

*Technical Papers*  
OF THE BUREAU OF SPORT FISHERIES AND WILDLIFE

69. Thermal Characteristics of  
Lake Michigan, 1954-55

By John F. Carr, James W. Moffett,  
and John E. Gannon

SH  
11  
A313  
m.69

United States Department of the Interior, Rogers C.B. Morton, Secretary  
Nathaniel P. Reed, Assistant Secretary for Fish and Wildlife and Parks  
Fish and Wildlife Service  
Bureau of Sport Fisheries and Wildlife, Spencer H. Smith, Director  
Washington, D.C. • April 1973



PAGE BRANCH  
LIBRARY  
AUG 1 1977  
NOVA.  
U. S. Dept of Commerce

2652 77

## CONTENTS

	Page
Abstract . . . . .	1
Introduction . . . . .	1
Methods . . . . .	4
Seasonal thermal changes in southern Lake Michigan, 1954 . . . . .	8
Seasonal thermal changes in northern Lake Michigan, 1955 . . . . .	9
Surface temperature distribution . . . . .	11
Vertical temperature distribution . . . . .	13
Heat content . . . . .	15
Literature cited . . . . .	16
Appendix tables . . . . .	77

# THERMAL CHARACTERISTICS OF LAKE MICHIGAN, 1954-55

John F. Carr, James W. Moffett and John E. Gannon  
Bureau of Sport Fisheries and Wildlife  
Great Lakes Fishery Laboratory, Ann Arbor, Michigan 48107

ABSTRACT.--The thermal regime of Lake Michigan is described on the basis of the analysis of 1,671 bathythermograph casts made in 1954 and 1955. The beginning, duration, geographic extent, and ending of thermal stratification were determined from 51 thermal profiles from all areas of the open lake. The lake gained heat for about 5 months (mid-March to mid-August) and lost heat over the rest of the year. It was thermally stratified during much of the warming cycle and vertically isothermal during much of the cooling cycle. The annual warming period began by April and was well underway by mid-May. During the transitional period between the isothermal conditions of winter and the thermal stratification of summer, the rate of warming was relatively fast. Seasonal warming began in the shallow inshore waters, which were usually thermally stratified by mid to late May. Stratification persisted in the deeper offshore water into December. Maximum surface temperatures and highest average metalimnion temperatures were reached in early August. Local variations in water temperatures during stratification, however, were a common feature of the thermal characteristics of Lake Michigan. These sometimes sudden changes were caused by upwellings of cold bottom waters that in some instances affected areas of hundreds of square miles. During the warming period of 1954, the heat content of Lake Michigan increased an average of 425 gm-cal/cm<sup>2</sup>/day. The annual heat budget of the lake for 1954 was 51,700 calories which is similar to that reported for 1942 (50,000 calories) and 1943 (62,000 calories). Heat was lost from mid-August until March, at a rate of about 250 gm-cal/cm<sup>2</sup>/day. Seasonal thermal characteristics differed little between 1954 and 1955, and were similar to those observed during studies in 1941 and 1942.

## INTRODUCTION

Surface and vertical temperature measurements taken aboard the U.S. Fish and Wildlife Service research vessel Cisco were the main basis for a description of the thermal characteristics of Lake Michigan. The study, which

Note.--Contribution 467 of the Great Lakes Fishery Laboratory. James W. Moffett died in 1967. John E. Gannon's present address is: Biological Station, University of Michigan, Pellston, Mich. 49769.

covered primarily the southern half of the lake in 1954 and the northern half in 1955, was made in conjunction with a fishery survey for comparison of the fish stocks with those that existed before the invasion of Lake Michigan by the sea lamprey, Petromyzon marinus (Moffett, 1957; Smith, 1964). Also included were studies of surface currents (Johnson, 1960), vertical migration of planktonic crustacea (Beeton, 1960; Wells, 1960), and distribution of bottom fauna (Merna, 1960).

Before the studies of Church (1942, 1945, 1946, 1947), very little was known about the thermal characteristics of the Great Lakes, particularly the vertical temperature distribution. The development of the Negretti-Zambra reversing thermometer near the turn of the century (Smith, 1957) led to the first record of 4° C water in the deeper waters of Lake Michigan during summer (Wright, 1931). Not until the development of the bathythermograph (BT) was it known that Lake Michigan regularly underwent extensive stratification (Church, 1942, 1945). Van Oosten (1960) presented data from series of vertical temperature measurements taken at 136 stations over a wide area in 1930-32. He also briefly reviewed thermal studies conducted on Lake Michigan from Conger (1899) through Ayers et al. (1958). More recently, thermal data from BT casts (Noble, 1967a) and thermographs at 19 buoy stations (Noble and Michaelis, 1968) in Lake Michigan were tabulated, and surface temperature patterns were investigated by aerial infrared radiometry (McFadden and Ragotzkie, 1963; Noble and Wilkerson, 1970). Other thermal data were gathered in conjunction with studies of circulation (Ayers, 1959; Huang, 1969; Noble, 1965, 1966, 1967b; Noble and Anderson, 1968; Noble, Huang, and Saylor, 1968; U.S. Department of Interior, 1967; Verber 1964, 1966), internal waves (Mortimer, 1963, 1968, 1971; Mortimer, McNaught, and Stewart, 1968), atmospheric conditions (Ayers, 1965; Ayers and Strong, 1967; Strong, 1968), and winter ice conditions (Heap and Noble, 1966). The possible threat to the ecology of Lake Michigan from heated effluents of electric power plants has prompted new interest in the thermal characteristics of the lake (Arnold, 1970; Denison and Elder, 1970; Stewart, 1969; U.S. Department of Interior, 1970).

During the 1954-55 investigations, thermal information was collected throughout Lake Michigan, except for the Straits of Mackinac region, Grand Traverse Bay, Green Bay, and the extreme southern end of the lake (fig. 1). Temperatures were measured with a recording thermograph, BT's, and reversing thermometers attached to Nansen water bottles. The data collected with reversing thermometers, mainly at hydrographic and fishing stations where water samples were col-

lected for chemical analysis, were published by Beeton and Moffett (1964). The present report is based on temperature data collected with the recording thermograph and BT's. A total of 1,671 BT casts were made during the study. Although these data are not adequate for detailed analyses of seasonal changes or conditions in specific locations, they augment materially the limited lakewide thermal data available for Lake Michigan.

## METHODS

Surface temperatures were recorded continuously by a thermograph aboard the *Cisco*. The thermistor was 5 ft (1.5 m) below the surface, in the sea chest of the vessel. BT casts were made at about 5-mile (8 km) intervals while the vessel was underway, during lake crossings and between fishing stations. Casts were also made at the beginning and end of each gill net set and trawl tow. Photographic prints were made of each BT tracing by using the glass slide in a grid mount as a negative. The enlarged prints (3 x 5 in; 7.7 x 12.8 cm) were about three times original size. The data presented here were read from the prints. The date, time, location, depth, and meteorological conditions for each BT cast, along with temperatures at the surface, in the metalimnion, and on the bottom are given in Appendix tables 1 (1954) and 2 (1955).

Schematic thermal profiles were prepared for all lake crossings during which BT casts were made at suitably close intervals, usually 5 miles (table 1). Each profile shows isotherms, usually at 1° C intervals, and surface temperatures. Bottom depths are those recorded by the ship's sonic depth finder at the time of the BT cast. No attempt was made to plot accurately the lake bottom contour between casts. The sequence of the consecutively numbered casts indicates the direction in which the vessel crossed the lake. As an aid to the interpretation of the thermal profiles, the mean and range of surface temperatures, along with the mean temperatures and mean depth distributions of the epilimnion, metalimnion, and hypolimnion, are presented in tables 2A (1954) and 2B (1955).

Interpretation of the thermal profiles, especially surface isotherms, should be undertaken with caution. One obvious consideration

Table 1.--Locations and dates of Lake Michigan crossings for which the schematic thermal profiles of Figures 2-52 were constructed.

Crossing and date <sup>1</sup>	Figure number
<u>Southern Lake Michigan</u>	
Milwaukee-Grand Haven:	
May 11, 1954.....	2
May 15, 1954.....	4
May 27, 1954.....	5
June 25, 1954.....	10
July 9, 1954.....	11
July 29, 1954.....	13
August 9, 1954.....	16
September 11, 1954.....	18
October 1, 1954.....	21
October 31, 1954.....	24
November 12, 1954.....	25
November 15, 1954.....	26
Racine-Holland:	
June 18, 1954.....	7
June 22, 1954.....	9
Racine-Grand Haven:	
May 13, 1954.....	3
October 22, 1954.....	23
Waukegan-South Haven:	
June 20, 1954.....	8
August 3, 1954.....	15
September 15, 1954.....	20
Racine-South Haven:	
September 13, 1954.....	19
Port Washington-White Lake:	
May 30, 1954.....	6
Milwaukee-Holland:	
August 1, 1954.....	14
<u>Northern Lake Michigan</u>	
Manitowoc-Ludington:	
July 13, 1954.....	12
August 25, 1954.....	17
October 4, 1954.....	22
May 13, 1955.....	27
June 26, 1955.....	32
August 4, 1955.....	38
August 5, 1955.....	39
August 11, 1955.....	40
August 13, 1955.....	41
August 15, 1955.....	42
August 16, 1955.....	43
September 26, 1955.....	48
November 8, 1955.....	52
Manistique-Charlevoix:	
June 5, 1955.....	29
July 14, 1955.....	33
July 15, 1955.....	34
July 17, 1955.....	35
July 21, 1955.....	36
September 5, 1955.....	45
October 19, 1955.....	49
Manistique-Frankfort:	
June 9, 1955.....	30
July 23, 1955.....	37
September 8, 1955.....	46
October 20, 1955.....	50
Sturgeon Bay-Frankfort:	
May 17, 1955.....	28
June 23, 1955.....	31
August 19, 1955.....	44
September 22, 1955.....	47
November 4, 1955.....	51

<sup>1</sup> See figure 1 for locations of ports.

is the time between observations. At the cruising speed of about 10 miles (16 km) per hour, the Cisco requires 6 to 10 hours to cross the lake. During this time, local temperatures can fluctuate considerably, as indicated by short-term temperature measurements made at single stations (Beeton, 1957; Mortimer, McNaught, and Stewart, 1968). Short-term temperature fluctuations observed at single stations can be as great as those recorded during a complete transect of Lake Michigan. An analysis of the problems in interpretation of data collected during lake crossings was made by Mortimer (1971).

The exact position of the 4° C isotherm on the schematic profiles has no particular significance, because the accuracy of the BT's used was only about  $\pm 0.5^{\circ}$  C. Since the temperature at depths greater than 75 to 100 m was usually within  $\pm 0.3^{\circ}$  C of 4° C, as measured with reversing thermometers (Beeton and Moffett, 1964), the depth of the 4° C isotherm could not be measured accurately with the BT's.

In the present paper the metalimnion is defined as the zone in which the vertical temperature gradient is steep, with layers of relatively homothermous water above and below. Although this definition makes the upper and lower limits of the metalimnion rather arbitrary, we selected an absolute boundary to simplify calculations. It was usually more difficult to set the lower limit (depth where the end of temperature stratification can be recognized) than the upper one (depth where onset of rapid temperature change occurs), because the rate of change with depth was much more gradual near the lower limit. Calculations were made only from those BT casts in which the metalimnetic layer neither reached the surface nor extended to the bottom.

The annual heat budget was computed for a midlake station 80 m deep between Milwaukee and Grand Haven, according to the method formulated by Birge (1915). Since data from this station were lacking for mid-June and

Table 2A.--Thermal characteristics of the surface, epilimnion, metalimnion, and hypolimnion during crossings of Lake Michigan, 1954

Date	Figure number	Transect <sup>1/</sup>	Surface temp. (° C) <sup>2/</sup>			Epilimnion			Metalimnion			Hypolimnion		
			Mean	Range	depth (m)	Mean depth (m)	Mean temp. (° C)	Mean upper limit (m)	Mean lower limit (m)	Mean thickness (m)	Mean temp. difference (° C)	Mean temp. change (° C/m)	Mean upper limit (m)	Mean temp. limit (° C)
May 11	2	GH-Mil	4.2	3.7-7.7	2.9	6.0	2.9	16.7	13.8	1.4	0.1	16.7	4.1	
May 13	3	GH-Rac	4.7	3.9-7.2	23.9	6.2	23.9	44.8	20.9	1.7	0.1	44.8	4.3	
May 15	4	GH-Mil	5.7	4.2-9.6	18.3	6.0	18.3	46.9	28.6	1.9	0.1	46.9	4.1	
May 27	5	GH-Mil	6.3	5.6-8.3	18.3	6.0	18.3	23.8	19.6	4.2	0.5	23.8	4.7	
May 30	6	WL-PW	6.4	5.1-8.1	4.2	16.2	4.2	33.2	27.4	9.6	0.4	33.2	4.9	
June 18	7	Hol-Rac	16.4	14.8-18.3	5.8	15.5	5.8	24.5	17.4	8.3	0.5	24.5	5.1	
June 20	8	SH-Wauk	15.6	13.2-20.1	7.1	15.0	7.1	18.4	11.8	8.8	0.8	18.4	5.1	
June 22	9	Hol-Rac	15.0	11.4-17.8	6.6	15.8	6.6	23.6	13.8	11.1	0.8	23.6	5.1	
June 25	10	GH-Mil	16.2	12.2-20.4	9.8	17.8	9.8	19.0	5.7	9.9	1.7	19.0	4.9	
July 9	11	GH-Mil	18.0	16.3-19.2	13.3	17.7	13.3	23.8	12.2	14.8	1.2	23.8	5.0	
July 13	12	Lud-Man	18.1	16.9-19.2	11.6	22.0	11.6	24.8	12.5	15.4	1.2	24.8	4.9	
July 29	13	GH-Mil	22.3	19.6-23.1	12.3	22.2	12.3	27.3	13.9	15.8	1.1	27.3	5.0	
Aug. 1	14	Hol-Mil	22.3	21.3-23.0	13.4	22.7	13.4	29.1	12.7	13.4	1.1	29.1	5.0	
Aug. 3	15	SH-Wauk	23.0	22.0-23.7	16.4	20.4	16.4	26.0	7.8	12.0	1.5	26.0	5.0	
Aug. 19	16	GH-Mil	20.6	16.9-23.0	13.2	19.8	13.2	30.4	9.5	12.8	1.4	30.4	5.0	
Aug. 25	17	Lud-Man	20.7	18.0-21.5	18.2	19.3	18.2	31.6	9.6	10.1	1.3	31.6	5.1	
Sept. 11	18	GH-Mil	18.9	12.5-20.8	20.9	19.6	20.9	36.9	13.5	8.8	0.5	36.9	5.0	
Sept. 13	19	SH-Rac	19.9	19.0-20.4	22.0	19.4	22.0	40.8	18.2	7.6	0.6	40.8	4.8	
Sept. 15	20	SH-Wauk	19.7	18.0-20.4	23.4	17.0	23.4	45.9	13.1	6.0	0.8	45.9	4.9	
Oct. 1	21	GH-Mil	16.6	15.1-18.3	32.8	13.8	32.8	44.9	8.0	3.9	0.3	44.9	5.1	
Oct. 4	22	Lud-Man	15.0	13.8-17.2	36.9	11.8	36.9	55.6	13.1	3.7	0.2	55.6	4.7	
Oct. 22	23	GH-Rac	14.1	13.2-14.4	42.5	9.5	42.5	58.9	16.1	3.7	0.2	58.9	4.7	
Oct. 31	24	GH-Mil	11.8	11.3-13.1	42.8	9.2	42.8							
Nov. 12	25	GH-Mil	9.9	9.0-11.5										
Nov. 15	26	GH-Mil	9.3	8.4-10.6										

<sup>1/</sup> GH = Grand Haven; Hol = Holland; Lud = Ludington; Man = Manitowoc; Mil = Milwaukee; PW = Port Washington; Rac = Racine; SH = South Haven; Wauk = Waukegan; and WL = White Lake.

<sup>2/</sup> Calculated from BT data. See also data from recording thermograph (Figs. 2-26).

Table 2B. Thermal characteristics of the surface, epilimnion, metalimnion, and hypolimnion during crossings of Lake Michigan, 1955

Date	Figure number	Transect <sup>1/</sup>	Surface temp. (° C) <sup>2/</sup>		Epilimnion		Metalimnion				Hypolimnion						
			Mean	Range	Mean depth (m)	Mean temp. (° C)	Mean upper limit (m)	Mean upper limit (m)	Mean lower limit (m)	Mean thickness (m)	Mean temp. difference (° C)	Mean temp. change (° C/m)	Mean upper limit (m)	Mean temp. limit (° C)			
May 13	27	Lud-Man	4.9	3.4-7.7													
May 17	28	Fr-SB	4.3	3.4-7.2	2.6	10.3	2.6	19.6	17.0	4.4	0.3	19.6	4.4				
June 5	29	Ch-Mst	10.6	6.9-14.0	3.6	9.9	3.6	20.7	17.1	3.9	0.2	20.7	4.4				
June 9	30	Fr-Mst	10.0	4.9-14.1	5.9	12.9	5.9	35.7	29.8	7.6	0.3	35.7	4.4				
June 23	31	Fr-SB	12.9	10.6-15.4	2.8	14.6	2.8	43.6	40.8	10.1	0.3	43.6	4.4				
June 26	32	Lud-Man	14.8	10.2-16.1	8.5	18.5	8.5	38.7	30.2	13.2	0.4	38.7	4.7				
July 14	33	Ch-Mst	18.6	17.5-19.3	9.6	19.2	9.6	31.0	21.4	13.3	0.6	31.0	4.7				
July 15	34	Ch-Mst	19.7	18.1-20.9	6.5	20.3	6.5	36.9	30.4	14.7	0.5	36.9	4.7				
July 21	35	Ch-Mst	20.6	20.0-21.2	5.6	22.0	5.6	31.9	26.3	16.1	0.6	31.9	4.8				
July 23	36	Fr-Mst	22.2	21.2-22.8	8.4	21.7	8.4	30.4	22.0	16.4	0.8	30.4	4.2				
Aug. 4	37	Lud-Man	21.7	17.8-23.4	4.9	23.4	4.9	28.4	23.5	18.1	0.8	28.4	4.5				
Aug. 5	38	Lud-Man	23.9	22.9-24.3	4.8	23.9	4.8	27.0	22.2	18.2	0.8	27.0	4.5				
Aug. 11	39	Lud-Man	24.3	21.9-25.1	12.8	22.0	12.8	26.5	13.7	15.8	1.2	26.5	4.5				
Aug. 13	40	Lud-Man	20.9	12.8-23.0	14.3	21.8	14.3	31.7	17.4	16.2	0.9	31.7	4.5				
Aug. 15	41	Lud-Man	18.5	9.0-22.8	15.9	22.0	15.9	28.4	12.5	15.8	1.3	28.4	4.3				
Aug. 16	42	Lud-Man	19.3	5.1-23.2	11.7	22.4	11.7	27.8	16.0	16.6	1.0	27.8	4.3				
Aug. 19	43	Lud-Man	22.0	18.6-23.1	13.2	22.1	13.2	27.4	14.2	16.0	1.1	27.4	4.4				
Aug. 19	44	Fr-SB	23.6	20.1-24.6	15.5	18.3	15.5	37.4	21.9	11.6	0.5	37.4	5.0				
Sept. 5	45	Ch-Mst	17.8	14.0-20.5	17.7	17.4	17.7	33.3	15.6	12.0	0.8	33.3	4.3				
Sept. 8	46	Fr-Mst	17.5	13.1-19.2	20.3	17.1	20.3	36.6	16.3	11.0	0.7	36.6	4.6				
Sept. 22	47	Fr-SB	16.2	13.7-17.3	16.6	14.4	16.6	33.4	15.8	8.5	0.5	33.4	4.3				
Sept. 26	48	Lud-Man	14.4	11.2-16.7	38.0	13.1	38.0	60.6	22.6	6.7	0.3	60.6	4.7				
Oct. 19	49	Ch-Man	13.2	11.3-14.1	33.2	13.1	33.2	47.8	14.6	7.3	0.5	47.8	4.7				
Oct. 20	50	Fr-Mst	12.5	8.7-13.4	48.1	10.3	48.1	61.3	13.2	5.2	0.4	61.3	3.9				
Nov. 4	51	Fr-SB	9.7	6.5-10.4	46.9	8.8	46.9	60.7	13.8	3.7	0.3	60.7	4.4				
Nov. 8	52	Lud-Man	8.2	5.1-10.2													

<sup>1/</sup> Ch = Charlevoix; Fr = Frankfort; Lud = Ludington; Man = Manistique; Mat = Manitowoc; Mst = Sturgeon Bay

<sup>2/</sup> Calculated from BF data. See also data from recording thermograph (Figs. 27-52).

December 1954 and January through March 1955, data from a station of the same depth 15 mi (24.2 km) west of Grand Haven were used for these periods. The annual heat budget was calculated for the total water column and for depth intervals of 0-20 m, 20-30 m, and 30-80 m. These intervals were chosen to correspond roughly to the mean thicknesses of the epilimnion, metalimnion, and hypolimnion.

To give appropriate consideration to the decrease in water volume in shallow areas due to the slope of the bottom (Dutton and Bryson, 1962), we calculated the volume contained in each 5-m depth interval from a hypsographic curve of Lake Michigan (Anderson, 1961). The heat content calculated for the midlake station was then reduced in proportion to the reduction in volume with depth by multiplying the mean temperature of the 5-m depth interval by its volume. The total heat content, in terms of gram-calories per  $\text{cm}^2$  of surface area, was obtained by summing the values for the 5-m depth intervals.

#### SEASONAL THERMAL CHANGES IN SOUTHERN LAKE MICHIGAN, 1954

The study area in 1954 was confined primarily to the portion of Lake Michigan south of a line from Milwaukee to Grand Haven (fig. 1). Twenty-one transects were made in this area, of which 12 were between Milwaukee and Grand Haven. Four transects were made outside the area--three between Manitowoc and Ludington and one between Port Washington and White Lake.

