FACTORS AFFECTING GROUND ICE MELTING

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by

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ABSTRACT:

The thaw rates of the active layer above the permafrost zone from a series of sites along the Hudson Bay coastline at lat. 56° have been examined with respect to temperature and moisture gradients, the characteristics of the surface layer and the bulk thermal properties for each profile. The thermal properties have been examined using firstly a Fourier approach with the parameter of degree days and using secondly a graphical approach employing thermal relationships obtained in the laboratory analyses by Kersten (1949).

It was found that thaw rates are controlled by the interaction of a number of environmental factors of which vegetation appears to be the most important.

The two approaches to the derivation of thermal properties give quite different results, such that the graphical approach is deemed to be unsuitable to field application.

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CHAPTER I

INTRODUCTION

It has recently been pointed out that approximately 1.3 million square miles, or roughly 50%, of North America is underlain by permafrost. (Stearns 1966, Brown 1960) Thus permafrost is an important environmental feature which becomes a significant problem to the current northward expansion in pursuit of natural resources exploitation.

While general studies of soil temperature have been long established, permafrost has been examined only relatively recently. Probably the first notable contribution in this area was made by Mueller (1943) who conducted an in-depth examination of permafrost with respect to the engineering problems it created.

Since that time, there have been a variety of investigators who have examined this topic, both as a physical phenomena and as an intriguing theoretical problem in thermodynamics. This has led to its current position of importance as a major factor to be considered in any attempt at northern construction. (Lachenbruch, Aldrich)

The vast majority of current research in this area is being focused on the economic or applied aspects of problems associated with the presence of permafrost. This is being conducted by such groups as the Division of Building Research - National Research Council of Canada and the United States Army Cold Regions Research and Engineering Laboratory. There is also a great deal of Russian research conducted by the Russian Academy of Sciences.

Due to the international aspect of permafrost distribution, there existed for a considerable period of time great confusion over the nomenclature used to describe permafrost features. This prompted the Russian Academy of Sciences to publish two major works dealing with the problem in 1956 and 1959. The first of these, entitled "Fundamental Concepts and Terms in Geocryology", helped to standardize the nomenclature, while the second, "Principles of Ceocryology", served to set forth many of the concepts involved. In this paper, both the terms "permafrost" and "active layer" shall be used as set out in "Fundamental Concepts and Terms in Geocryology". Permafrost refers to that zone which stays frozen for at least three years running, while the active layer is that zone which annually thaws and then refreezes with the advent of winter.

In the past a great deal of the research has investigated the freezing processes in the active layer and disproportionately little has been directed towards the thawing processes. This trend appears to be reversing somewhat at present with the result that there is currently a large amount of interest in such topics as the effects of heated pipelines and other human modifications on the permafrost zone. (Lachenbruch 1970, Gold 1967)

The study of these freeze/thaw processes has developed along several lines based primarily on the availability of field data. The first approach uses theoretical thermodynamics to explain heat conduction and was developed in its pure form by Carslaw and Jaeger (1956), and in modified form by Ingersoll, Zobel, and Ingersoll (1947) and Terzaghi (1953). The thermodynamics approach has been applied in the laboratory particularly in the noteable work of M.S. Kersten (1949) who examined the thermal properties of nineteen different soils. Other approaches have involved the examination of individual aspects of each of the processes involved (Williams 1963) or the application of theory to field data in the form of measurable parameters such as degree days. (Aldrich 1956)

These studies have tended to show that both the active layer and the permafrost are strongly controlled by such parameters as air temperature, surface topography, vegetation, soil moisture, and the thermal properties of the particular soil involved. It has further shown that minor changes in these parameters can cause relatively large changes in the depth of the active layer on an annual basis or the permafrost zone itself over a longer period. This paper applies some of the existing theory in an attempt to show how each of these parameters controls the active layer and the rate of ice degradation at a subarctic site on the shores of Hudson Bay.

CHAPTER II

SITES AND INSTRUMENTATION

SITES:

In this study, ten sites were chosen close enough to a base site so that several sets of data could be collected on a daily basis.

The base site (Fig. 1) was located on the west coast of Hudson Bay opposite East Pen Island (56°30'N, 88°45'W). The topography of the area consisted of a raised beach system characterized by swamp areas between ridges. In addition, a major dune system extended along the front ridge. The dune was characterized by several recent blowouts and related structures.

The ten sites were chosen subjectively so that each could be either representative of a particular surface type or act as a control for another site nearby. In this manner, a ridge, swamp area, burned area, vehicle track, ice hummock and bare ground were examined.

Each of these surfaces had a differing surface cover associated with it, as can be seen in Table 1.

Site 1 was located in a vehicle track which had been produced by a caterpillar tractor. This site had no vegetation, but rather a mulch layer produced by the tractor's treads which ground and mixed the lichen mat with a thin layer of sand on the soil surface. Similar conditions to these were examined by Bliss and Wien (1971). Depression

FIGURE 1

SCHEMATIC DIAGRAM SHOWING LOCATION OF RESEARCH SITES

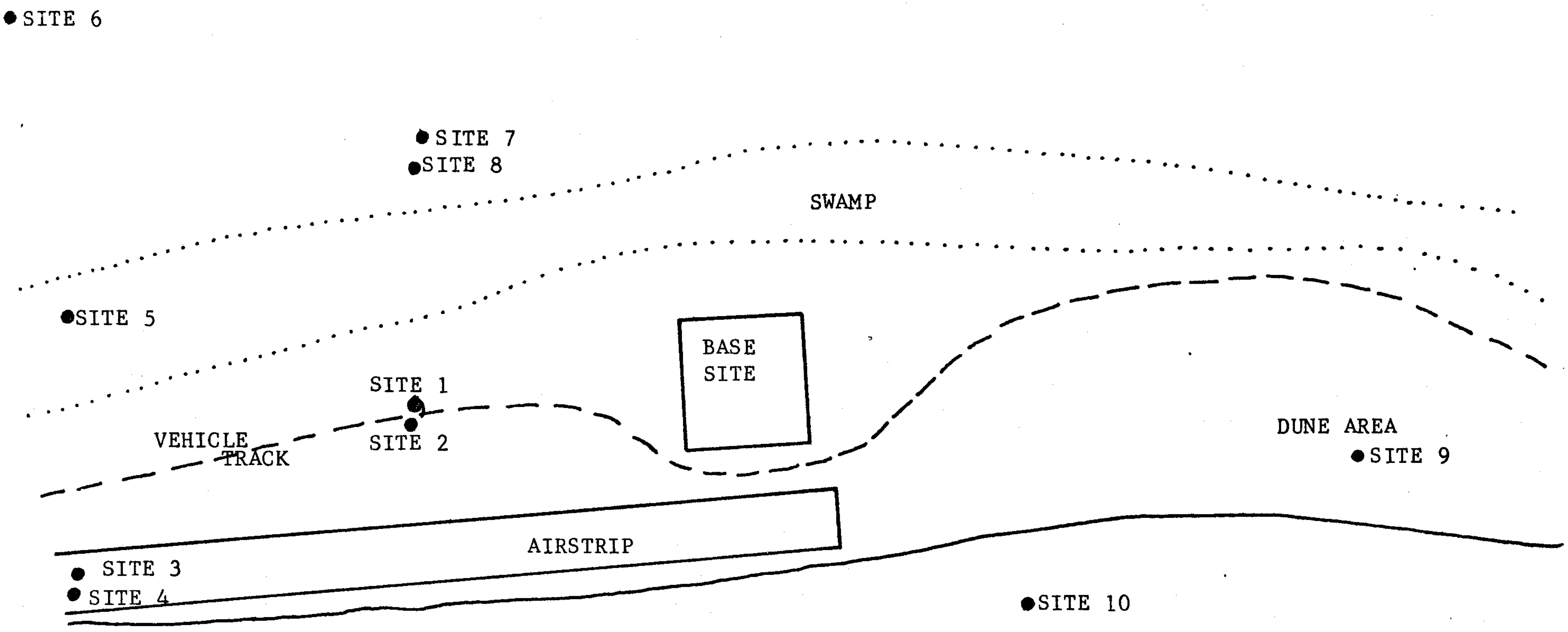


TABLE 1

SURFACE VEGETATION CHARACTERISTICS - PERCENT OCCURRENCE

PLANT SPECIES	SITES									
	1	2	3	4	5	6	7	8	9	10
<u>LICHENS</u>:										
Cetraria islandica		17		11		18		14		
Cetraria nivalis		45		9		40		39		
Alectoria ochroleuca		33		66		38		16		
Cornicularia divergens		49		14		31		32		
Thamnolia vermicularis				13		2		5		
Alectoria nigricans								1		
Alectoria nitidula								13		
Cetraria cucullata		1		3						
<u>TOTAL LICHEN COVER</u>		135		116		129		120		
<u>TOTAL OVERALL COVER</u>		69		60		57		62		
<u>HIGHER PLANTS</u>:										
Hedysarum mackenzii		2		14				4	9	
Astragalus alpinus									1	
Equisetum variegatum									7	
Salix arctophila									2	
Elymus									8	
Saxifraga tricuspidata									2	
Dryas integrifolia		31		64		17		36		
Vaccinium uliginosum		9				15		9		
Rhododendron lapponicum		13				16		17		
Arctostaphylos rubra		2								
Salix reticulata		1								
Carex glacialis		4				5				

TABLE 1 (Con't)

PLANT SPECIES	SITES									
	1	2	3	4	5	6	7	8	9	10
HIGHER PLANTS(Con't):										
Calamagrostis neglecta										20
Carex aquatilis					21					9
Potentilla palustris										15
Luzula wahlenbergii										5
Stellaria										5
Triglochin palustre					3					
Juncus albescens					3					
Salix caespitosis					20					
Carix chordorrhiza					7					
Tofieldia pusilla						2		3		
Empetrum nigrum						9				
Ledum decumbens						2				
TOTAL HIGHER PLANT COVER		62		78	51	66		69	29	54
TOTAL OVERALL COVER		31		40	31	30		36	100	35
MOSSES:										
Brachthecium oxycladon						2				
Dicranum scoparium						25		4		
Polytrichum juniperinum						4				
Scorpidium scorpioides					65					
Drepanocladus revolvens					25					
Meesia longiseta					8					
Cinclidium stygium					3					
Campylium stellatum					8					
Acrocladium giganteum										100
TOTAL MOSS COVER					112	31		4		100
TOTAL OVERALL COVER					69	14		2		65

TABLE 2

SOIL MECHANICAL ANALYSIS - APPROXIMATE WEIGHTED VALUES(1)

SITE	% GRAVEL(2)	% SAND(3)	% SILT(4)
1	13.5	86.0	0.5
2	13.5	86.0	0.5
3	19.5	80.0	0.5
4	19.5	80.0	0.5
5		PEAT	
6	25.0	73.5	1.5
7	8.0	90.0	2.0
8	8.0	90.0	2.0
9	4.0	94.0	2.0
10		PEAT	

(1) Percentage composition weighted on the basis of the thickness of individual horizontal layers of differing composition

(2) Diameter of greater than 2 mm.

(3) Diameter between 0.05 and 2 mm.

(4) Diameter of less than 0.05 mm.

of the caterpillar track below the surrounding landscape had been further enhanced by the weight of the vehicle.

Site 2 was located approximately 5 m. from Site 1 and was similar to it in all respects except that it had not had vehicles crossing it. This, in turn, had the effect that the lichen mat was fully intact.

Site 3 was situated on a bare ground surface having a soil composed of coarser sands and gravels (Table 2). Due to its location, on the extreme front edge of the first ridge, it is likely that horizontal moisture flow took place across both this and Site 4, resulting in the transfer of heat and an accentuated melt rate.

Site 4 had a vegetative cover consisting of an expanding dryas patch approximately 2 m. by 3 m. and was used as a control for the bare ground surface of Site 3. Patches of this type of vegetation characterized the entire area surrounding Sites 3 and 4. The surface was extremely flat due to earlier bulldozing during the airstrip construction.

Site 5 was located in a swamp area which was supersaturated for the majority of the measurement period. This site was characterized by an organic layer 48 cm. thick covering a fine sand and silt mixture.

Site 6 was located on the top of a well-drained ridge. It had a well-developed covering of both lichens and respiring plants and was representative of a ridge environment.

Sites 7 and 8 were a matched pair. Site 7 was a circular burned area with approximately a 2 m. radius that had been burned the previous summer for experimental purposes. Site 8 had a complete vegetative cover of lichens and higher plants and served as a control for the burned patch.

Site 9 comprised a shallow amphitheatre caused by a blowout within the dune system. While all the other sites were located in areas having surfaces that were relatively flat, this site was chosen specifically because of its shape, in hopes that the amphitheatre in conjunction with the relative lack of vegetation would result in the attainment of a maximum depth of the active layer.

Site 10 was chosen within an area of minor thermokarst and ice lensing activity. The ice lens examined measured 2 m. by 4 m. at the start of the measurement period and was overlain by peat and moss (Table 1). It was hoped that this would show the insulating effects of this type of vegetative cover.

INSTRUMENTATION:

Soil Temperature:

Since the soil temperature is representative of the presence or absence of ground ice, the basis of this investigation involved the determination of the soil temperature profile. Soil temperature was measured with specially-designed probes which employed single junction thermocouples as sensing elements. These probes consisted of heavy gauge brass pipe, 1/4" O.D., which was drilled and shaped so that a thermocouple mounted in the tip would be electrically insulated while still having a good soil contact. This construction allowed for easy installation into the relatively coarse-grained soils common to the area. The sensors were inserted into the vertical face of a pit dug from the surface to the top of the frozen layer and were installed at intervals of 1, 2, 5, 10, 20, 50 and 100 cm. When either the 100 cm. or higher levels could not be reached due to the frozen state of the soil, the bottom-most probe of the profile was placed as near as possible to the freeze/thaw interface.

Readings were taken with a portable Pye potentiometer on a twice daily basis. In a test prior to the field season, these probes were found to have a calibration of $T = 0.038+0.249(Mv)$ where T is temperature in °C and Mv is the millivolt output.

Soil Moisture:

Volumetric soil moisture was measured at each site using the Neutron Moderation technique. In most cases, soil moisture was sampled only to a depth of 70 cm. Difficulty in installing the access tubes in the coarse gravelly soils disallowed driving the tube down in order to follow the ice retreat. Sampling was considered necessary here only on a weekly basis due to the derived accuracy limits imposed by the technique. (Wilson 1970)

A surface neutron probe was used to measure the soil moisture in the top 20 cm. of the soil profile examined. The surface soil moisture was derived from the average of ten randomly located plots at each site. The measurement was made on a bare soil surface by peeling back the lichen mat where necessary in order to eliminate the effects of excessive organic content.

The probes used had the following calibrations: depth probe $\theta = -0.008 +((1.20\times10^{-5})r)$; surface probe $\theta = 0.039 +((1.26\times10^{-4})r)$; where θ is volumetric soil moisture and r is the counts per minute.

Albedo:

Albedo was determined at each site from measurements made on a clear day. The incoming and reflected solar radiation was measured with two Epply pyranometers, one facing up and the other facing down. Their calibrations were 7.43 and 7.34 $mV/cal/cm^2/min.$ respectively.

Vegetation Cover:

The density and composition of the vegetative cover at each site was examined by the use of the pin-frame technique used at ten randomly chosen locations at each site.

Depth of the Active Layer:

The depth to the top of the frozen layer was taken as the mean depth of three auger holes drilled at each site. Sampling was carried out on four occasions equally spaced over the research period.

Temperature and Precipitation:

Continuous measurements of air temperature were made with a clock driven thermohygrograph. Precipitation was measured with four 5" diameter rain gauges which were spaced to give an average rainfall determination for each of the sites.

