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DEPARTMENT OF ENGINEERING AND SCIENCE

RIDGES AND RAFTED ICE ON LAKE MELVILLE

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INTRODUCTION

Lake Melville's one hundred and forty mile long commercial shipping route inland from the Labrador coast (see Figure 1) is closed by fast ice each year, generally from the month of December until that of June. Icebreaker probes into the lake during this period have demonstrated thus far that formations of ridged, hummocked and overthrust ice constitute the most serious obstacles to ship progress. Thus, in any study aimed toward an extension of the Lake Melville shipping season, the consideration of these deformed ice features; their mode of formation, locations, size and structure is paramount. This paper presents some of the results from the first year's study of their occurrence on the lake.

FORMATION AND LOCATION

During the relatively short freeze-up period bodily movements of newly-formed ice occur, induced primarily by the action of wind stresses. Continuous and impact pressures which develop between neighbouring floes give rise to ice deformation and failure. Hence, ridged and overthrust structures are formed. Once a fast ice cover has been established, these structures retain their position and remain substantially unmodified in external form throughout the entire winter until melting of the upper surface becomes significant in the spring. Thus, the prevailing weather conditions during the freeze-up period determine the variable roughness of the ice cover, its geographical distribution over the lake and therefore determines ice navigation strategy for the remainder of the season.

The area of most intense ice deformation generally develops toward the east end of Lake Melville proper. The unconsolidated ice-field, driven by winds predominantly from the west and north-west, encounters resistance to motion when confronted by the southern shore and the presence of several islands in its drift path. The formation of a complex ice cover, particularly to the west of St. John and Green Islands, and in lesser intensity eastward from there, is quite typical. Thicknesses involved at the time of formation, however rarely exceed 1 m (3.3 ft.), with a few ridges of significantly greater depth also forming. By contrast, for the 1972-1973 winter season, thicknesses of 1.5 - 2.0 m (5 - 6 ft.) were not at all uncommon throughout the entire eastern half of the lake system. Accumulations of intensely pressured ice in the form of ridges and hummocked fields occurred, extending below the water level to depths typically of the order of 5 meters (16 ft.) and in a few places were estimated at twice this depth. The ridges were quasi - linear features, often several miles long. The most notable hummocked field measured at least two miles wide and six miles long and was located on the central axis of the lake, several miles west of St. John Island. Nine evenly spaced measurements encompassing a one square mile area of this hummocked field revealed ice thicknesses ranging from 1.2 - 7 m (4 - 23 ft.) with an average value of 3.2 m (10.6 ft.), even though drilling sites of low surface relief were deliberately chosen.

Several of the factors contributing to this heavy ice year on the lake are now discussed.

(a) Strong and sustained surface winds occurred at a time when significant quantities of ice, still unconsolidated, had been formed. Figure 2, sketched from an ERTS satellite photograph of the region taken on November 26, 1972, indicates the extent of ice coverage at that time. A light icebreaker sailed from the west to the east end of the lake on December 2 without difficulty. On board observations of ice coverage showed that there had been little change in conditions since the 26th and the edge of the only heavy ice reported was encountered just south of Eskimo Island. From December 1st to the 5th a very strong gusty wind storm prevailed. Table 1 gives the wind speed and direction extracted from the ship's log for this period.

During the night of December 2nd and 3rd a rapid westward migration of the heavy ice edge occurred. On December 5th it was reported just to the west of St. John Island; by the 9th, the ice formed a rough, continuous, consolidated cover abeam of Lowland Point and to the east. Between December 10th - 13th Lake Melville had frozen over completely. West of Julia Point, the lake, partly evacuated of ice by the strong winds, had refrozen in the calmer conditions that followed and the resultant ice cover subsequently developed a remarkably uniform thickness. Rafting of both the simple and interlocking (finger) types which formed in very thin ice were observed in this area.

(b) The wind direction during December 2nd - 5th was from the south-west and west, i.e. almost directly along the length of the lake. Thus the full cross-sections of the narrow channels in the St. John Island area were able to convey drifting ice from the main lake into the narrow eastern section which, this winter, was covered with an unusually thick and rough ice cover. In other years it is felt that these islands have presented a much greater impediment to the migration of ice floes since the predominant winds are from the north-west and thus the ice has tended to drift across these channels rather than through them.

(c) The ice pans present at the time of the storm ranged from about 5-30 cm (3 - 12 inches) thickness and thus were liable to intense deformation and failure. Matsuoka[1] has calculated the limiting thickness for ice sheets below which overthrusting can readily occur to be 20 cm.

RIDGE PROFILES

Cross sectional profiles were determined at four different ridge sites on Lake Melville during the latter half of March, 1973. The measurement was repeated at one of these sites in mid-May to see whether any changes had occurred. The locations of these sites are shown on Figure 3 and the corresponding profiles on Figures 4 - 8. Three of the four ridge sites investigated, RA1, RA2 and RA3, were located along a particular ridge, one of the longest and most noticeable of those which formed on the lake during this winter. In general it was intended that there should be a minimum of peripheral roughness at each site.

Transverse profiles were obtained in a manner similar to Kovacs[2]. At one yard intervals along the profile line the relative elevation of the upper snow surface was determined by levelling techniques. At each of these same points the snow depth was measured by probing down with a one inch drill until the hard upper ice surface was felt. Ice thicknesses were determined at five yard intervals, where possible, solely by manual drilling, using a six inch Swedish auger and a one inch SIPRE ice drill, both with extension. The maximum ice thickness penetrated was 6.1 m (20 ft.).

Profile RA1 - March (see Figure 4)

RA1, the largest profile measured, had a maximum sail height of 2.2 m (7.2 ft.) above the water level. This was a somewhat anomalous height for the ridge as a whole and did not persist for any great distance along its length. The ice at the centre of this ridge profile was too thick to be penetrated with the equipment available. Using the slope angle observed on the left side of the keel, a maximum keel depth of approximately 10.7 m (35 ft.) below water level is estimated. This is felt to be a reasonable estimate in view of the lateral extent of the ridge keel, the direction of the resultant sail-keel displacement and the value of the maximum sail height to maximum keel depth ratio which agrees well with the corresponding ratios derived from the other ridge A profiles. The maximum snow depth accumulated on RA1 was 2.5 m (8.1 ft.), which is in marked contrast to a depth of 10 cm. (0.3 ft.) registered on a flat ice surface nearby.

