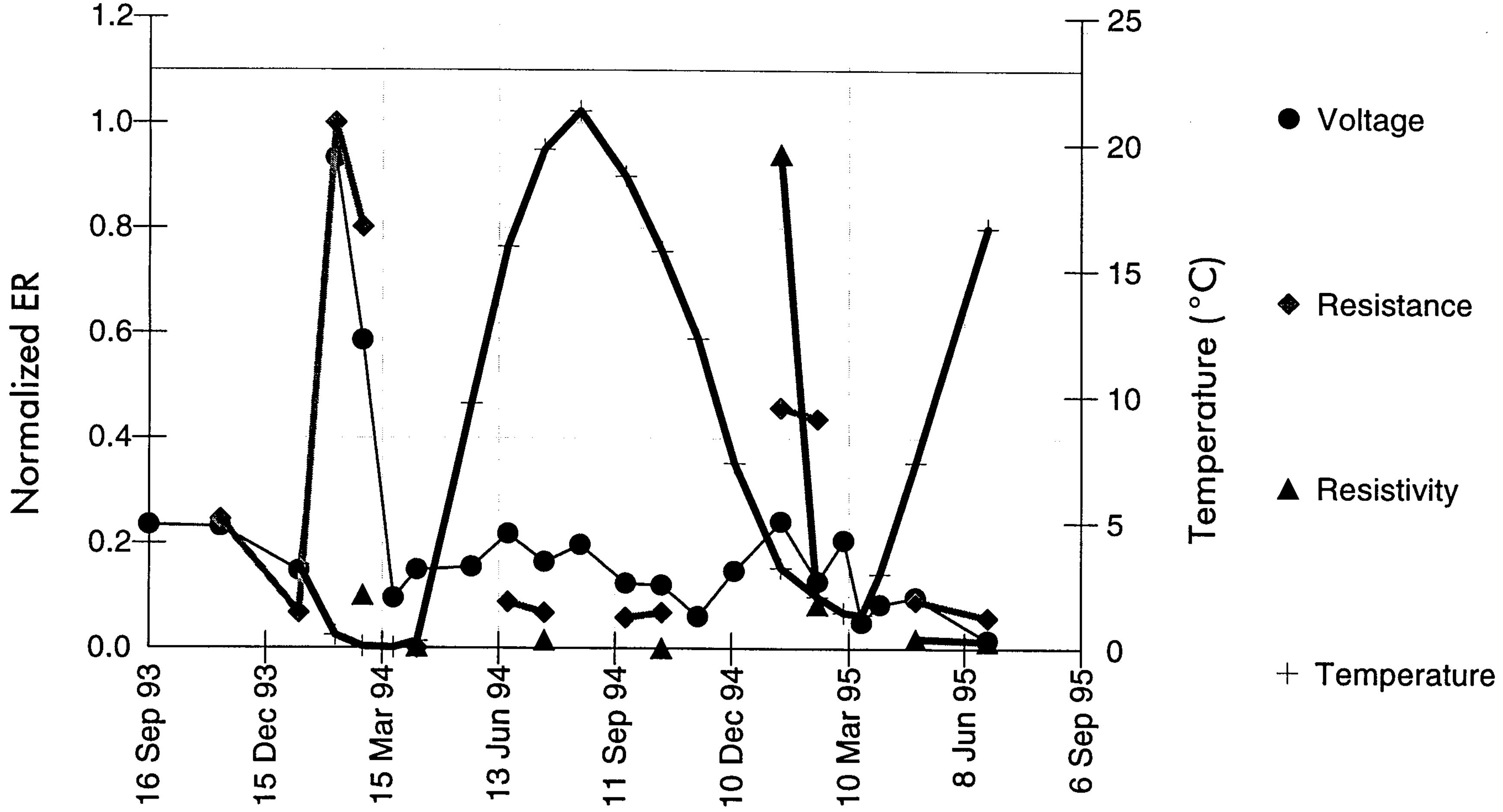
Section 231026: Maine
Depth = 1.69 m



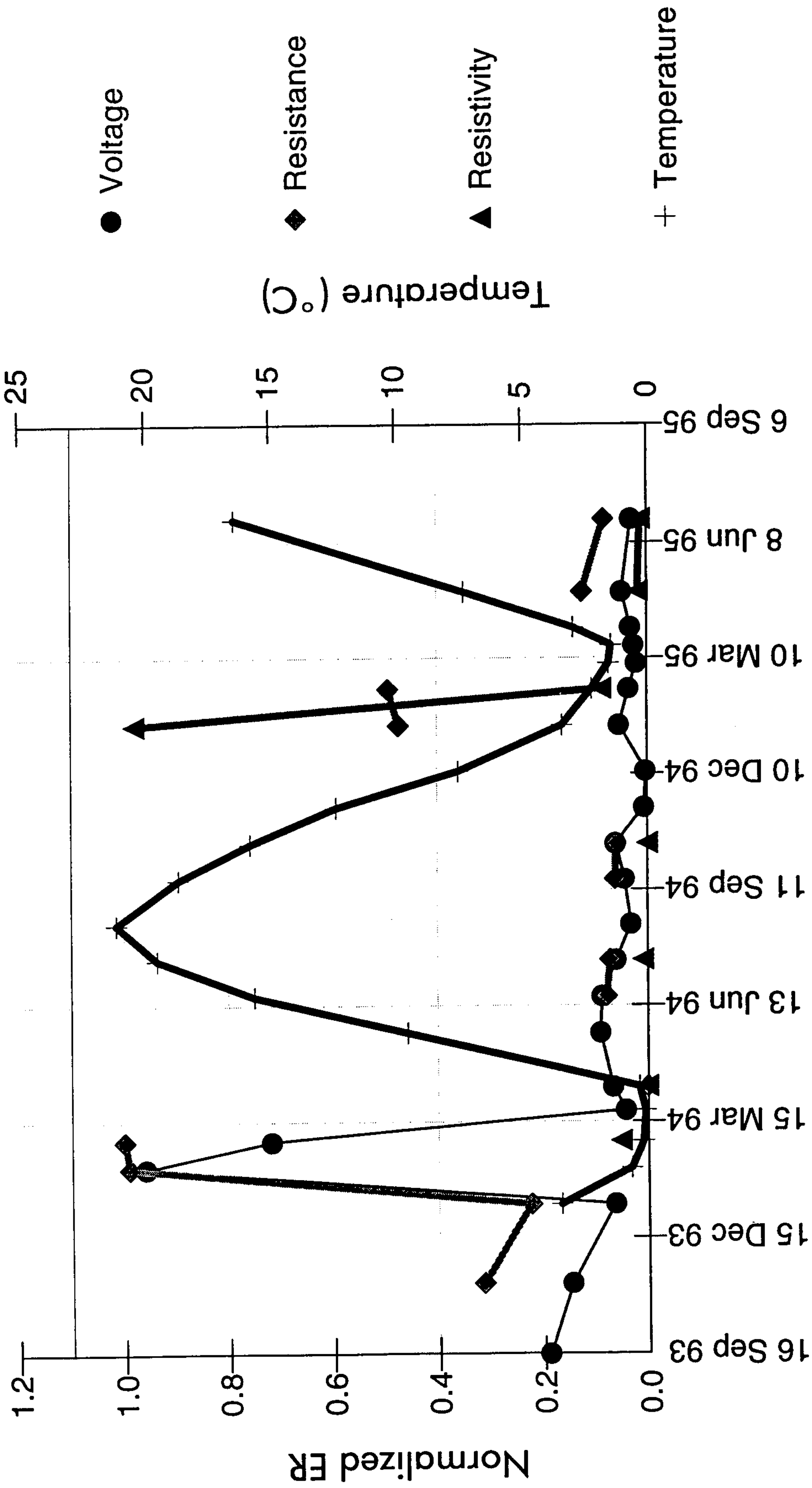
Section 231026: Maine
Depth = 1.74 m



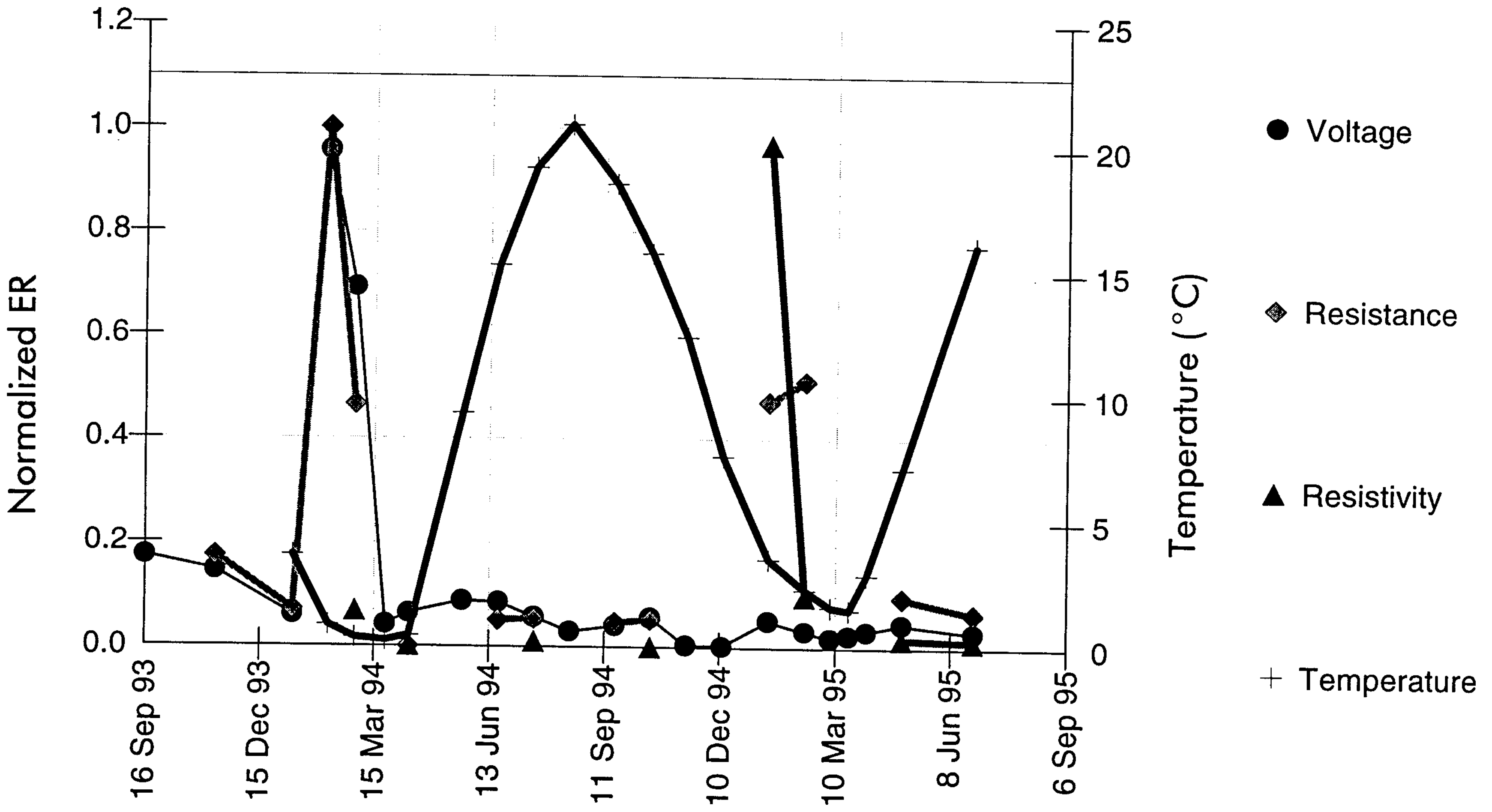
Section 231026: Maine
Depth = 1.79 m



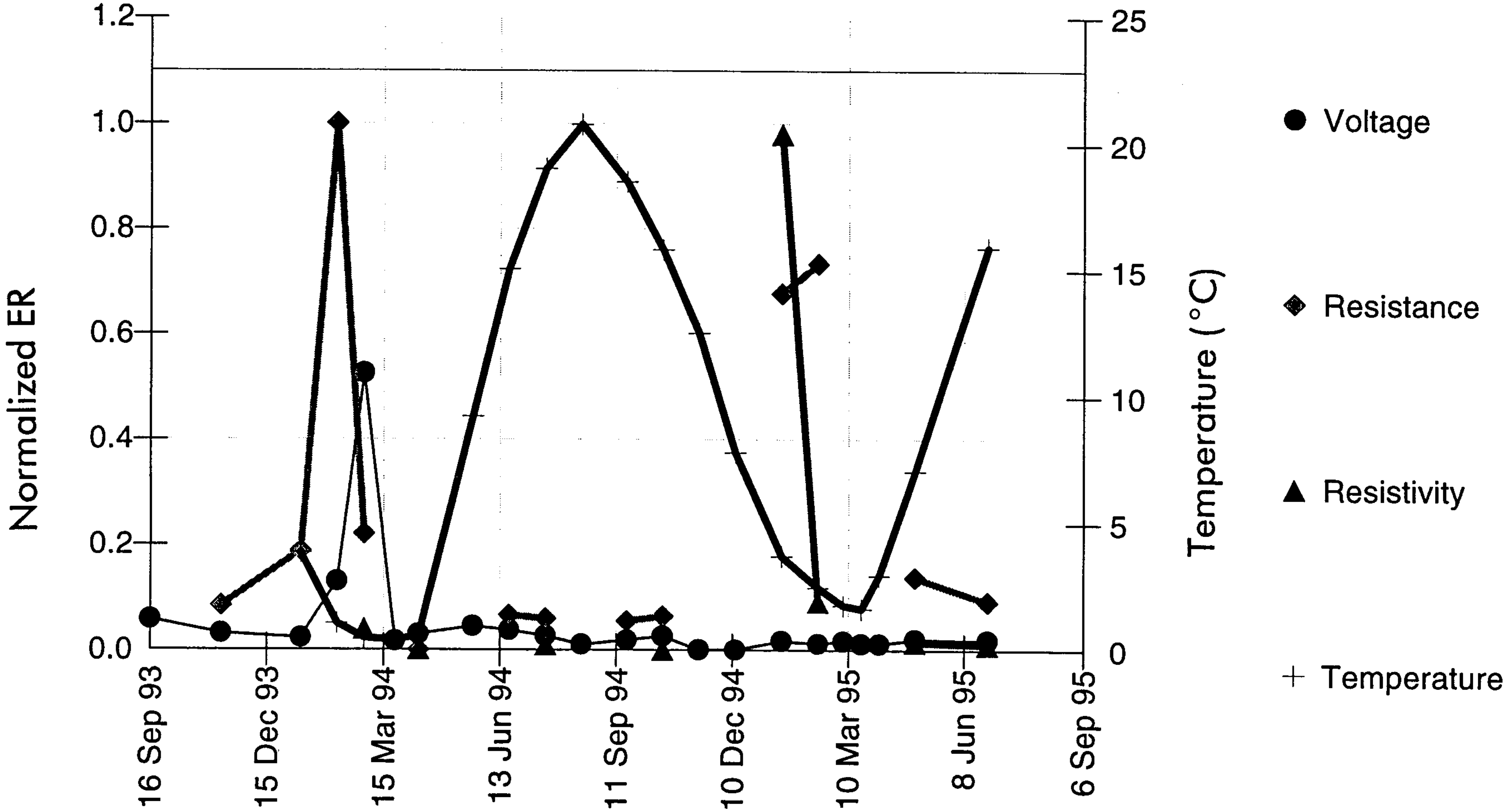
Section 231026: Maine
Depth = 1.85 m



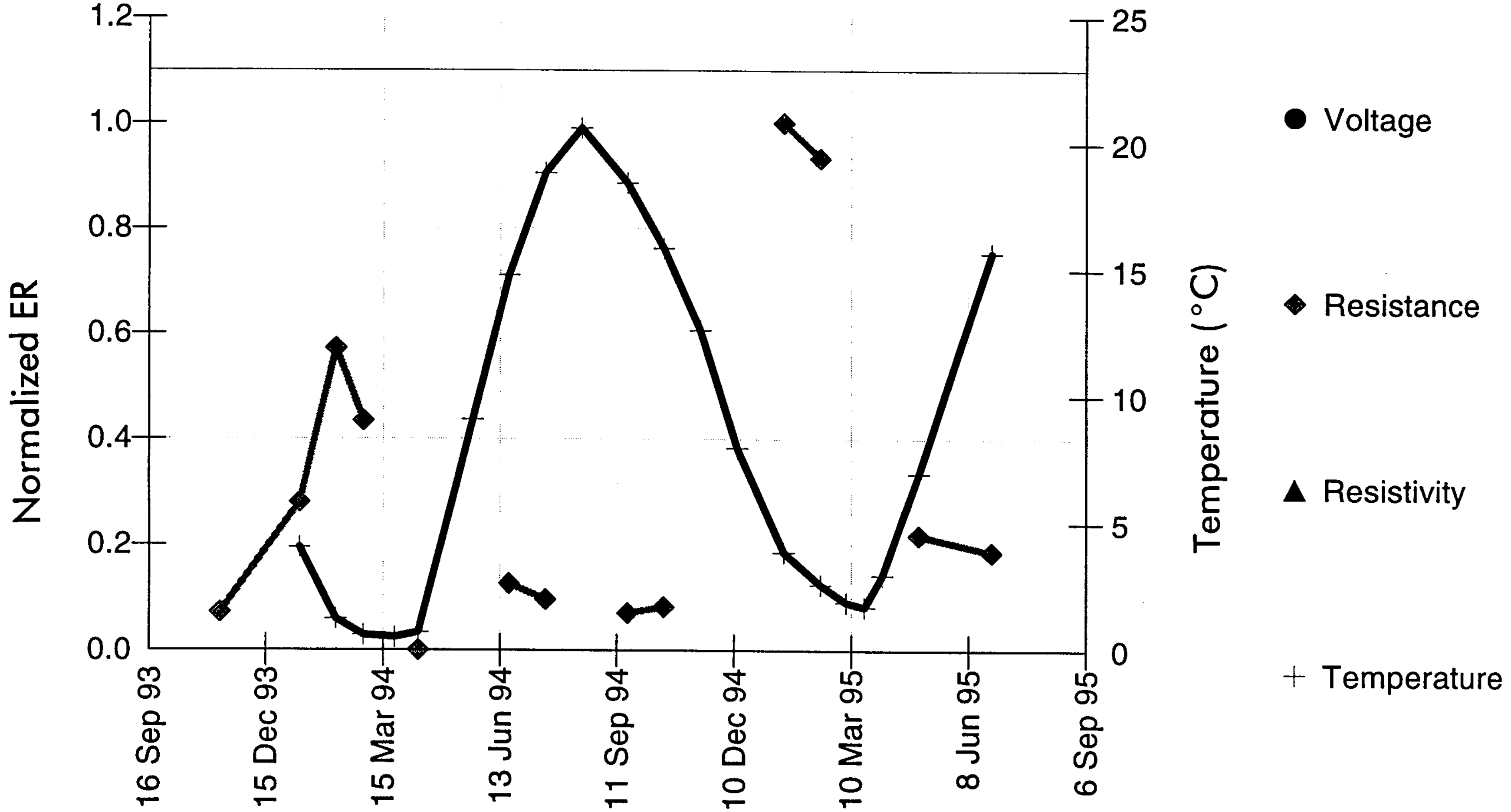
Section 231026: Maine
Depth = 1.90 m



Section 231026: Maine
Depth = 1.95 m



Section 231026: Maine
Depth = 2.00 m



APPENDIX C – TABLE SMP_FROST_PENETRATION

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
4	1024	10/12/1995	0	1	A		
4	1024	11/9/1995	0	1	A		
4	1024	12/7/1995	0	1	A		
4	1024	1/11/1996	0	1	A		
4	1024	2/8/1996	0	1	A		
4	1024	6/13/1996	0	1	A		
4	1024	7/11/1996	0	1	A		
4	1024	8/15/1996	0	1	A		
8	1053	11/9/1993	0	1	A		
8	1053	12/6/1993	0	1	A		
8	1053	1/18/1994	0	1	A		
8	1053	2/14/1994	0	1	A		
8	1053	3/14/1994	0	1	A		
8	1053	3/28/1994	0	1	A		
8	1053	4/11/1994	0	1	A		
8	1053	5/2/1994	0	1	A		
8	1053	6/16/1994	0	1	A		
8	1053	7/13/1994	0	1	A		
8	1053	8/7/1994	0	1	A		
8	1053	8/8/1994	0	1	A		
8	1053	9/12/1994	0	1	A		
8	1053	10/21/1994	0	1	A		
8	1053	11/10/1994	0	1	A		
8	1053	1/17/1995	0	1	A		
8	1053	2/13/1995	0	1	A		
8	1053	11/14/1996	0	1	A		
8	1053	12/11/1996	0	1	A		
8	1053	1/16/1997	0	1	A		
8	1053	2/13/1997	0	1	A		
8	1053	3/7/1997	0	1	A		
8	1053	3/20/1997	0	1	A		