When the study began in early May, the water had been warming for several weeks, but the lake was not yet stratified. The open lake was vertically homothermous at about  $4^{\circ}\text{C}$  on May 11 and 13 (figs. 2 and 3). On May 15, however, all surface temperatures were slightly above  $4^{\circ}\text{C}$  (fig. 4).

By late May, weak stratification was common in southern Lake Michigan and was characterized by a rather deep epilimnion and a gentle temperature gradient in the metalimnion (figs. 5 and 6). Throughout the month, the

temperatures were highest near shore. Church (1945) reported similar conditions in May 1942.

Rapid warming, steepening of the temperature gradient, and narrowing of the epilimnion must have occurred in early June, since conditions had changed markedly by late June (figs. 7-10). The lowest surface temperature recorded during the last 2 weeks in June was much higher than the highest recorded during late May, and the weak vertical temperature stratification observed during late May had become stable. During four crossings from June 18 to 25, the mean depth of the epilimnion was only about 6 m--the shallowest observed in 1954 (except on May 15). Mean thickness of the metalimnion was 19 m and mean temperature gradient was  $0.5^{\circ}\text{C}$  per m. Midlake surface temperatures were  $15^{\circ}$  to  $17^{\circ}\text{C}$ --an increase of  $10^{\circ}\text{C}$  over those of late May. Surface water was generally warmer along the eastern shore than along the western shore; in contrast, Church (1945) usually found the warmer water along the western shore.

The metalimnion on July 9 (fig. 11) was narrower (13.8 m) and had a steeper temperature gradient ( $0.8^{\circ}\text{C}$  per m) than during June. Measurements between Manitowoc and Ludington on July 13 (fig. 12) revealed the narrowest metalimnion (mean of 5.7 m) and the greatest mean temperature gradient ( $1.7^{\circ}\text{C}$  per m) observed during the 2-year study. This gradient was often exceeded over a short distance along other transects and sometimes was greater than  $4^{\circ}$  or  $5^{\circ}\text{C}$  per m; the average, however, was never more than  $1.7^{\circ}\text{C}$  per m for an entire transect.

The warmest surface temperatures of the year were observed during late July and early August. Surface temperatures greater than  $22^{\circ}\text{C}$  were common along all three transects made during this period (figs. 13-15). Development of summer stratification was maximal; the mean temperature gradient within the metalimnion was greater than  $1^{\circ}\text{C}$  per m for all three transects. The mean temperature difference of about  $15^{\circ}\text{C}$  within the metalimnion was the highest recorded in 1954.

Thermal conditions during middle and late August were similar to those of late July and early August, except that surface temperatures were 1° to 3° C lower, the metalimnion was slightly deeper, and mean temperature differences within the metalimnion were 1° to 2° C less. Although the Grand Haven to Milwaukee crossing of August 19 (fig. 16) was about 70 mi (113 km) south of the Manitowoc to Ludington transect of August 25 (fig. 17), the horizontal and vertical thermal profiles for the two transects were very similar. Both revealed an upwelling of cold water about 10 mi (16 km) off the eastern shore.

Thermal conditions during mid-September (figs. 18-20) continued to be rather stable and were similar to those during late July and August. The epilimnion cooled and deepened slightly and the characteristics of the metalimnion differed somewhat from those in August--the average thickness was 3 to 5 m less and the rate of temperature change per meter was 0.3° C greater.

Rapid changes in water temperatures had taken place by October 1 (fig. 21). Surface temperatures had cooled 4° to 5° C, the temperature difference within the limits of the metalimnion was about 3° C less than in summer, and the rate of change was less than 1° C per m for the first time since early July. During the 40-day period between the Manitowoc to Ludington crossings of August 25 (fig. 17) and October 4 (fig. 22), the surface temperatures had dropped from values above 20° C to 15° C; the epilimnion had increased almost 10 m in depth; and the metalimnion had increased more than 9 m in depth and more than 5 m in thickness and the mean temperature difference between its upper and lower limits had decreased 5.7° C. On October 22 (fig. 23) the epilimnion was 10 m deeper than on October 4; by October 31 (fig. 24) it extended to about 35 m. The mean surface temperature decreased 3° C between October 22 and 31. The temperature difference within the metalimnion in late October was 2° to 4° C less than that observed on October 1 and 4. The water was still stratified and the temperature gradient within the metalimnion was fairly steep (0.7° C per m).

When the last two lake crossings of 1954 were made, on November 12 (fig. 25) and November 15 (fig. 26), the depth of the epilimnion had increased to more than 42 m--almost double that recorded in early October. The thickness of the metalimnion had changed little, but the mean difference in temperature within this zone was less than 4° C and the rate of temperature change decreased to about 0.3° C per m. Surface temperatures continued to decrease; the mean in the open lake was about 10° C. Surface and epilimnetic temperatures were about 2° C higher in the eastern third of the lake than in the rest of the lake.

Although no transects were made during December, a series of BT tracings obtained near Grand Haven on December 14 showed that water was nearly homothermous, decreasing gradually from about 7° C at the surface to 5° C at the bottom (Appendix table 1). Church (1942) found that the lake overturned in December 1941 when surface temperatures were 6.0° to 6.5° C.

### SEASONAL THERMAL CHANGES IN NORTHERN LAKE MICHIGAN, 1955

Thermal data collected in 1955 were from 26 transects confined principally to the northern section of Lake Michigan, north of a line from Ludington to Manitowoc (fig. 1). Although no transects were made during January through March, thermal data collected near Grand Haven during that period indicated that the lake was vertically homothermous and was colder near shore than in the open lake (Appendix table 2). Water temperatures were 0.1° C near shore and 4.2° C about 15 mi (24 km) offshore during late January, and 0.2° and 2.4° C, respectively, during early March. The lake thus lost heat between late January and early March, and probably continued to cool until late March. If so, the cooling cycle in Lake Michigan in 1954-55 lasted about 7 months, from mid-August to mid-March. Church (1942) found a net loss of heat until the third or fourth week of March in 1942.

The lake had begun to absorb heat by mid-May. Although midlake temperatures were vertically homothermous near 3.5° C, the

water temperatures within about 10 mi (16 km) from shore were 1-6° C higher than in mid-lake (figs. 27 and 28). Slight stratification, due to local surface warming, was present at some of the stations where surface temperatures were above 6° C. In general, thermal conditions near mid-May were about the same as they had been in southern Lake Michigan in 1954 (figs. 2-4).

During the 3 weeks between May 17 and June 9, warming had been sufficient to produce thermal stratification in northern Lake Michigan (figs. 29 and 30). During the early June transects, surface temperatures ranged from 4.6° C in part of the open lake to 15° C near shore. The mean temperature in the epilimnion was about 10° C--or about 5° C higher than that observed in mid-May. Mean depth of the epilimnion was the shallowest of the entire year (2.6 m on June 5 and 3.6 m on June 9). The thickness of the metalimnion was 17 m and the mean temperature difference between its upper and lower limits was about 4° C. Rapid warming continued into late June, when the mean epilimnetic temperature was about 13° C on June 23 between Frankfort and Sturgeon Bay (fig. 31) and near 14.5° C on June 26 between Manitowoc and Ludington (fig. 32). The mean depth of the epilimnion was about 6 m on June 23 but less than 3 m on June 26, when air temperatures were higher and the lake was calm. The thickness of the metalimnion reached its 1955 maximum June 23 (30 m) and June 26 (41 m). Temperature differences across the metalimnion were 7.6° C on June 23 and 10.1° C on June 26 (rate of change, 0.3° C per m on both dates). An upwelling about 8 mi (13 km) west of Ludington on June 26 caused surface temperatures to drop 5° to 6° C.

During four crossings between Charlevoix and Manistique (figs. 33-36) and one between Manistique and Frankfort (fig. 37) in July, the mean epilimnetic temperatures were 4° to 7° C higher than during June. Maximum surface temperatures increased from 17.4° C during June to 24.3° C by the end of July. Mean temperature of the epilimnion increased from 18.5° C on July 14 to 22.0° C on July 21. This rapid warming increased the depths of the 10° to 20° C isotherms and decreased the

distance between them. The depth of the epilimnion decreased as the mean surface temperature increased and as the 19°, 20°, and 21° C isotherms became successively incorporated into the metalimnion.

Six crossings between Ludington and Manitowoc from August 4 to 16 (figs. 38-43) and one between Frankfort and Sturgeon Bay on August 19 (fig. 44) covered a period of rapid thermal changes due to a slight upwelling near the western shore and a massive upwelling near the eastern shore. On August 4 surface temperatures varied between 23° and 24° C (fig. 38). The mean depth of the epilimnion was only 4.8 m and its average temperature was the highest of the year (23.0° C). The sharply stratified metalimnion (mean temperature change, 0.8° C per m) extended to a mean depth of 27 m. On August 5 the slight upwelling first observed on August 4 was most pronounced about 5 mi (8 km) off Manitowoc, where the surface temperature dropped to 20.5° C (fig. 39).

On August 11 a well-defined upwelling extended about 15 mi (24 km) off the eastern shore near Ludington (fig. 40). Surface temperatures were fairly uniform at 23° C outside the area of upwelling but were about 11° C near its center. Ayers et al. (1958) reported that on the previous day, August 10, a massive upwelling extended from Michigan City to Waugoshance Point (west of Mackinaw City) and was most pronounced (surface temperature, 10°-11° C) from Muskegon to Manistee. By August 13 the surface temperature had dropped as low as 6° C in the upwelling, which then extended about 25 mi (40 km) offshore from Ludington (fig. 41). Concurrently, in the downwelling near the western shore, 22° C water extended down to 15 m. The upwelling reached maximum development on August 15 (fig. 42) when surface water was 4.8° C off Ludington. Only 10 days earlier the surface temperature in the same area had been 25.1° C (fig. 39).

On August 16 the upwelling was much less intense (fig. 43); its lowest surface temperature was only about 13° C, and it was confined to an area within about 12 mi (19.4 km) of the eastern shore. The subsidence of the upwelling

was also evident 50 mi (80.6 km) north of Ludington, where the surface temperatures were near  $19^{\circ}\text{C}$  on August 19 (fig. 44).

By early September evidence of the massive upwelling of August had disappeared and the first signs of epilimnetic cooling had begun. Midlake surface temperatures were  $17^{\circ}$  to  $18^{\circ}\text{C}$  and the mean temperature of the epilimnion was about  $18^{\circ}\text{C}$ . On September 5 the metalimnion was tilted toward the surface near Manistique and depressed to 32 m near Charlevoix (fig. 45). A slight upwelling probably was present near Manistique, where  $14^{\circ}\text{C}$  water was observed at the surface. The tilted metalimnion was less pronounced on September 8 (fig. 46), although surface temperatures were higher near Frankfort ( $19^{\circ}\text{C}$ ) than near Manistique ( $13^{\circ}\text{C}$ ). Either a slight upwelling still persisted off Manistique or surface waters were cooling faster there than off Frankfort.

During late September surface cooling continued, especially near shore. Surface temperatures during crossings of September 22 and 26 (figs. 47 and 48) ranged from  $10.5^{\circ}$  to  $17.5^{\circ}\text{C}$  inshore and from  $14^{\circ}$  to  $16^{\circ}\text{C}$  in midlake. The mean epilimnetic temperature dropped slightly to about  $15^{\circ}\text{C}$ . A sharp temperature gradient was present in the metalimnion, except near the western shore, where a slight upwelling was evident about 10 mi (16 km) off Manitowoc on September 26. The depths of the epilimnion and metalimnion gradually increased from mid-August through September.

By mid-October surface temperatures ranged from  $5.4^{\circ}$  to  $14.8^{\circ}\text{C}$  inshore and from  $13^{\circ}$  to  $14^{\circ}\text{C}$  at midlake. The mean temperature of the epilimnion was  $13.1^{\circ}\text{C}$ . On the October 19 crossing from Charlevoix to Manistique (fig. 49), mean depth of the epilimnion was 38 m and the temperature gradient in the metalimnion was only  $0.3^{\circ}\text{C}$  per m. On October 20, the metalimnion was strongly tilted; its upper limits ranged from as deep as 50 m near Manistique to the surface near Frankfort (fig. 50). The tilt and depression were accompanied by a sharp temperature gradient of over  $1^{\circ}\text{C}$  per m in the metalimnion in midlake.

Cooling continued during early November. On November 4, surface temperatures ranged from  $10.4^{\circ}\text{C}$  near the eastern shore to  $6.5^{\circ}\text{C}$  in an upwelling off the western shore near Sturgeon Bay (fig. 51). The mean epilimnetic temperature ( $10.3^{\circ}\text{C}$ ) was about  $3^{\circ}\text{C}$  cooler than that recorded in mid-October. The metalimnion was strongly tilted; it rose to the surface off Sturgeon Bay and was depressed to 61 m off Frankfort. An upwelling was also evident farther south off Manitowoc during the last crossing of the year, November 8 (fig. 52). Surface temperatures were as low as  $5.1^{\circ}\text{C}$  in the upwelling area and as high as  $10^{\circ}\text{C}$  outside it. The mean epilimnetic temperature was only  $8.8^{\circ}\text{C}$ . Thermal stratification was still present, but much less distinct; the mean difference between the upper and lower limits of the metalimnion was only  $4^{\circ}\text{C}$ .

## SURFACE TEMPERATURE DISTRIBUTION

The most characteristic aspect of surface temperature distribution in Lake Michigan was its great variability, caused by short-term and seasonal changes in meteorological conditions operating over the lake basin and by advective processes of thermal transport within the lake (as has been repeatedly demonstrated also in other large temperate lakes). Although our data are not truly synoptic, the extent of variation of surface temperatures is indicated by each of the lake transect thermal profiles (figs. 2-52) as well as by the monthly range of surface temperatures recorded during the study (table 3). The large differences in surface temperatures recorded in May and

Table 3.--Monthly range in surface temperatures ( $^{\circ}\text{C}$ ) recorded in Lake Michigan, May-November 1954 and 1955

Month	1954	1955
May	3.3-11.7	3.5- 7.8
June	12.2-20.4	6.2-17.8
July	12.8-19.6	17.2-23.9
August	13.8-23.8	4.8-25.1
September	12.5-21.0	12.5-21.3
October	11.3-14.9	7.0-14.8
November	8.4-12.0	4.9-10.4

November are due to unequal heating and cooling over the lake surface during spring and fall. Temperatures near shore were higher in spring (see figs. 2-5 and 27-30) and lower in late fall and early winter (Church, 1942) than at midlake. More rapid heat exchange in the shallower waters and inflow of tributary waters are responsible for this difference. A "thermal bar" develops near shore between water less than and greater than 4° C. This zone of maximum-density water is an effective barrier to mixing of inshore and offshore waters and perpetuates horizontal temperature differences during its existence in spring and late fall to early winter (Rodgers, 1965; Noble and Anderson, 1968).

Variability in surface temperatures during summer (table 3) is mainly due to upwellings (table 4). A dramatic example of the effect of

upwellings on surface temperature distribution was the massive upwelling of August 1955, when surface temperatures near Ludington dropped from 25.1° C on August 5 to only 4.8° C on August 15, during maximum development of the upwelling (fig. 53).

Because of inherent variability, mean surface temperatures recorded during the crossings cannot be particularly meaningful, except to describe the gross seasonal changes in the lake. Mean surface temperatures for the Milwaukee-Grand Haven transect in 1954 were closely similar to those reported by Millar (1952) at a station near Milwaukee in 1935-41 and to those measured by Church (1945) during Milwaukee-Muskegon transects in May-November 1942 (fig. 54). Millar (1952) noted that mean surface temperatures were consistently lower in the northern portion of Lake Michigan than in the southern basin during 1935-41; this difference reached a maximum of 4.1° C during September. Since Lake Michigan traverses more than 4 degrees of latitude, these variations are due to the slightly cooler climatic conditions over the northern portion of the lake.

The annual warming period in Lake Michigan was well underway by the beginning of the sampling periods in early May, in both 1954 and 1955. Maximum surface temperatures were reached in early August (table 3) and cooling began in late August and continued to the end of the study in November (fig. 54). The few temperature data obtained during the winter of 1954-55 indicated that, in general, the water continued to cool and surface temperatures were lower inshore than offshore (Appendix table 2). Church (1945) showed that surface temperatures in 1942 were below 4° C from early January to the end of April and were lowest in mid-March. He therefore concluded (Church, 1946) that the annual temperature cycle in Lake Michigan consists of a 5-month warming period from late March to early August and a 7-month cooling period from late August to early March.

No data are available on the extent or duration of ice cover in Lake Michigan during the winter of 1954-55. A large portion of Lake

Table 4.--Upwellings observed in Lake Michigan, 1954 and 1955

Date	Location	Figure number
1954		
May 15	Off Grand Haven	4
June 20	Off Waukegan	8
June 22	Off Racine	9
June 25	Off Milwaukee	10
July 13	Off Manitowoc	12
July 29	Off Milwaukee	13
August 19	Off Grand Haven	16
August 25	Off Ludington	17
September 11	Off Grand Haven	18
1955		
June 23	Between Sturgeon Bay and Frankfort	31
June 26	Off Ludington	32
August 11-19	Off Michigan shore, Michigan City to Waugoshance Point	40-44
September 16	Off Ludington	40-43
September 26	Off Manitowoc	45
October 20	Off Frankfort	50
November 4	Off Sturgeon Bay	51

Michigan does not freeze over, and large accumulations of ice are limited to sheltered bays and shore zones. Extensive ice cover normally develops only north of a line from Frankfort to Sturgeon Bay (Heap, 1963). Ice is usually oldest and heaviest along the north and east shores of the lake. The shallow, protected waters of Green Bay freeze over completely nearly every winter. Records at Menominee, on the western shore of Green Bay indicate that ice was fast from December 23, 1954, to April 9, 1955. These dates are close to the mean dates of freeze-up (December 29) and break-up (April 6) for Green Bay reported by Heap (1963). Although these data do not indicate the amount or duration of ice cover in the main lake, they suggest that ice development was probably near average during the winter of 1954-55.

### VERTICAL TEMPERATURE DISTRIBUTION

Lake Michigan is nearly isothermous from about mid-December through mid-May. Since inshore waters cool faster than offshore waters in late fall to early winter, isothermy probably is never absolute. Water temperatures decrease from about 6° C in December to the yearly minimum in March. The lowest temperature for the entire water column at a station 90 m deep, 10 mi (16 km) west of Grand Haven, was 2.2° C on March 9, 1955; temperatures closer to shore ranged from 0.4° to 0.9° C (Appendix table 2). Church (1942) recorded a minimum of 2.5° C at mid-lake and about 1.5° C near shore on March 21, 1942. Heap and Noble (1966) suggested a separation in circulation patterns between the colder inshore waters and the warmer offshore waters during this time. Circulation in the open lake is assumed to be holomictic. Since, however, the deep water in very deep lakes has the inherent stability associated with the temperature of maximum density under conditions of increased pressure, and since that temperature decreases with increased pressure, temperatures of the bottom waters of Lake Michigan are commonly below 4° C (Wright, 1931; Beeton and Moffett, 1964). A mechanically stable temperature profile can thus be established that inhibits complete mixing to the bottom (Eklund, 1969). The

degree and frequency of mixing to the bottom has not been investigated in Lake Michigan but Johnson (1966) found that circulation in Great Bear Lake was complete only once in 3 years of investigation.

During the transitional period between the essentially isothermal conditions of winter and the typical thermal stratification of summer, the rate of warming is faster near shore than offshore. From mid-April to mid-May the thermal bar inhibits offshore movement of water and heat exchange with the main portion of the lake (Rodgers, 1965, 1966; Noble and Anderson, 1968). The thermal bar may be important in impeding movement of runoff and pollutants to offshore waters in spring. As the inshore waters warm, the bar extends farther out into the lake. Temperature profiles for May 11 and 13, 1954 (figs. 2 and 3), and May 13 and 17, 1955 (figs. 27 and 28), represent late stages in thermal bar development, when mid-lake temperatures have risen to nearly 4° C. Temperature profiles for May 15 and 27, 1954 (figs. 4 and 5), illustrate the transition between vertical stratification associated with the thermal bar and horizontal stratification characteristic of summer.

During formation and development of the metalimnion in 1954 (fig. 55), a temporary, shallow metalimnion (3-17 m) was first observed on May 15 (fig. 55). It was much deeper (20-46 m) on May 27, but again nearer the surface (6-24 m) by early June. During this May to early June developmental period, temporary thermal gradients appear near the surface as a result of high heat input from insolation during calm weather. These gradients are soon partially dissipated and mixed with deeper waters by wind action and currents. Many such temporary metalimnetic layers are probably formed before density differences between the upper and lower limits of the thermal gradient become great enough to establish stable stratification. Mean epilimnetic temperatures were 15° C by June 18, and thermal stratification was stable. Heat input continued throughout June and July until a maximum of about 22° C was observed in the epilimnion by mid-August. Meanwhile, mixing in the epilimnion slowly lowered the

depth of the metalimnion and gradually reduced its thickness (fig. 55). The upper limit of the metalimnion was lowered from 6 m in late June to more than 40 m in early November. Thickness of the metalimnion decreased from 16 to 13 m from June through August and was about 12 m from September to November.

During the period of thermal stratification in 1954, the mean temperature in the epilimnion increased about  $0.3^{\circ}\text{C}$  per day from May to mid-July (table 2A). Temperatures were nearly constant from mid-July to late August and decreased  $0.2^{\circ}\text{C}$  per day from early September to mid-November. The mean temperature difference within the metalimnion rose from less than  $2^{\circ}\text{C}$  in May to a peak of  $15.8^{\circ}\text{C}$  in early August and then dropped steadily to less than  $4^{\circ}\text{C}$  in mid-November (fig. 55). Likewise, change in temperature per meter within the metalimnion rose steadily from May to late July and decreased from early September through mid-November. The mean temperature gradient never exceeded  $1.5^{\circ}\text{C}$  per m throughout a transect (table 2a).