Profile RA2 - March (see Figure 5)

At this point of the ridge the profile dimensions were more typical, with a maximum sail height of 0.8 m (2.6 ft.) and a maximum keel depth of 3.8 m (12.4 ft.). It can be seen that in mid-March the snow cover almost obscured this section of the ridge. The maximum acculuIated snow depth measured at this site was 1.1 m (3.6 ft.).

Profile RA3 - March (see Figure 6)

Situated closer to the central axis of the lake, profile RA3 possessed a maximum sail height of 1.1 m (3.5 ft.) and the keel extended to a depth of 5.7 m (18.8 ft.). In this case the sail did not stand out from the surrounding rough ice so clearly. A maximum snow thickness of 1.4 m (4.5 ft.) accumulated at a distance of 4.6 m (15 ft.) to the east of the ridge sail.

Summary of Ridge A Properties

Certain points in common emerge between the three ridge A profiles sampled in mid-March even though their sites were separated by relatively large distances. To facilitate their discussion pertinent ridge parameters are presented in Table 2.

It is evident that by far the greater mass of these ridges resided below the water line. The thickness of the surrounding relatively flat ice cover at the time of measurement is included for comparison.

The ridge sails, which offered some of the higher forms of surface relief on the cover, arrested significant quantities of drifting snow. In each case the average snow depth to the east of the sail exceeded that to the west, perhaps since it lay on the leeward side to the prevailing winds. This snow was dense and wind-packed. An average snow density value of 0.44 gm/cc was obtained from twelve snow samples extracted at different depths from the three ridge A sites. The weight of snow alone which lay along a 25 m length of the ridge at site RA1, for example, has been calculated on the basis of this density to be no less than 700 tons-weight. The beam width of a large icebreaker is about 25 m.

The centre of ice mass in the keel was consistently displaced to the east of the much smaller sail. This was clearly the case for ridge site RA2 and RA3; for RA1, the mass centres of both the hard ice and the extrapolated profile also showed this tendency.

The ratio of maximum sail height to maximum keel depth and that of sail width (at the water line) to keel width (determined at its half depth) are given. In each case the height ratio was remarkably similar in magnitude, indicating that a ridge of this nature may be submerged to a depth of five times the sail height. The width ratios for RA2 and RA3 had almost the same value. Note however, that for the two smaller profiles the sail was outlined by a few abutting ice blocks frozen into their angular positions, whereas the sail at RA1 was composed of a pile of many ice blocks which may have reached equilibrium in a different manner. The sail slopes, grouped around angles of approximately 20° and 40°, had an overall average of 31°. The subsurface ridge slope angles are more difficult to determine; the average value for the more typical profiles, RA2 and RA3 was surprisingly low, being a mere 12°. This compares with an average of 24° for the surface faces and 36° for the subsurface faces of newly formed Arctic pressure ridges, Kovacs[2].

Profile RC1 - March (see Figure 7)

Profile RC1, located to the north-east of St. John Island, showed a maximum sail height of 1.0 m (3.2 ft.) and a keel depth of 3.6 m (11.9 ft.). The keel profile exhibited a more complicated shape and its centre of mass was displaced westward of the sail. The ice surrounding the ridge was of non-uniform thickness suggesting that compound rafting and ridging had taken place. The maximum snow depth of 1.1 m (3.5 ft.) occurred to the west of the sail.

Profile RA2 - May (see Figure 8)

Profile RA2 was remeasured in mid-May. By this time several wide open cracks had formed in the ice cover and conditions were deteriorating rapidly around the shores due to spring run-off. Most of the snow had by this time melted from around the ridge and, in addition, a considerable portion of the ridge sail itself had preferentially melted down, contributing to the numerous pools of water which lay on the surface of the ice. A radical change from the rough impenetrable January scene!

Unfortunately, the level of the water line was not determined in this case. The keel width discrepancy may be due to experimental difficulties, e.g. (a) the profile marker flags had melted out and fallen down, and (b) profiles obtained by drilling are limited due to the discontinuity of the information they provide.

The distance from maximum sail height to maximum keel depth was 3.9 m (12.9 ft.) in May, 0.6 m (2.1 ft.) less than that for March profile. This difference may be accounted for almost solely by the melting of the sail. Apparently there was negligible keel ablation during this period of two months. The ice thickness was substantially unaltered west of station W36 ft. and at station E72 ft., in which places the surface elevations were lower and where minimal melting was to be expected. Thus, a change in the overall isostatic adjustment must have occurred and it is possible that this change was responsible for the upward bending of the ice sheet observed to the west of the ridge. Although the ice cover appeared to be in a generally advanced state of decay, the subsurface ridge dimensions proved to be as formidable as ever.

INTERNAL RIDGE STRUCTURE

The projecting component ice blocks at each of the ridge sites measured 0.2 - 0.3 m (8 - 12 inches). This indicated the thickness of the interacting ice sheets at the time of ridge formation. The ice blocks composing each sail were firmly bonded together at their points of contact in such a way as to give large cavities and a porosity value of 40-50%. Plate I is a photographic representation of one side of a trench dug through the ridge sail near RAI in mid-May. Although the sail was reduced by melting, the overlying structure of different sized ice blocks could be clearly seen. The average length of the visible ice blocks was 1.1 m (3.6 ft.), about five times its average thickness, supporting evidence already presented to that effect by Kovacs[2] and Weeks and Kovacs[3].

During drilling at each site the following was noted. After penetrating the ridge sail, hard ice was encountered with few small voids being apparent. However, below a certain depth there occurred a transition, more or less sharp, (sometimes in the form of a few alternate layers) to soft ice. It was possible to push or punch the one inch drill down through this soft ice. A porosity value of 20-30% for the keel seems reasonable and agrees with estimates elsewhere - Weeks and Kovacs[3]. Using these values of porosity, the mean snow density and an assumed value of ice density, the ratio of snow and ice mass above the water line to that below has been calculated at as many ridge profile points as possible. Its value remains between 1 to 3 and 1 to 10.

RIDGE MODEL

A kinematic model which simulates the formation of pressure ridges has been constructed, following in principle that of Parmerter and Coon[4], with a view to testing its applicability to Lake Melville conditions. The flexural strength and Young's modulus values taken by Matsuoka[1] for his study of the fracture of sea ice in leads have been adopted for this study, since the ice thickness, mean temperature and salinity ranges he considered encompass those values which were indicated for the newly formed Lake Melville ice at the time of ridge formation. The other parametric values employed are similar to those used in reference [4].