8	1053	4/8/1997	0	1	A		
8	1053	4/23/1997	0	1	A		
8	1053	6/13/1997	0	1	A		
9	1803	8/19/1993	0	1	A		
9	1803	9/2/1993	0	1	A		
9	1803	11/15/1993	0	1	A		
9	1803	2/17/1994	0	1	A		
9	1803	3/10/1994	0	1	A		
9	1803	3/30/1994	0	1	A		
9	1803	4/21/1994	0	1	A		
9	1803	6/9/1994	0	1	A		
9	1803	6/30/1994	0	1	A		
9	1803	7/28/1994	0	1	A		
9	1803	8/25/1994	0	1	A		
9	1803	9/29/1994	0	1	A		
9	1803	10/27/1994	0	1	A		
9	1803	11/30/1994	0	1	A		
9	1803	1/5/1995	0	1	A		
9	1803	1/26/1995	0	1	A		
9	1803	3/2/1995	0	1	A		
9	1803	3/15/1995	0	1	A		
9	1803	3/29/1995	0	1	A		
9	1803	4/12/1995	0	1	A		
9	1803	5/25/1995	0	1	A		
9	1803	6/22/1995	0	1	A		
9	1803	10/8/1996	0	1	A		
9	1803	11/7/1996	0	1	A		
9	1803	12/5/1996	0	1	A		
9	1803	1/9/1997	0	1	A		

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
9	1803	2/6/1997	0	1	A		
9	1803	3/6/1997	0	1	A		
9	1803	4/3/1997	0	1	A		
9	1803	4/17/1997	0	1	A		
9	1803	5/8/1997	0	1	A		
9	1803	6/5/1997	0	1	A		
9	1803	7/10/1997	0	1	A		
9	1803	8/7/1997	0	1	A		
9	1803	9/11/1997	0	1	A		
9	1803	10/16/1997	0	1	A		
16	1010	10/1/1993	0	1	A		
16	1010	11/18/1993	0	1	A		
16	1010	12/16/1993	1	1	A	0.359	0.410
16	1010	1/27/1994	1	1	A	0.359	0.459
16	1010	2/25/1994	1	1	A	0.561	0.763
16	1010	3/21/1994	0	1	A		
16	1010	4/4/1994	0	1	A		
16	1010	4/22/1994	0	1	A		
16	1010	5/9/1994	0	1	A		
16	1010	6/1/1994	0	1	A		
16	1010	7/27/1994	0	1	A		
16	1010	8/25/1994	0	1	A		