Formation and development of the metalimnion and its thermal characteristics in 1955 (fig. 56) were basically similar to those in 1954. In the prolonged, cool spring of 1955, rapid heating late in the spring caused rapid development of a stable metalimnetic layer. Although the lake was still isothermous on May 17, a nearly stable metalimnion was present on June 5. Epilimnetic temperatures in August were slightly higher than in 1954 and the mean temperature difference within the metalimnion ( $18^{\circ}\text{C}$ ) was  $2^{\circ}\text{C}$  greater.

Local variations in temperature structure during summer stratification, in the form of upwellings, are a common feature of the thermal structure of Lake Michigan. Upwellings seem to be caused primarily by the driving force of the wind, but also appear to be associated with general circulation and internal waves. The dominant feature of summer circulation in the open lake appears to be a

clockwise rotation of current vectors in phase with internal waves of near-inertial frequency (U.S. Department of Interior, 1967). These waves have been modeled by Mortimer (1963, 1968, 1971) as a system of "Poincare" waves with periods varying from 16-19 hours. This open-lake circulation seems to be separated from the inshore (0-12 mi, 0-19.4 km) system of currents, which are parallel to shore and are produced by geostrophic currents and internal waves. The massive upwelling of August 1955 (figs. 38-43 and 54) and similar upwellings are associated with a counterclockwise progression of a "temperature front" which can be detected at municipal water intakes along the south and east coasts of Lake Michigan, from Chicago to Ludington (Mortimer, 1963). A model for such a progression is an internal wave of the Kelvin type; its period is so long that a complete traverse of the basin is usually prevented by fresh wind disturbances. Moffett (1962) suggested that the upwelling of August 1955 was generated by strong north and northeast winds. An analysis of wind direction and velocity over Lake Michigan immediately before and during the upwelling revealed that the primary generating force was a strong northeast wind that began August 7 and persisted for 6 days (fig. 57). The upwelling was probably dissipated by the strong southwest winds of August 15 and 16.

Because the field observations in 1954 and 1955 ended while the lake was still stratified, we could not determine exactly when the lake became vertically isothermal. The date can be approximated, however, by comparing our data with those collected in 1941 by Church (1942). On November 22, 1941, surface temperatures were  $7^{\circ}$  -  $8^{\circ}\text{C}$  and the epilimnion was 40 m deep along a Milwaukee to Muskegon transect. Stratification was still present on November 29, but only at depths greater than about 60 m; temperature difference within the metalimnion was less than  $2^{\circ}\text{C}$  and the greatest difference between the surface and bottom temperatures was only  $3^{\circ}\text{C}$ . By December 7, the lake was essentially homothermous at about  $5^{\circ}\text{C}$  in all areas between Milwaukee and Muskegon. On our last transect of 1954 (November 15; fig. 26), from Milwaukee to

Grand Haven, the epilimnion was also 40 m deep but temperatures were higher at the surface ( $9^{\circ}$  -  $10^{\circ}$  C) than in Church's transect of November 22, 1941. On December 14, 1954, a temperature profile about 10 miles (16 km) west of Grand Haven revealed surface temperatures of  $7.2^{\circ}$  C and an epilimnion 70 m deep. Overturn and vertically isothermous conditions probably ensued shortly after that date, when surface water temperature decreased to about  $6^{\circ}$  C. In 1955, between Ludington and Manitowoc, the surface temperature was  $8^{\circ}$  -  $10^{\circ}$  C and the epilimnion was already 55 m deep on November 8 (fig. 52); thus overturn may have occurred somewhat earlier in 1955 than in either 1941 or 1954.

Theoretically, a thermal bar could be present shortly after overturn each winter when water is lower than  $4^{\circ}$  C near shore and higher offshore--the reverse of the situation present in spring (Rodgers, 1965). The 1954 and 1955 field seasons ended, however, before this separation would be expected.

Temperature in the hypolimnion varied little throughout the year in Lake Michigan. During isothermous conditions, water temperatures in deep water ranged from near  $6^{\circ}$  C at the time of overturn to a minimum near  $2^{\circ}$  C in March. Inverse stratification is at most very slight in the Great Lakes in winter (Chandler, 1964) and is mainly confined to inshore waters. Although Church (1942) recorded slight inverse stratification during January-March 1942 in Lake Michigan, a limited number of BT casts in January and March 1955 showed isothermal conditions (Appendix table 2). Throughout the 1954-55 periods of stratification, the temperatures remained near  $5^{\circ}$  C at about 50 m and  $4^{\circ}$  C in depths greater than 75 m.

## HEAT CONTENT

The heat content and annual heat budget of Lake Michigan were calculated from temperature data collected at a midlake station 80 m

deep between Milwaukee and Grand Haven. The annual heat budget, i.e., the difference in heat content between the time of minimum mean temperature in winter and the maximum mean temperature in summer, was 51,700 calories for Lake Michigan in 1954. Church (1945) calculated similar values (50,000 calories in 1942 and 62,000 in 1943) for a station 77 m deep between Muskegon and Milwaukee. For many temperate lakes in North America and Europe, the annual heat budgets range from 20,000 to 40,000 calories (Birge, 1916; Hutchinson, 1957). Of the lakes that have been studied, only Lake Baikal (U.S.S.R.) has an annual heat budget (57,300 cal) as high as those calculated for Lake Michigan. The unusually high heat content of Lake Michigan has been attributed to several factors; the morphometry of its basin; mixing of cold, deep water with warmer surface waters during frequent upwellings (Hutchinson, 1957); and heavy condensation of fog over the lake, especially during June (Church, 1945).

Heat input into Lake Michigan in 1954 increased at the rate of about  $425 \text{ gm-cal/cm}^2 / \text{day}$  from early May until mid-August (fig. 58), and reached a peak of almost  $64,000 \text{ gm-cal/cm}^2$  in late August. The lake lost heat at the rate of about  $250 \text{ gm-cal/cm}^2 / \text{day}$  from early September 1954 to early March 1955. The lowest heat content of  $12,100 \text{ gm-cal/cm}^2$  was recorded on March 9, 1955.

The relative stability of the summer stratification period is reflected in the heat content of the upper waters of Lake Michigan (fig. 58). The heat content of the 0-20 m stratum was about  $35 \text{ gm-cal/cm}^2$  from July through September. The heat content of the 20-30 m interval was nearly constant throughout the year (about  $5 \text{ gm-cal/cm}^2$ ), except for a slight rise from late August through November. This rise reflects the gradual erosion by wind action of the upper portion of the metalimnion during late summer and early fall. The heat content of the 30-80 m interval was constant throughout the year except in December, when considerable heat was added to the bottom waters at the onset of homothermous mixing.

## LITERATURE CITED

- Anderson, D. V.  
1961. A note on the morphology of the basins of the Great Lakes. *J. Fish. Res. Bd. Canada* 18: 273-277.
- Arnold, Dean E.  
1970. Thermal pollution, nuclear power, and the Great Lakes. *Limnos* 3(1): 4-12.
- Ayers, John C.  
1959. The currents of Lakes Michigan and Huron. *Univ. Mich., Great Lakes Res. Inst., Spec. Rep. no. 5*, 51 p.  
1965. The climatology of Lake Michigan. *Univ. Mich., Great Lakes Res. Div., Publ. no. 12*, 73 p.
- Ayers, John C., David C. Chandler, George H. Lauff, Charles F. Powers, and E. Bennette Hensen.  
1958. Currents and water masses of Lake Michigan. *Univ. Mich., Great Lakes Res. Inst., Publ. no. 3*, 169 p.
- Ayers, John C., and Alan E. Strong.  
1967. A supplement to "The climatology of Lake Michigan," p. 308-315. In Ayers, John C. and David C. Chandler (ed.), *Studies on the environment and eutrophication of Lake Michigan*, *Univ. Mich., Great Lakes Res. Div., Spec. Rep. no. 30*, 415 p.
- Beeton, Alfred M.  
1957. The vertical migration of *Mysis relicta* in Lakes Huron and Michigan. Ph.D. thesis, *Univ. Mich.*, 131 p.
- Beeton, A. M.  
1960. The vertical migration of *Mysis relicta* in Lakes Huron and Michigan. *J. Fish. Res. Bd. Canada* 17: 517-539.
- Beeton, Alfred M., and James W. Moffett.  
1964. Lake Michigan chemical data, 1954-55, 1960-61. *U.S. Fish Wildl. Serv., Bur. Comm. Fish. Data Rep. no. 6*, 102 p. on 3 microfiches.
- Birge, Edward A.  
1915. The heat budgets of American and European lakes. *Trans. Wis. Acad. Sci., Arts, and Lett.* 18: 166-213.  
1916. The work of wind in warming a lake. *Trans. Wis. Acad. Sci., Arts, and Lett.* 18: 341-391.
- Chandler, David C.  
1964. The St. Lawrence Great Lakes. *Verh. Internat. Verein. Limnol.* 15: 59-75.
- Church, Phil E.  
1942. The annual temperature cycle of Lake Michigan. I. Cooling from late autumn to the terminal point, 1941-42. *Univ. Chicago, Inst. Meteorol., Misc. Rep. no. 4*, 48 p.
- Church, Phil E.  
1945. The annual temperature cycle of Lake Michigan. II. Spring warming and summer stationary periods, 1942. *Univ. Chicago, Inst. Meteorol., Misc. Rep. no. 18*, 100 p.  
1946. The annual temperature cycle of Lake Michigan. *Trans. Amer. Geophys. Union* 27: 109-110.  
1947. Convection in the annual temperature cycle of Lake Michigan. *Ann. N.Y. Acad. Sci.* 48: 789-800.
- Conger, Norman B.  
1899. Water temperatures of the Great Lakes. *Monthly Weather Rev.* 27: 352.
- Denison, P. J., and F. C. Elder.  
1970. Thermal inputs to the Great Lakes. *Int. Ass. Great Lakes Res., Proc. 13th Conf. Great Lakes Res.*: 811-828.
- Dutton, John A., and Reid A. Bryson.  
1962. Heat flux in Lake Mendota. *Limnol. Oceanogr.* 7: 80-97.
- Eklund, Henning.  
1969. Potential pollution effects in deep lakes. *J. Fed. Wat. Pollut. Contr. Fed.* 41: R155-R159.
- Heap, John A.  
1963. Some characteristics of the winter ice cover of Lake Michigan, 1962-63. *Proc. 6th Conf. Great Lakes Res., Univ. Mich., Great Lakes Res. Div., Publ. no. 10*: 216-218.
- Heap, John A., and Vincent E. Noble.  
1966. Growth of ice on Lake Michigan. *Univ. Mich., Great Lakes Res. Div., Spec. Rep. no. 26*, 94 p.
- Huang, Chi Kan.  
1969. The thermal current structure in Lake Michigan: A theoretical and observational model study. *Univ. Mich., Great Lakes Res. Div., Spec. Rep. no. 43*, 169 p.
- Hutchinson, G. Evelyn.  
1957. A treatise on limnology. Vol. I, Geography, physics, and chemistry. *John Wiley, New York*, 1015 p.
- Johnson, James H.  
1960. Surface currents of Lake Michigan, 1954 and 1955. *U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish.* 338, 120 p.
- Johnson, L.  
1966. Temperature of maximum density of fresh water and its effect on circulation in Great Bear Lake. *J. Fish. Res. Bd. Canada* 23: 963-973.

- McFadden, J. D., and R. A. Ragotzkie,  
1963. Aerial mapping of surface temperature pattern of Lake Michigan. Proc. 6th Conf. Great Lakes Res., Univ. Mich., Great Lakes Res. Div., Publ. no. 10: 55-58.
- Merna, James W.  
1960. A benthological investigation of Lake Michigan M.S. thesis, Mich. State Univ. 74 p.
- Millar, F. Graham.  
1952. Surface temperatures of the Great Lakes, J. Fish. Res. Bd. Canada 9: 329-376.
- Moffett, James W.  
1957. Recent changes in the deep-water fish population of Lake Michigan. Trans. Amer. Fish. Soc. 86: 393-408.  
1962. An instance of upwelling along the east shore of Lake Michigan, 1955. Proc. 5th Conf. Great Lakes Res., Univ. Mich., Great Lakes Res. Div., Publ. no. 9: 126 (Abstract).
- Mortimer, C. H.  
1963. Frontiers in physical limnology, with particular reference to long waves in rotating basins. Proc. 6th Conf. Great Lakes Res., Univ. Mich., Great Lakes Res. Div. Publ. no. 10: 9-42.  
1968. Internal waves and associated currents observed in Lake Michigan during the summer of 1963. Univ. Wisconsin-Milwaukee, Center for Great Lakes Stud., Spec. Rep. no. 1, 24 p + 120 figs.  
1971. Large-scale oscillatory motions and seasonal temperature changes in Lake Michigan and Lake Ontario. Univ. Wisconsin-Milwaukee, Center for Great Lakes Stud., Spec. Rep. no. 12. Part I (Text), 111 p., Part II (Illustrations), 106 p.
- Mortimer, C. H., D. C. McNaught, and K. M. Stewart.  
1968. Short internal waves near their high-frequency limit in central Lake Michigan. Int. Ass. Great Lakes Res., Proc. 11th Conf. Great Lakes Res.: 39-60.
- Noble, Vincent E.  
1965. Winter temperature structure of Lake Michigan. Proc. 8th Conf. Great Lakes Res., Univ. Mich., Great Lakes Res. Div., Publ. no. 13: 334-341.  
1966. Observations of the fall overturn of Lake Michigan. Limnol. Oceanogr. 11: 413-415.  
1967a. Temperature structure of Lake Michigan, p. 340-365. In Ayers, J. C. and David C. Chandler (ed.), Studies on the environment and eutrophication of Lake Michigan, Univ. Mich., Great Lakes Res. Div., Spec. Rep. no. 30, 415 p.  
1967b. Evidences of geostrophically defined circulation in Lake Michigan. Int. Ass. Great Lakes Res., Proc. 10th Conf. Great Lakes Res.: 289-298.
- Noble, Vincent E., and Robert F. Anderson.  
1968. Temperature and current in the Grand Haven, Michigan, vicinity during thermal bar conditions. Int. Ass. Great Lakes Res., Proc. 11th Conf. Great Lakes Res.: 470-479.
- Noble, Vincent E., Joseph C. Huang, and James H. Saylor.  
1968. Vertical current structure in the Great Lakes. Univ. Mich., Great Lakes Res. Div., Spec. Rep. no. 37, 94 p.
- Noble, Vincent E., and April Michaelis.  
1968. Winter temperature data from Federal Water Pollution Control Administration (Great Lakes-Illinois River Basins Project) buoy stations. Univ. Mich., Great Lakes Res. Div., Spec. Rep. no. 39, 387 p.
- Noble, Vincent E., and John C. Wilkerson.  
1970. Airborne temperature surveys of Lake Michigan, October 1966 and 1967. Limnol. Oceanogr. 15: 289-295.
- Rodgers, G. K.  
1965. The thermal bar in the Laurentian Great Lakes. Proc. 8th Conf. Great Lakes Res., Univ. Michigan., Great Lakes Res. Div., Publ. no. 13: 358-363.  
1966. The thermal bar in Lake Ontario, spring 1965 and winter 1965-66. Proc. 9th Conf. Great Lakes Res., Univ. Mich., Great Lakes Res. Div., Publ. no. 15: 369-374.
- Smith, Stanford H.  
1957. Limnological surveys of the Great Lakes--early and recent. Trans. Amer. Fish. Soc. 86: 409-418.  
1964. Status of the deepwater cisco population of Lake Michigan. Trans. Amer. Fish. Soc. 93: 155-163.
- Stewart, Ronald.  
1969. Thermal discharge from nuclear plants and related weather modification. Int. Ass. Great Lakes Res., Proc. 12th Conf. Great Lakes Res.: 488-491.
- Strong, Alan E.  
1968. The spring lake anticyclone: Its inducement on the atmospheric and water circulations. Univ. Mich. Great Lakes Res. Div., Spec. Rep. no. 34, 146 p.
- U.S. Department of Interior.  
1967. Water quality investigations, Lake Michigan basin: Lake currents. Fed. Water Pollut. Contr. Admin., Great Lakes Region, Chicago, 364 p.

U.S. Department of Interior.

1970. Physical and ecological effects of waste heat on Lake Michigan. Great Lakes Fish. Lab., Ann Arbor, Mich., 101 p.

Van Oosten, John.

1960. Temperatures of Lake Michigan, 1930-32, U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish, no. 332, 34 p.

Verber, James L.

1964. The detection of rotary currents and internal waves in Lake Michigan. Proc. 7th Conf. Great Lakes Res., Univ. Mich., Great Lakes Res. Div., Publ. no. 11: 382-389.

Verber, James L.

1966. A study of Lake Michigan: chemical, biological, and physical. Verh. Internat. verein. Limnol. 16: 29-46.

Wells, LaRue.

1960. Seasonal abundance and movements of planktonic crustacea in Lake Michigan. U.S. Fish Wildl. Serv., Fish. Bull. 60: 343-369.

Wright, Stillman.

1931. Bottom temperatures in deep lakes. Science 74: 413.

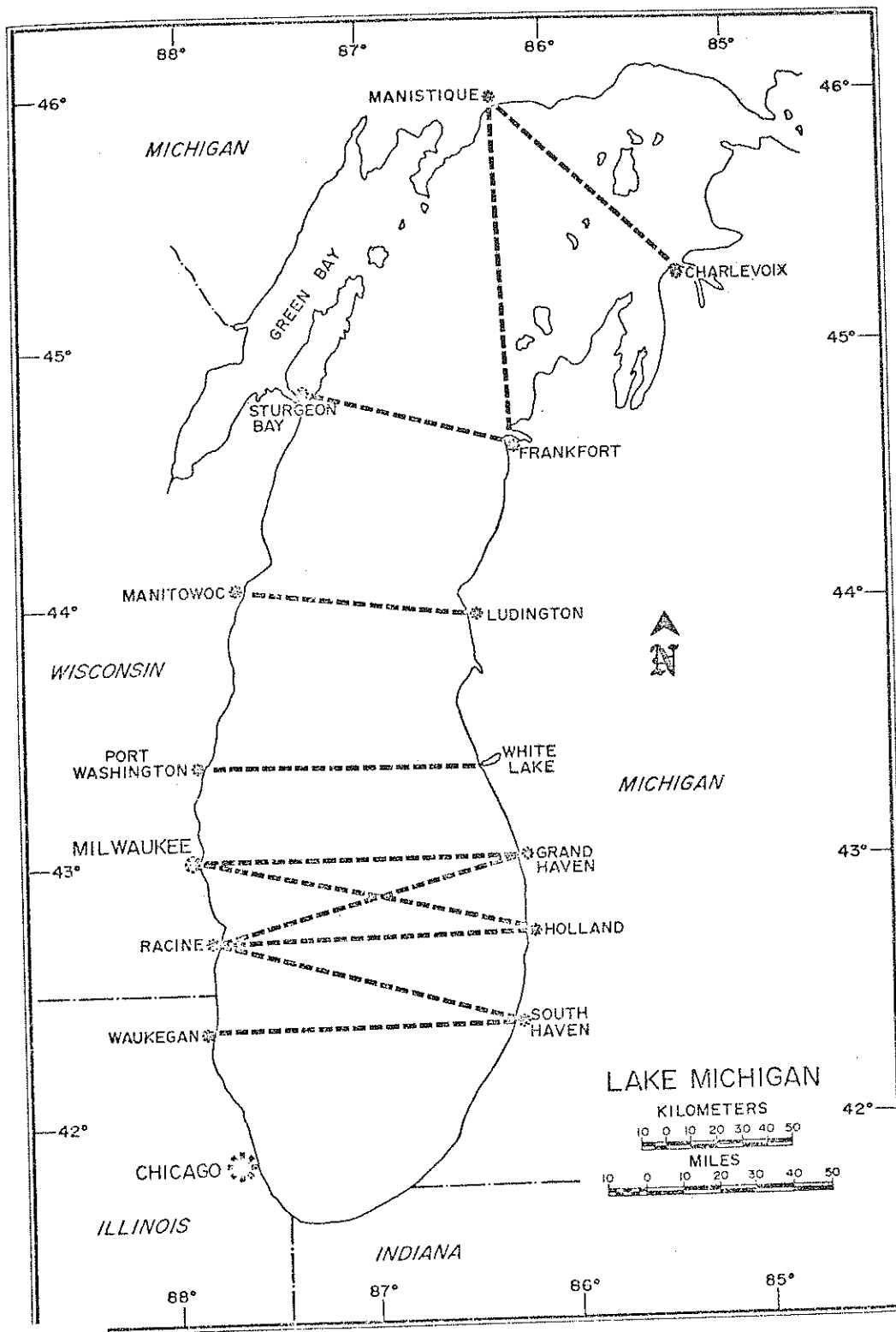


Figure 1.--Lake Michigan, showing the routes (dashed lines) along which temperature data were collected in 1954 and 1955. Shaded areas were not included in the study.