For an ice thickness of 0.3 m it was possible to reproduce typical values of sail height and keel depth. The underwater extent of the keel far exceeded that of the sail peak and a keel-sail displacement was noted. However, the lateral extent of the keel and the subsurface slope angles were not reproduced.

In another attempt, using an ice thickness of 0.25 m, the model was run for an extended period of time. The ridge first grew until a limiting value of keel depth (3.5 m) was attained and then continued to augment laterally. By this means a realistic keel width and sail-keel displacement were also obtained. The computed profile is shown in Figure 9 (c.f. profile RA2).

It must be remembered, however, that the measured profiles did not represent newly-formed ridges and have been subject to changes in internal porosity, snow loading and possible keel ablation. Thus, the profile shape and overall equilibrum position may have changed since formation. The results are, nevertheless, sufficiently encouraging to pursue these investigations further.

ACKNOWLEDGEMENTS

The author would like to thank Mr. C. Langford and Messrs. W. Baikie, H. Campbell and R. Baikie for their valuable assistance in the field.

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[2] Kovacs, A. 1971, "On Pressured Sea Ice." Paper presented at the International Sea Ice Conference, National Research Council of Iceland, Reykjavik, Iceland.

[3] Weeks, W. F., Kovacs, A. 1970. "On Pressure Ridges, Report, U. S. Cold Regions Research and Engineering Laboratory, Hanover, N. H.

[4] Parmerter, R. R., Coon, M. D., 1972. "Model of Pressure Ridge Formation in Sea Ice." Journal of Geophysical Research. Vol. 77, No. 33.

TABLE 2

Ridge Site	Date	Sail Height	Keel Depth	Ice Sheet	Av. Snow Depth W	E	S-K Disp.	A	B	Upper Angles W	E	Lower Angles W	E
RA1	Mar.	2.2	10.7m*	1.8m	0.9m	1.9m	E4.2m*	0.21*	-	19°	41°	25°	-
RA2	Mar.	0.8m	3.8m	1.1m	0.5m	0.7m	E4.3m	0.21	0.08	18°	45°	16°	8°
RA3	Mar.	1.1m	5.7	1.5	0.8m	0.9m	E4.5m	0.17	0.10	44°	26°	17°	9°
RC1	Mar.	1.0m	3.6m	1.6m	0.8m	0.6m		0.28	-	47°	31°	-	-

A = Maximum Sail Height/Maximum Keel Depth; B = Sail Width/Keel Width (as defined in the text).

* = Estimated Quantity

RIDGE PROFILE SPECIFICATIONS

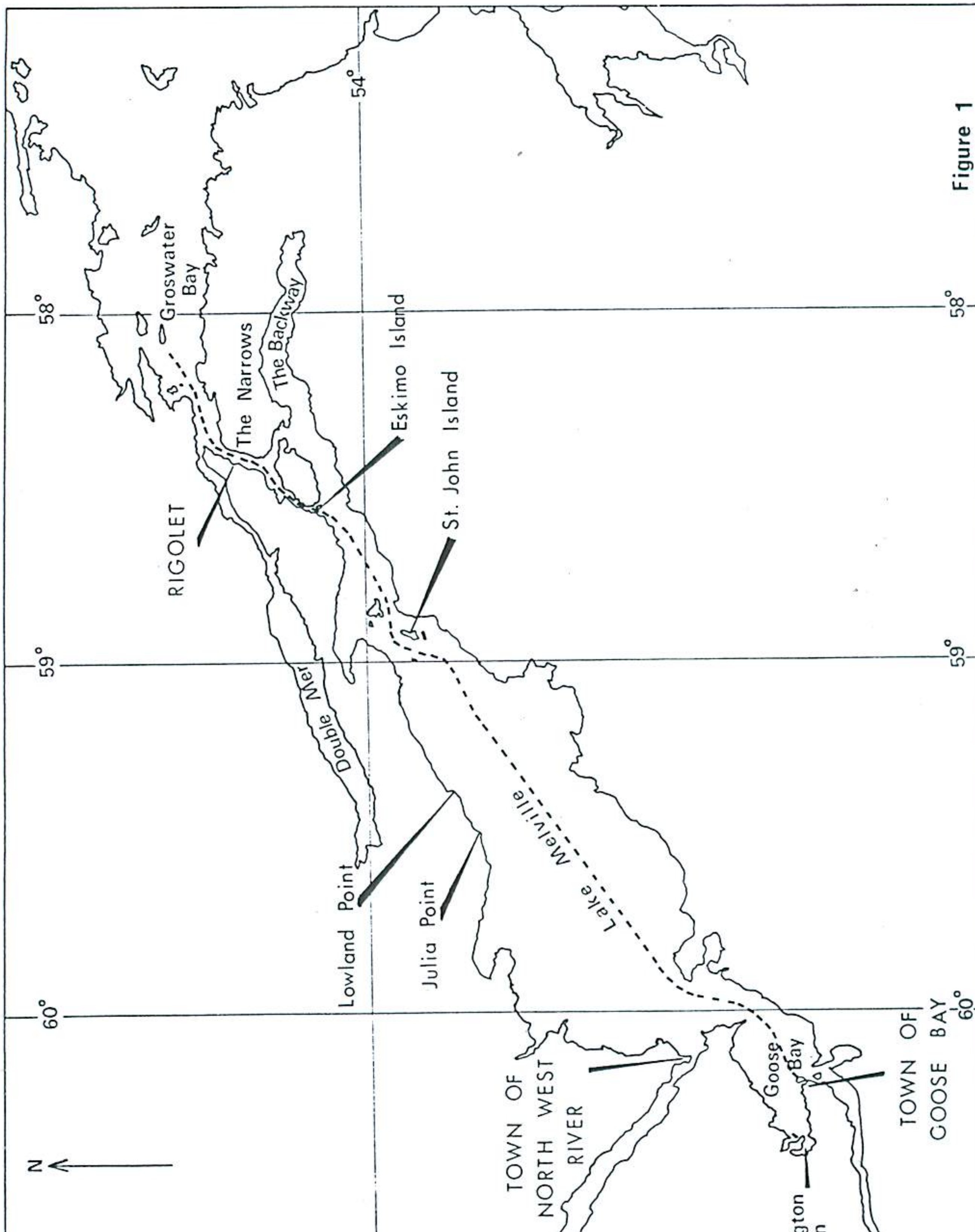
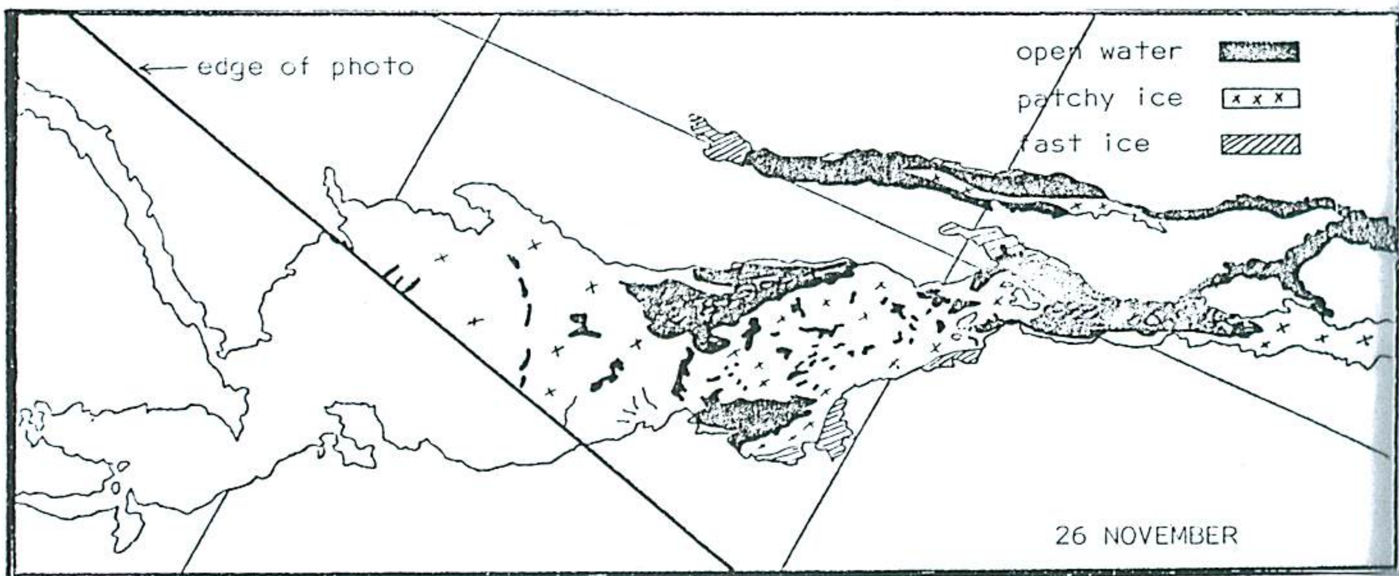