16	1010	9/27/1994	0	1	A		
16	1010	11/2/1994	0	1	A		
16	1010	11/17/1994	0	1	A		
16	1010	12/13/1994	1	1	A	0.359	0.662
16	1010	1/25/1995	1	1	A	0.359	0.763
16	1010	2/21/1995	0	1	A		
16	1010	11/25/1996	0	1	A		
16	1010	12/19/1996	1	1	A	0.359	0.612
16	1010	1/27/1997	1	1	A	0.359	0.509
16	1010	2/25/1997	0	1	A		
16	1010	3/14/1997	0	1	A		
16	1010	3/28/1997	0	1	A		
16	1010	4/16/1997	0	1	A		
16	1010	4/30/1997	0	1	A		
16	1010	6/2/1997	0	1	A		
16	1010	6/26/1997	0	1	A		
18	3002	9/8/1995	0	1	A		
18	3002	10/13/1995	0	1	A		
18	3002	11/20/1995	0	1	A		
18	3002	12/8/1995	0	1	A		
18	3002	1/26/1996	0	1	A		
18	3002	3/11/1996	0	1	A		
18	3002	4/30/1996	0	1	A		
18	3002	8/2/1996	0	1	A		
20	4054	8/25/1995	0	1	A		
20	4054	9/21/1995	0	1	A		
20	4054	10/18/1995	0	1	A		
20	4054	11/16/1995	0	1	A		
20	4054	12/11/1995	0	1	A		
20	4054	1/24/1996	0	1	A		
20	4054	3/8/1996	0	1	A		
20	4054	4/25/1996	0	1	A		
23	1026	9/16/1993	0	1	A		
23	1026	11/10/1993	0	1	A		
23	1026	1/10/1994	1	1	A	0.245	0.600
23	1026	2/7/1994	1	1	A	0.245	1.515
23	1026	2/28/1994	1	1	A	0.245	1.770
23	1026	3/24/1994	1	1	A	1.312	1.618

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
23	1026	4/11/1994	0	1	A		
23	1026	5/23/1994	0	1	A		
23	1026	6/20/1994	0	1	A		
23	1026	7/18/1994	0	1	A		
23	1026	8/15/1994	0	1	A		
23	1026	9/19/1994	0	1	A		
23	1026	10/17/1994	0	1	A		
23	1026	11/14/1994	0	1	A		
23	1026	12/12/1994	0	1	A		