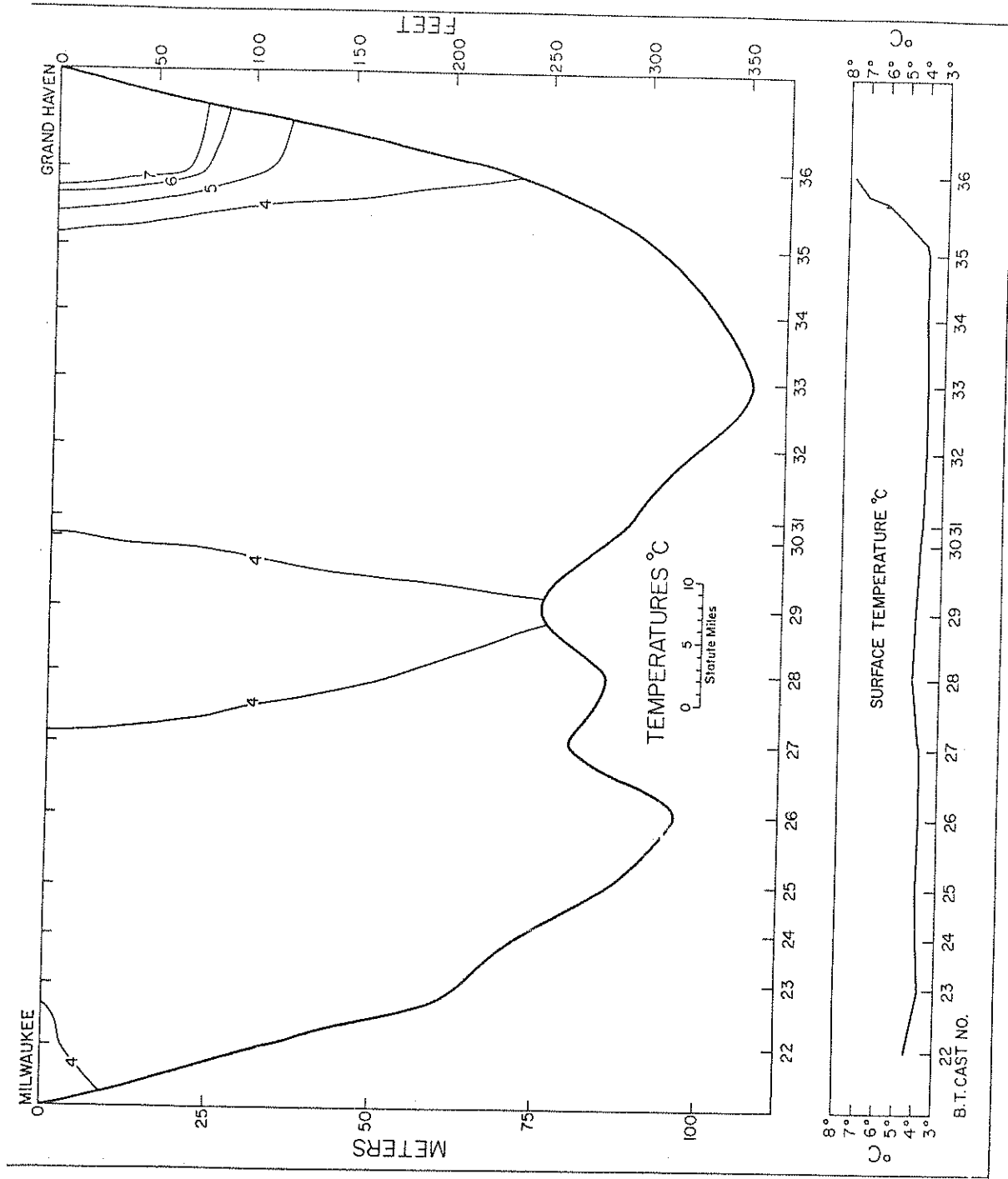


Figure 2.---Thermal profile, Milwaukee to Grand Haven, May 11, 1954.

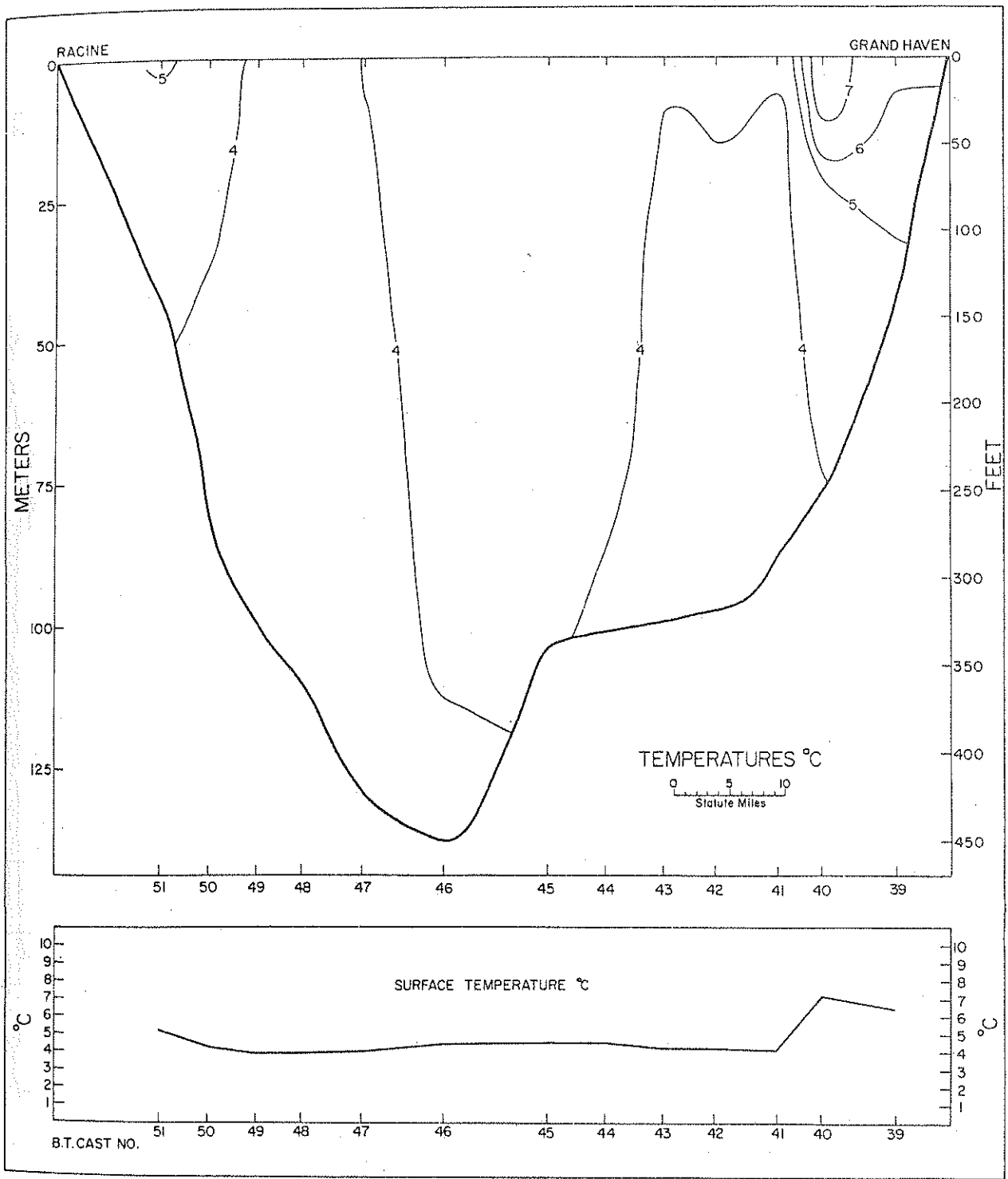


Figure 3.--Thermal profile, Grand Haven to Milwaukee, May 13, 1954.

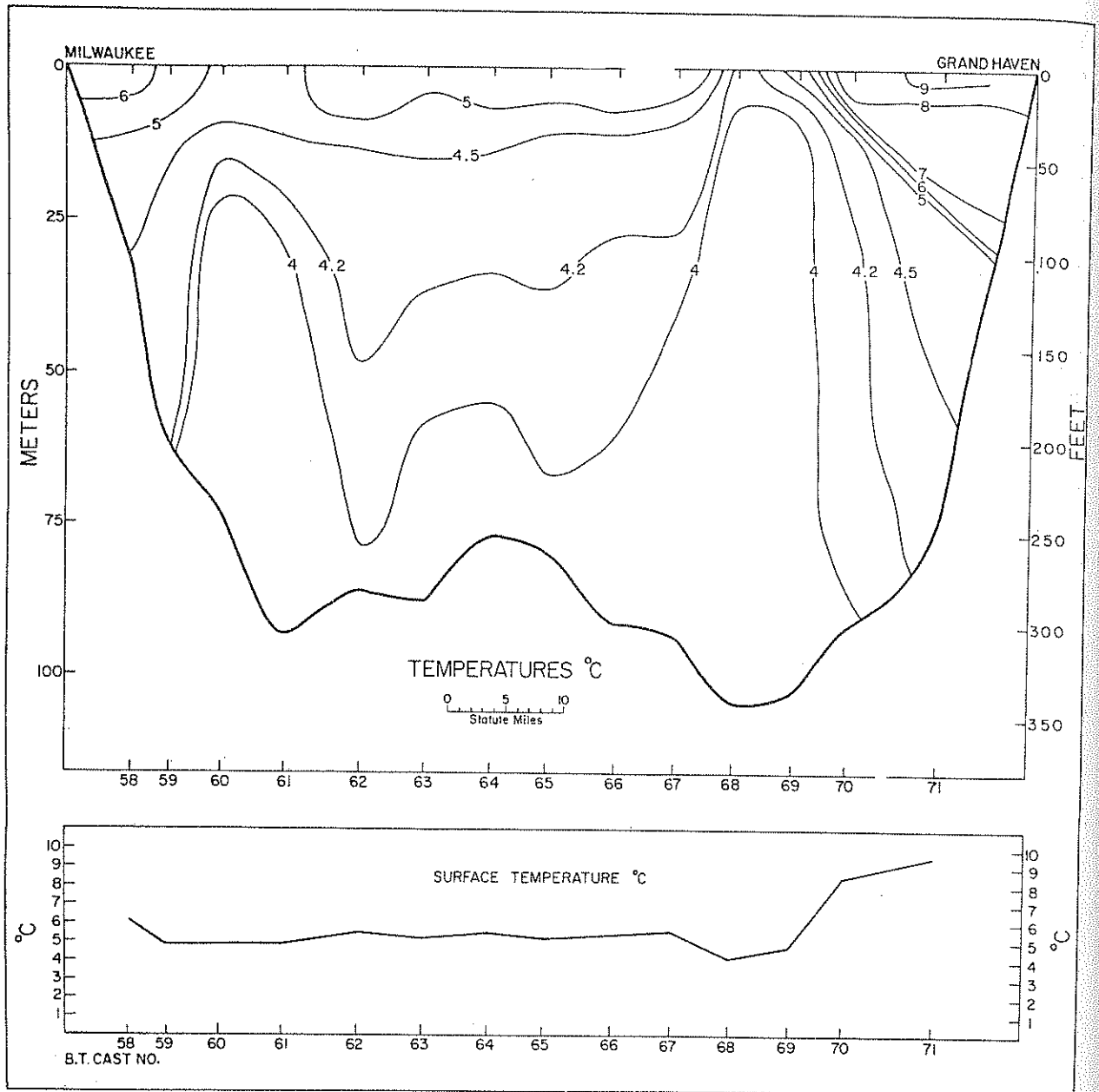


Figure 4.--Thermal profile, Milwaukee to Grand Haven, May 15, 1954.

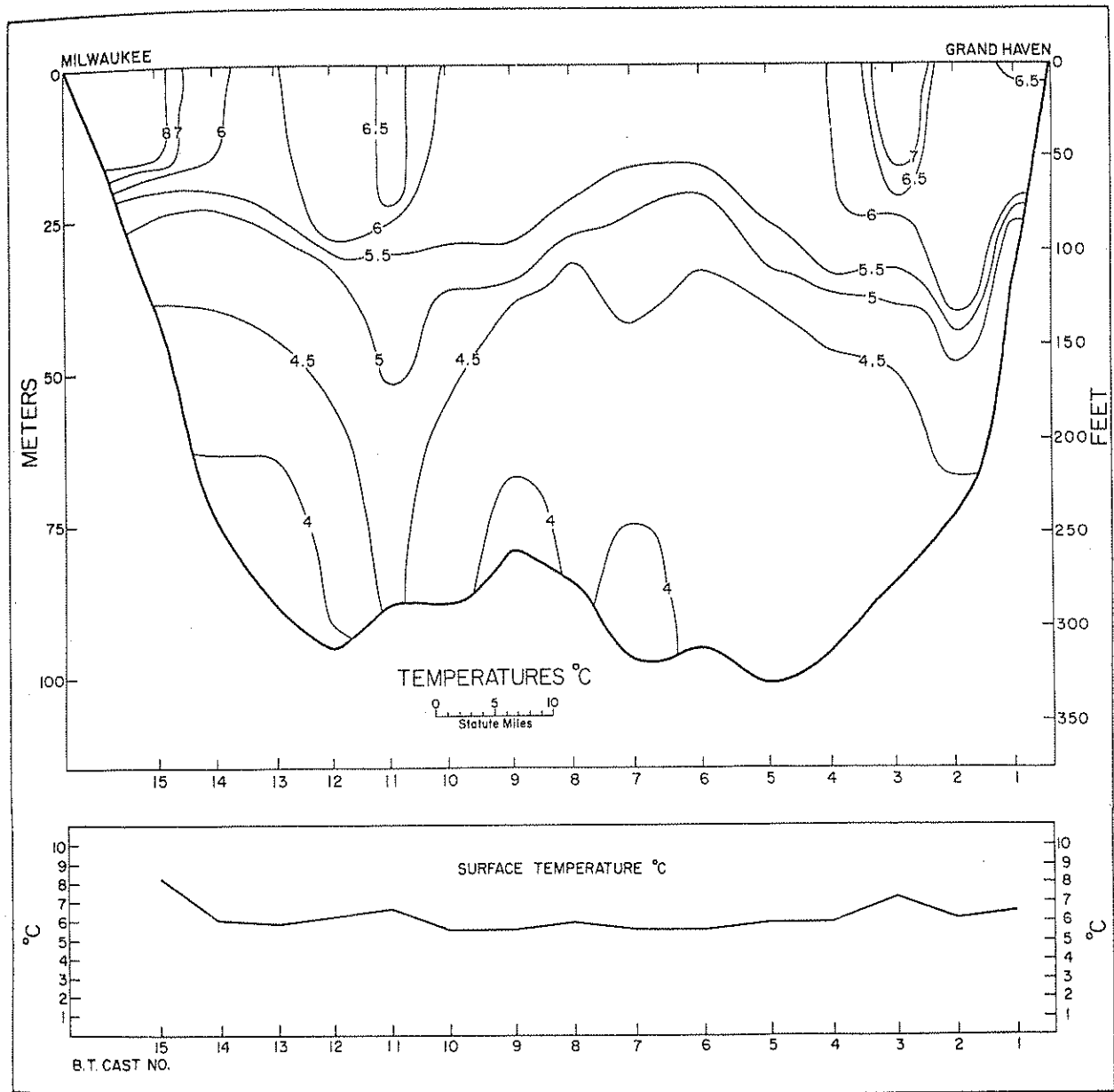


Figure 5.--Thermal profile, Grand Haven to Milwaukee, May 27, 1954.

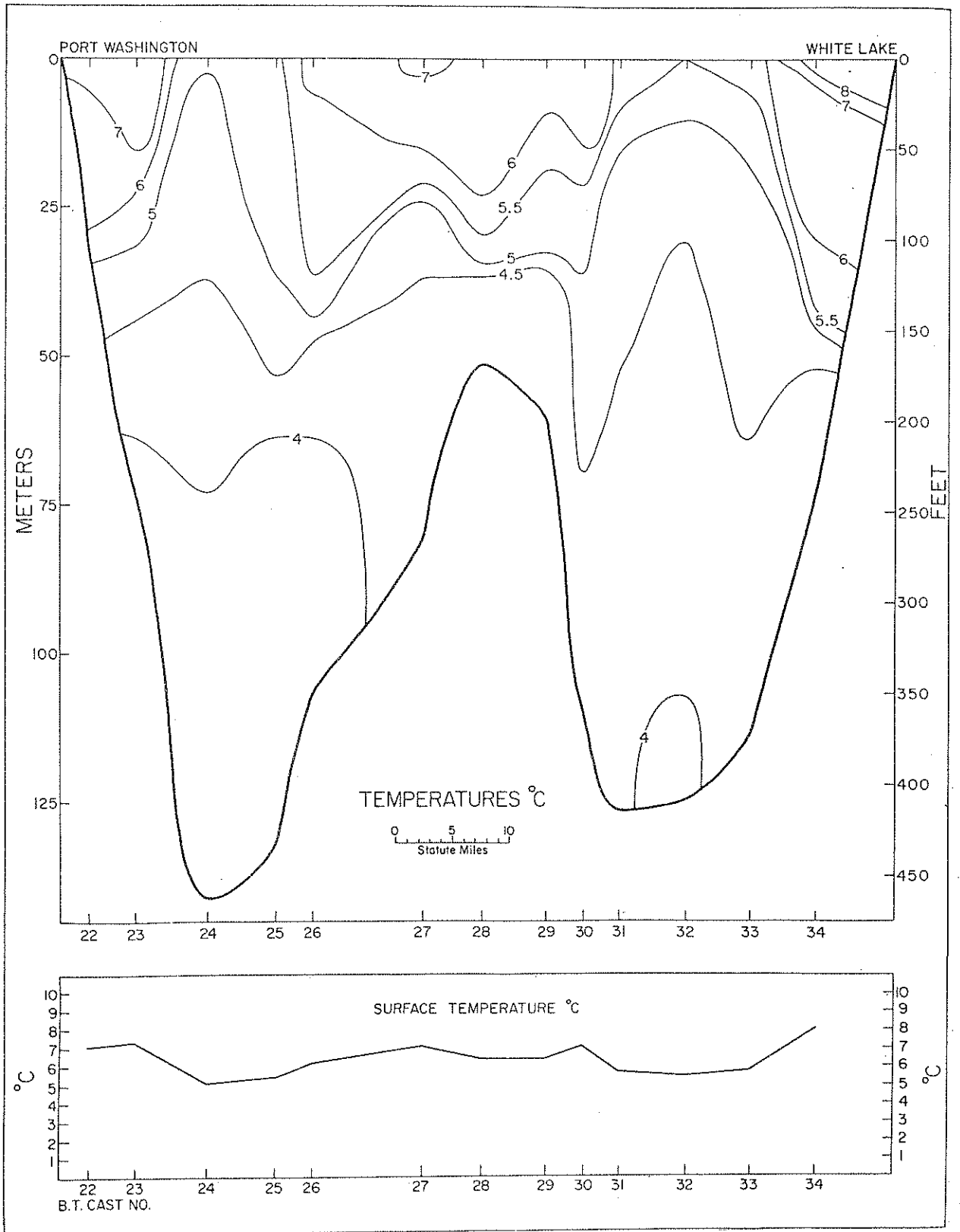


Figure 6.—Thermal profile, Port Washington to White Lake, May 30, 1954.

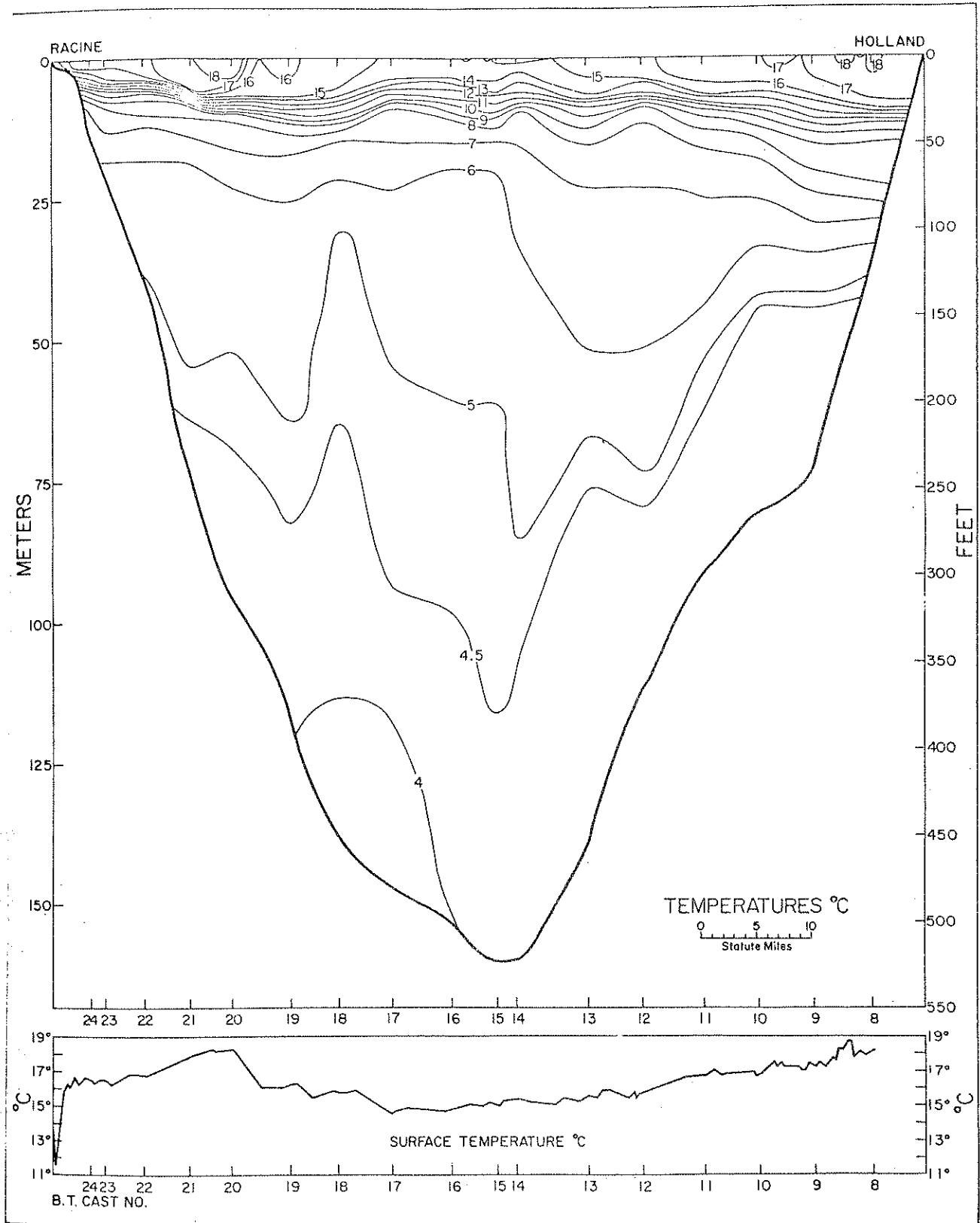


Figure 7.---Thermal profile, Holland to Racine, June 18, 1954.