Groswater Bay
The Narrows
The Backway
Eskimo Island
St. John Island
RIGOLET
Double Mer
Lowland Point
Julia Point
Lake Melville
TOWN OF NORTH WEST RIVER
Goose Bay
TOWN OF GOOSE BAY
Terrington Basin
N
54°
58°
59°
60°

Figure 1



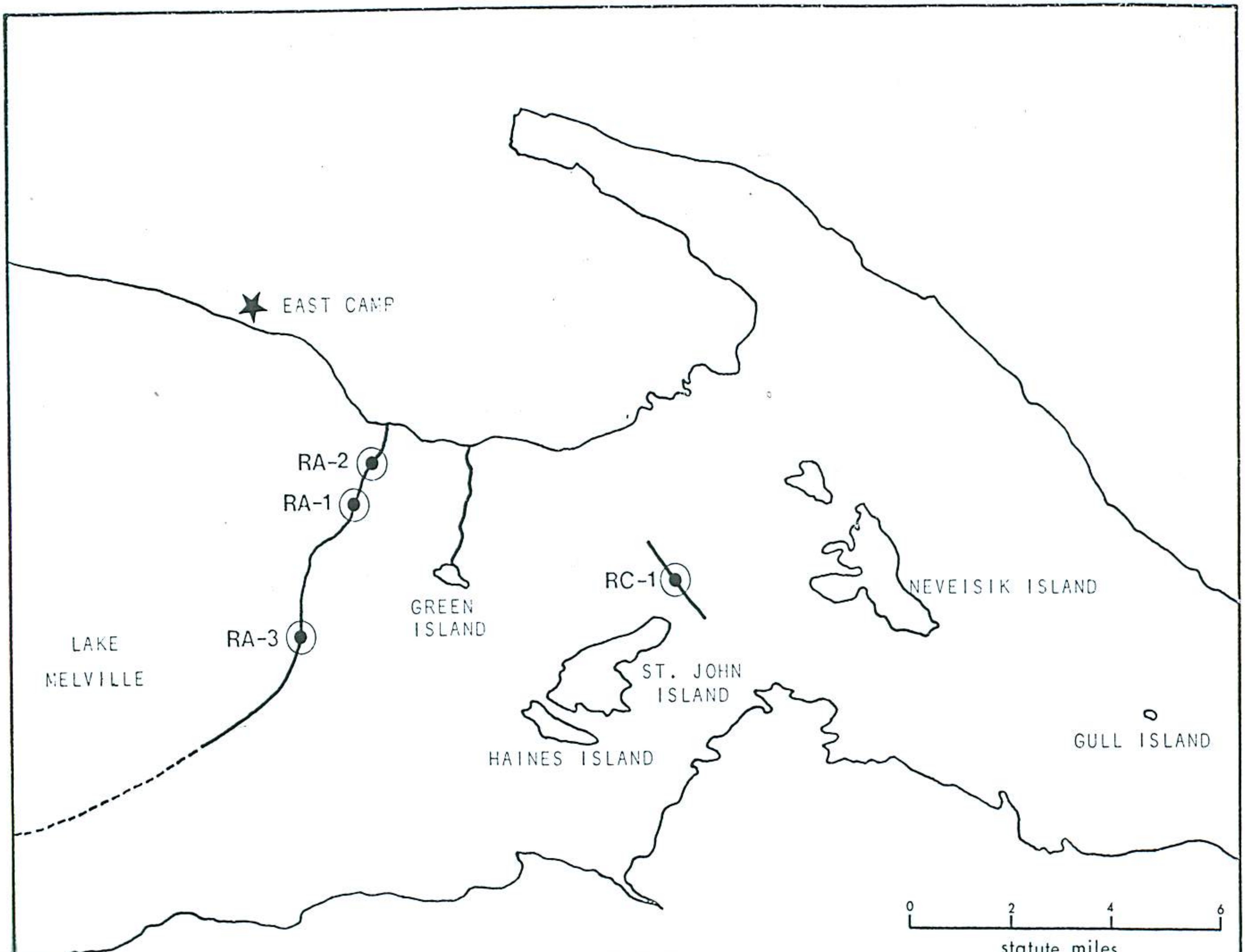
SKETCH OF SATELLITE PHOTOGRAPH

FIGURE 2

TABLE I.