Soil Thermal Characteristics:

The thermal parameters for the soil at each site were determined from the theoretical consideration which will follow and from laboratory analysis. The laboratory analysis undertaken was the determination of the particle grain size distribution and density at each site. Grain size was determined through sieving of dried samples. The sieves separated the samples into gravels, sands and fines based on 2 mm. and 0.05 mm. limits. Density was determined with dried samples which were packed into containers of known volume and weighed.

Using the data obtained through the above methods and the work of Kersten (1949), approximate values for thermal conductivity, specific heat and thermal diffusivity were determined. This entailed selecting one of the nineteen soils studied by Kersten which resembled those of the research site. Each of his soils had graphs for the thermal properties versus moisture, temperature and density. Use of these allowed extrapolation of values for soils of the research area.

Theoretical values for thermal conductivity, diffusivity and specific heat were obtained by solving the equations presented in the next chapter for these properties. The values that resulted were used in the production of theoretical temperature regimes through an interaction process. This was continued until the projected values coincided with the actual field data. At this time, the conditions used were considered to be representative of those at each site.

CHAPTER III

THEORY

When different sections of a semi-infinite body are subjected to different temperatures, there exists a flow of heat from the hotter surface to the colder by the processes of conduction, convection and radiation. In a soil, most of the heat is transferred by the process of conduction. (Carslaw & Jaeger 1965) This soil heat flux q can be represented in terms of the soil thermal conductivity k and the temperature gradient over distance $\partial T/\partial x$ in the equation

$$q = -k \frac{\partial T}{\partial x} \qquad (1)$$

where the negative sign indicates that the flow is from the hot to the cold.

The amount of heat which any body will store for any given input or output is represented by its heat capacity C_p. This is the product of the medium density and specific heat.

The rate at which the temperature of a body changes is subject to the relationship between the thermal conductivity and the heat capacity of that body. This relationship is referred to as the thermal diffusivity λ and can be shown to take the form of equation (2)

$$\lambda = \frac{k}{C_p} \qquad (2)$$

When dealing with the periodic flow of heat below a surface, it becomes necessary to modify the unidimensional flow expressed in Eq. (1) into a three-dimensional form such that we can examine the properties of the medium in relation to the planes of the heat flow as they exist. Such a procedure as this is referred to as the Fourier Equation of heat conduction.

The Fourier analysis starts with a cube of homogenous soil having dimensions $\Delta x, \Delta y, \Delta z$. The temperature of any point in the cube may be expressed relative to the distance from the centre and the mean temperature T. The temperature of a point on the end face of the block may be represented as

$$1/2 \frac{\partial T}{\partial x} \Delta x \qquad (3)$$

In similar fashion, the temperature at any face is given as the mean temperature plus or minus a quantity depending on its position relative to the reference point of the block, in this case its centre.

In relation to Eq. (1), the flow of heat is given by

$$q = -k\Delta y\Delta z \frac{\partial}{\partial x} (T - 1/2 \frac{\partial T}{\partial x} \Delta x) \qquad (4)$$

where the sign inside the parenthesis can be altered relative to the centre of the cube. By taking the differences expressed in Eq. (4), one gets the heat gain along each axis which gives the total heat flow for the cube as

$$q_{x,y,z} = k \frac{\partial^2 T}{\partial x^2} \Delta x\Delta y\Delta z + k \frac{\partial^2 T}{\partial y^2} \Delta x\Delta y\Delta z + k \frac{\partial^2 T}{\partial z^2} \Delta x\Delta y\Delta z \qquad (5)$$

Since this is equivalent to the amount of heat gained per unit time, then

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = Cp \frac{\partial T}{\partial t} \qquad (6)$$

and

$$\frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (7)$$

When the periodic nature of soil heat flow is considered, Eq. (7) must be simplified to a unidirectional form given as

$$\frac{\partial T}{\partial t} = (\lambda)\frac{\partial^2 T}{\partial z^2} \qquad (8)$$

where z is the vertical axis. In the ideal case, where the surface temperature wave follows a sine function,

$$T = T_0 \sin\omega t \qquad \text{at } z=0 \qquad (9)$$

where T is the surface temperature, T_0 is the surface temperature amplitude, t is time, and ω is the angular frequency equalling $\frac{2\pi}{24}$ when t is in hours.

When Eq. (9) is expanded to include a phase shift and an exponential decrease of T_0 with depth, it can be rewritten to represent any temperature at any time at any depth as shown by Eq. (10).

$$T = T_0 e^{-z\sqrt{\omega/2\lambda}} \sin(\, t - z\sqrt{\omega/2\lambda}) \qquad (10)$$

Eq. (10) is based on the concept of the temperature amplitude being controlled by the periodicity of the sine function. By this, in turn, it stands to reason that the temperature range that will be expreienced at any given depth will simply be twice the amplitude as determined by the first half of Eq. (10) or

$$T_R = 2T_0 e^{-z\sqrt{\omega/2\lambda}} = 2T_0 e^{-z\sqrt{\pi/\lambda P}} \qquad (11)$$

where $\omega = \frac{2\pi}{P}$ and P is the period.

The temperature wave can also be thought of in terms of its lag behind the surface, its velocity of penetration or its wavelength. Each of these properties may be derived from Eq. (10) as follows

$$t = \frac{z}{2}\sqrt{P/\pi\lambda} \qquad (12)$$

$$V = \frac{z}{t} = 2\sqrt{\frac{\pi\lambda}{P}} \qquad (13)$$

$$\gamma = VP = 2\sqrt{\pi\lambda P} \qquad (14)$$

These above relationships can be of even further use on the basis that substitution into Eq. (12), (13) and (14) will allow a determination of the soil thermal diffusivity from a small number of measurements or a short measurement period.

One can examine the melting of the active layer using an energy balance approach. This entails, as a first approximation, the assumption that all heat entering the soil is used for purposes of melting ground ice. This assumption can be represented as

$$q = \frac{(T_1 - T_2)}{z/k} A\ t = \frac{\Delta T}{R} At \qquad (15)$$

where q = the soil heat flux
ΔT = the temperature between the two partial planes
z = the depth of soil
R = thermal resistance = z/k
k = thermal conductivity
T_1 = temperature on one of the parallel planes
T_2 = temperature on the other parallel plane
A = Area
t = time

If we subsequently assume unit area and time with a daily period, we may see that Eq. (15) reduces to

$$q = \frac{\Delta T}{R} = \frac{24\Delta Tt}{R} = \frac{24I}{R} \qquad (16)$$

where $I = Tt$, the maximum number of degree days thawing index based on surface temperature.

This is simply the product of the temperature excess above freezing and the time in days. By this, one degree day would be a daily mean temperature of 1°C for one twenty four hour period. In the form used here, the temperature is that of the soil surface rather than that of the air.

As can be seen, the above is based on the thawing index of the surface temperature, data which is not always available. In light of this, a relationship between the thawing indices of the air and the surface has been established thereby providing a series of correction factors which can be applied to normally available air temperature data. (Carlson 1952) For the surfaces in question here, this correction factor has a value ranging from $c = 0.75$ to $c = 2.00$.

Continuing with the assumption that all heat entering the soil is used for melting purposes, we can see that

$$q = zL \qquad (17)$$

where z = the depth of thaw
L = latent heat of fusion of water in soil
$L = 1.434\ w.d.$
when w = % water content
d = dry density
1.434 = Latent heat of fusion of 1 lb. of ice (BTU)

The average resistance to melting over this period will be simply $R/2$ or $z/2k$. If we take the above and combine Eqs. (16) and (17), the amount of heat required or the depth of melt for a single homogenous layer of depth z is given respectively as

$$q = zL = \frac{24I}{R/2} = \frac{48kIc}{z} \qquad (18)$$

and

$$z = \sqrt{\frac{48kIc}{L}} \qquad (19)$$

This can be further broken down in the case of a layered soil such that the resultant thaw is simply the summation of the partial thawing indices, I_i for each layer.

Eqs. (18) and (19) assume that all heat is used for melting, which is not strictly true. Eq. (19) may be modified by the addition of terms for the effects of soil heating in either the frozen or unfrozen state. Each of these additional terms may be approximated as

$$q_2 = \frac{Idz}{2t} \cdot \frac{w}{100} + C \qquad (20)$$

for the amount of heat required to raise the temperature of the thawed soil to the mean temperature through the period where

z = thickness of soil layer
C = specific heat of soil
t = the number of days where the surface temperature is above freezing

In addition, the amount of heat used to bring the temperature of the frozen soil up to the melting point is

$$q_3 = (32-TM)(0.5 \frac{wd}{100} x + Cdx) \qquad (21)$$

when 32 = melting point
TM = mean annual temperature of soil surface
0.5 = specific heat of ice

When the above factors are incorporated into Eq. (19) and all units are corrected to the cgs. system, the depth of the thaw equation becomes

$$z = \sqrt{\frac{48kIc}{L+\frac{Id}{2t}\,\frac{(w+C)}{100} + (0-TM)(0.5\,\frac{wd}{100} + Cd)}} \qquad (22)$$

CHAPTER IV

RESULTS

SOIL TEMPERATURE:

Figs. 3 through 13 show values for soil temperature over both depth and time. It can be seen that there are large diurnal fluctuations with rapid heating and cooling rates. In addition, there are often crossover effects present due to rapid cooling of the surface layers, thereby reversing the thermal gradients. This effect was usually seen at or above the 20 cm. level.

The highest surface temperature readings occurred in all cases over the bare soil surfaces with the exception of the ice hummock. The maximum recorded value was 26.4°C.

The lag of the temperature wave with increasing depth can be seen clearly by comparing the positions of peak temperature in Fig. 3.

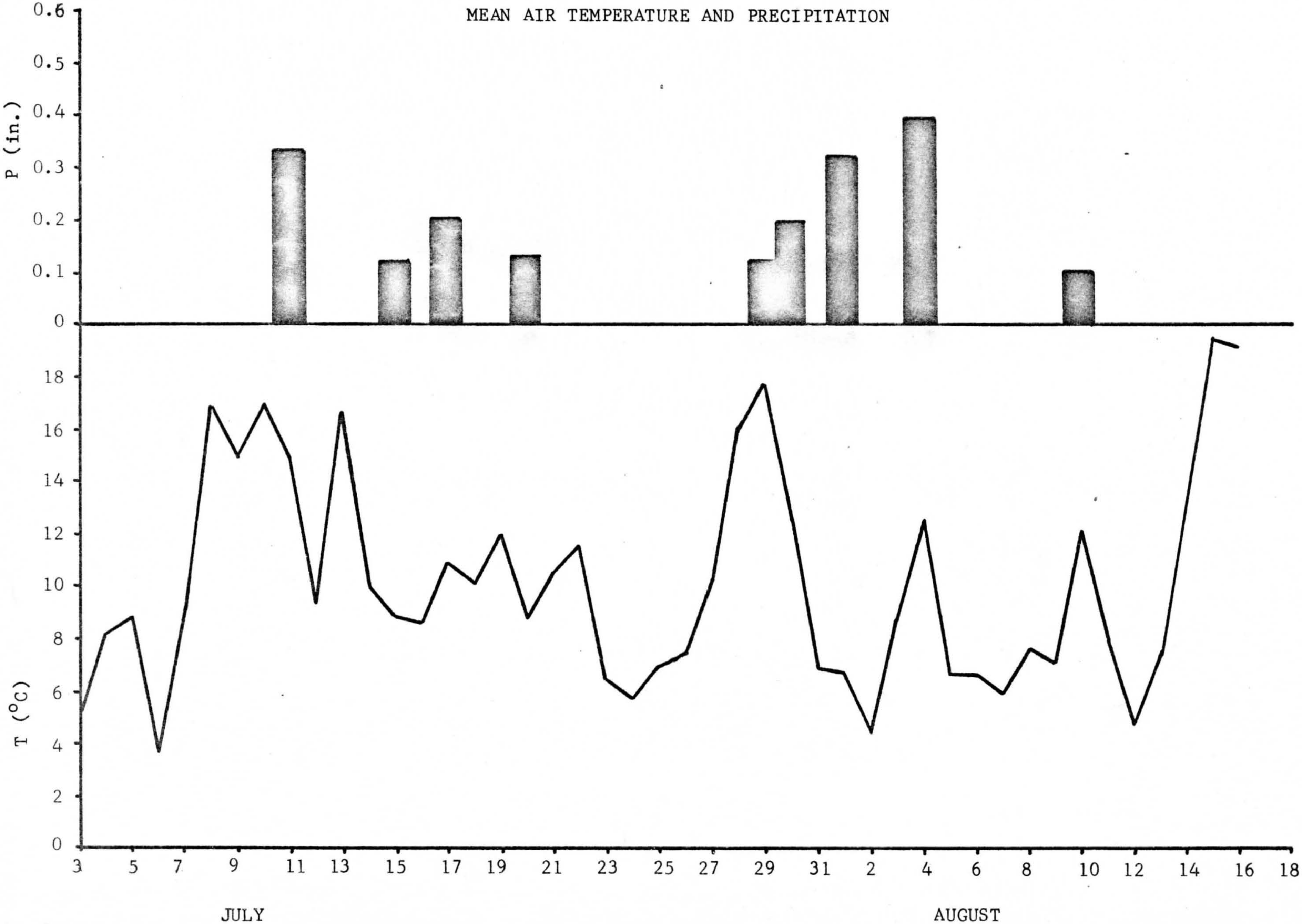
At nearly all the sites, the lowest soil layers achieved a general increase in temperature over time, implying that melting is taking place. The sites which do not show this have a temperature profile which becomes isothermal at the base, implying that sufficient depth has been reached to dampen the daily and monthly temperature waves.