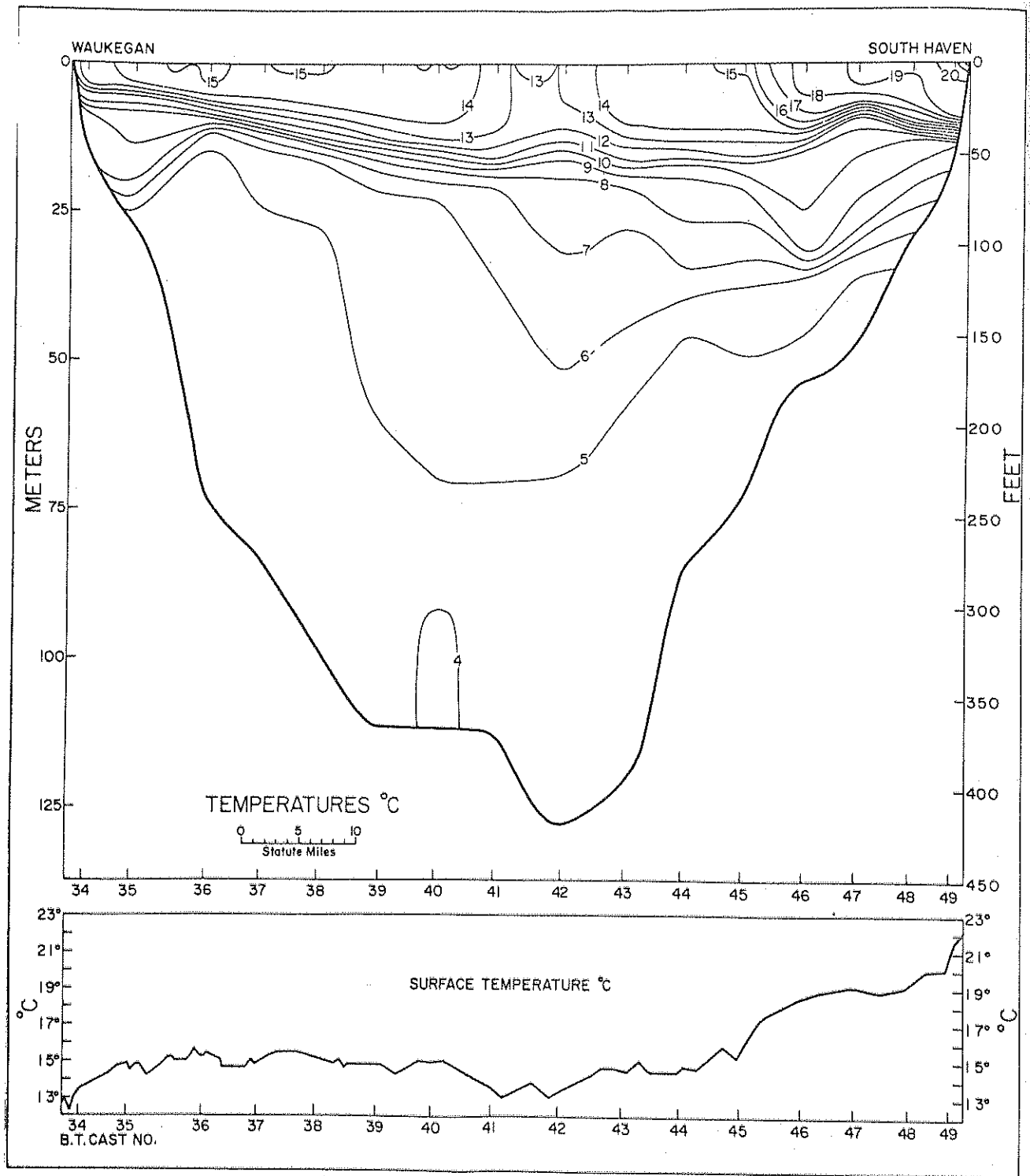


Figure 8.--Thermal profile, Waukegan to South Haven, June 20, 1954.

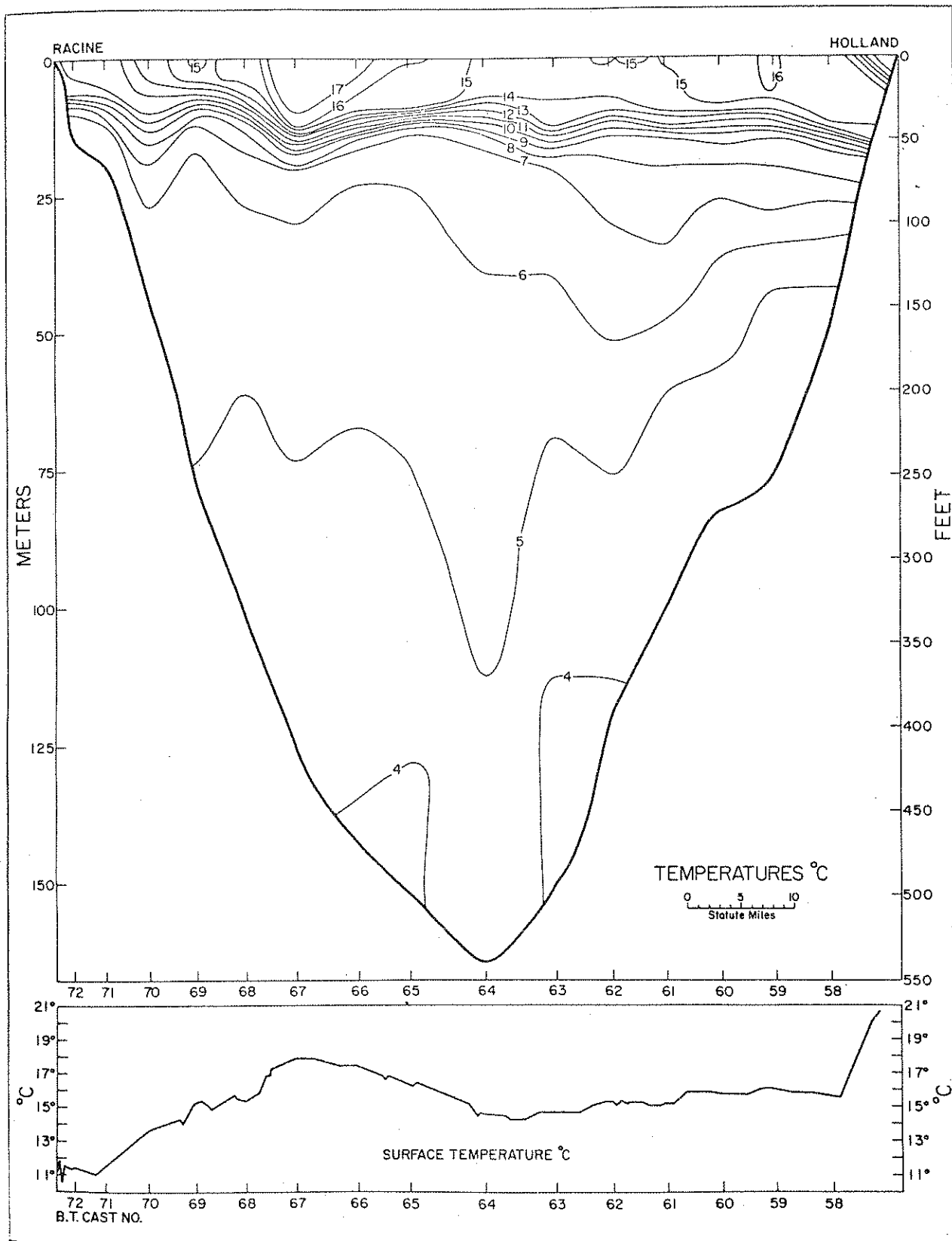


Figure 9.--Thermal profile, Holland to Racine, June 22, 1954.

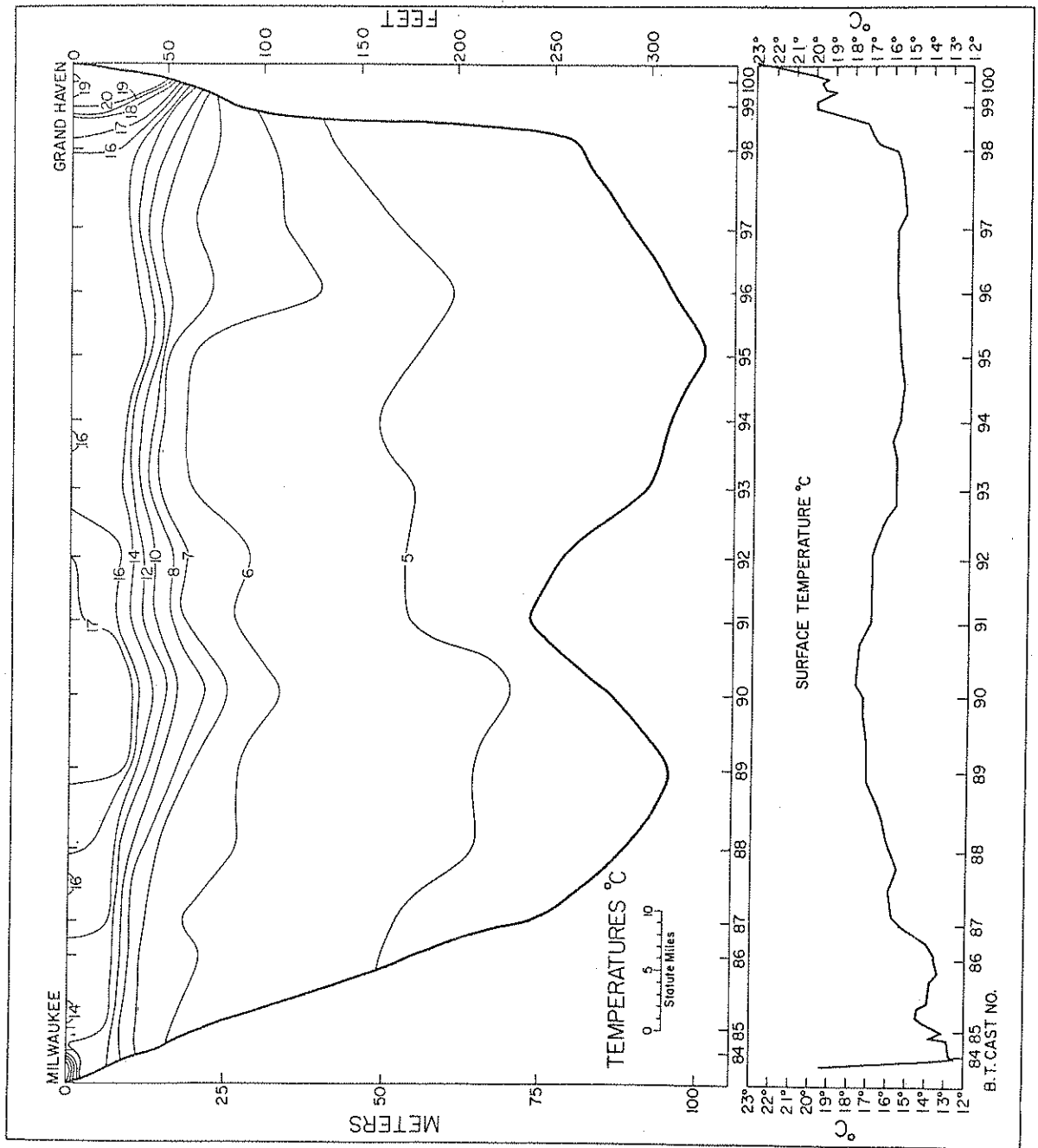


Figure 10. Thermal profile, Milwaukee to Grand Haven, June 25, 1954.

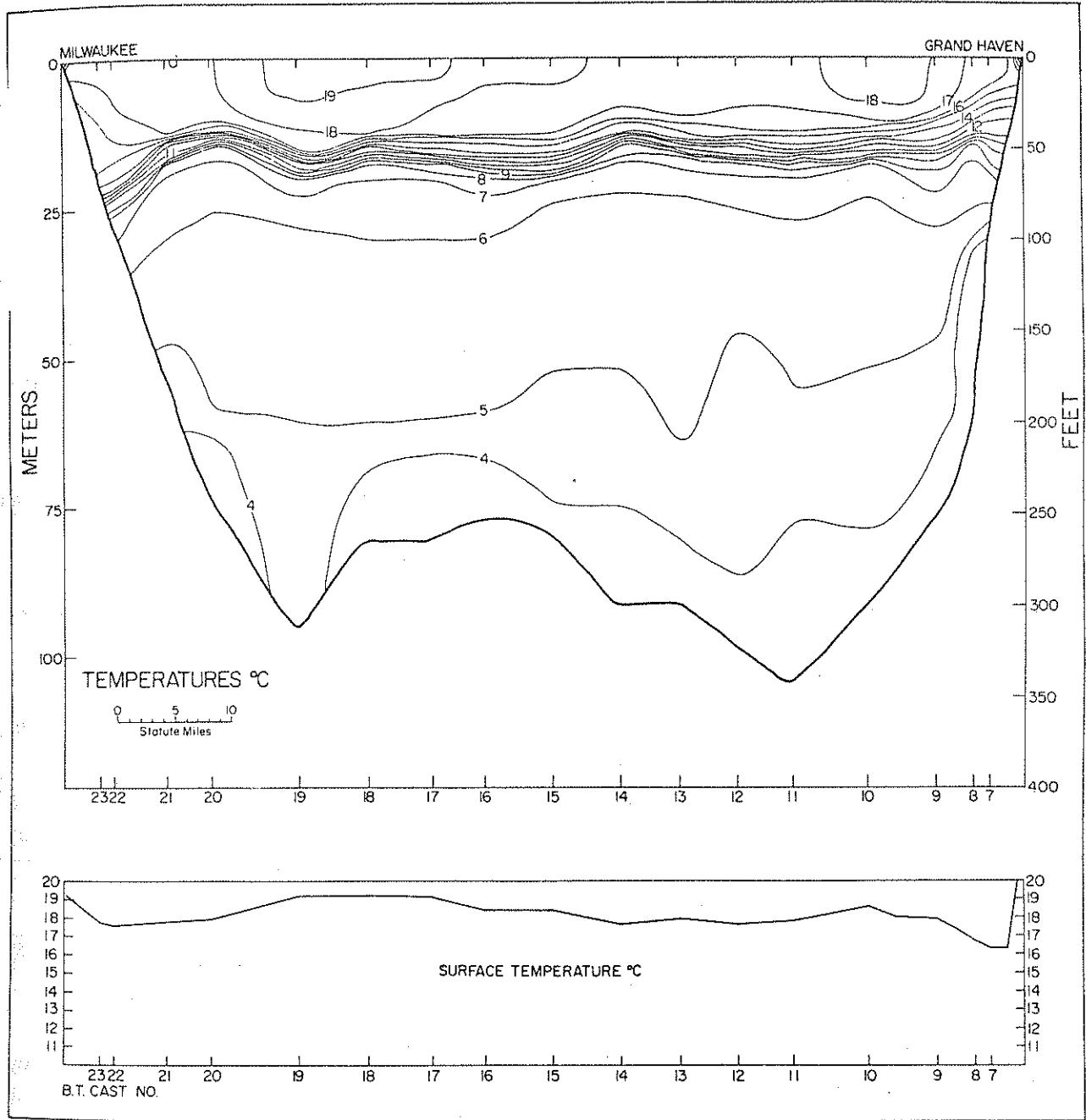


Figure 11.---Thermal profile, Grand Haven to Milwaukee, July 9, 1954.

Figure 10.---Thermal profile, Milwaukee to Grand Haven, June 25, 1954.

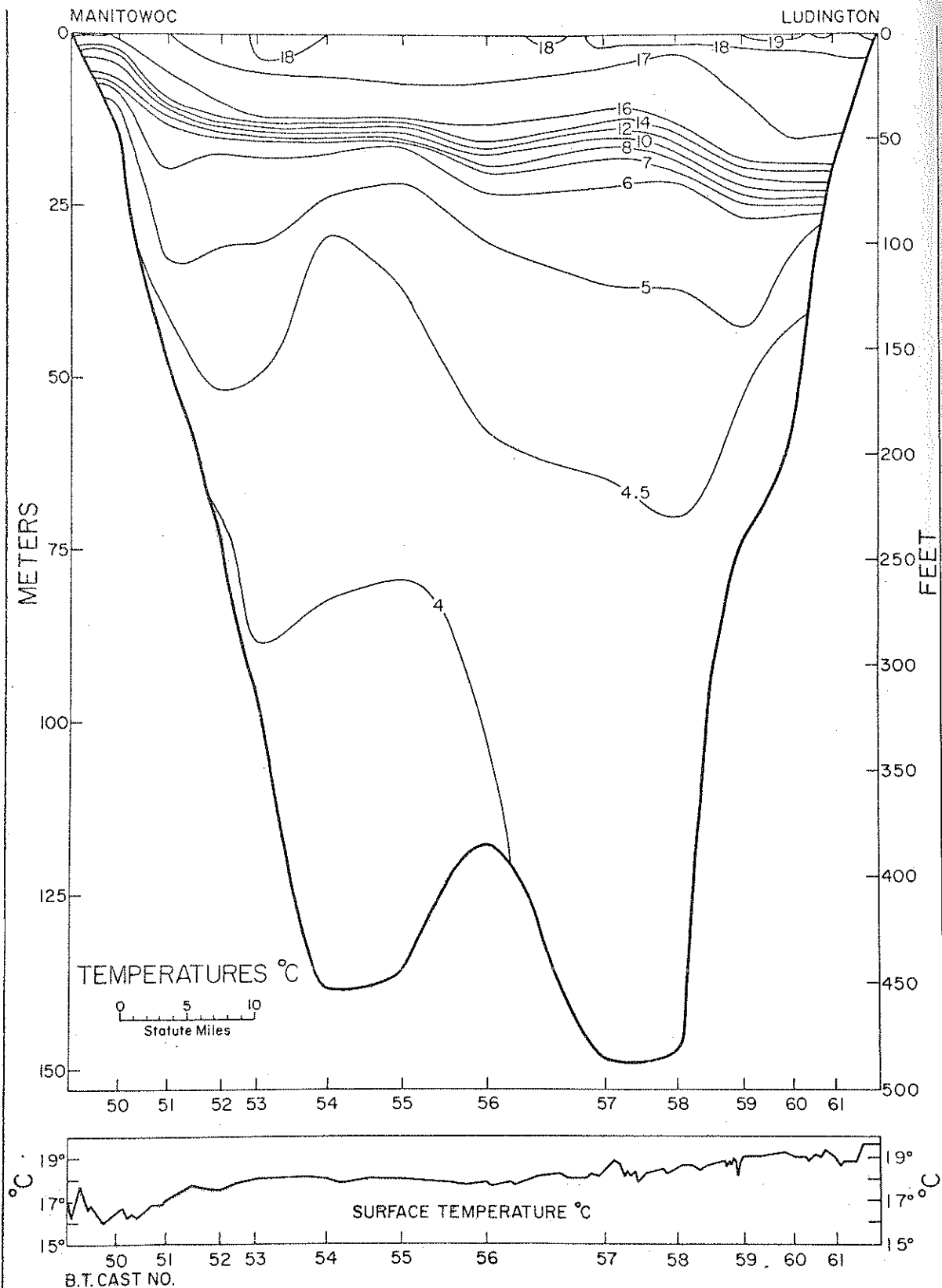


Figure 12.--Thermal profile, Manitowoc to Ludington, July 13, 1954.

FEET

°C

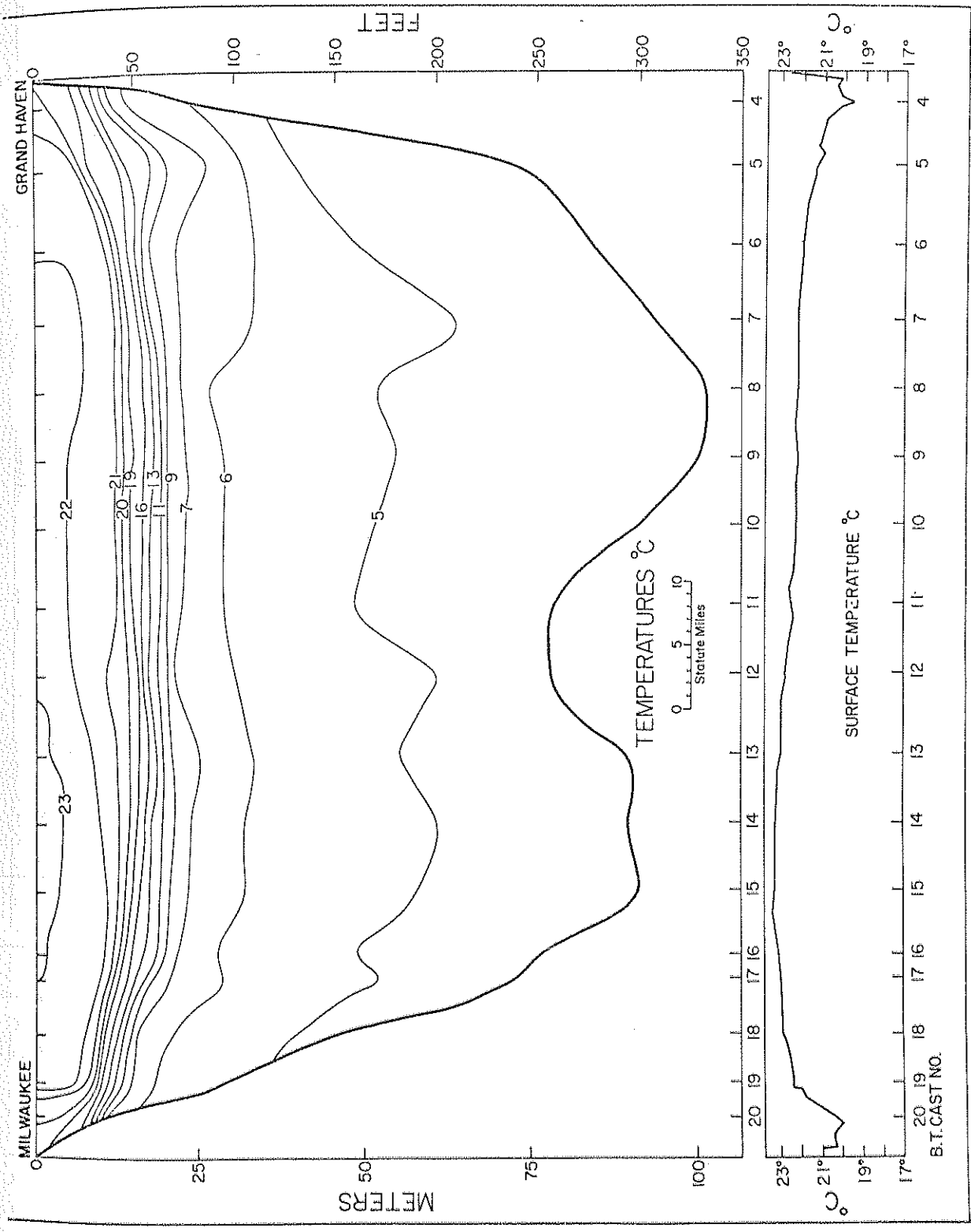


Figure 13.---Thermal profile, Grand Haven to Milwaukee, July 29, 1954.