Date	Time	Direction	Speed
Dec. 1	1200	light	airs
	1600	NNE	25
	2000	E	35
	2400	NE	40
Dec. 2	0400	NNE	45
	0800	NW	28
	1200	W	40
	1600	SW	45
	2000	SW	55
	2400	SW	40/60
Dec. 3	0400	WSW	50
	0800	WSW	65
	1200	SW	45/65
	1600	SW	40/60
	2000	NW	50
	2400	-	-
Dec. 4	0400	W	40/60
	0800	W	40/60
	1200	W	40/60
	1600	W	45/60
	2000	W	50
	2400	SW	50
Dec. 5	0400	SW	35/45
	0800	SW	40
	1200	SW	30/40
	1600	NW	30/35

LAKE MELVILLE WIND DATA - December 1 - December 5, 1972



LOCATION OF RIDGE STUDY SITES

Figure 3

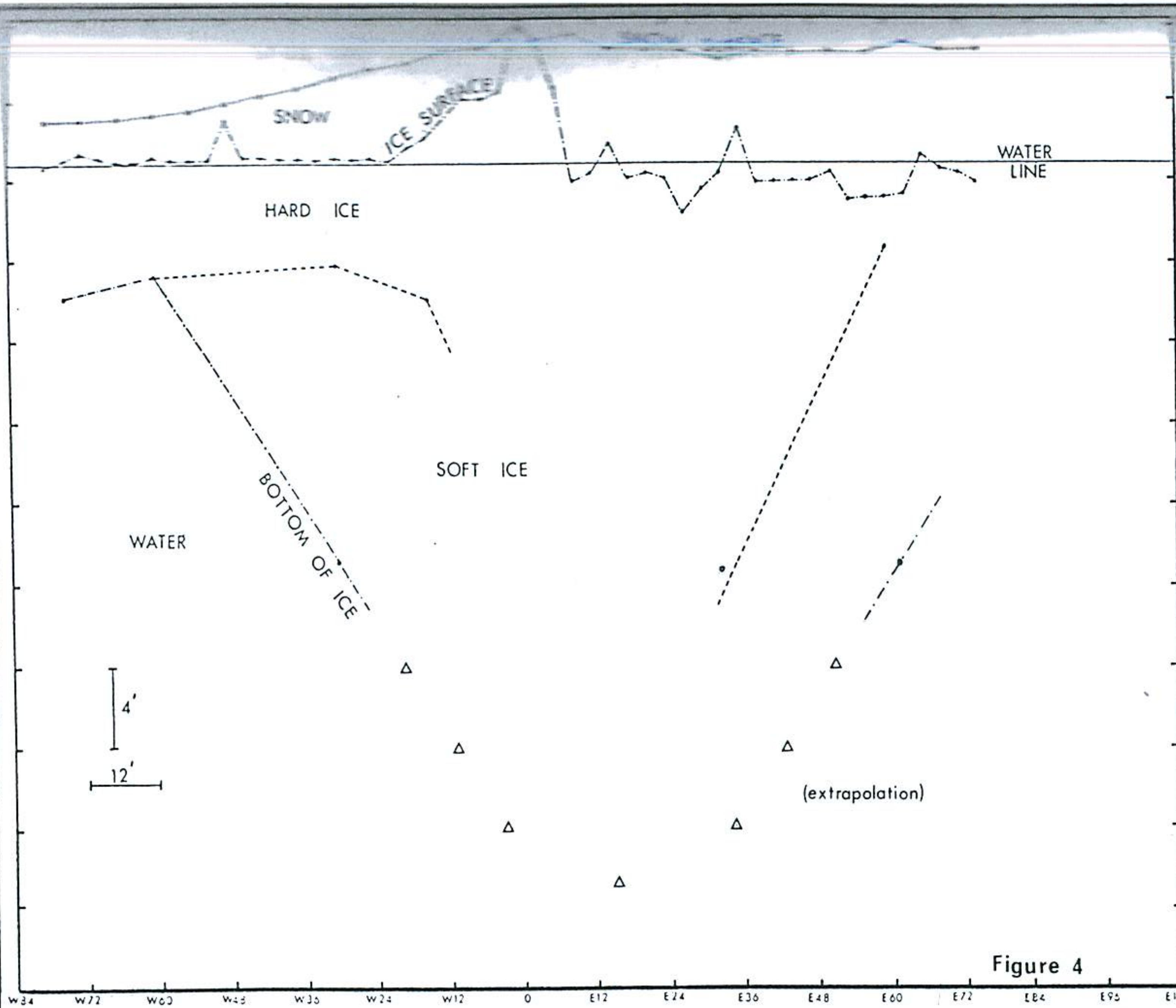


Figure 4

PLOT OF RIDGE, SNOW AND ICE PROFILE AT RA-1, MARCH 17, 1973

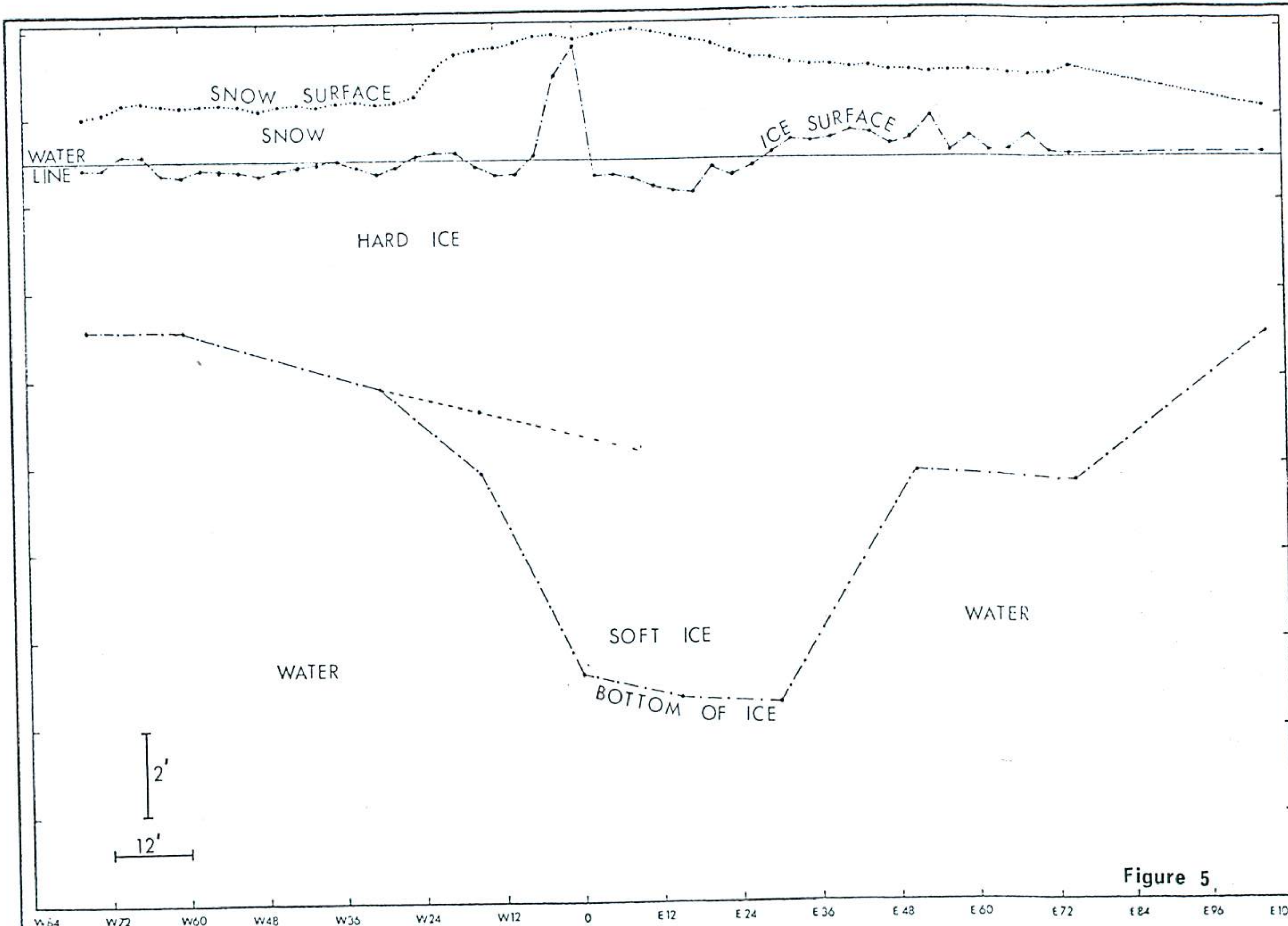
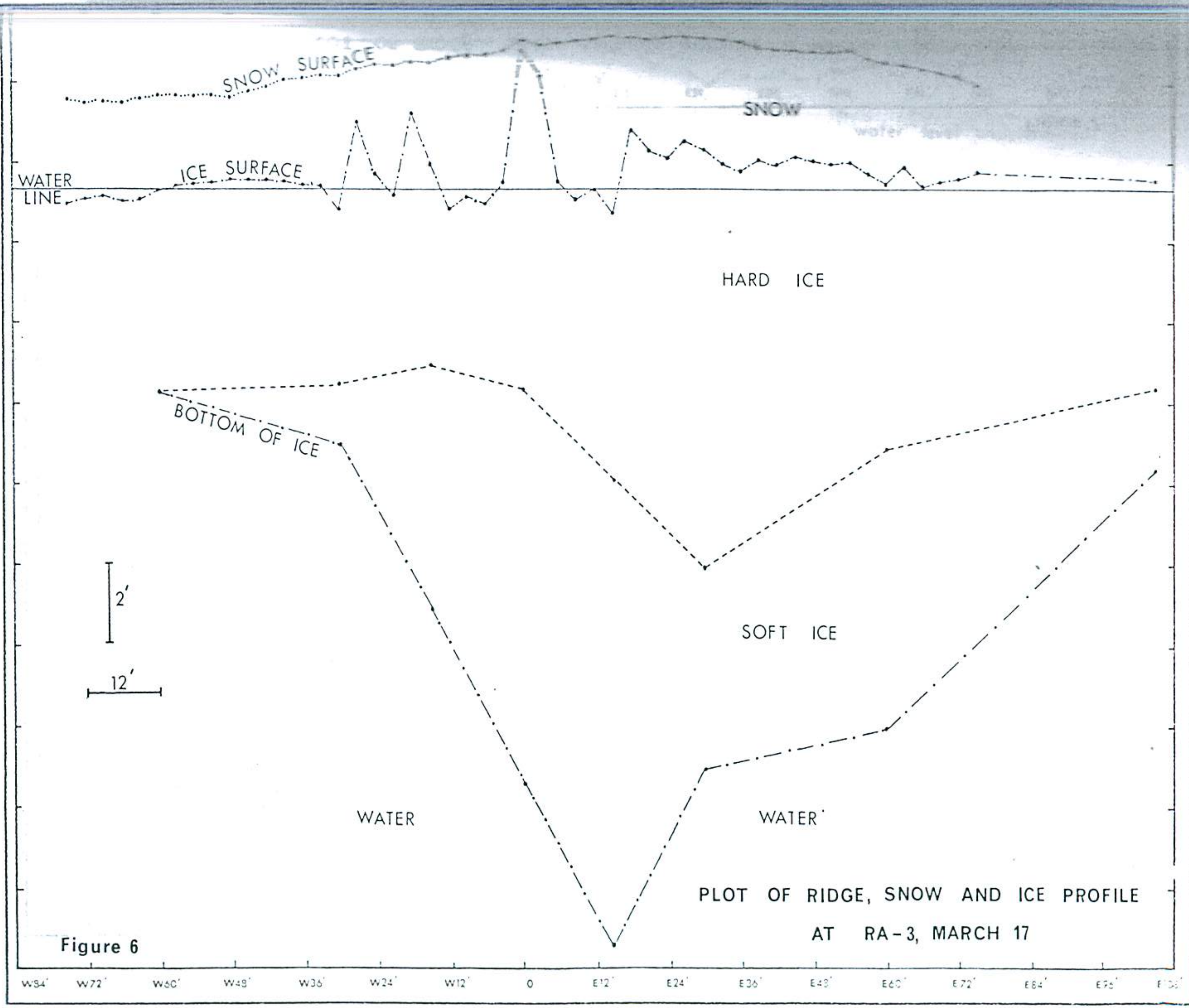