SOIL MOISTURE:

Several serious problems arose in the measurement of the soil

FIGURE 2

MEAN AIR TEMPERATURE AND PRECIPITATION



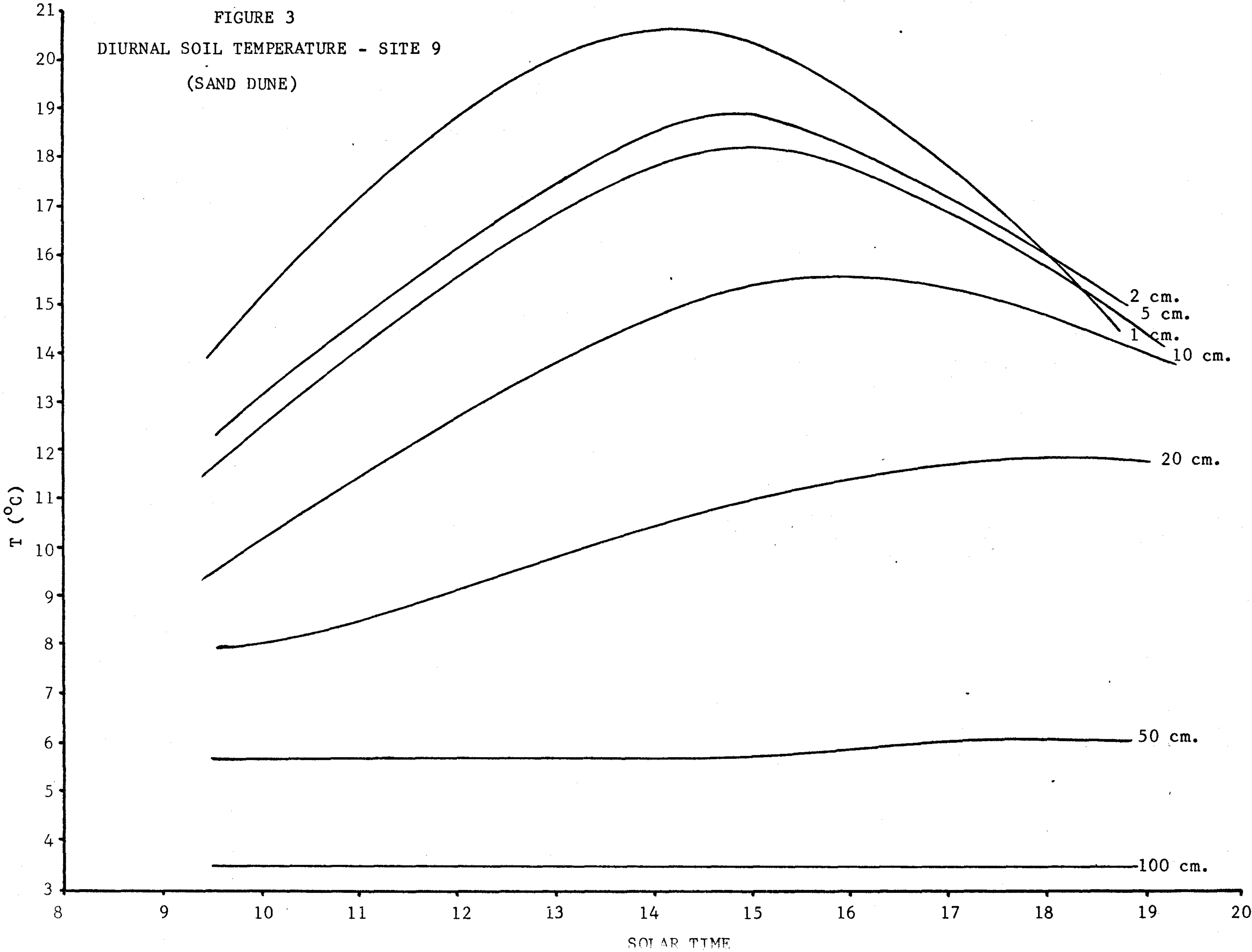


FIGURE 3

DIURNAL SOIL TEMPERATURE - SITE 9

(SAND DUNE)

FIGURE 4

SOIL TEMPERATURE - SITE 1 (VEHICLE TRACK)

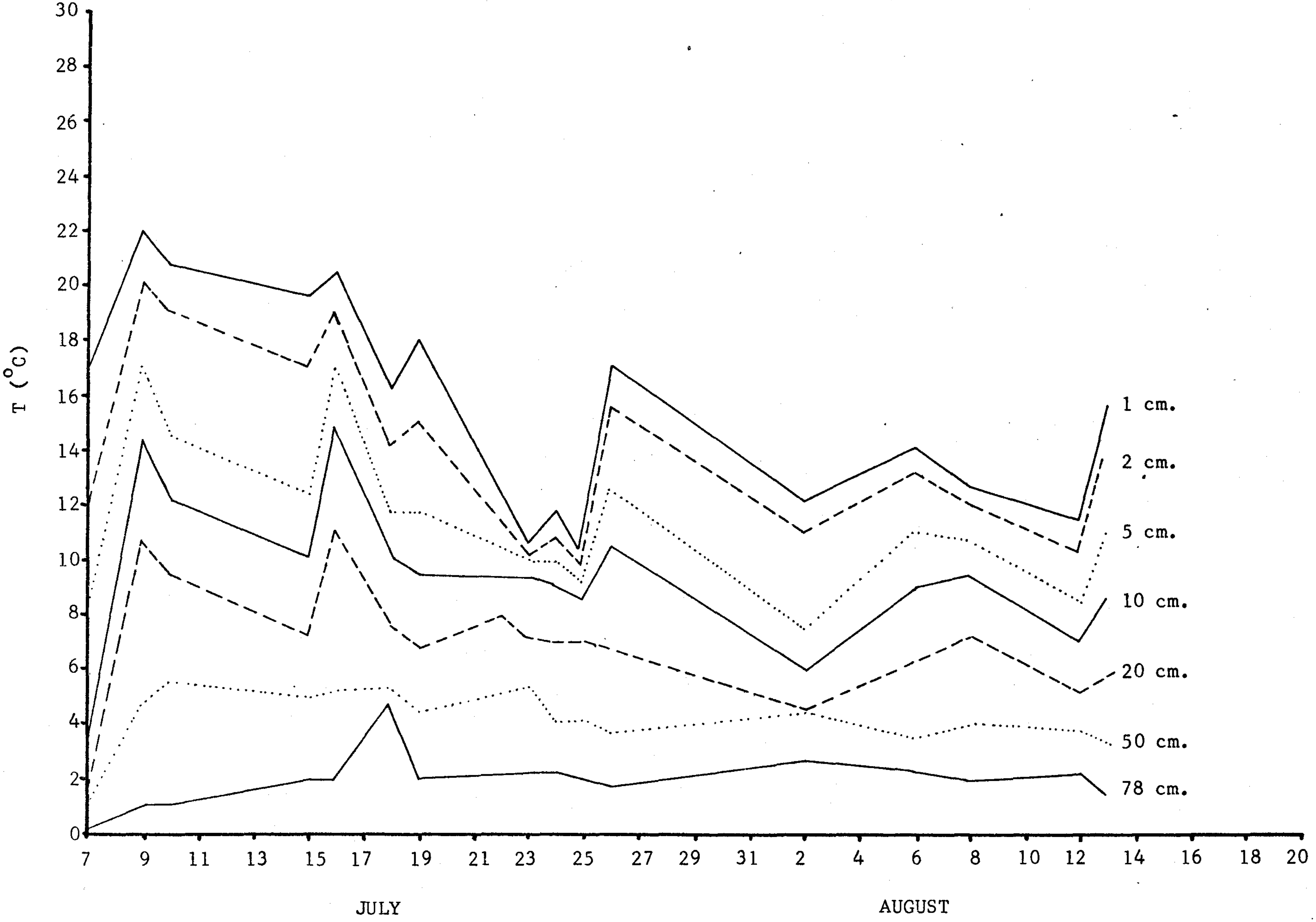


FIGURE 5

SOIL TEMPERATURE - SITE 2 (VEHICLE TRACK CONTROL)

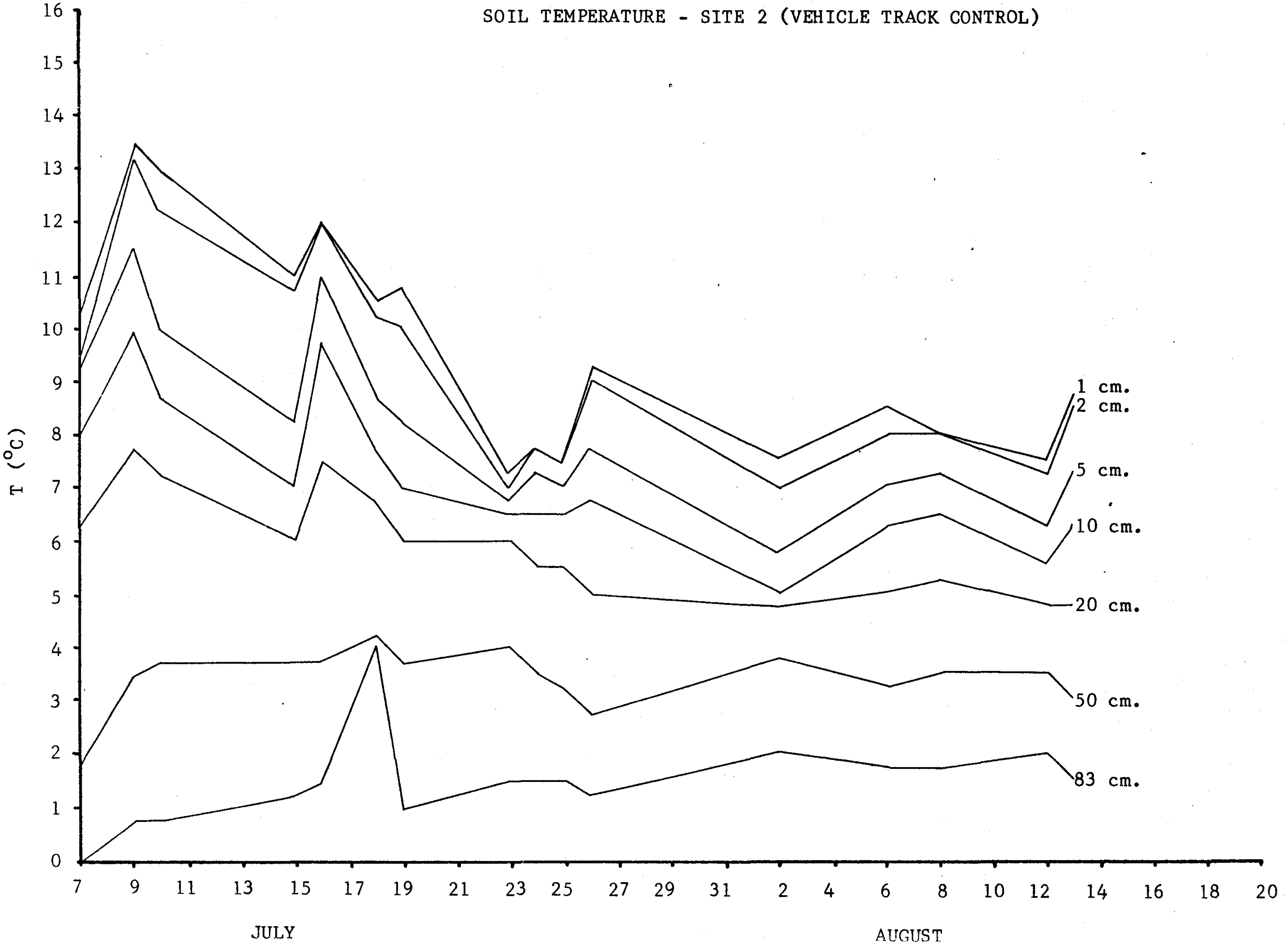


FIGURE 6

SOIL TEMPERATURE - SITE 3 (AIRSTRIP)

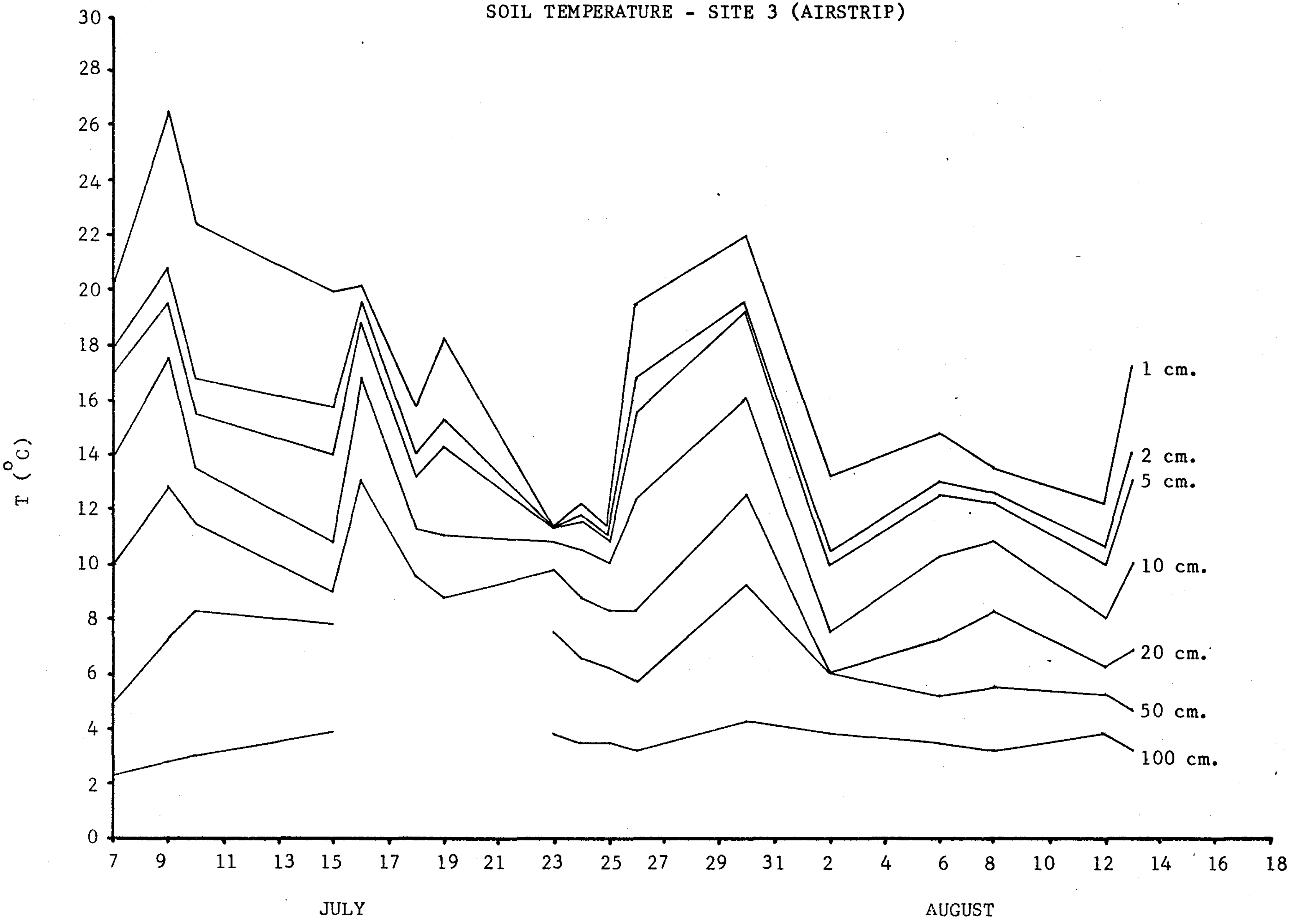
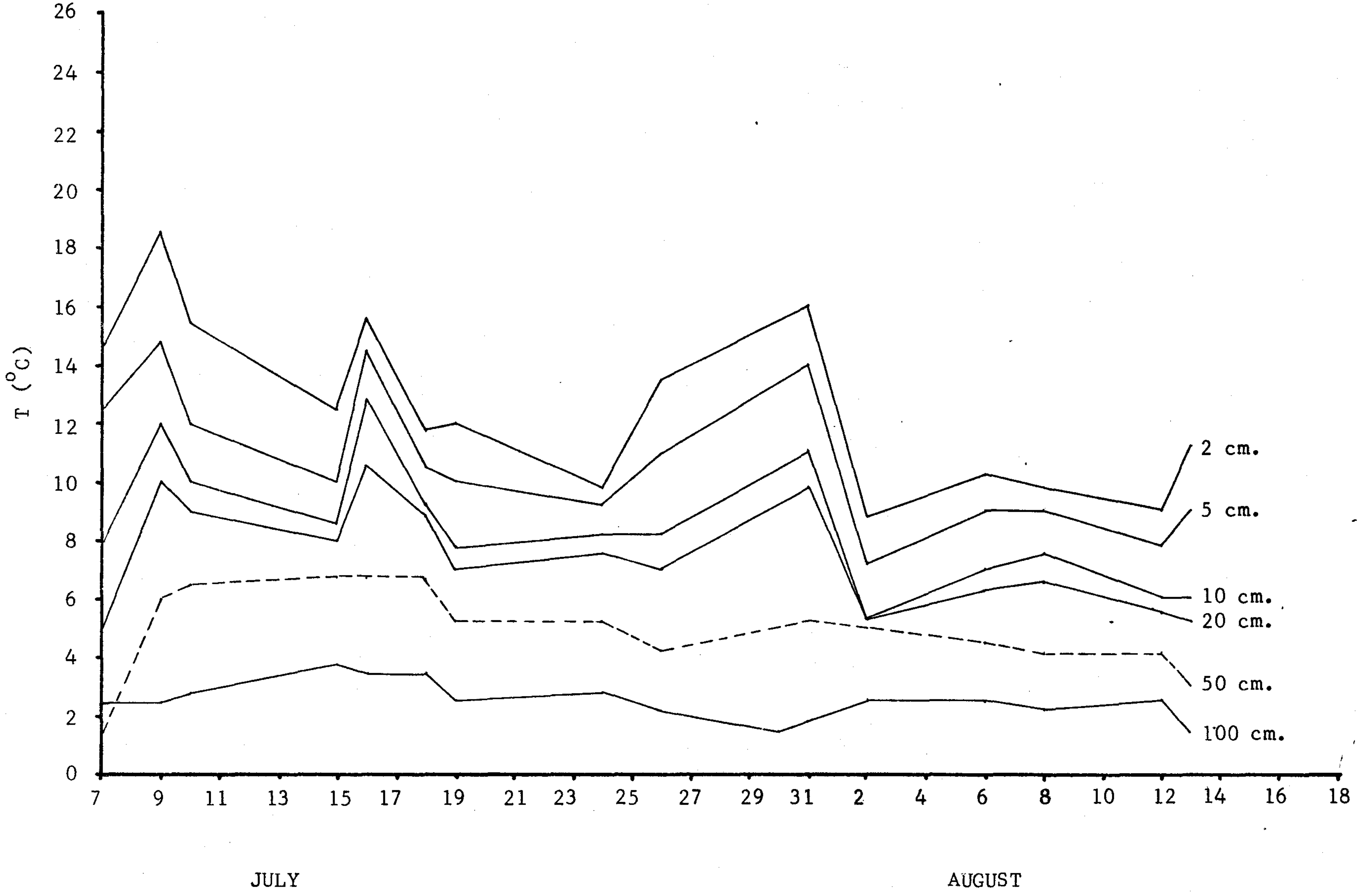