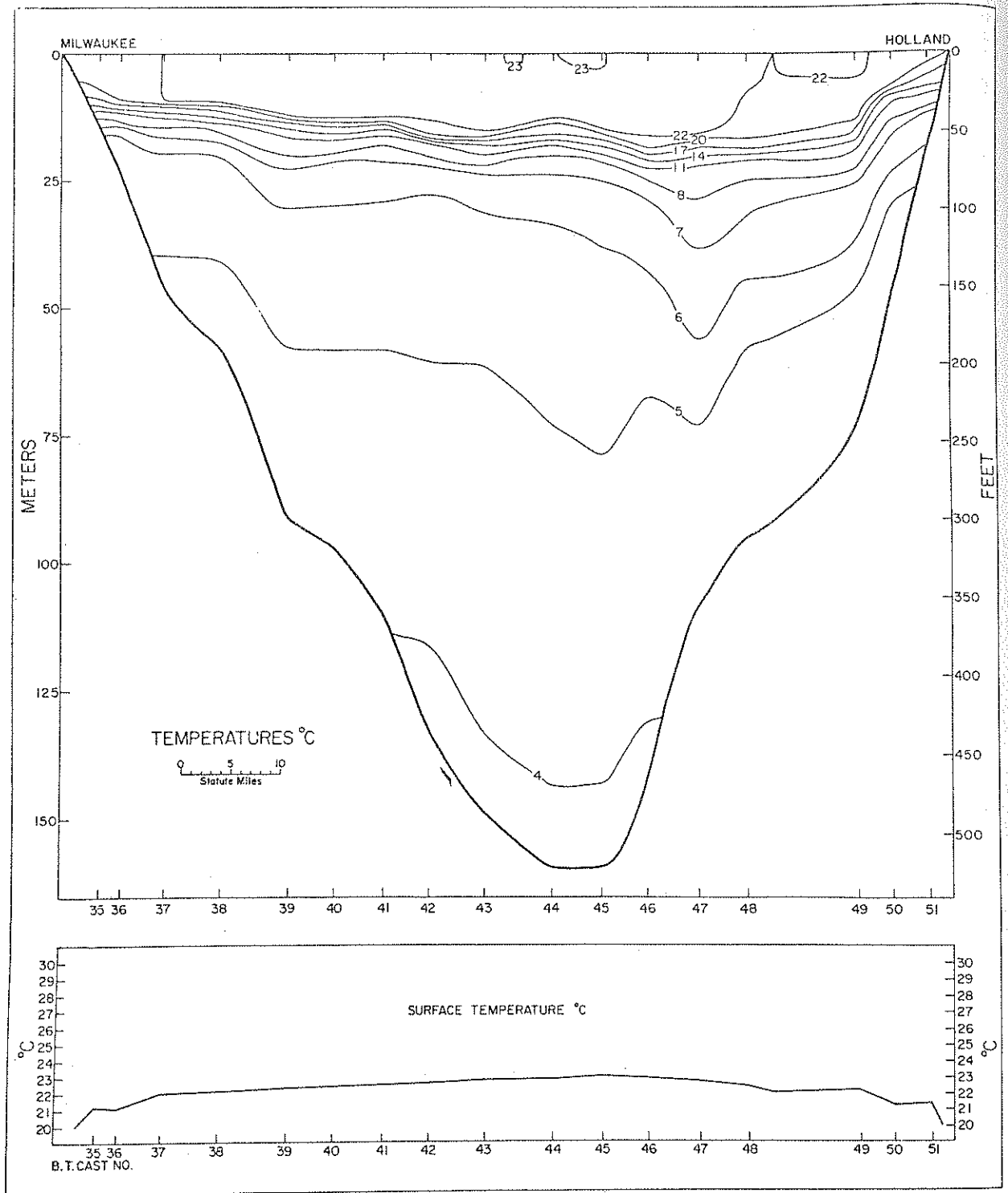


Figure 14.—Thermal profile, Milwaukee to Holland, August 1, 1954.

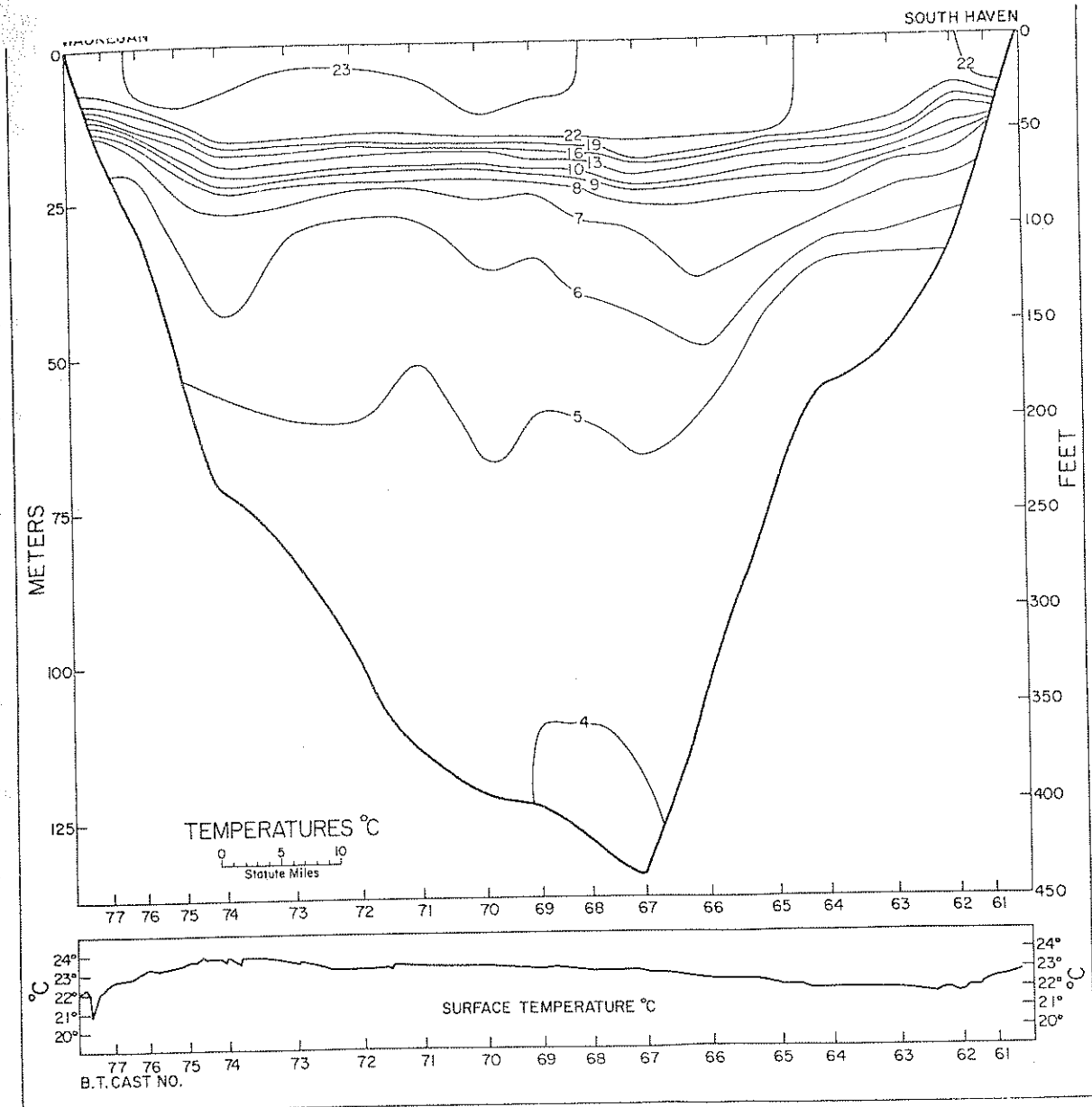


Figure 15.---Thermal profile, South Haven to Waukegan, August 3, 1954.

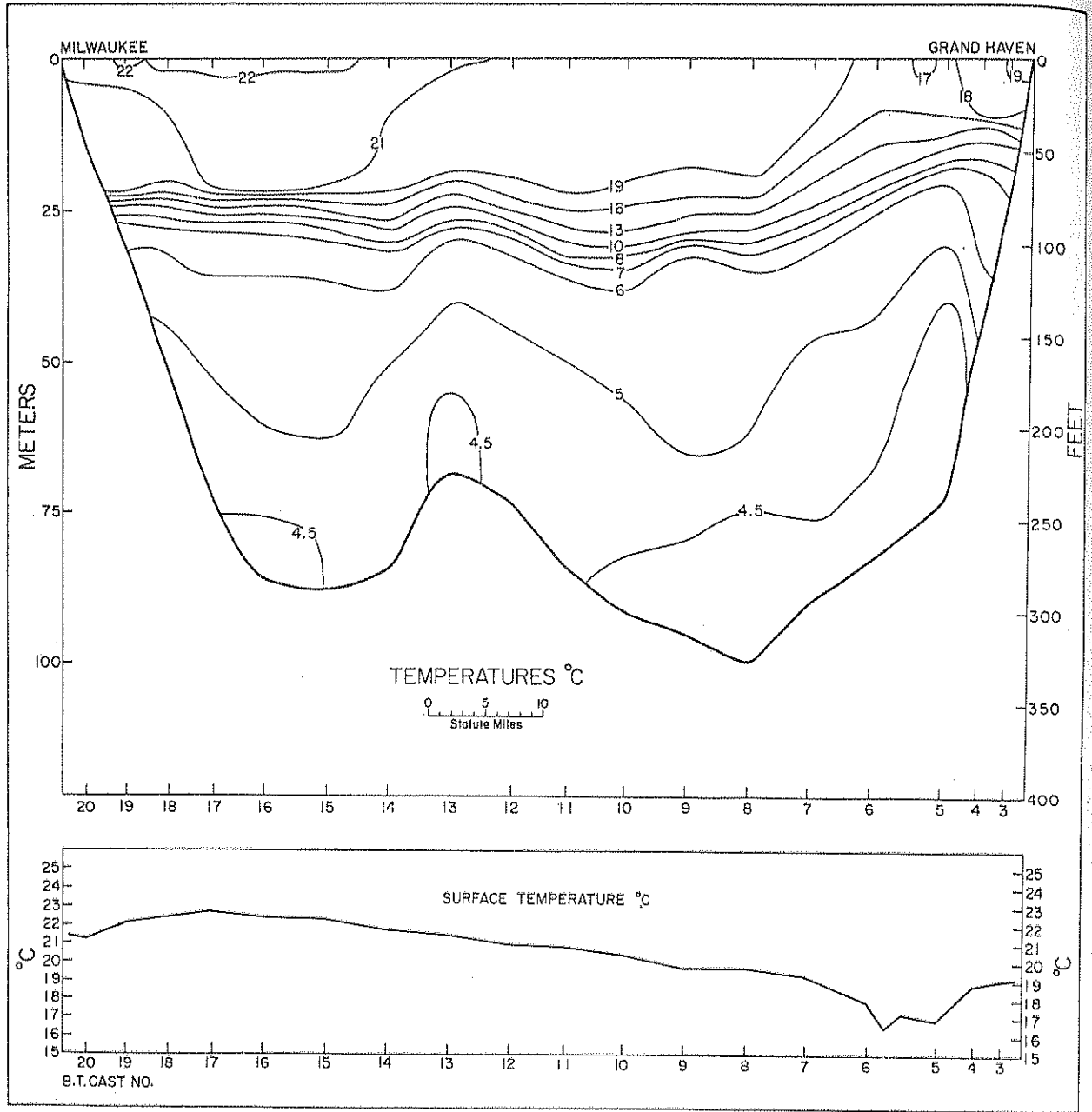


Figure 16.—Thermal profile, Grand Haven to Milwaukee, August 19, 1954.

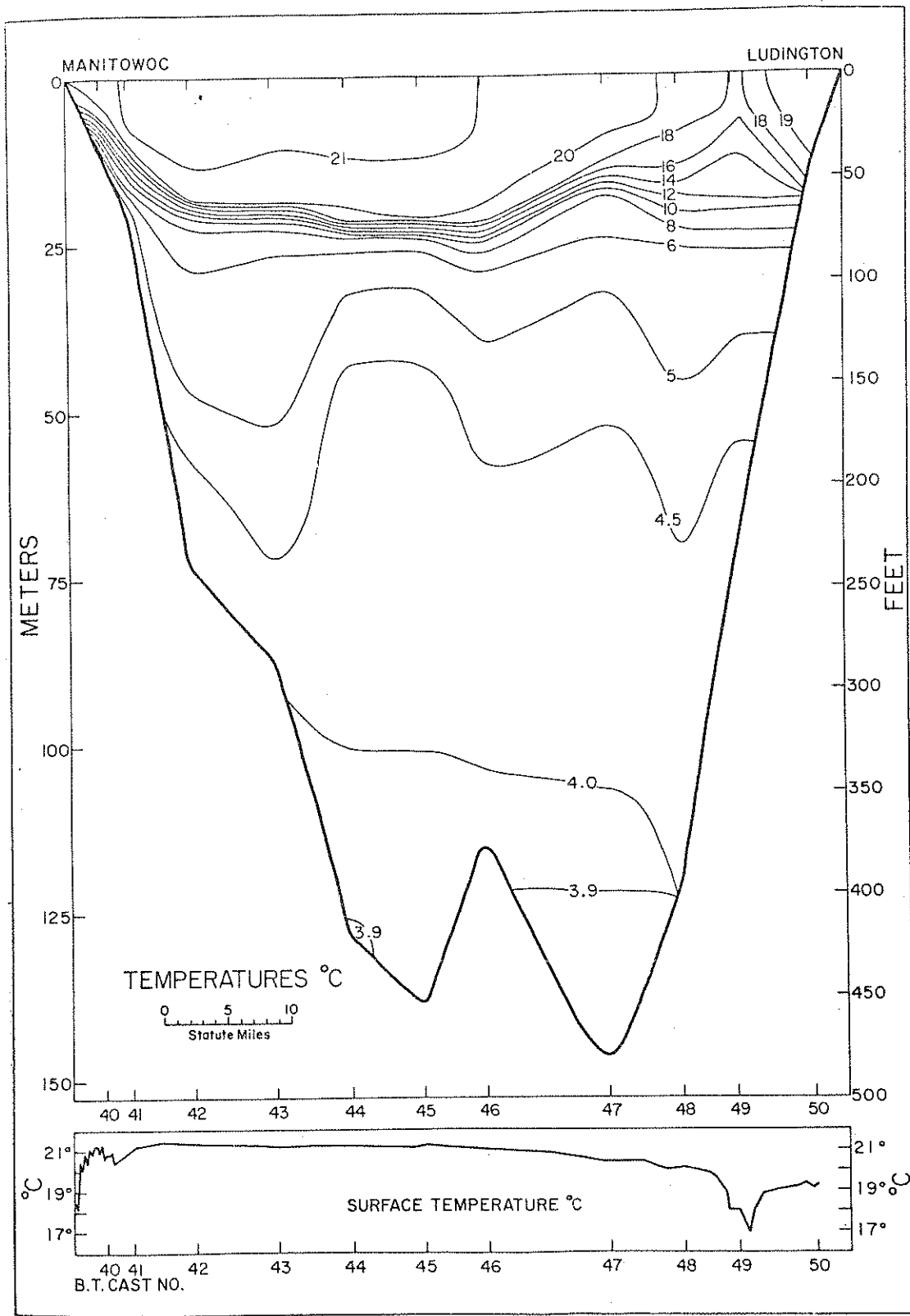


Figure 17.--Thermal profile, Manistowoc to Ludington, August 25, 1954.

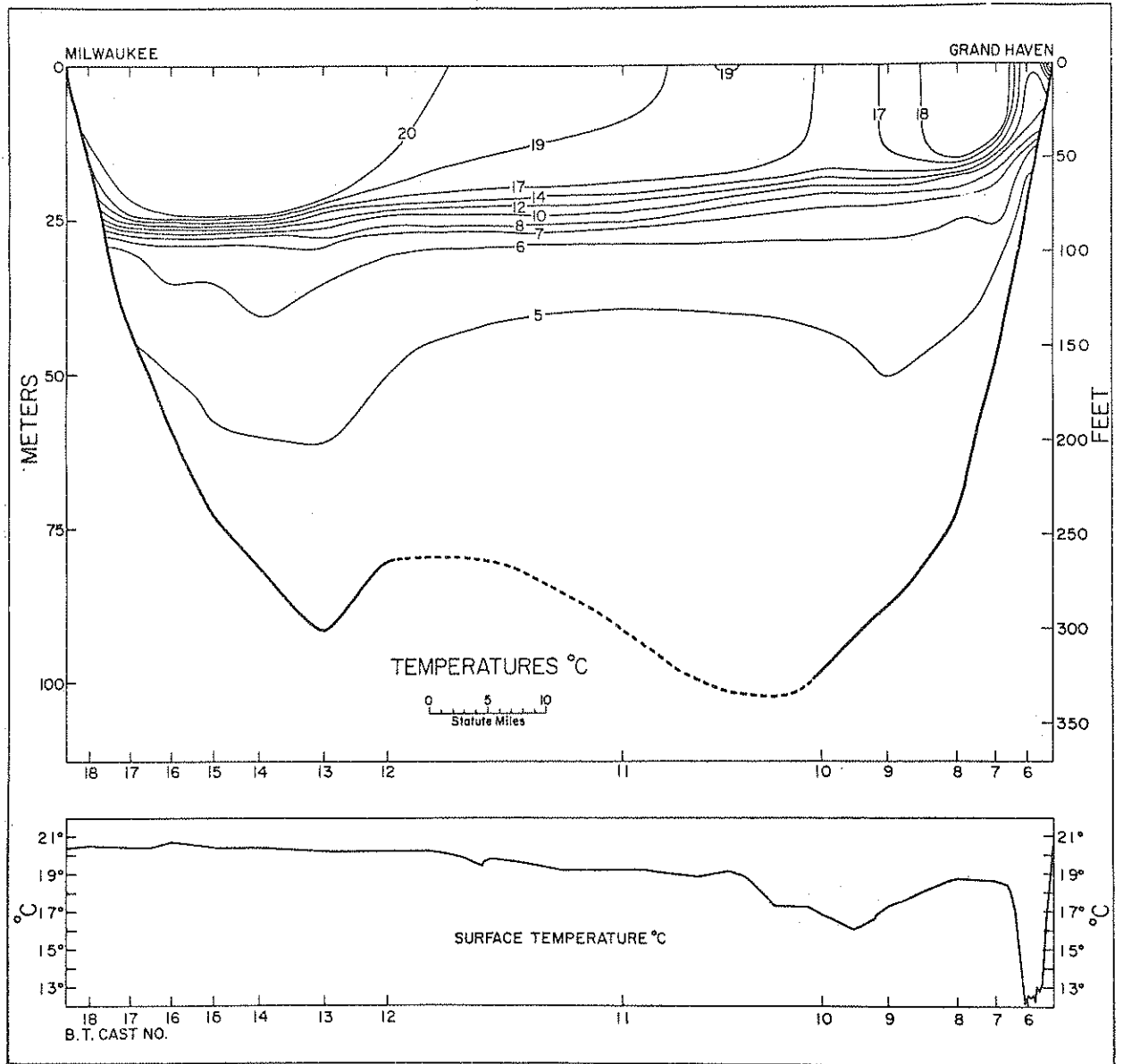


Figure 18.--Thermal profile, Grand Haven to Milwaukee, September 11, 1954.