23	1026	1/17/1995	1	1	A	0.499	0.907
23	1026	2/14/1995	1	1	A	0.245	1.008
23	1026	3/6/1995	0	1	A		
23	1026	3/20/1995	0	1	A		
23	1026	4/3/1995	0	1	A		
23	1026	5/1/1995	0	1	A		
23	1026	6/26/1995	0	1	A		
24	1634	5/13/1995	0	1	A		
24	1634	7/6/1995	0	1	A		
24	1634	9/19/1995	0	1	A		
24	1634	10/19/1995	0	1	A		
24	1634	11/15/1995	0	1	A		
24	1634	12/13/1995	0	1	A		
24	1634	1/17/1996	0	1	A		
24	1634	2/14/1996	0	1	A		
24	1634	2/28/1996	0	1	A		
24	1634	3/13/1996	0	1	A		
24	1634	4/17/1996	0	1	A		
24	1634	5/8/1996	0	1	A		
24	1634	7/17/1996	0	1	A		
24	1634	8/14/1996	0	1	A		
24	1634	9/25/1996	0	1	A		
24	1634	10/30/1996	0	1	A		
24	1634	9/4/1997	0	1	A		
24	1634	10/1/1997	0	1	A		
24	1634	11/12/1997	0	1	A		
25	1002	9/1/1993	0	1	A		
25	1002	11/16/1993	0	1	A		
25	1002	2/16/1994	1	1	A	0.252	0.762
25	1002	3/9/1994	0	1	A		
25	1002	3/29/1994	0	1	A		
25	1002	4/20/1994	0	1	A		
25	1002	6/8/1994	0	1	A		
25	1002	6/29/1994	0	1	A		
25	1002	7/27/1994	0	1	A		
25	1002	8/24/1994	0	1	A		
25	1002	9/28/1994	0	1	A		
25	1002	10/26/1994	0	1	A		
25	1002	11/29/1994	0	1	A		
25	1002	1/4/1995	0	1	A		
25	1002	2/1/1995	0	1	A		
25	1002	3/1/1995	0	1	A		
25	1002	3/14/1995	0	1	A		
25	1002	3/28/1995	0	1	A		
25	1002	4/11/1995	0	1	A		
25	1002	5/24/1995	0	1	A		
25	1002	6/21/1995	0	1	A		
25	1002	10/9/1996	0	1	A		
25	1002	11/6/1996	0	1	A		
25	1002	12/4/1996	0	1	A		
25	1002	1/8/1997	0	1	A		