Figure 5

PLOT OF RIDGE, SNOW AND ICE PROFILE AT RA-2, MARCH 17, 1973



PLOT OF RIDGE, SNOW AND ICE PROFILE
AT RA-3, MARCH 17

Figure 6

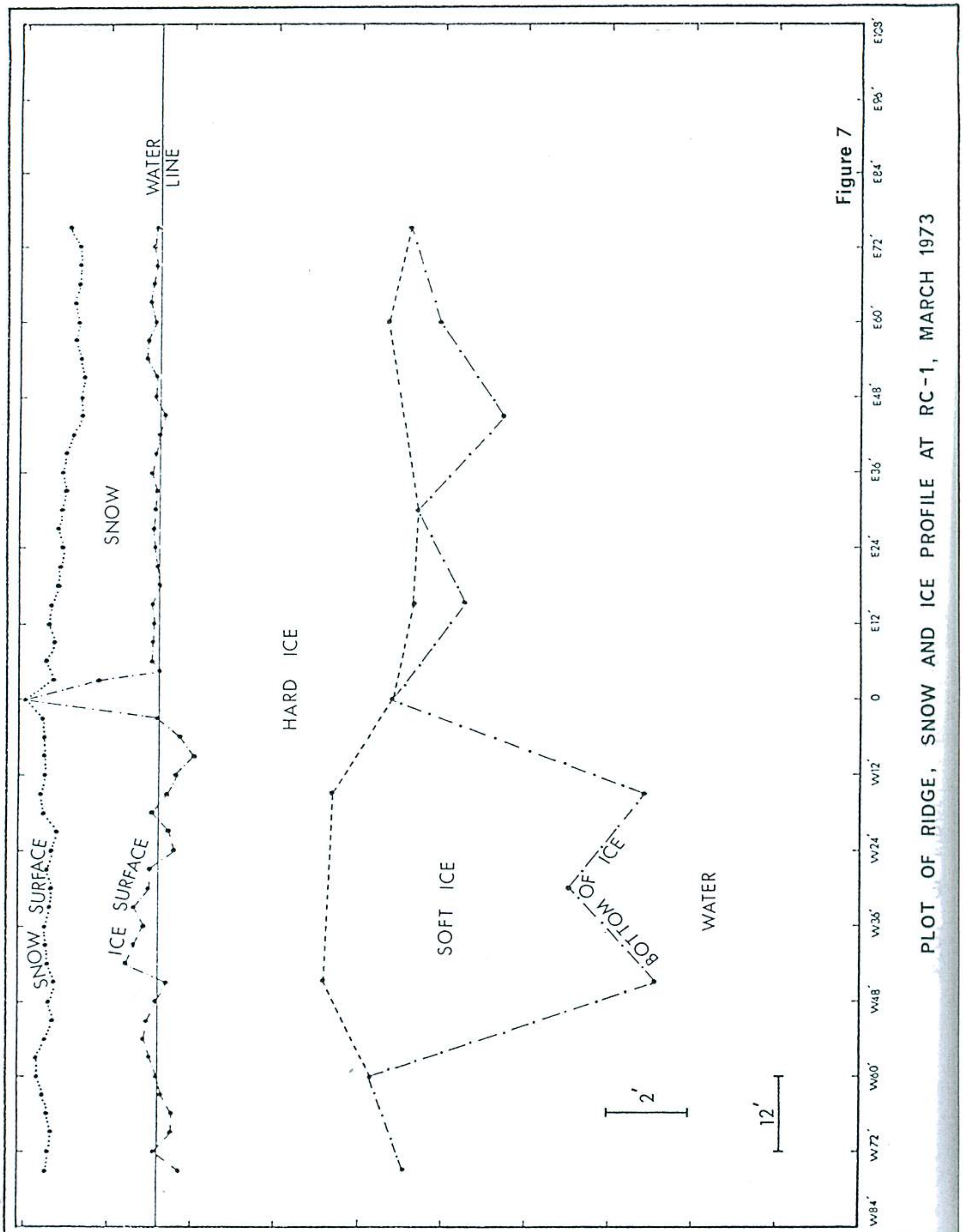


Figure 7

PLOT OF RIDGE, SNOW AND ICE PROFILE AT RC-1, MARCH 1973