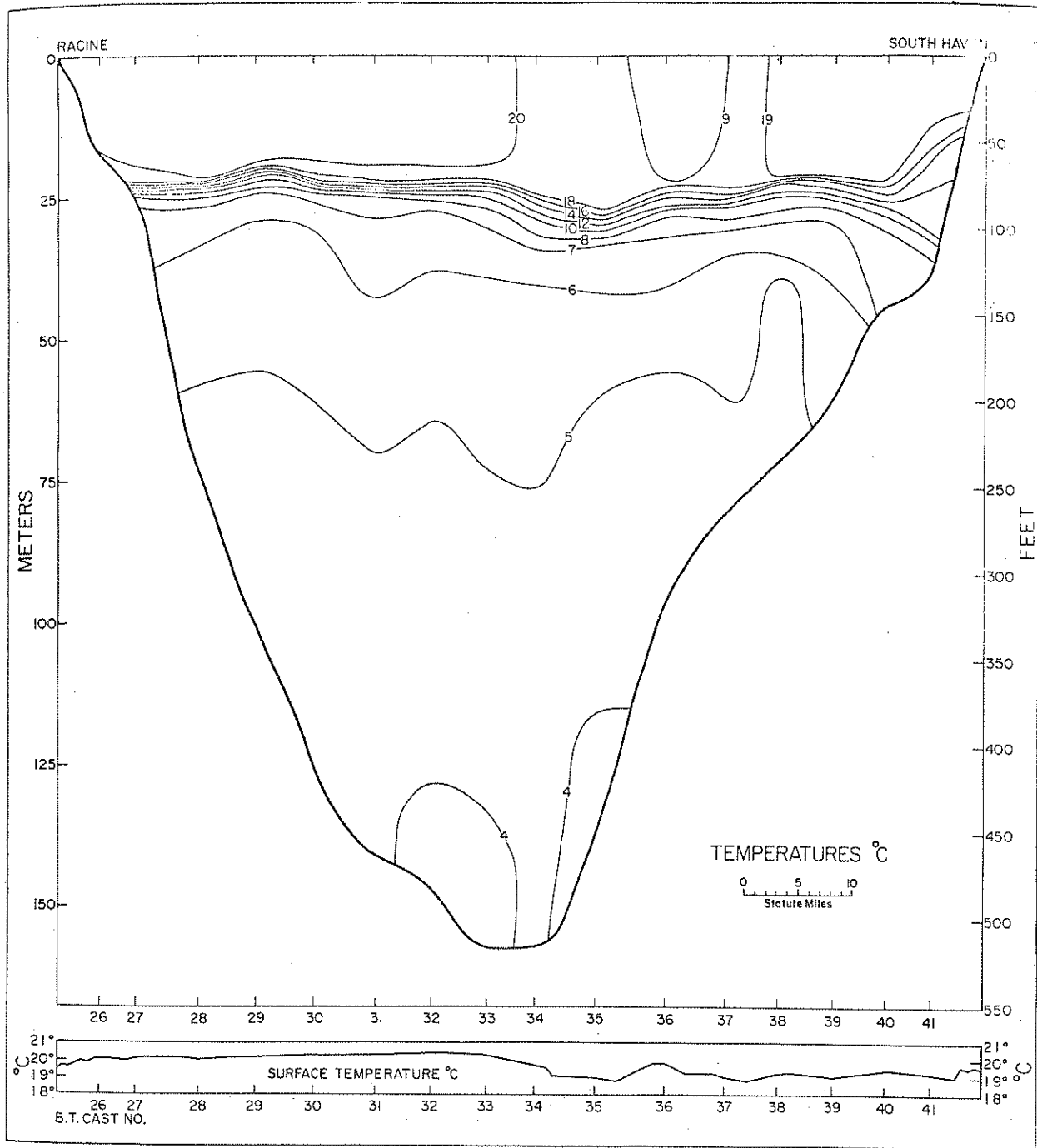


Figure 19.--Thermal profile, Racine to South Haven, September 13, 1954.

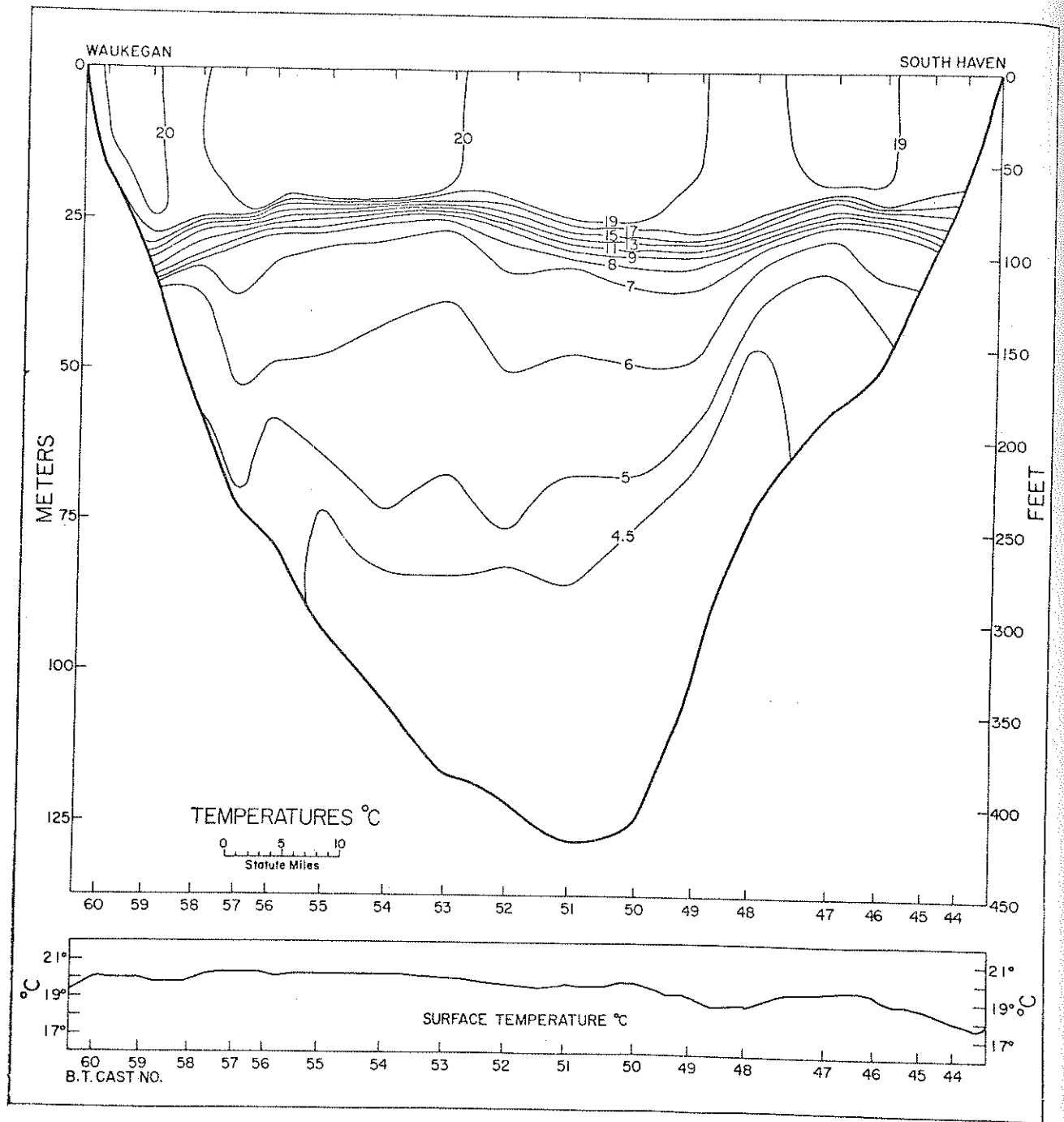


Figure 20.---Thermal profile, South Haven to Waukegan, September 15, 1954.

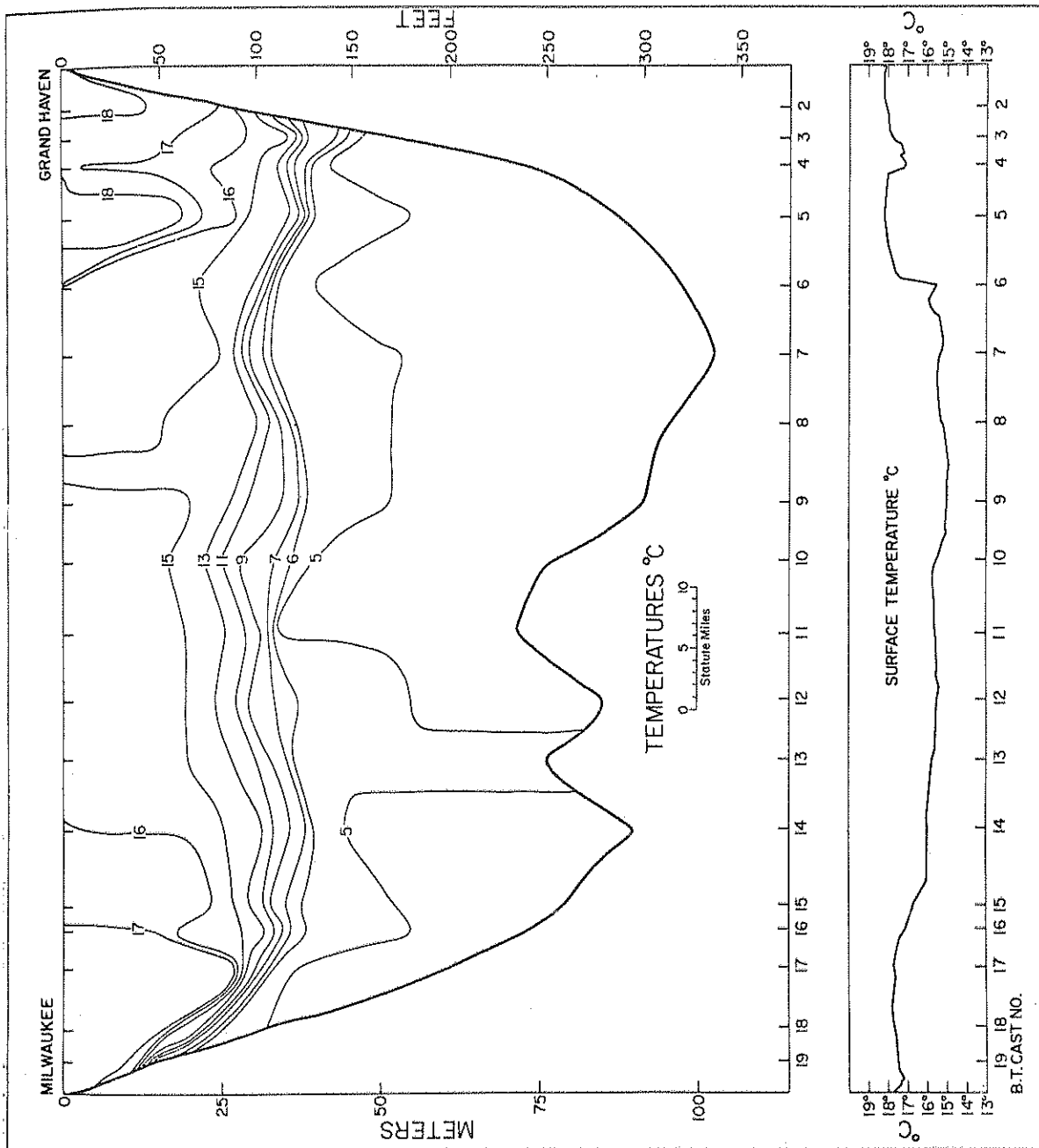


Figure 21. Thermal profile, Grand Haven to Milwaukee, October 1, 1954.

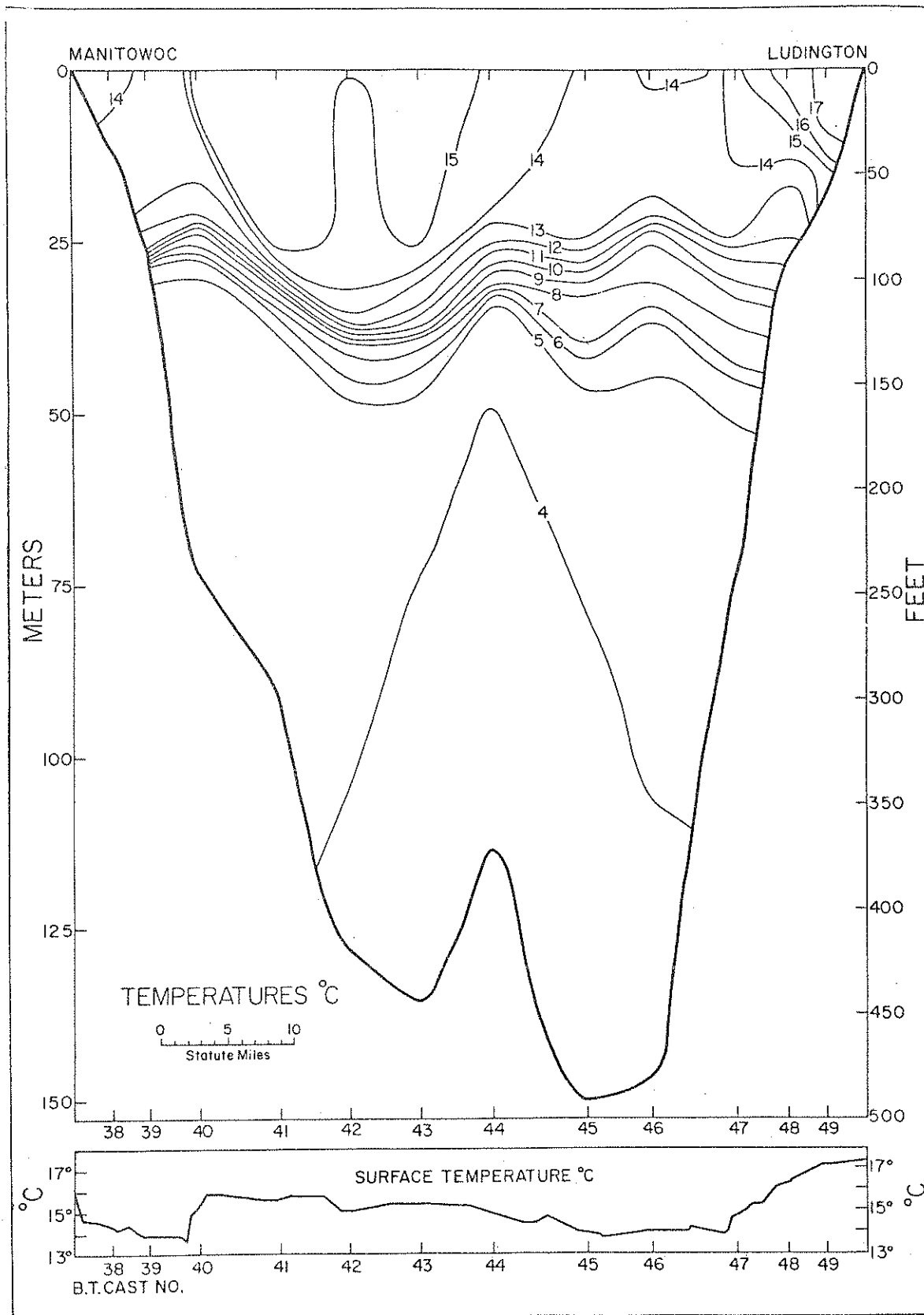


Figure 22.--Thermal profile, Maniwoc to Ludington, October 4, 1954.

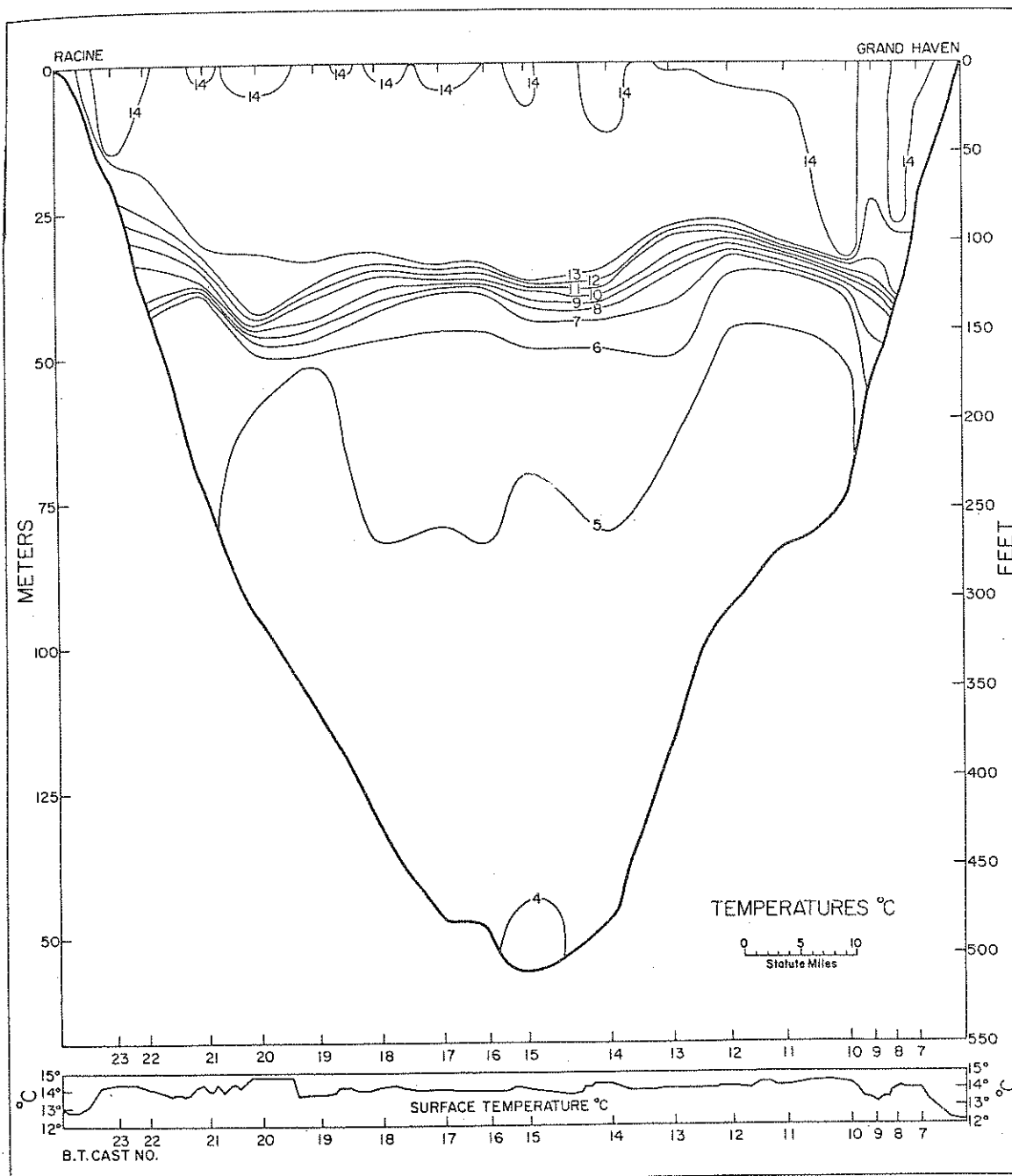


Figure 23.—Thermal profile, Holland to Racine, October 22, 1954.

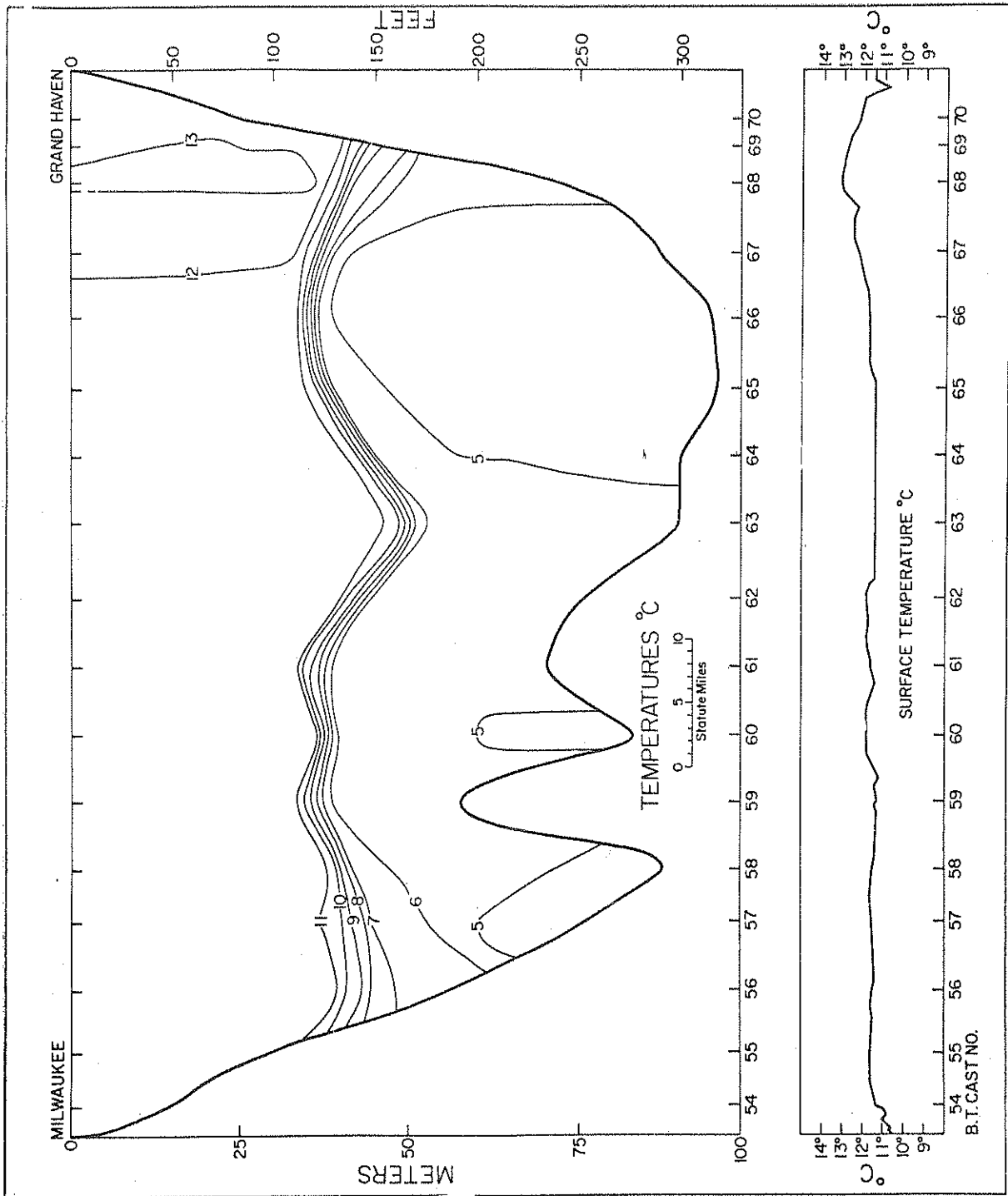


Figure 24. Thermal profile, Milwaukee to Racine, October 31, 1954.