FIGURE 7

SOIL TEMPERATURE - SITE 4 (AIRSTRIP CONTROL)



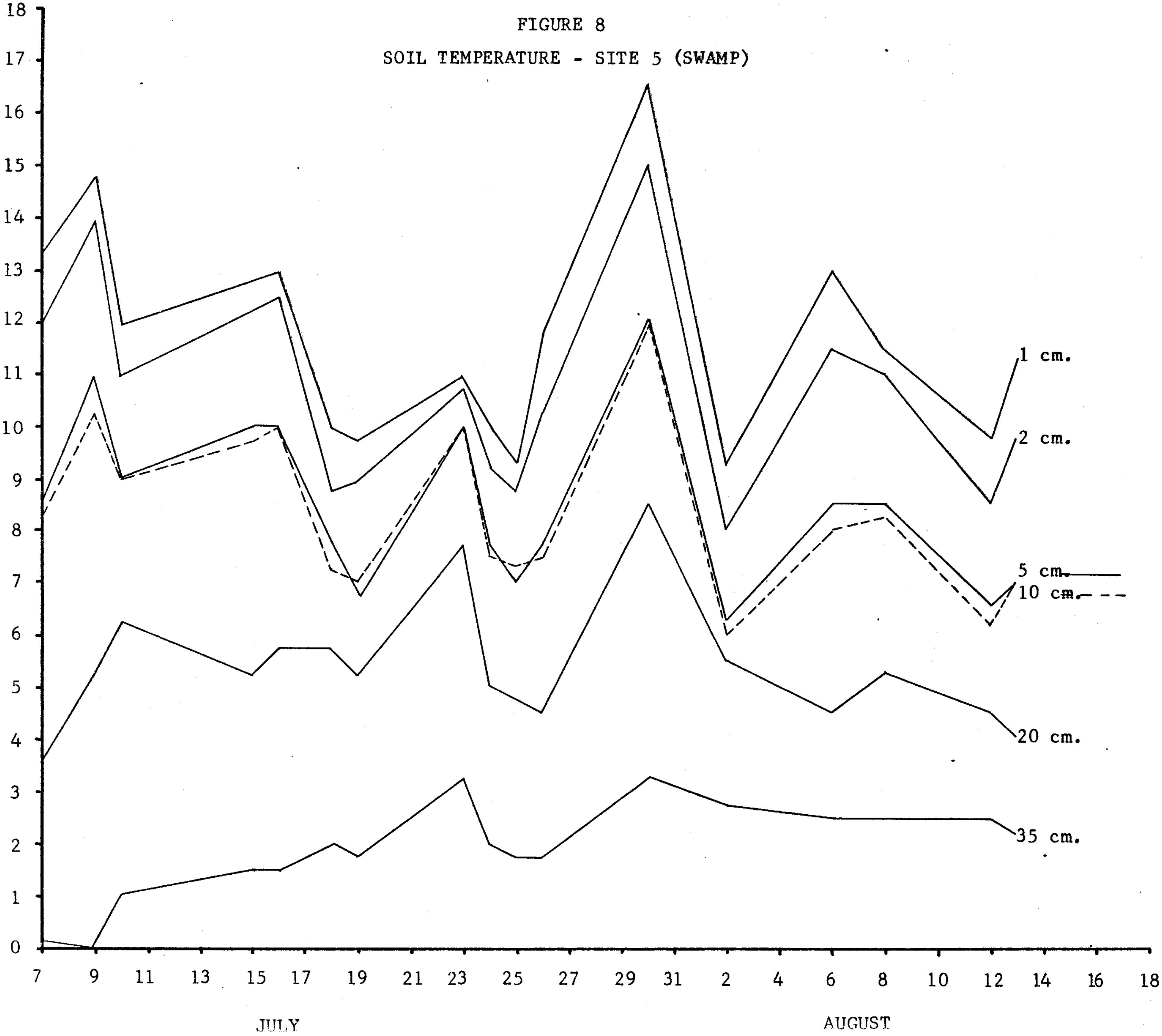


FIGURE 8

SOIL TEMPERATURE - SITE 5 (SWAMP)

FIGURE 9

SOIL TEMPERATURE - SITE 6 (RIDGE)

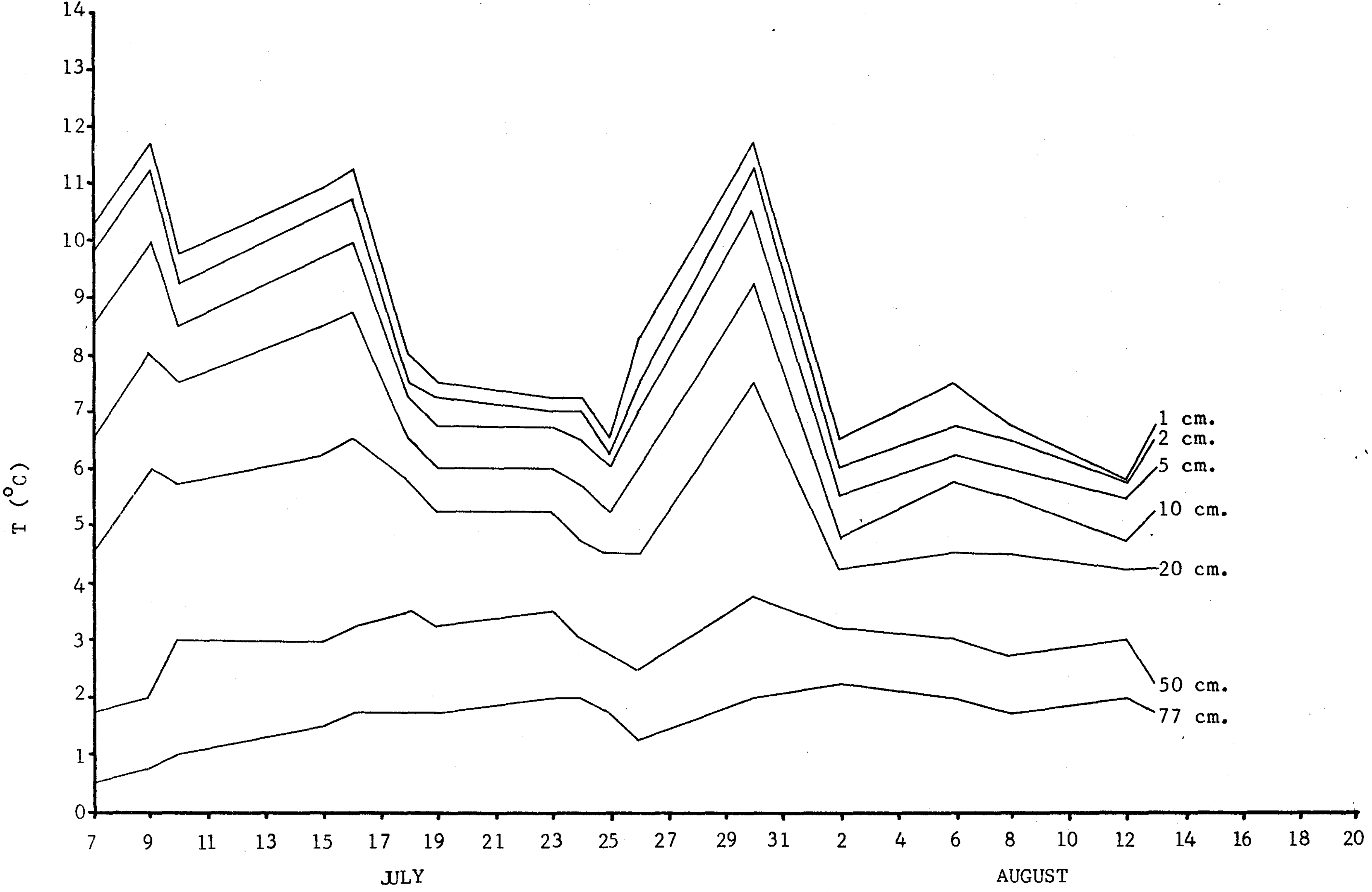


FIGURE 10

SOIL TEMPERATURE - SITE 7 (BURN)

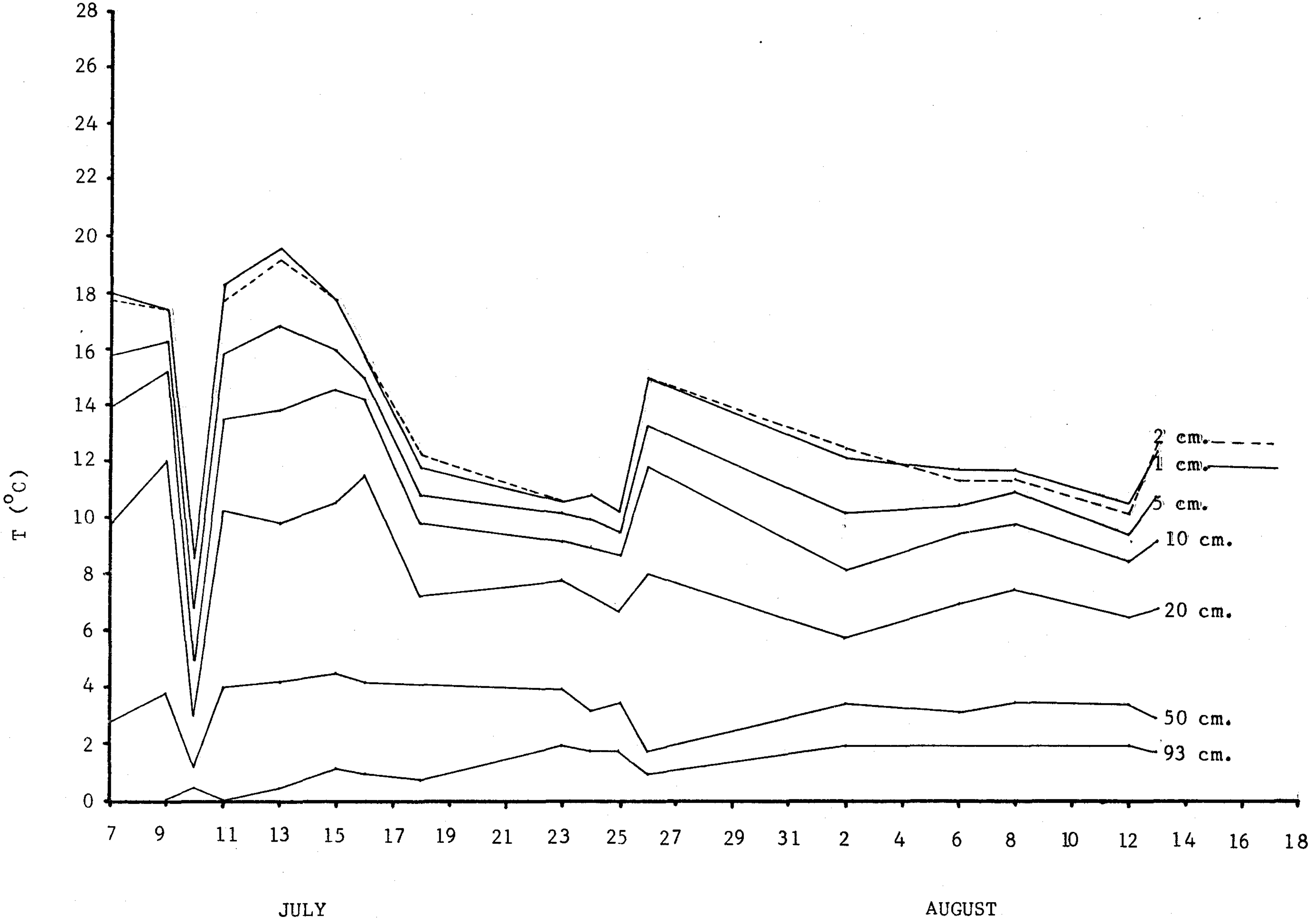


FIGURE 11

SOIL TEMPERATURE - SITE 8 (BURN CONTROL)

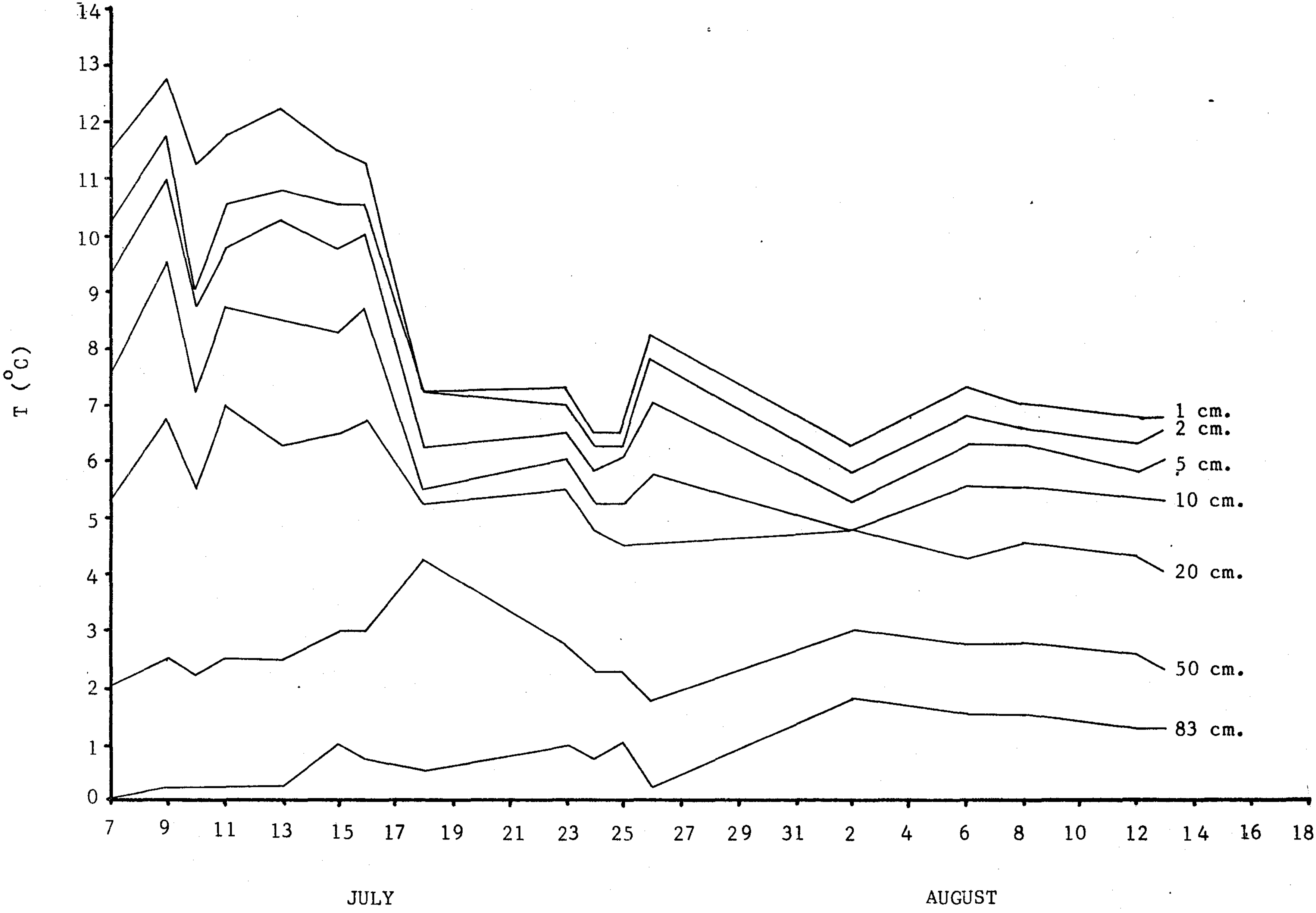


FIGURE 12

SOIL TEMPERATURE - SITE 9 (SAND DUNE)