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
25	1002	2/5/1997	0	1	A		
25	1002	3/5/1997	0	1	A		
25	1002	4/2/1997	0	1	A		
25	1002	4/16/1997	0	1	A		
25	1002	5/7/1997	0	1	A		
25	1002	6/4/1997	0	1	A		
25	1002	7/9/1997	0	1	A		
25	1002	8/6/1997	0	1	A		
25	1002	9/10/1997	0	1	A		
25	1002	10/15/1997	0	1	A		
27	1018	8/24/1993	0	1	A		
27	1018	9/23/1993	0	1	A		
27	1018	10/20/1993	0	1	A		
27	1018	11/19/1993	0	1	A		
27	1018	12/7/1993	1	1	A	0.404	0.506
27	1018	1/11/1994	1	1	A	0.404	1.422
27	1018	2/8/1994	1	1	A	0.404	2.030
27	1018	3/8/1994	1	1	A	0.456	2.182
27	1018	3/22/1994	1	1	A	1.321	2.131
27	1018	4/4/1994	1	1	A	1.574	1.828
27	1018	4/25/1994	1	1	A	1.625	1.777
27	1018	5/9/1994	0	1	A		
27	1018	6/13/1994	0	1	A		
27	1018	7/11/1994	0	1	A		
27	1018	8/8/1994	0	1	A		
27	1028	9/9/1993	0	1	A		
27	1028	10/20/1993	0	1	A		
27	1028	11/18/1993	0	1	A		
27	1028	12/8/1993	1	1	A	0.610	0.968
27	1028	1/12/1994	1	1	A	0.610	2.084
27	1028	3/9/1994	1	1	A	0.610	2.387
27	1028	3/23/1994	1	1	A	1.173	2.387
27	1028	4/5/1994	1	1	A	1.983	2.286
27	1028	4/26/1994	0	1	A		
27	1028	5/10/1994	0	1	A		
27	1028	6/14/1994	0	1	A		
27	1028	7/12/1994	0	1	A		
27	1028	8/9/1994	0	1	A		
27	1028	9/19/1994	0	1	A		
27	1028	10/11/1994	0	1	A		
27	1028	11/8/1994	0	1	A		
27	1028	12/6/1994	1	1	A	0.610	0.865
27	1028	1/10/1995	1	1	A	0.610	1.782
27	1028	2/7/1995	1	1	A	0.610	2.084
27	1028	3/8/1995	1	1	A	0.610	2.387
27	1028	3/21/1995	1	1	A	1.070	2.387
27	1028	5/9/1995	0	1	A		
27	1028	5/15/1995	0	1	A		
27	1028	6/14/1995	0	1	A		
27	1028	10/8/1996	0	1	A		
27	1028	11/5/1996	0	1	A		
27	1028	12/5/1996	1	1	A	0.660	1.478
27	1028	4/10/1997	1	1	A	2.084	2.387
27	1028	4/24/1997	0	1	A		
27	1028	5/8/1997	0	1	A		
27	1028	5/30/1997	0	1	A		
27	1028	6/12/1997	0	1	A		
27	1028	8/14/1997	0	1	A		
27	1028	9/10/1997	0	1	A		
27	4040	9/22/1993	0	1	A		

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
27	4040	10/18/1993	0	1	A		
27	4040	11/16/1993	0	1	A		
27	4040	12/16/1993	1	1	A	0.639	1.047
27	4040	1/19/1994	1	1	A	0.538	1.708
27	4040	2/17/1994	1	1	A	0.588	1.758
27	4040	3/17/1994	1	1	A	0.845	2.012
27	4040	4/14/1994	0	1	A		
27	4040	5/4/1994	0	1	A		
27	4040	5/18/1994	0	1	A		
27	4040	6/23/1994	0	1	A		
27	4040	7/28/1994	0	1	A		
27	4040	8/25/1994	0	1	A		
27	4040	9/30/1994	0	1	A		
27	4040	10/13/1994	0	1	A		
27	4040	11/10/1994	0	1	A		
27	4040	12/8/1994	1	1	A	0.588	0.793
27	4040	1/12/1995	1	1	A	0.538	1.402
27	4040	2/9/1995	1	1	A	0.538	1.708
27	4040	3/31/1995	1	1	A	0.997	1.961
27	4040	5/11/1995	0	1	A		
27	4040	6/16/1995	0	1	A		
27	4040	10/9/1996	0	1	A		
27	4040	2/5/1997	1	1	A	0.538	1.961
27	4040	3/17/1997	1	1	A	1.251	2.217
27	4040	3/18/1997	1	1	A	0.639	1.911
27	4040	4/8/1997	1	1	A	1.098	1.708
27	4040	4/22/1997	1	1	A	1.251	2.064
27	4040	5/6/1997	1	1	A	1.758	2.012
27	4040	5/28/1997	0	1	A		
27	4040	6/10/1997	0	1	A		
27	4040	7/11/1997	0	1	A		
27	4040	8/13/1997	0	1	A		
27	4040	9/9/1997	0	1	A		
27	6251	9/15/1993	0	1	A		
27	6251	10/19/1993	0	1	A		
27	6251	11/17/1993	0	1	A		
27	6251	12/15/1993	0	1	A		
27	6251	1/19/1994	1	1	A	0.479	2.107
27	6251	2/16/1994	1	1	A	0.580	2.259
27	6251	3/16/1994	1	1	A	1.191	2.208
27	6251	3/30/1994	0	1	A		
27	6251	4/13/1994	0	1	A		
27	6251	5/3/1994	0	1	A		
27	6251	5/17/1994	0	1	A		
27	6251	6/22/1994	0	1	A		
27	6251	7/27/1994	0	1	A		
27	6251	8/24/1994	0	1	A		
27	6251	9/29/1994	0	1	A		
27	6251	10/12/1994	0	1	A		
27	6251	11/9/1994	0	1	A		
27	6251	12/7/1994	1	1	A	0.479	0.834
27	6251	2/8/1995	1	1	A	0.479	2.157
27	6251	3/16/1995	1	1	A	1.141	2.259
27	6251	3/30/1995	1	1	A	1.548	2.208
27	6251	4/27/1995	0	1	A		
27	6251	5/10/1995	0	1	A		
27	6251	6/15/1995	0	1	A		
27	6251	10/10/1996	0	1	A		
27	6251	11/8/1996	0	1	A		
27	6251	12/4/1996	1	1	A	0.479	1.446