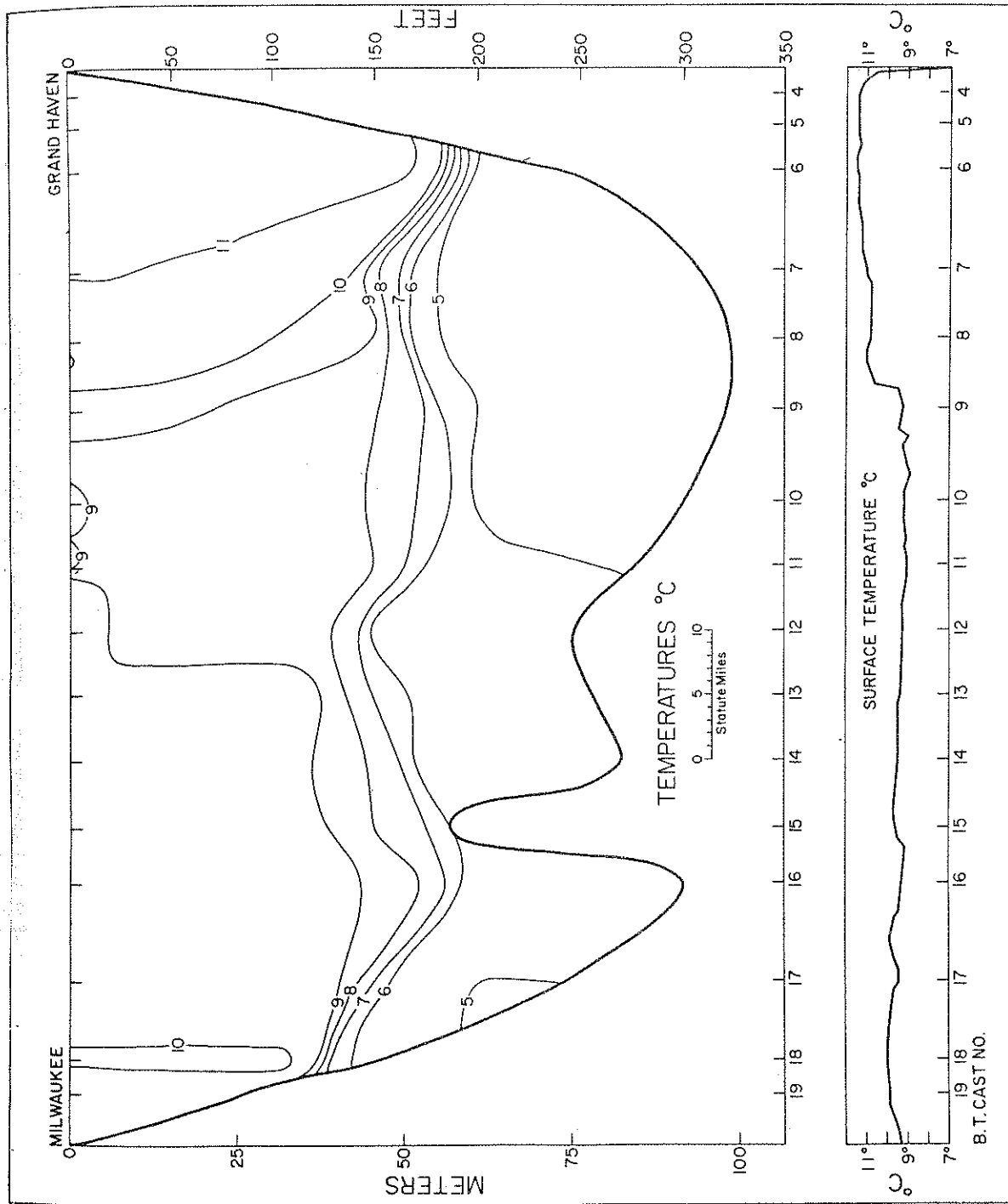


Figure 25.---Thermal profile, Grand Haven to Milwaukee, November 12, 1954.

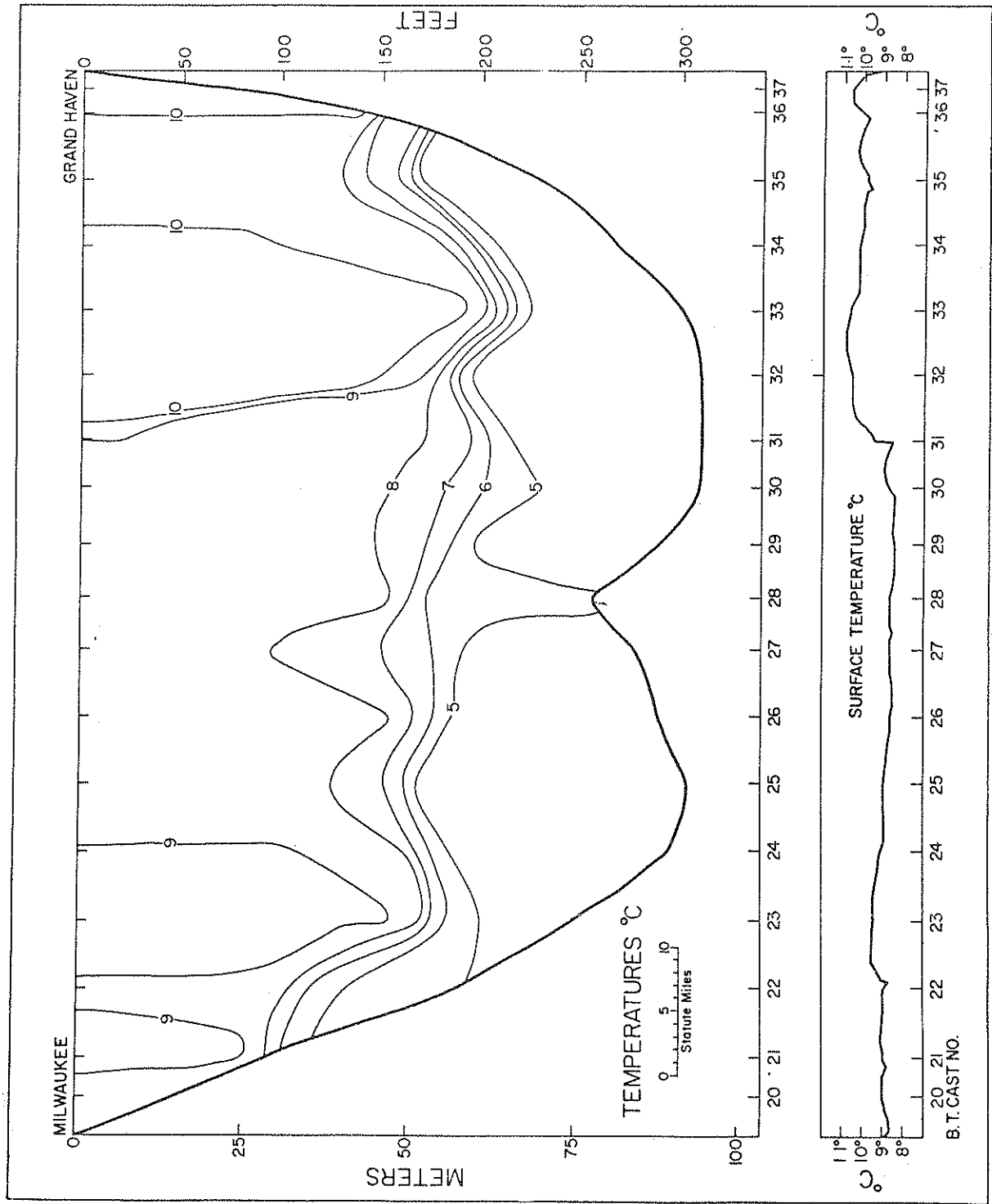


Figure 26.---Thermal profile, Milwaukee to Grand Haven, November 15, 1954.

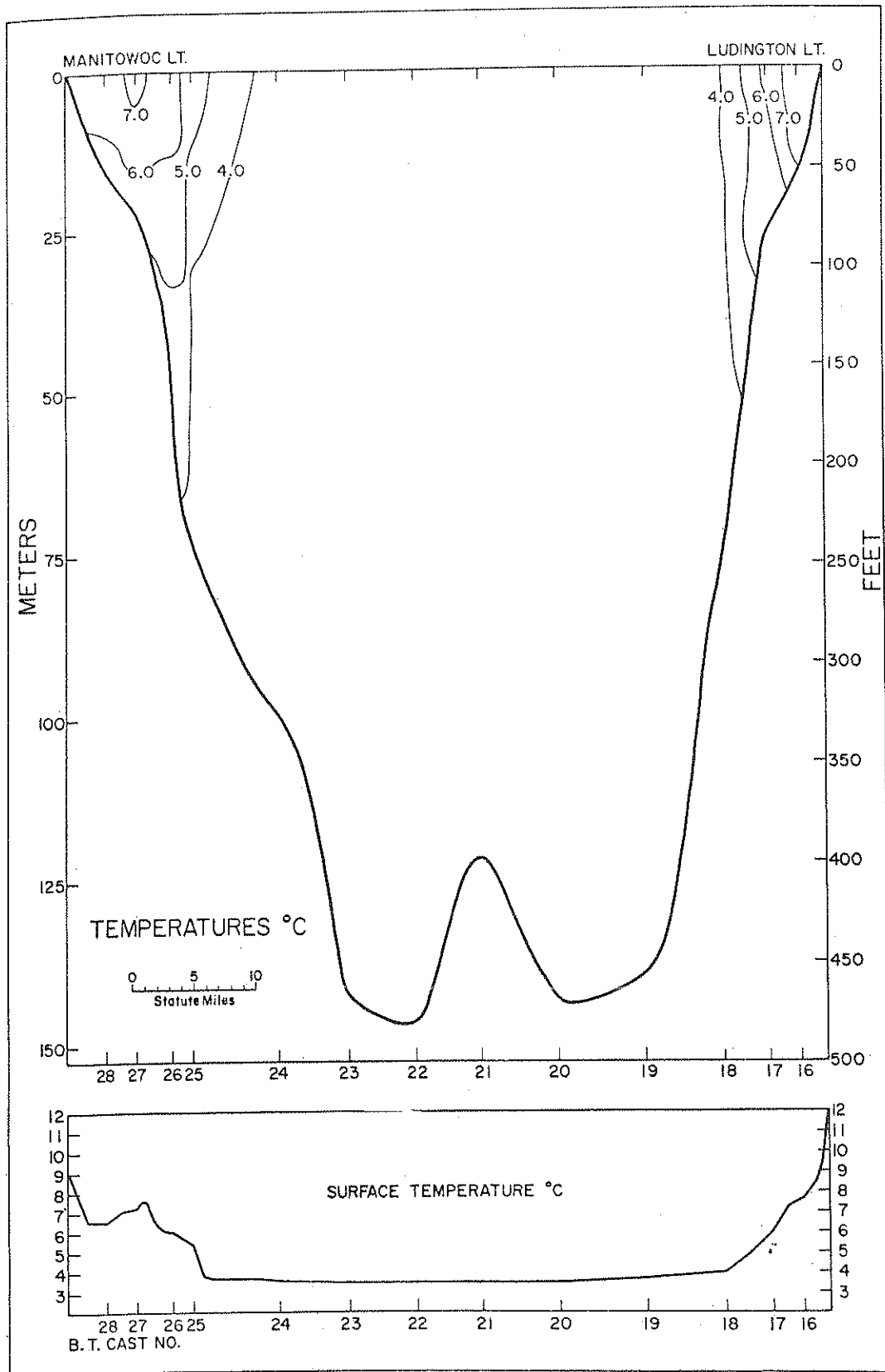


Figure 27.—Thermal profile, Ludington to Milwaukee, May 13, 1955.

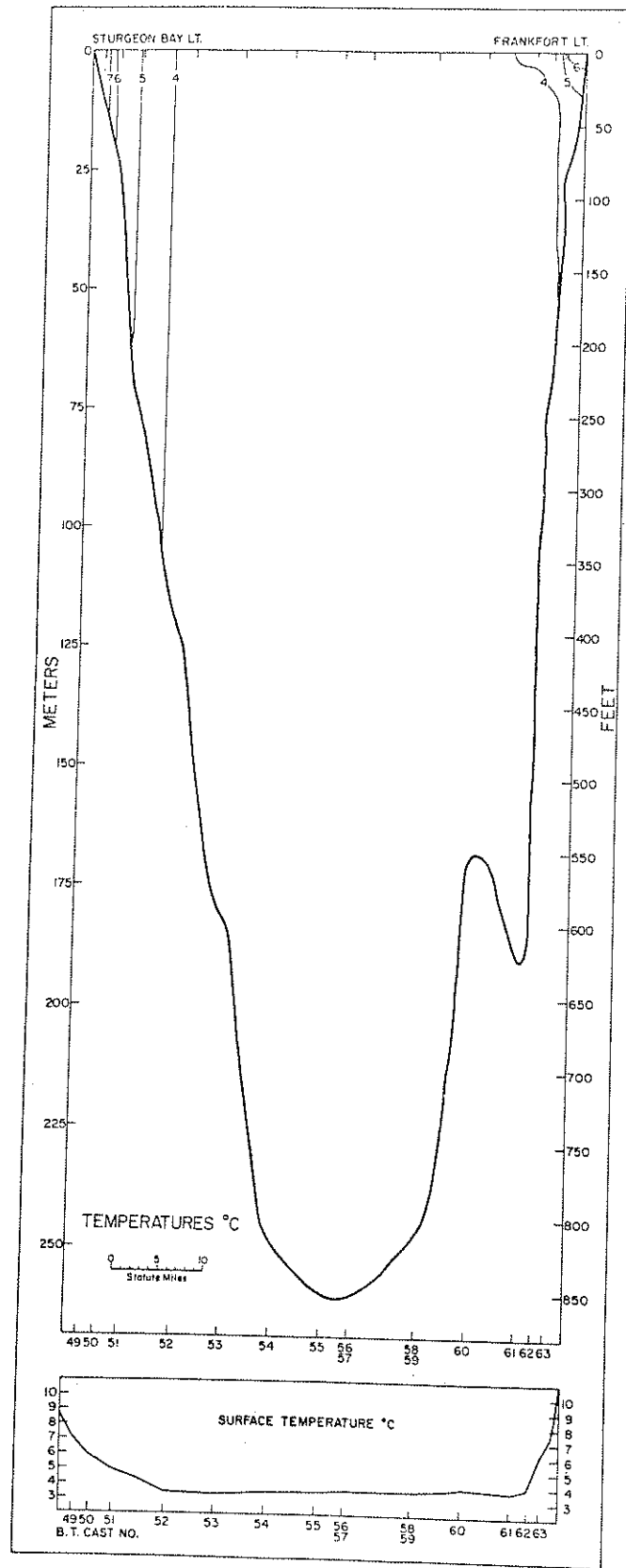


Figure 28.--Thermal profile, Sturgeon Bay to Frankfort, May 17, 1955.

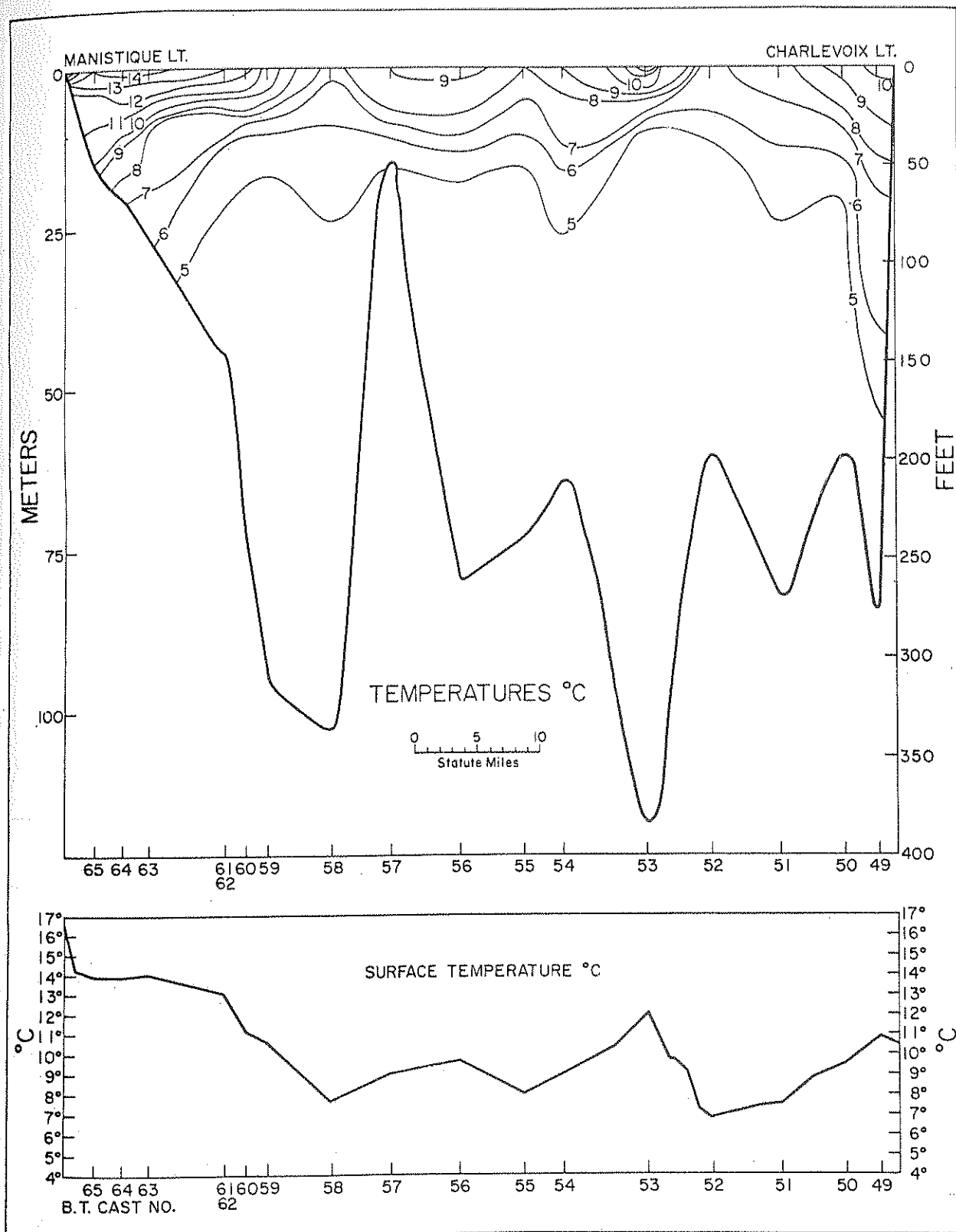


Figure 29.---Thermal profile, Charlevoix to Manistique, June 5, 1955.

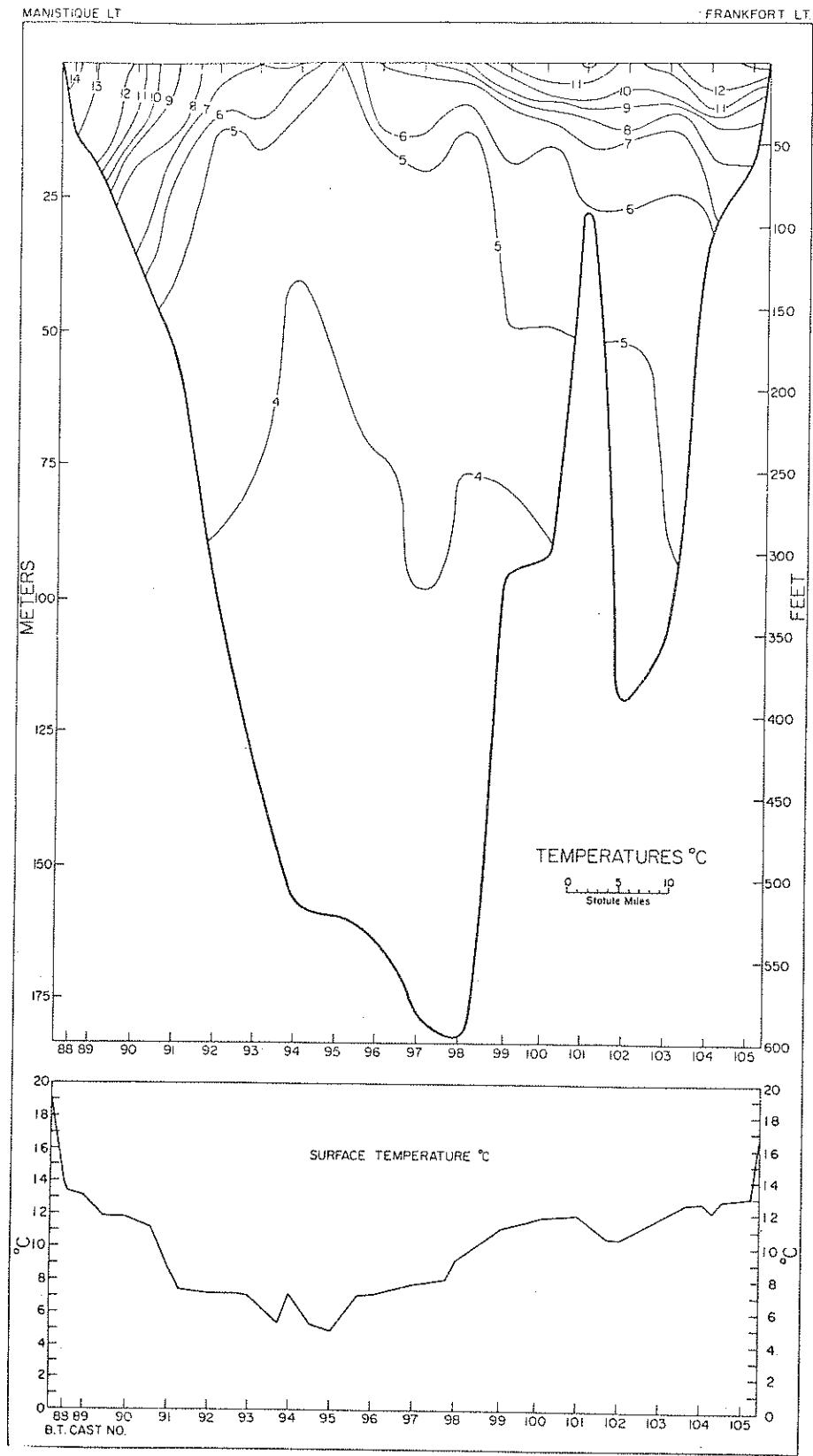


Figure 30.--Thermal profile, Manistique to Frankfort, June 9, 1955.