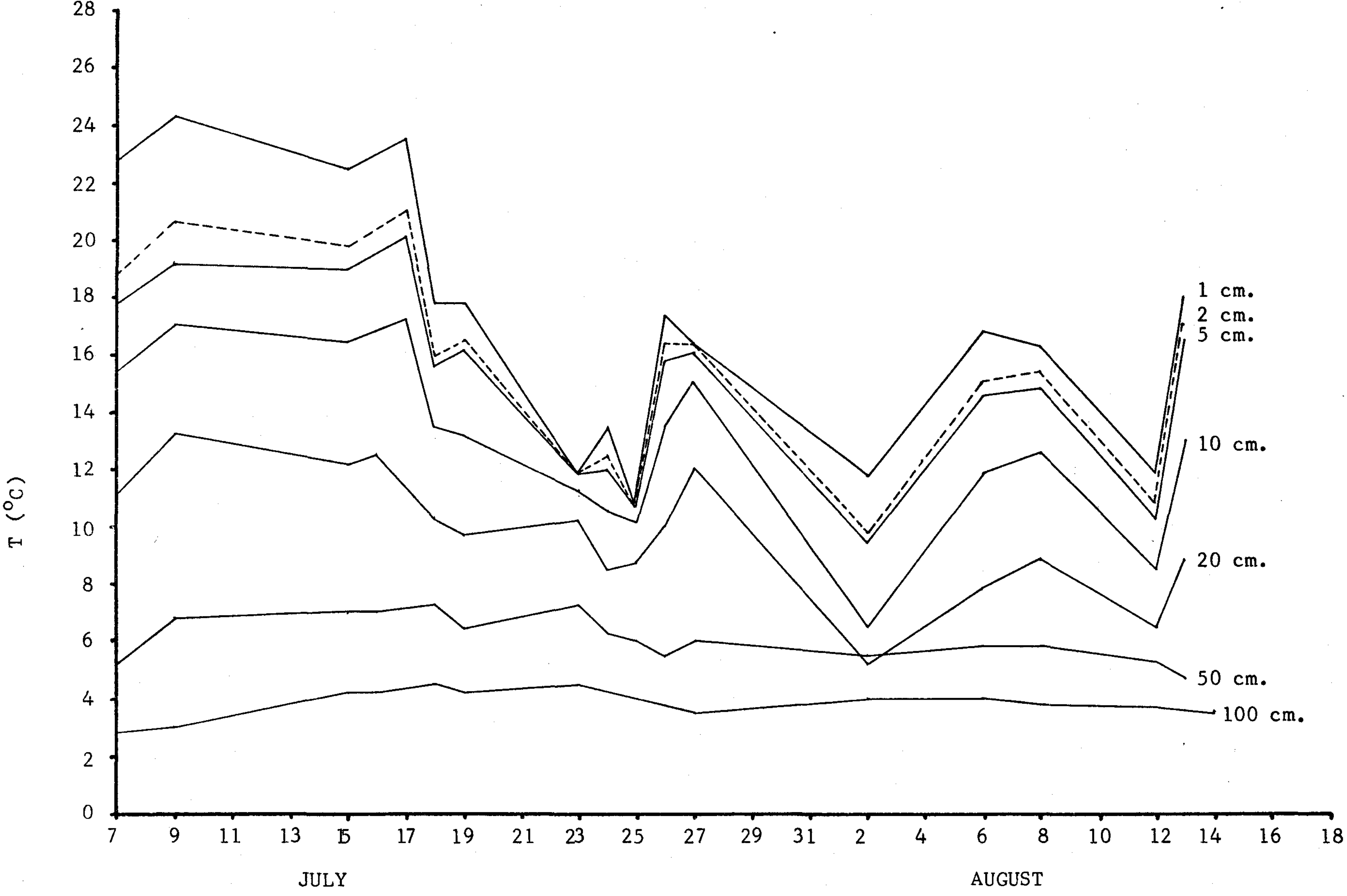
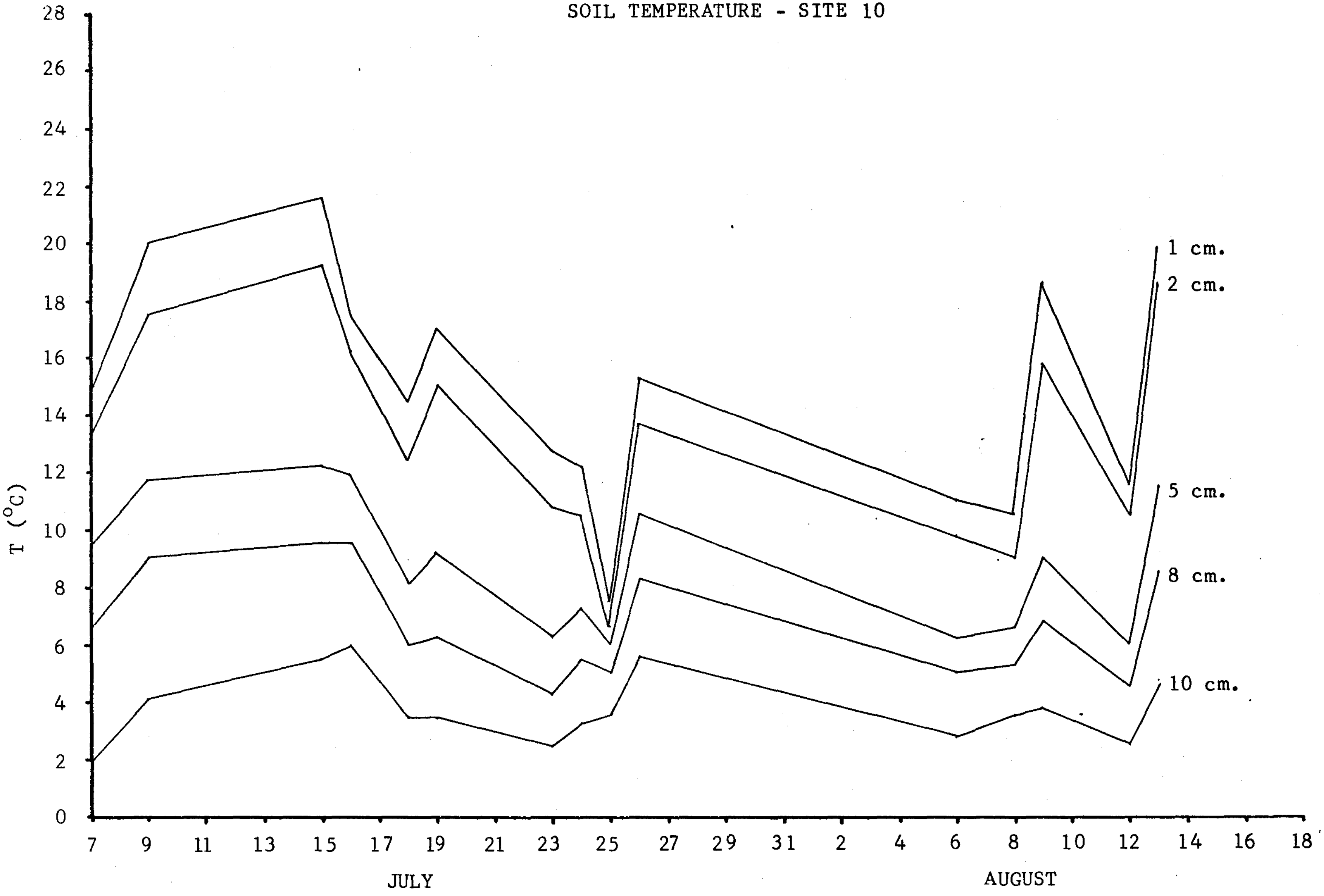


FIGURE 13

SOIL TEMPERATURE - SITE 10



moisture data shown in Figs. 14 to 23. As stated earlier, it was not practical to follow the retreat of the frozen layer due to the difficulty of augering into the saturated zone and the difficulty of sealing access tubes against moisture.

Measurement of the swamp site was difficult due, initially, to the high ice level and subsequently to the flooded conditions of the area. Finally, no depth measurements of soil moisture were made at the ice hummock site due to the thinness and fragility of the moss layer covering the ice below.

The overall trend of these data shows that over the summer there is a decrease in volumetric soil moisture with depth. This is most noticable at the burn control site, Fig. 22, where at the 60 cm. depth, the soil moisture decreased from 14% to 5% over the period.

Opposed to this, the surface soil moisture, Fig. 14, while ranging from 5% to approximately 15% for the soil sites, appeared to keep fairly constant values at each site, flucuating only 2% or 3% at most.

It was noted that it was often common for the soil moisture to have a similar value over the 30 cm. to 50 cm. range, possibly indicating rapid gravitational drainage through that zone.

VEGETATIVE COVER:

Table 1 shows that the surfaces are predominantly lichen covered with higher plants being the second most widespread group. However some individual sites are characterized by one predominant plant type. Due to the sampling technique used, a given plant type can cover more than 100% of the ground surface through its establishment in a series of layers.

FIGURE 14

SURFACE SOIL MOISTURE

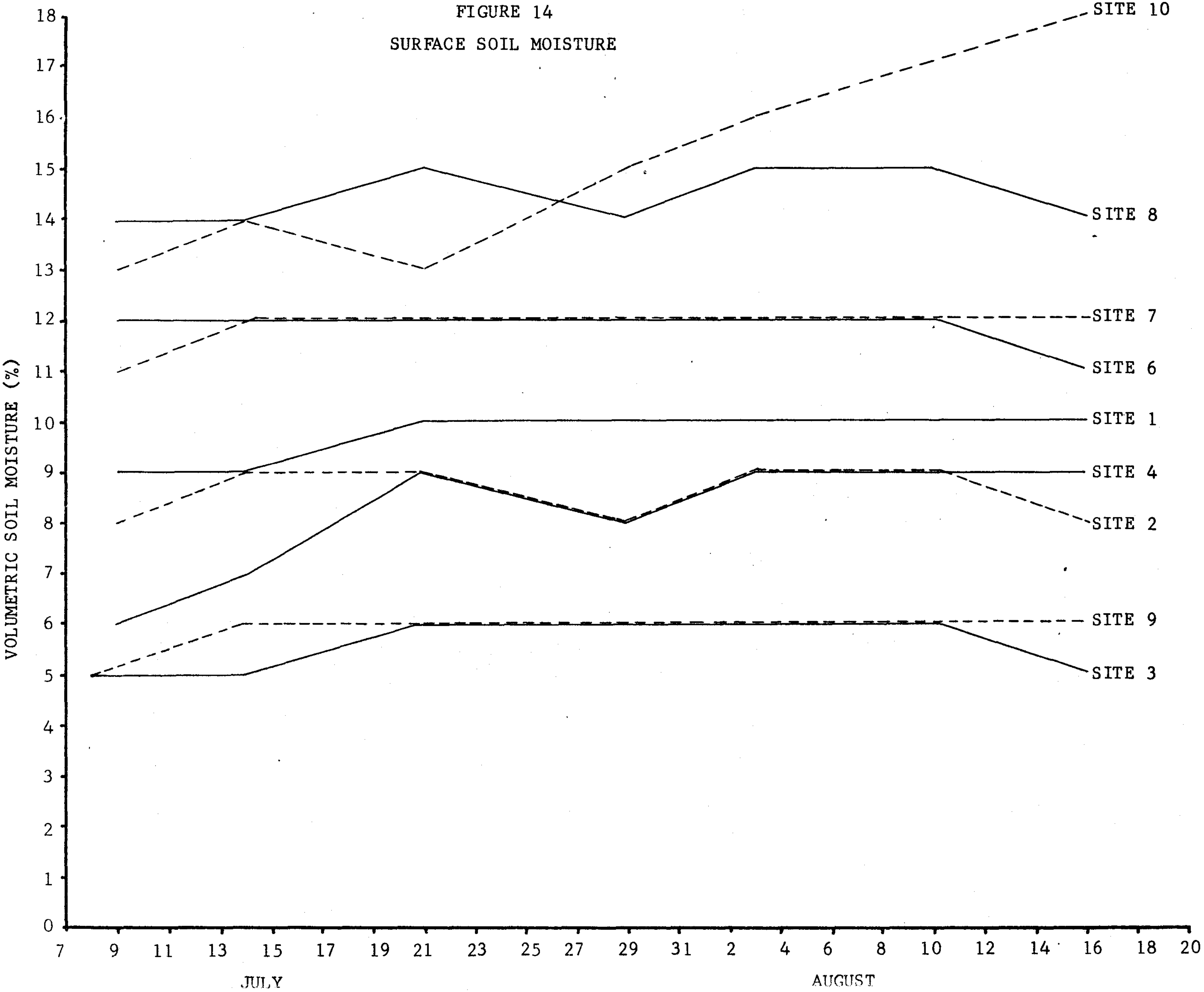


FIGURE 15

SOIL MOISTURE - SITE 1 (VEHICLE TRACK)