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
27	6251	2/6/1997	1	1	A	0.479	2.259
27	6251	3/19/1997	1	1	A	0.529	0.937
27	6251	3/19/1997	2	1	A	1.039	2.259
27	6251	4/9/1997	1	1	A	1.191	1.446
27	6251	4/23/1997	0	1	A		
27	6251	5/7/1997	0	1	A		
27	6251	5/29/1997	0	1	A		
27	6251	6/11/1997	0	1	A		
27	6251	7/10/1997	0	1	A		
27	6251	8/14/1997	0	1	A		
27	6251	9/10/1997	0	1	A		
30	8129	11/15/1993	0	1	A		
30	8129	12/14/1993	0	1	A		
30	8129	1/25/1994	1	1	A	0.320	0.624
30	8129	2/22/1994	1	1	A	0.523	0.929
30	8129	3/17/1994	0	1	A		
30	8129	3/31/1994	0	1	A		
30	8129	4/20/1994	0	1	A		
30	8129	5/5/1994	0	1	A		
30	8129	6/6/1994	0	1	A		
30	8129	7/22/1994	0	1	A		
30	8129	8/22/1994	0	1	A		
30	8129	9/23/1994	0	1	A		
30	8129	10/31/1994	0	1	A		
30	8129	11/15/1994	0	1	A		
30	8129	12/9/1994	1	1	A	0.165	0.470
30	8129	1/23/1995	1	1	A	0.165	0.829
30	8129	2/17/1995	1	1	A	0.165	0.573
30	8129	11/21/1996	1	1	A	0.165	1.032
30	8129	12/17/1996	1	1	A	0.165	1.032
30	8129	1/23/1997	1	1	A	0.320	0.470
30	8129	3/12/1997	0	1	A		
30	8129	3/25/1997	0	1	A		
30	8129	4/11/1997	0	1	A		
30	8129	4/28/1997	0	1	A		
30	8129	5/28/1997	0	1	A		
30	8129	6/18/1997	0	1	A		
30	8129	8/11/1997	0	1	A		
30	8129	10/1/1997	0	1	A		
31	3018	8/11/1995	0	1	A		
31	3018	9/19/1995	0	1	A		
31	3018	10/16/1995	0	1	A		
31	3018	11/14/1995	0	1	A		
31	3018	12/13/1995	0	1	A		
31	3018	1/22/1996	1	1	A	1.019	1.222
31	3018	3/6/1996	0	1	A		
31	3018	4/23/1996	0	1	A		
33	1001	10/14/1993	0	1	A		
33	1001	3/21/1994	0	1	A		
33	1001	4/14/1994	0	1	A		
33	1001	5/26/1994	0	1	A		
33	1001	6/23/1994	0	1	A		
33	1001	7/21/1994	0	1	A		
33	1001	8/16/1994	0	1	A		
33	1001	9/22/1994	0	1	A		
33	1001	10/20/1994	0	1	A		
33	1001	11/17/1994	0	1	A		
33	1001	12/15/1994	0	1	A		
33	1001	1/24/1995	0	1	A		
33	1001	2/21/1995	0	1	A		

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
33	1001	3/16/1995	0	1	A		
33	1001	3/30/1995	0	1	A		
33	1001	4/27/1995	0	1	A		
33	1001	6/1/1995	0	1	A		
33	1001	6/29/1995	0	1	A		
33	1001	10/10/1996	0	1	A		
33	1001	11/13/1996	0	1	A		
33	1001	12/11/1996	0	1	A		
33	1001	1/22/1997	0	1	A		
33	1001	2/12/1997	0	1	A		
33	1001	3/26/1997	0	1	A		
33	1001	4/9/1997	0	1	A		
33	1001	4/23/1997	0	1	A		
33	1001	5/14/1997	0	1	A		
33	1001	6/11/1997	0	1	A		
33	1001	7/16/1997	0	1	A		
33	1001	8/13/1997	0	1	A		
33	1001	9/17/1997	0	1	A		
33	1001	10/22/1997	0	1	A		
36	4018	10/28/1993	0	1	A		
36	4018	2/15/1994	1	1	A	0.334	1.951
36	4018	3/8/1994	1	1	A	0.787	2.052
36	4018	3/28/1994	1	1	A	1.192	1.293
36	4018	4/19/1994	0	1	A		
36	4018	6/7/1994	0	1	A		
36	4018	6/28/1994	0	1	A		
36	4018	7/29/1994	0	1	A		
36	4018	8/23/1994	0	1	A		
36	4018	9/27/1994	0	1	A		
36	4018	10/25/1994	0	1	A		
36	4018	11/22/1994	0	1	A		
36	4018	12/20/1994	0	1	A		
36	4018	1/31/1995	0	1	A		
36	4018	2/28/1995	0	1	A		
36	4018	3/13/1995	0	1	A		
36	4018	3/27/1995	0	1	A		
36	4018	4/10/1995	0	1	A		
36	4018	4/24/1995	0	1	A		
36	4018	5/23/1995	0	1	A		
36	4018	6/20/1995	0	1	A		
36	4018	9/19/1996	0	1	A		
36	4018	12/3/1996	0	1	A		
36	4018	1/7/1997	0	1	A		
36	4018	2/4/1997	1	1	A	0.484	1.040
36	4018	3/4/1997	0	1	A		
36	4018	4/15/1997	0	1	A		
36	4018	5/6/1997	0	1	A		
36	4018	6/3/1997	0	1	A		
36	4018	7/8/1997	0	1	A		
36	4018	8/5/1997	0	1	A		
36	4018	9/9/1997	0	1	A		
36	4018	10/14/1997	0	1	A		
42	1606	8/10/1995	0	1	A		
42	1606	9/28/1995	0	1	A		
42	1606	10/12/1995	0	1	A		
42	1606	11/9/1995	0	1	A		
42	1606	12/7/1995	0	1	A		
42	1606	1/15/1996	0	1	A		
42	1606	3/7/1996	0	1	A		
42	1606	4/11/1996	0	1	A		