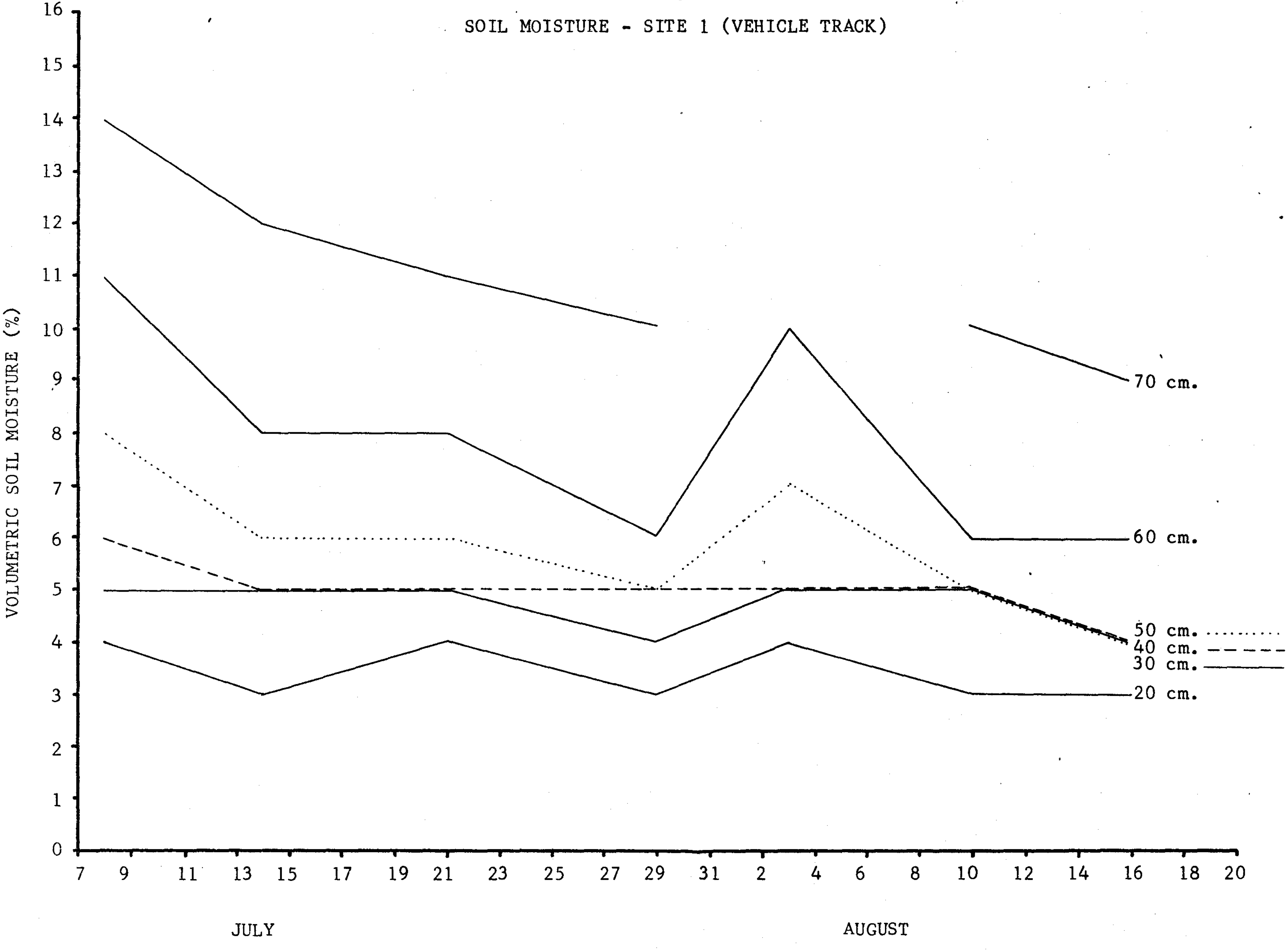


FIGURE 16

SOIL MOISTURE - SITE 2 (VEHICLE TRACK CONTROL)

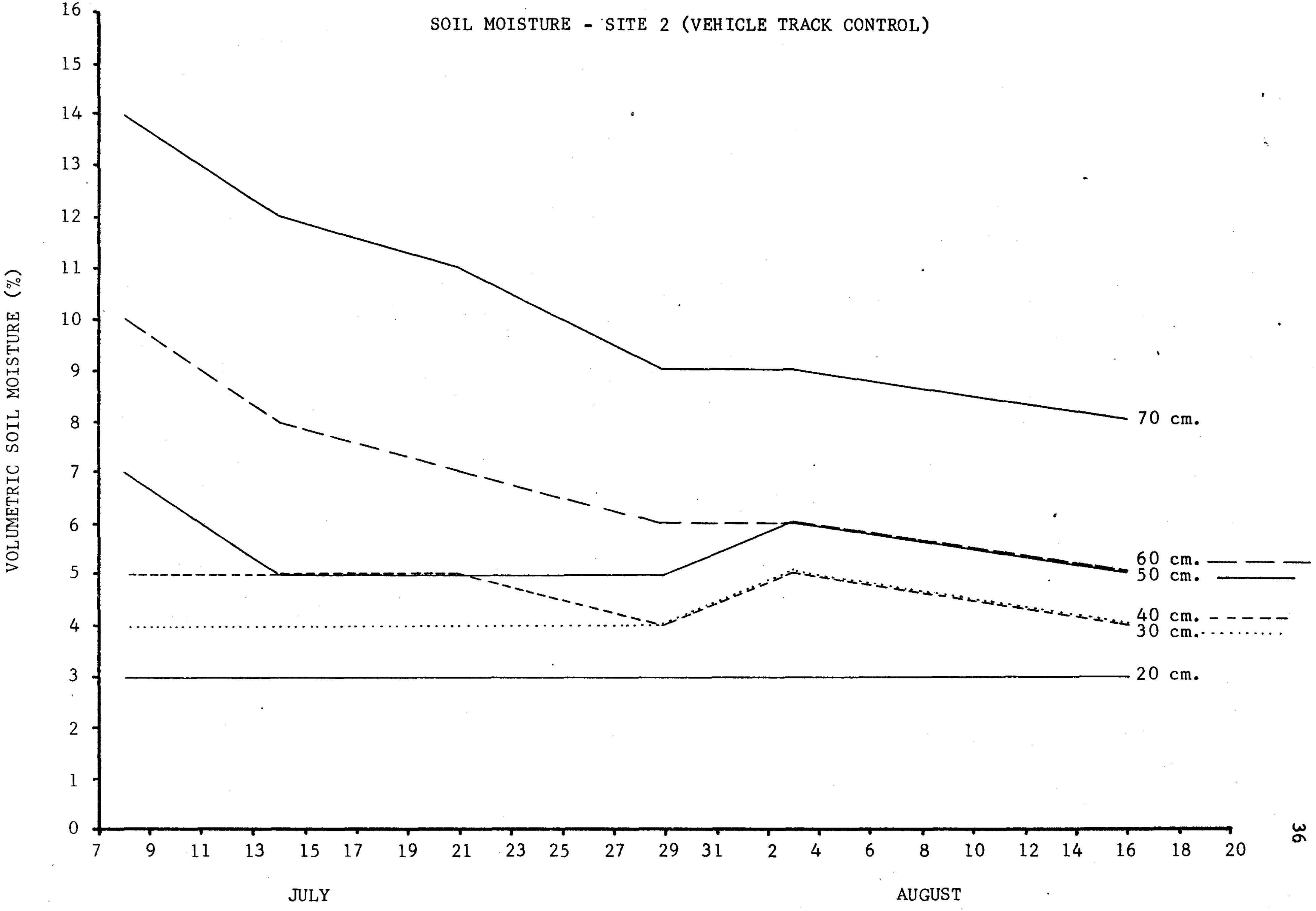


FIGURE 17

SOIL MOISTURE - SITE 3 (AIRSTRIP)

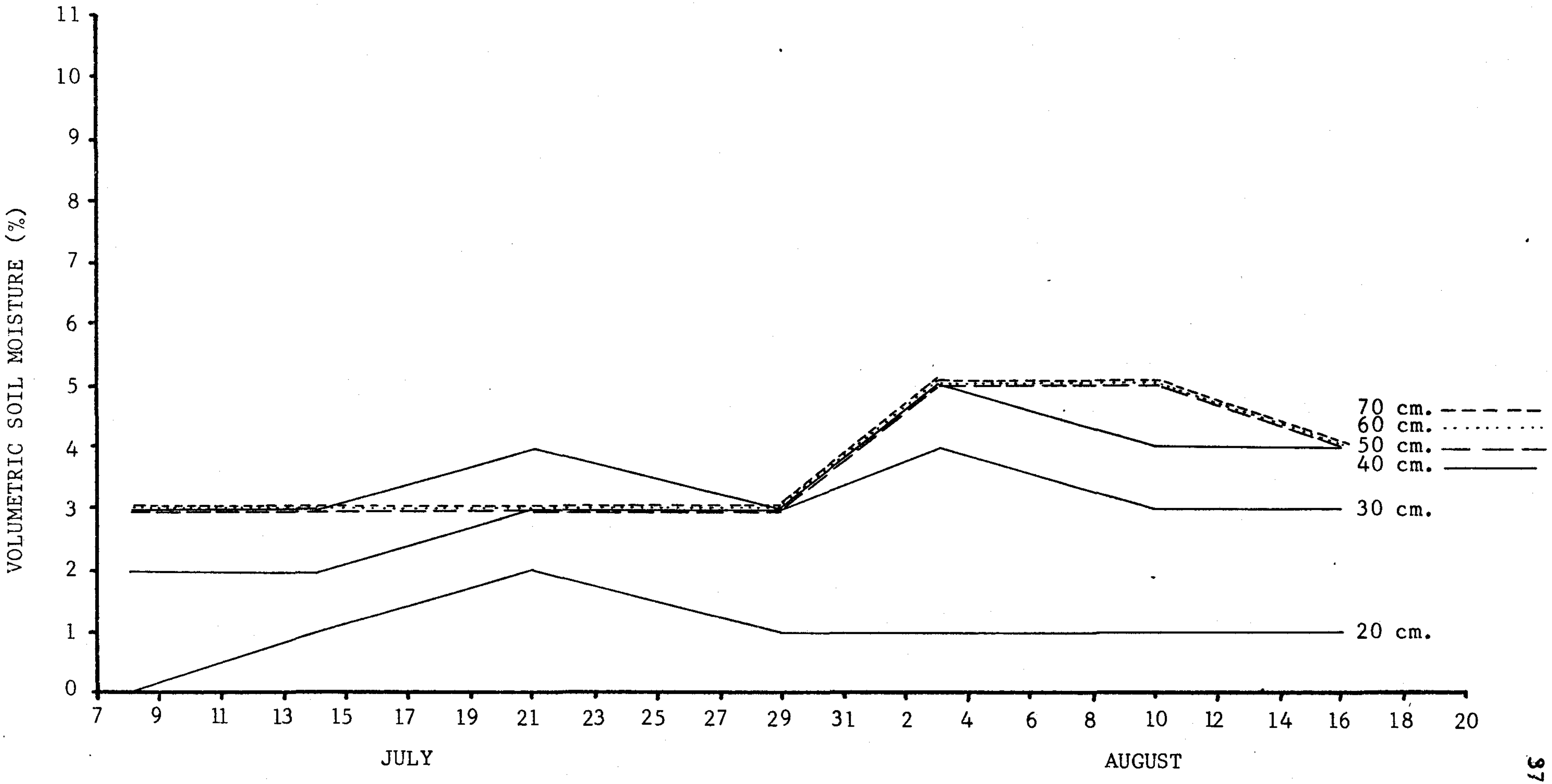
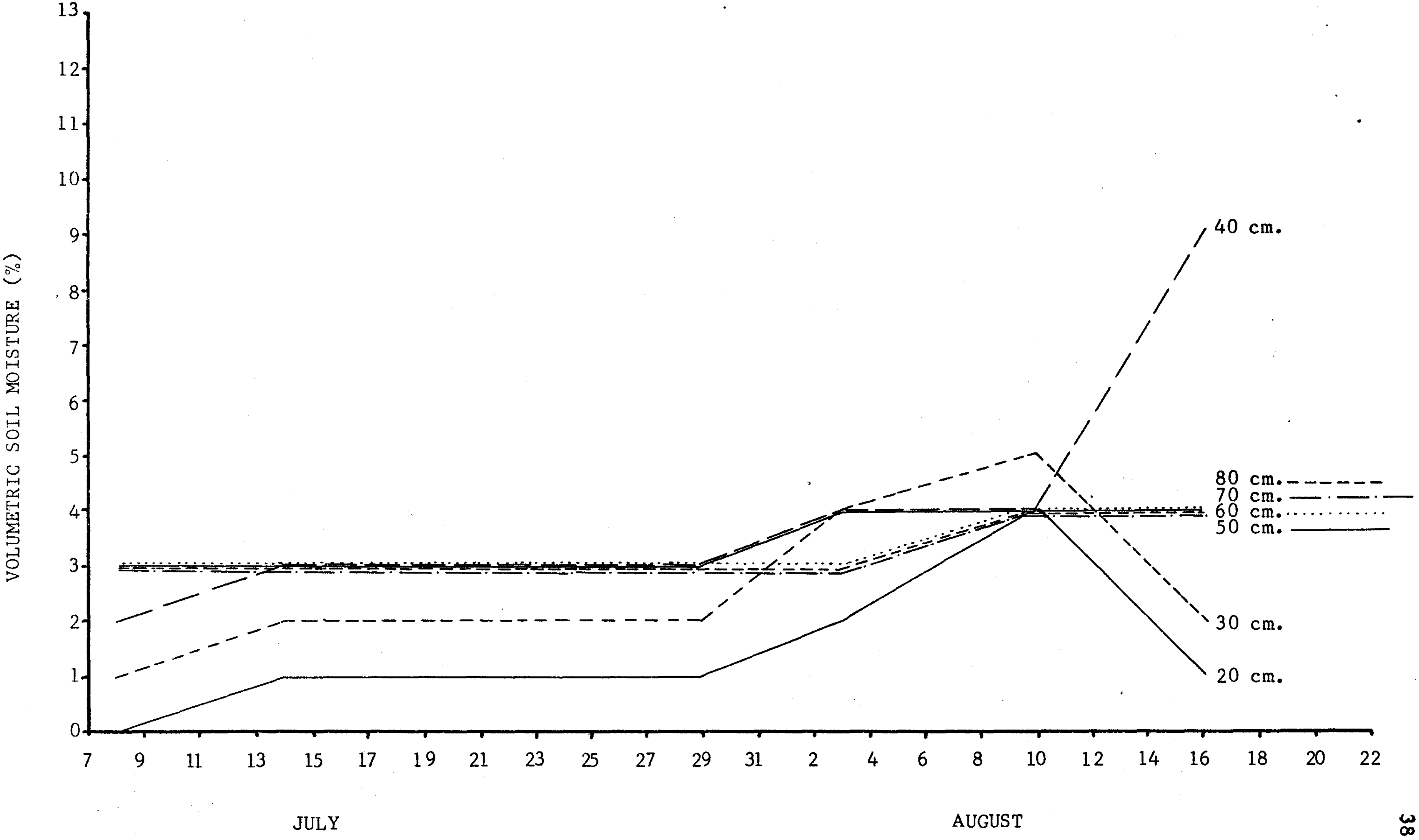


FIGURE 18

SOIL MOISTURE -- SITE 4 (AIRSTRIP CONTROL)



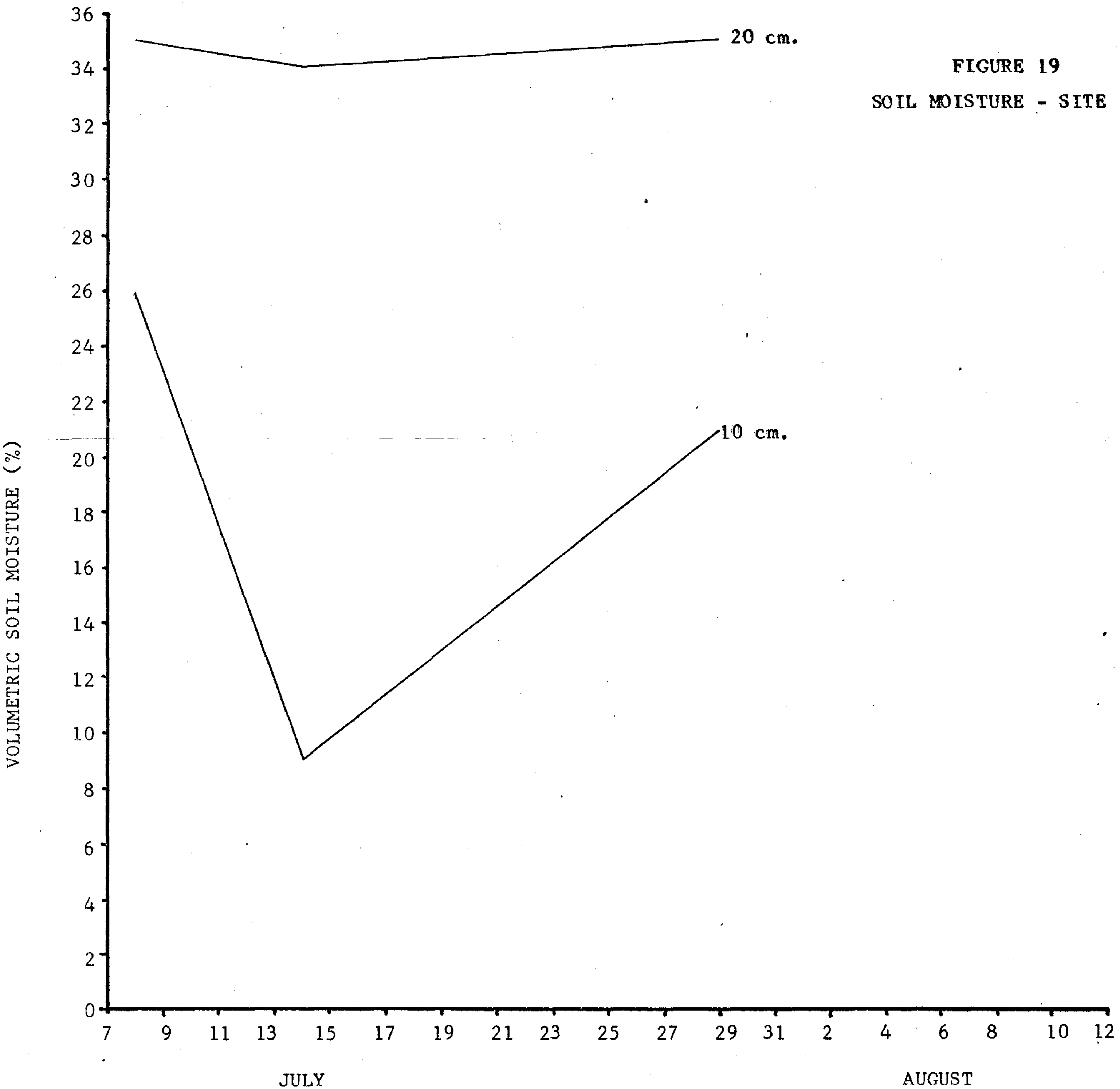


FIGURE 19

SOIL MOISTURE - SITE 5 (SWAMP)

FIGURE 20

SOIL MOISTURE -- SITE 6 (RIDGE)

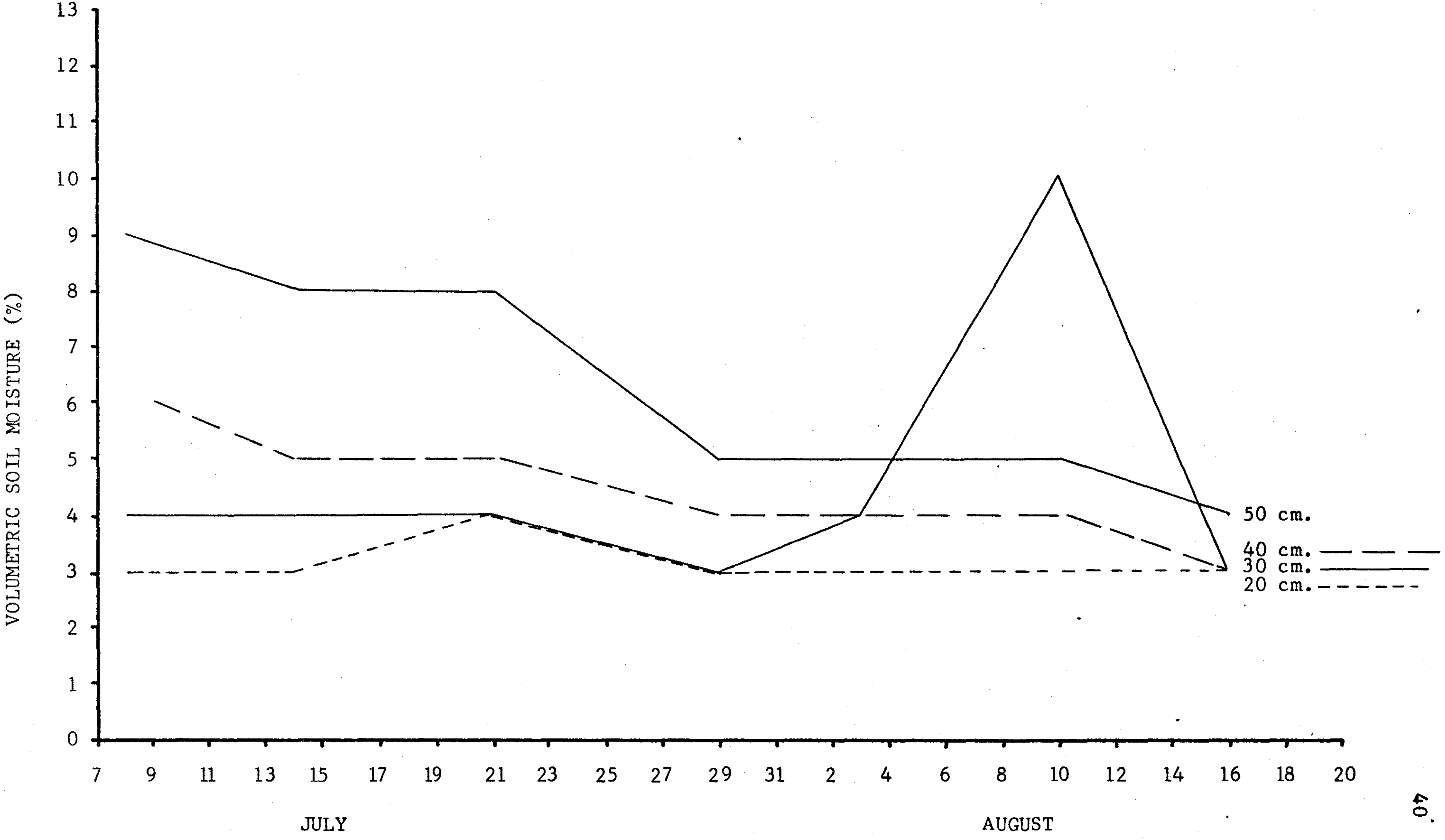


FIGURE 21

SOIL MOISTURE - SITE 7 (BURN)

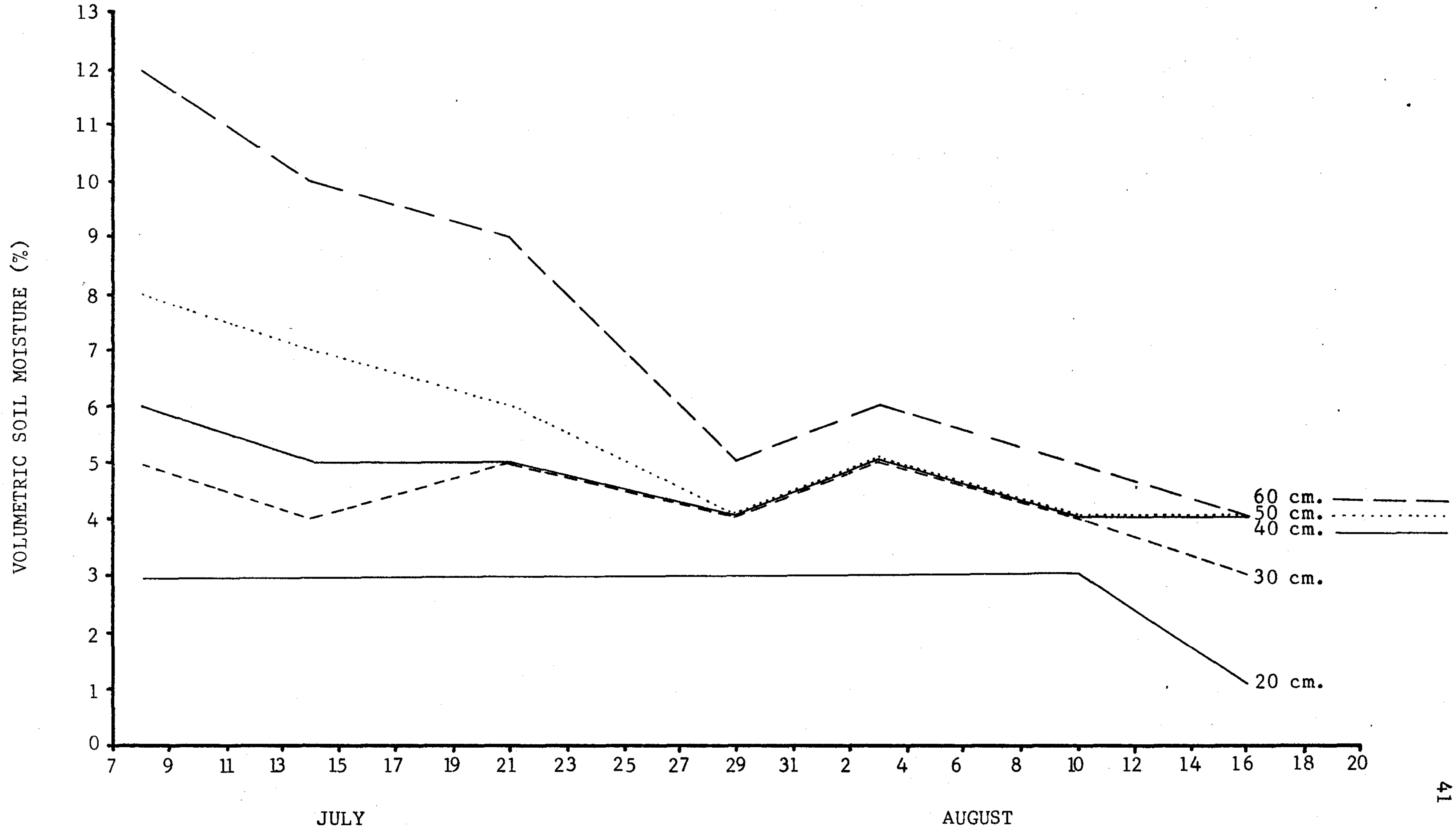
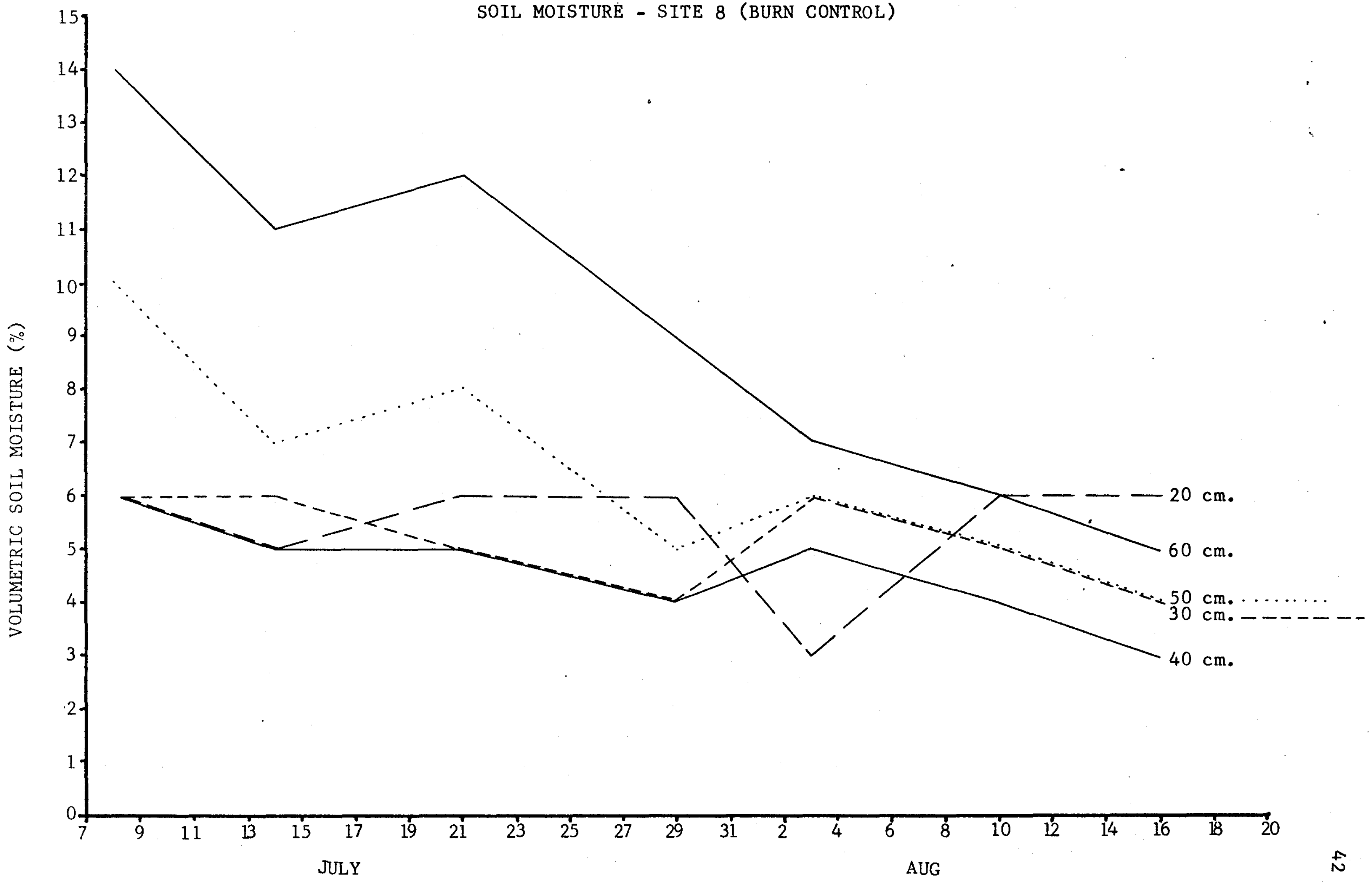


FIGURE 22

SOIL MOISTURE - SITE 8 (BURN CONTROL)