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
42	1606	5/2/1996	0	1	A		
42	1606	6/6/1996	0	1	A		
42	1606	7/11/1996	0	1	A		
42	1606	8/8/1996	0	1	A		
46	804	7/15/1994	0	1	A		
46	804	8/12/1994	0	1	A		
46	804	9/27/1994	0	1	A		
46	804	10/25/1994	0	1	A		
46	804	11/22/1994	0	1	A		
46	804	12/20/1994	1	1	A	0.526	1.135
46	804	3/23/1995	0	1	A		
46	804	5/23/1995	0	1	A		
46	804	6/27/1995	0	1	A		
46	804	10/24/1996	0	1	A		
46	804	2/18/1997	1	1	A	0.526	0.982
46	804	4/15/1997	0	1	A		
46	804	4/29/1997	0	1	A		
46	804	5/15/1997	0	1	A		
46	804	6/5/1997	0	1	A		
46	804	6/24/1997	0	1	A		
46	804	7/22/1997	0	1	A		
46	804	8/24/1997	0	1	A		
46	804	9/22/1997	0	1	A		
49	1001	11/4/1993	0	1	A		
49	1001	12/2/1993	0	1	A		
49	1001	1/14/1994	0	1	A		
49	1001	2/11/1994	0	1	A		
49	1001	3/11/1994	0	1	A		
49	1001	3/25/1994	0	1	A		
49	1001	4/8/1994	0	1	A		
49	1001	4/28/1994	0	1	A		
49	1001	6/17/1994	0	1	A		
49	1001	7/15/1994	0	1	A		
49	1001	8/5/1994	0	1	A		
49	1001	9/9/1994	0	1	A		
49	1001	10/20/1994	0	1	A		
49	1001	11/9/1994	0	1	A		
49	1001	12/1/1994	0	1	A		
49	1001	1/13/1995	0	1	A		
49	1001	11/12/1996	0	1	A		
49	1001	12/9/1996	0	1	A		
49	1001	2/11/1997	0	1	A		
49	1001	3/6/1997	0	1	A		
49	1001	4/7/1997	0	1	A		
49	1001	4/22/1997	0	1	A		
49	1001	5/20/1997	0	1	A		
49	1001	6/12/1997	0	1	A		
49	1001	8/4/1997	0	1	A		
49	1001	9/24/1997	0	1	A		
49	3011	11/2/1993	0	1	A		
49	3011	11/30/1993	0	1	A		
49	3011	1/12/1994	0	1	A		
49	3011	1/13/1994	0	1	A		
49	3011	2/9/1994	0	1	A		
49	3011	3/9/1994	0	1	A		
49	3011	3/23/1994	0	1	A		
49	3011	4/26/1994	0	1	A		
49	3011	6/20/1994	0	1	A		
49	3011	7/11/1994	0	1	A		
49	3011	8/2/1994	0	1	A		

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
49	3011	9/7/1994	0	1	A		
49	3011	10/18/1994	0	1	A		
49	3011	11/4/1994	0	1	A		
49	3011	11/29/1994	0	1	A		
49	3011	1/12/1995	0	1	A		
49	3011	2/10/1995	0	1	A		
49	3011	11/8/1996	0	1	A		
49	3011	12/5/1996	0	1	A		
49	3011	1/10/1997	0	1	A		
49	3011	2/7/1997	0	1	A		
49	3011	3/5/1997	0	1	A		
49	3011	3/17/1997	0	1	A		
49	3011	4/3/1997	0	1	A		
49	3011	4/21/1997	0	1	A		
49	3011	5/16/1997	0	1	A		
49	3011	6/10/1997	0	1	A		
49	3011	7/31/1997	0	1	A		
49	3011	9/22/1997	0	1	A		
50	1002	10/7/1993	0	1	A		
50	1002	11/8/1993	0	1	A		
50	1002	1/12/1994	1	1	A	0.284	0.638
50	1002	3/2/1994	1	1	A	0.284	0.385
50	1002	3/22/1994	0	1	A		
50	1002	4/13/1994	0	1	A		
50	1002	5/25/1994	0	1	A		
50	1002	6/22/1994	0	1	A		
50	1002	7/20/1994	0	1	A		
50	1002	8/17/1994	0	1	A		
50	1002	9/21/1994	0	1	A		
50	1002	10/19/1994	0	1	A		
50	1002	11/16/1994	0	1	A		
50	1002	12/14/1994	0	1	A		
50	1002	1/19/1995	0	1	A		
50	1002	2/15/1995	1	1	A	0.284	0.791
50	1002	3/17/1995	0	1	A		
50	1002	3/31/1995	0	1	A		
50	1002	4/13/1995	0	1	A		
50	1002	4/28/1995	0	1	A		
50	1002	5/31/1995	0	1	A		
50	1002	6/28/1995	0	1	A		
50	1002	10/17/1996	0	1	A		
50	1002	11/14/1996	0	1	A		
50	1002	12/12/1996	0	1	A		
50	1002	1/23/1997	0	1	A		
50	1002	2/13/1997	0	1	A		
50	1002	3/27/1997	0	1	A		
50	1002	4/10/1997	0	1	A		
50	1002	4/24/1997	0	1	A		
50	1002	5/15/1997	0	1	A		
50	1002	6/12/1997	0	1	A		
50	1002	7/17/1997	0	1	A		
50	1002	8/14/1997	0	1	A		
50	1002	9/16/1997	0	1	A		
50	1002	10/23/1997	0	1	A		
56	1007	8/7/1997	0	1	A		
56	1007	9/30/1997	0	1	A		
83	1801	10/13/1993	0	1	A		
83	1801	11/12/1993	0	1	A		
83	1801	12/13/1993	0	1	A		
83	1801	1/17/1994	1	1	A	0.359	1.168

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
83	1801	2/14/1994	1	1	A	0.408	1.117
83	1801	3/14/1994	0	1	A		
83	1801	3/28/1994	0	1	A		
83	1801	4/11/1994	0	1	A		
83	1801	4/29/1994	0	1	A		
83	1801	5/13/1994	0	1	A		
83	1801	6/17/1994	0	1	A		
83	1801	7/25/1994	0	1	A		
83	1801	8/18/1994	0	1	A		
83	1801	9/21/1994	0	1	A		
83	1801	10/19/1994	0	1	A		
83	1801	11/16/1994	0	1	A		
83	1801	1/25/1995	1	1	A	0.359	0.864
83	1801	2/15/1995	1	1	A	0.359	1.472
83	1801	3/14/1995	1	1	A	0.660	0.915
83	1801	4/25/1995	0	1	A		
83	1801	5/17/1995	0	1	A		
83	1801	6/21/1995	0	1	A		
83	1801	10/16/1996	0	1	A		
83	1801	12/11/1996	1	1	A	0.359	1.066
83	1801	12/11/1996	2	1	A	1.370	1.472
83	1801	2/11/1997	1	1	A	0.359	1.421
83	1801	3/25/1997	1	1	A	0.813	1.117
83	1801	3/25/1997	2	1	A	1.218	1.371
83	1801	4/17/1997	1	1	A	1.016	1.371
83	1801	5/1/1997	0	1	A		
83	1801	6/2/1997	0	1	A		
83	1801	6/18/1997	0	1	A		
83	1801	7/16/1997	0	1	A		
83	1801	8/19/1997	0	1	A		
83	1801	9/16/1997	0	1	A		
83	3802	10/15/1993	0	1	A		
83	3802	11/12/1993	0	1	A		
83	3802	11/15/1993	0	1	A		
83	3802	12/14/1993	1	1	A	0.700	1.460
83	3802	1/18/1994	1	1	A	0.647	1.510
83	3802	2/15/1994	1	1	A	0.647	1.510
83	3802	3/15/1994	1	1	A	0.801	1.510
83	3802	3/29/1994	1	1	A	0.902	1.460
83	3802	4/12/1994	1	1	A	1.002	1.104
83	3802	5/2/1994	0	1	A		
83	3802	5/16/1994	0	1	A		
83	3802	6/20/1994	0	1	A		
83	3802	7/26/1994	0	1	A		
83	3802	8/22/1994	0	1	A		
83	3802	9/20/1994	0	1	A		
83	3802	10/18/1994	0	1	A		
83	3802	11/15/1994	0	1	A		
83	3802	1/26/1995	1	1	A	0.647	1.411
83	3802	3/15/1995	1	1	A	0.647	1.510
83	3802	3/29/1995	1	1	A	0.902	1.510
83	3802	4/26/1995	0	1	A		
83	3802	5/16/1995	0	1	A		
83	3802	6/20/1995	0	1	A		
83	3802	10/15/1996	0	1	A		
83	3802	12/10/1996	1	1	A	0.647	1.207
83	3802	4/16/1997	1	1	A	0.751	1.510
83	3802	5/31/1997	0	1	A		
83	3802	6/20/1997	0	1	A		
83	3802	7/17/1997	0	1	A		