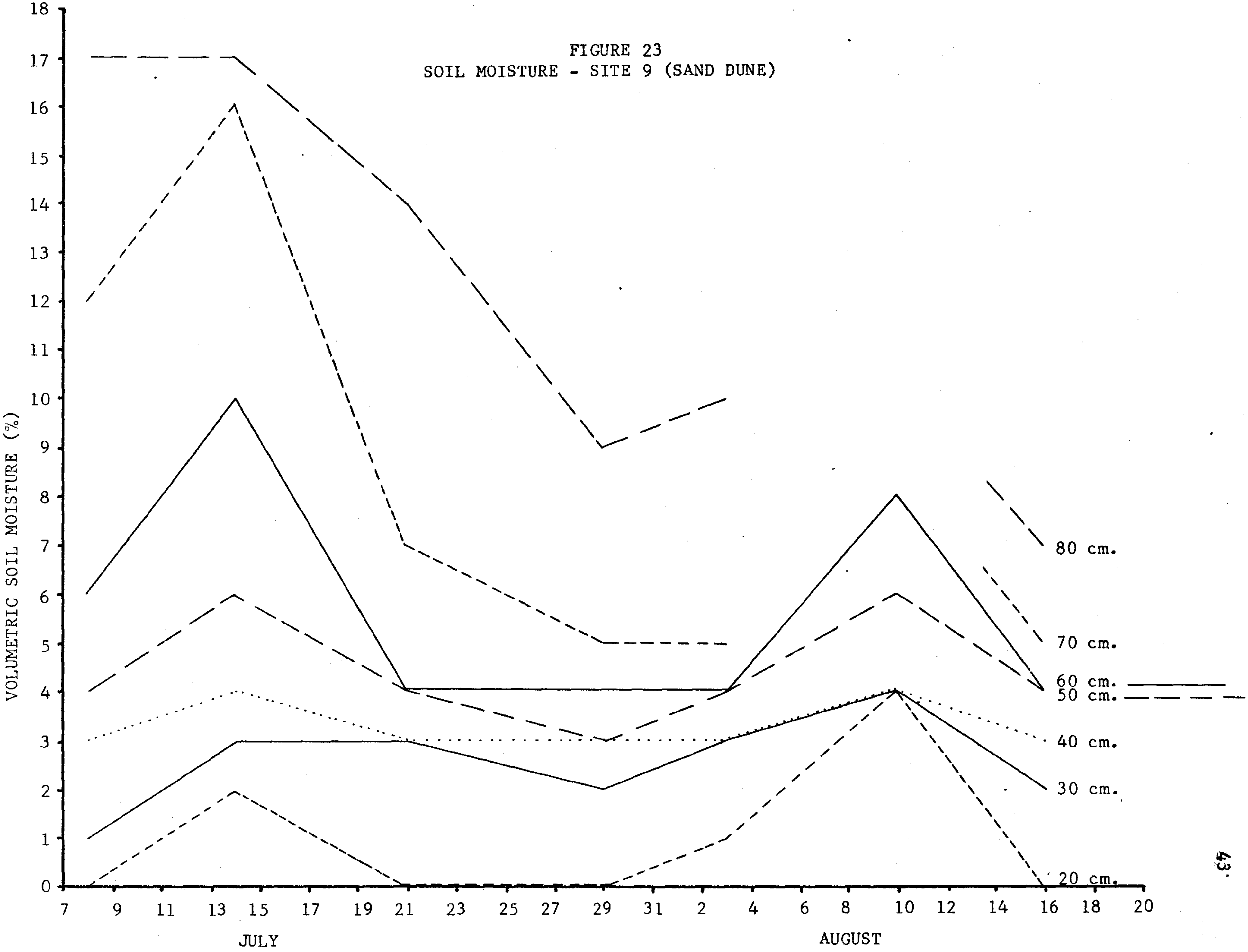


FIGURE 23
SOIL MOISTURE - SITE 9 (SAND DUNE)

In general there is a predominance of mosses at the swamp and ice hummock sites, a predominance of lichen cover on the ridge tops, while the dune displays a thin covering of higher plant types.

ALBEDO:

The clear day albedo values are shown in Table 3. The lowest values occurred at the swamp site when it was under water and the highest occurred in the amphitheatre-shaped dune site. Coarser surface gravels are thought to be the cause of the slightly lower value for the bare airstrip site. The variation of other values is considered to be due to surface vegetation differences and colour effects.

AIR TEMPERATURE AND PRECIPITATION:

Data representing the mean daily air temperature and precipitation may be seen in Fig. 2. These data show the high variability associated with both of these parameters. Over the measurement period, precipitation was seen to vary from 0.10 in. to 0.39 in. and totalled 1.94 in. Similarly, the mean air temperature ranged from 37°C to 19.4°C and had a mean of 10.8°C.

DEPTH TO 0°C PLANE:

When the rates of melting of the active layer are examined in Fig. 24, it can be seen that this is not a simple linear relationship over time as might be expected. It appears that soil damping effects become greater with increased depth resulting in an exponential curve.

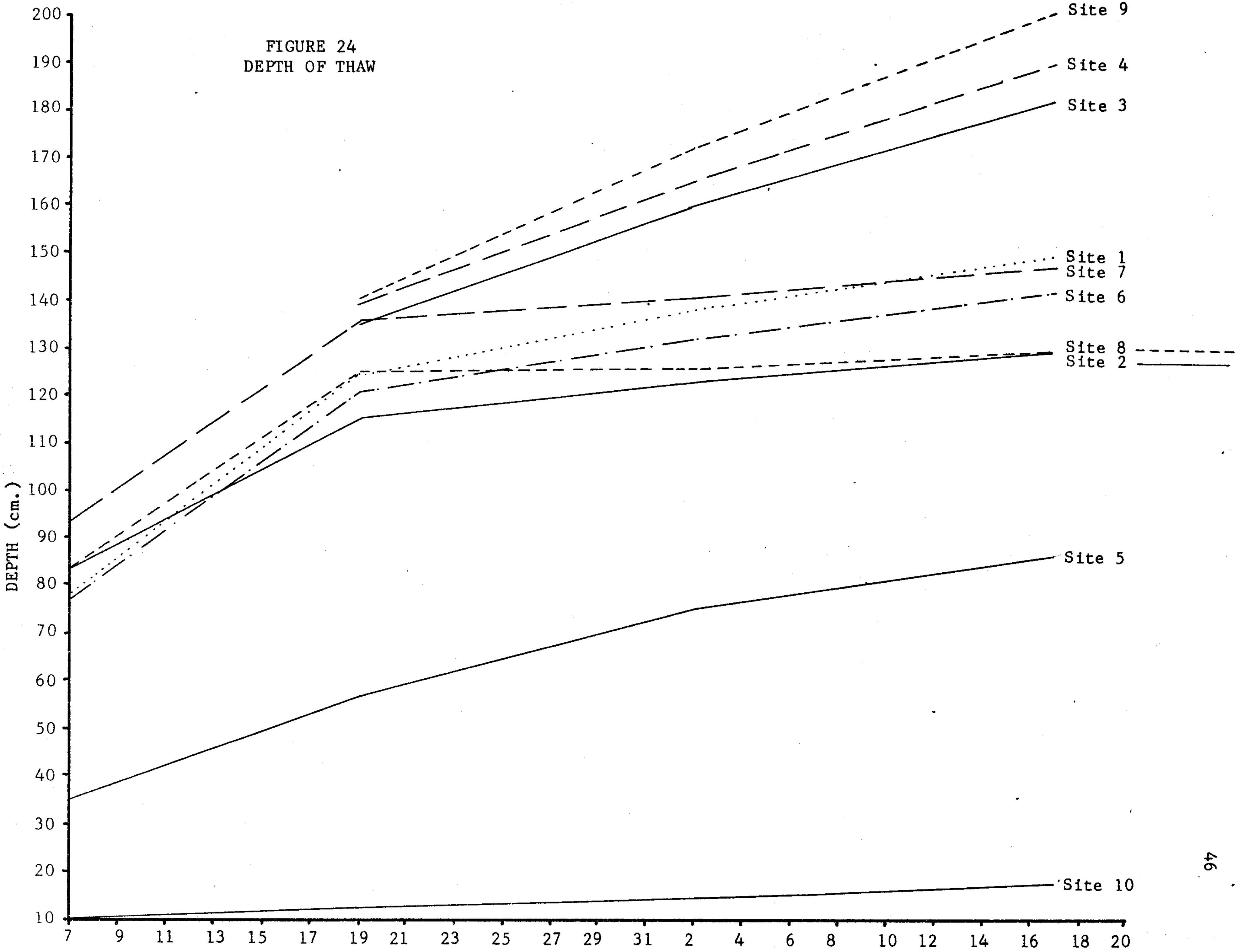
The dune site showed the greatest depth of thaw and the ice

TABLE 3

ALBEDO AT SOLAR NOON

#	SITE	ALBEDO (%)
1	Bare Track	14.0
2	Vegetated Track	18.0
3	Bare Strip	28.0
4	Vegetated Strip	17.0
5	Swamp	≃6
6	Ridge	≃18
7	Bare Burn	13.1
8	Vegetated Burn	≃18
9	Sand Dune	31.5
10	Ice Hummock	18.5

FIGURE 24
DEPTH OF THAW



hummock the least. The airstrip control site showed a greater thaw rate than did the bare ground, despite its vegetative cover. The reason for this will be considered later. The thaw rate of most sites appears to behave in a reasonably similar manner, however the actual amounts of thaw in any given time period varied between them.

SOIL THERMAL PROPERTIES:

The determinations of thermal conductivity and diffusivity are presented in Table 4 using both the graphical interpretation of Kersten (1949) and the theoretical approach outlined earlier. Both of these approaches have used the actual data from the research period as their basis.

In order to use the Kersten approach, it was necessary to choose the soil most closely approximating that at each site. This afforded a serious limitation since the soils in question were Alaskan in origin and of specific mineralogic composition. Despite the approximation associated with this approach, it was chosen on the basis of the widespread reputation of Kersten's work, the ease of usage and the desire to see if his values could be successfully extrapolated to field conditions.

It was decided that the more theoretical approach would be used for comparison due to its applicability to specific sites. It was hoped that these methods would be capable of detecting small differences between sites.

Table 4 shows that the two approaches outlined above give quite drastic differences for both conductivity and diffusivity. It should be noted that when the theoretical approach is used very small errors in initial measurement may be compounded several times throughout the equation. It should also be noted that the Kersten approach has accuracy limits of only plus or minus 25% of the indicated values. This is most evident when sites 5 and 10 are considered. These show differences consisting of an order of magnitude. This is due to the fact that not only did Kerston spend little analysing peat soils and did not specify their exact composition, but also it was these that were most difficult to analize in the laboratory.

TABLE 4

THERMAL PROPERTIES OF SOILS

		KERSTEN		THEORETICAL	
#	SITE	Conductivity[1]	Diffusivity[2]	Conductivity[1]	Diffusivity[2]
1	Track	.00379	.0108	.00757	.0215
2	Track Control	.00379	.0108	.00660	.0188
3	Airstrip	.00413	.0114	.00859	.0237
4	Airstrip Control	.00413	.0114	.00892	.0247
5	Swamp	.00055	.0090	.00413	.0679
6	Ridge	.00344	.0103	.00757	.0227
7	Burn	.00241	.0079	.00757	.0248
8	Burn Control	.00241	.0079	.00722	.0237
9	Dune	.00344	.0109	.00892	.0284
10	Ice Hummock	.00013	.0028	.000066	.00014

(1) Conductivity = cal cm^{-1} sec^{-1} $°C^{-1}$

(2) Diffusivity = cm^2 sec^{-1}

CHAPTER V

DISCUSSION

The bare soil sites, with the exception of the airstrip, showed a greater amount of melt than did the vegetated sites. The vehicle track and the burn sites had approximately 16% and 14% greater melt than their respective control sites.

The greatest amount of melt occurred at the dune site. This was due to the lack of an insulating vegetative layer, allowing a large soil heat flux. This was accentuated by the concentration of solar radiation through the amphitheatre shape of the surface.

The bare surfaces on the airstrip had less melt occur under them than did the vegetated surfaces. This disparity in the results is interesting since the soil temperatures of the bare areas were higher (Fig. 6). Possible explanations for this behaviour could be the effects of melting from two directions as a result of the exposed slope of a steep topographical gradient nearby, increased moisture under the vegetation increasing the thermal properties or transferring heat. There could also be less radiative cooling taking place at night over the control surface due to the insulating effects of the vegetation. This would result in a greater daily net accumulation of energy over the vegetated surface.

Fig. 24 shows that less melt occurred at the swamp and ice hummock sites than at others These sites were the only ones characterized by a significant amount of moss in the vegetation layer. This may be seen in Table 1.

The greater amount of melting at the swamp site was possibly due to the effects of the increased water content. The swamp and ice hummock respectively had about 61% and 12% of the melt that occurred at the ridge site.

There did not appear to be a relationship between the depth of thaw and the surface albedo. This appeared to be true even when an attempt at correlating this to the vegetation type was made.

Fig. 3 shows that the soil temperature regimes behaved in a predictable manner. This shows that on a diurnal basis the temperature of the lowest levels is constant, however over the research period there was a general warming at all but the airstrip sites.

Another characteristic of the soil temperature profile is the depth to which daily fluctuations are felt. There were strong temperature fluctuations present at 20 cm. but very weak ones at the 50 cm. depth. Below 20 cm. the change in temperature per unit depth was much less than in the upper layers. This is the same as the insulating effects of the moss layer and shows the equivalent effects of the soil, although not to the same degree.

Melting of the active layer appeared to be accentuated by increased soil moisture. In all but the airstrip case, soil moisture was greatest above the melting zone. It was also higher earlier in the experimental period. There was a sudden increase in soil moisture as the melt layer was approached. Over the research period, this saturated zone retreated with the ice.

The airstrip sites showed reasonably constant but low soil moisture values over the research period. This was taken as evidence of lateral moisture flow out of the area, possibly due t the previously mentioned topographical gradient.

Since the sand dune also had high moisture values, the rapid melt is probably due to the effects of accumulated radiation. This was due to the amphitheatre shape and substantiated by the high soil temperatures.

Moisture profiles generally showed a minimum at approximately 20 cm. with reasonably constant values from 30 cm. to 50 cm. and the aforementioned increase in the lowest levels. These characteristics are respectively due to evaporation loss, gravitational drainage and accumulation due to the presence of the ice layer. These findings agree with those of Koslovic (1972). The burn control site was an exception to this since moisture loss was felt down to the 40 cm. level.

A large discrepancy existed between the thermal properties derived from Kersten's work and those derived from theoretical calculations. It should be pointed out that an increase in the theoretically derived conductivity was in all cases matched by an increase in the depth of thaw.

Compared to the bare surfaces, the vegetative layer correlated to a 4.8% decrease in the thermal conductivity at the track site and a 14.6% decrease at the burn site. This assumes other factors such as density to be equal. In absolute terms, the conductivity of the burn control site was greater than that of the vehicle track control site.

Despite this, the relative difference in melt between the bare and control surfaces was greater at the vehicle track sites than at the burn sites. This implies that the ash layer present at the burn site was responsible for significantly decreasing the bulk conductivity at that site when compared to the bare surface of the vehicle track. If this is true, then differences in the amount of melt between theses sites are due not to surface vegetation differences but to the condition of the bare soil.

The effects of density and soil moisture differences are reflected in the thermal conductivity and diffusivity values. With similar thermal conductivity values, differences in soil density at sites 6 and 7 and sites 4 and 9 show the same effects with increased soil moisture when the density is held constant.

The above observations were also noted by Kersten in his works. Kersten also detected up to 50% differences in thermal conductivity and diffusivity due to mineralogical composition and grain shape.

CHAPTER VI

SUMMARY AND CONCLUSIONS

SUMMARY:

Increases in soil density resulted in increases in thermal conductivity. Likewise, increases in the volumetric soil moisture caused increases in both the thermal conductivity and the thermal diffusivity. These relationship were evident in calculations based on actual field data and on theoretical considerations.

The effects of density and soil moisture variations on the thermal properties mentioned above were also supplemented by the effects of varying surface conditions.

The presence of a vegetative layer acted to insulate the soil and decrease the bulk thermal conductivity and diffusivity values for that site. This was particularly noticable when a large percentage of moss was present in the surface vegetation.

Use of Kersten's calculations has shown that there are large inherent errors present in that approach. This approach should be used only when the soil composition is homogenous and identical to those soils which Kersten studied in the laboratory. When a theoretical approach is used, any non-periodicity of the surface temperature wave over 24 hour periods should be noted. Large differences in the soil surface temperature and air temperature regimes should also be noted in addition to any obvious lateral moisture flow. If data of the above nature are available, it should be possible to correct any theoretical errors. This would be done by the use of appropriate phase and correctional factors. This would result in an accurate assessment of the soil thermal properties and therefore temperature regimes for any site.

CONCLUSION:

In conclusion, it has been shown that the rate at which the active layer melts in permafrost areas is determined not by a single factor but by the interaction of a series of factors. Of these, the vegetative cover was shown to be of the greatest importance and of any probably the most independent.

To better access the influence of these factors and their variability, it shall require carefully controlled, long term studies under naturally homogenous conditions rarely if ever present in the active layer. Despite this, it is hoped that with the continual development of the north, such studies will be forthcoming wherever conditions permit.

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