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
83	3802	8/18/1997	0	1	A		
83	3802	9/15/1997	0	1	A		
87	1622	9/23/1993	0	1	A		
87	1622	12/13/1993	1	1	A	0.222	0.374
87	1622	12/13/1993	2	1	A	1.032	1.133
87	1622	1/4/1994	1	1	A	0.222	0.273
87	1622	1/4/1994	2	1	A	0.373	0.981
87	1622	1/25/1994	1	1	A	0.222	1.183
87	1622	2/23/1994	1	1	A	0.222	1.234
87	1622	4/6/1994	0	1	A		
87	1622	5/17/1994	0	1	A		
87	1622	6/14/1994	0	1	A		
87	1622	7/12/1994	0	1	A		
87	1622	9/13/1994	0	1	A		
87	1622	10/13/1994	0	1	A		
87	1622	11/1/1994	0	1	A		
87	1622	12/22/1994	0	1	A		
87	1622	1/12/1995	1	1	A	0.475	0.930
87	1622	2/9/1995	1	1	A	0.273	1.031
87	1622	2/23/1995	1	1	A	0.527	1.031
87	1622	3/9/1995	1	1	A	0.779	0.879
87	1622	3/23/1995	1	1	A	0.930	1.031
87	1622	4/6/1995	0	1	A		
87	1622	4/20/1995	0	1	A		
87	1622	5/4/1995	0	1	A		
87	1622	6/15/1995	0	1	A		
87	1622	9/11/1996	0	1	A		
87	1622	11/28/1996	0	1	A		
87	1622	12/19/1996	0	1	A		
87	1622	1/30/1997	1	1	A	0.578	0.879
87	1622	2/20/1997	1	1	A	0.628	1.031
87	1622	3/18/1997	0	1	A		
87	1622	5/1/1997	0	1	A		
87	1622	5/22/1997	0	1	A		
87	1622	6/19/1997	0	1	A		
87	1622	7/24/1997	0	1	A		
87	1622	8/21/1997	0	1	A		
87	1622	9/25/1997	0	1	A		
87	1622	10/30/1997	0	1	A		
89	3015	9/30/1993	0	1	A		
89	3015	2/3/1994	1	1	A	0.271	1.384
89	3015	4/8/1994	0	1	A		
89	3015	5/19/1994	0	1	A		
89	3015	6/16/1994	0	1	A		
89	3015	7/14/1994	0	1	A		
89	3015	8/11/1994	0	1	A		
89	3015	9/15/1994	0	1	A		
89	3015	10/6/1994	0	1	A		
89	3015	11/3/1994	0	1	A		
89	3015	12/8/1994	0	1	A		
89	3015	1/10/1995	1	1	A	0.271	0.978
89	3015	2/16/1995	1	1	A	0.371	0.574
89	3015	3/7/1995	0	1	A		
89	3015	3/21/1995	0	1	A		
89	3015	4/4/1995	0	1	A		
89	3015	4/18/1995	0	1	A		
89	3015	5/3/1995	0	1	A		
89	3015	6/13/1995	0	1	A		
89	3015	9/12/1996	0	1	A		
89	3015	11/19/1996	0	1	A		

State_Code	SHRP_ID	SMP_Date	Frozen_Layer_No	Construction_No	Record_Status	Freeze_From	Freeze_To
89	3015	12/17/1996	0	1	A		
89	3015	1/28/1997	1	1	A	0.271	0.625
89	3015	2/18/1997	1	1	A	0.271	1.232
89	3015	3/20/1997	1	1	A	0.321	0.522
89	3015	4/29/1997	0	1	A		
89	3015	5/20/1997	0	1	A		
89	3015	6/17/1997	0	1	A		
89	3015	8/19/1997	0	1	A		
89	3015	9/23/1997	0	1	A		
89	3015	11/6/1997	1	1	A	0.928	1.537
90	6405	10/6/1993	1	1	A	0.993	1.144
90	6405	10/7/1993	1	1	A	1.044	1.144
90	6405	11/10/1993	0	1	A		
90	6405	1/14/1994	1	1	A	0.284	1.754
90	6405	2/11/1994	1	1	A	0.284	2.059
90	6405	3/11/1994	1	1	A	0.534	1.094
90	6405	3/11/1994	2	1	A	1.449	2.059
90	6405	3/25/1994	1	1	A	0.943	1.044
90	6405	3/25/1994	2	1	A	1.856	2.059
90	6405	4/8/1994	1	1	A	1.856	2.059
90	6405	4/28/1994	0	1	A		
90	6405	5/12/1994	0	1	A		
90	6405	6/16/1994	0	1	A		
90	6405	7/21/1994	0	1	A		
90	6405	8/16/1994	0	1	A		
90	6405	9/22/1994	0	1	A		
90	6405	10/20/1994	0	1	A		
90	6405	11/17/1994	0	1	A		
90	6405	12/16/1994	1	1	A	0.284	1.346
90	6405	1/23/1995	1	1	A	0.284	1.144
90	6405	3/13/1995	1	1	A	0.638	2.059
90	6405	3/27/1995	1	1	A	0.638	2.059
90	6405	4/24/1995	1	1	A	1.703	2.007
90	6405	5/18/1995	0	1	A		
90	6405	6/23/1995	0	1	A		
90	6405	10/18/1996	0	1	A		
90	6405	12/12/1996	1	1	A	0.284	0.534
90	6405	2/10/1997	1	1	A	0.284	0.942
90	6405	2/10/1997	2	1	A	1.094	2.059
90	6405	4/18/1997	1	1	A	1.044	2.059
90	6405	5/2/1997	0	1	A		
90	6405	6/3/1997	0	1	A		
90	6405	6/16/1997	0	1	A		
90	6405	8/21/1997	0	1	A		
90	6405	9/19/1997	0	1	A		