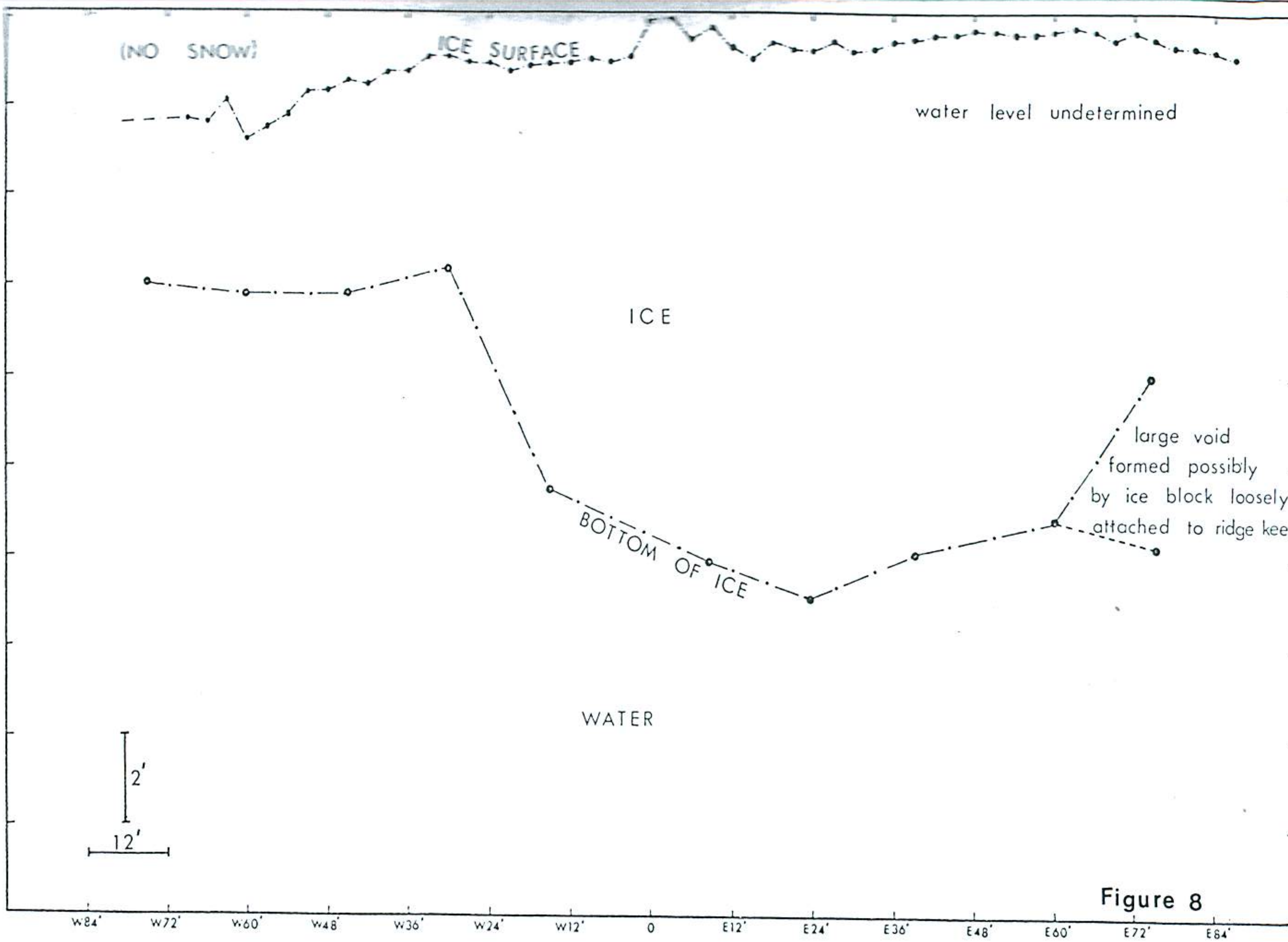


Figure 8

PLOT OF RIDGE, ICE PROFILE AT RA-2, MAY 13, 1973

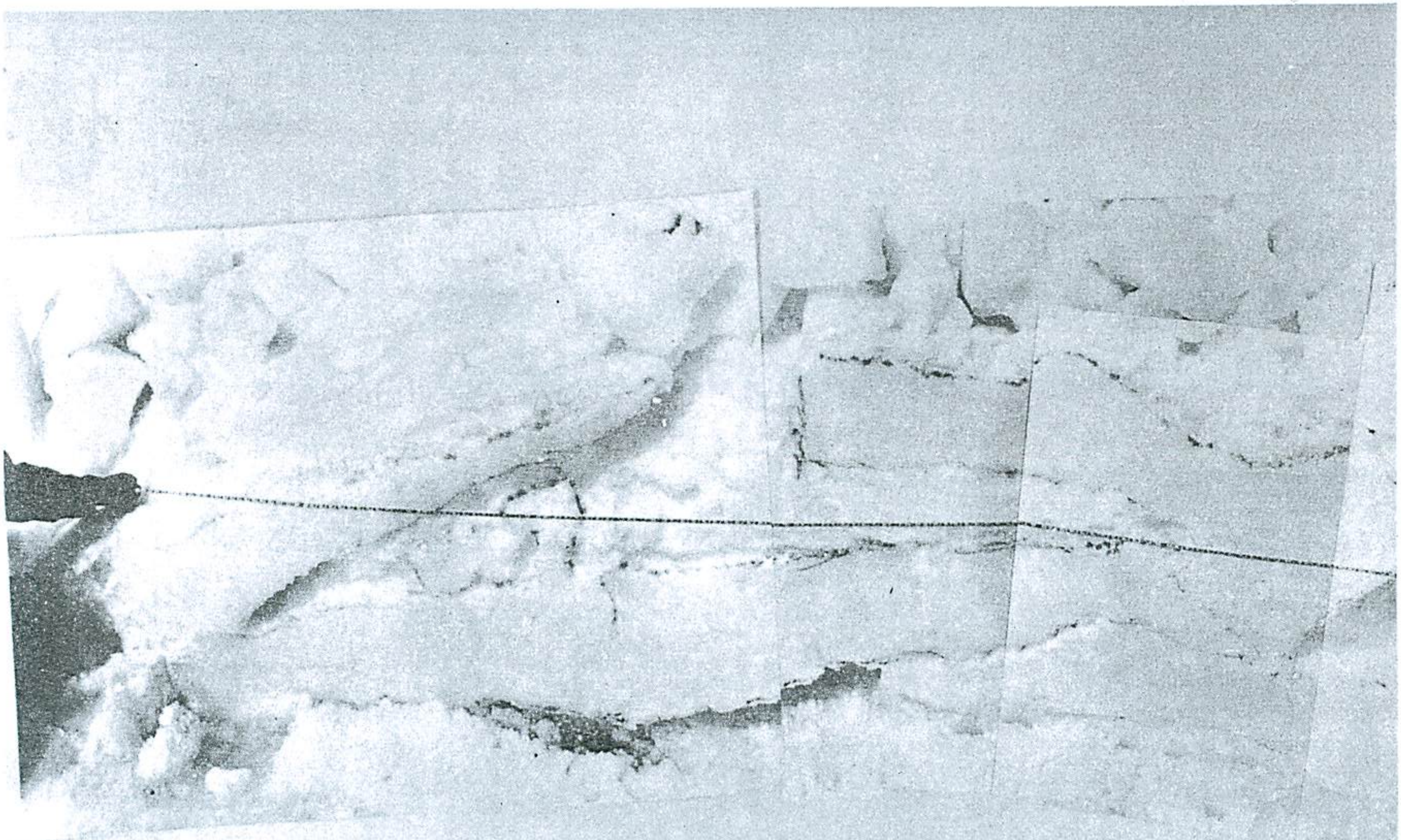


PLATE 1 Internal Ridge Sail Structure– near RA–1

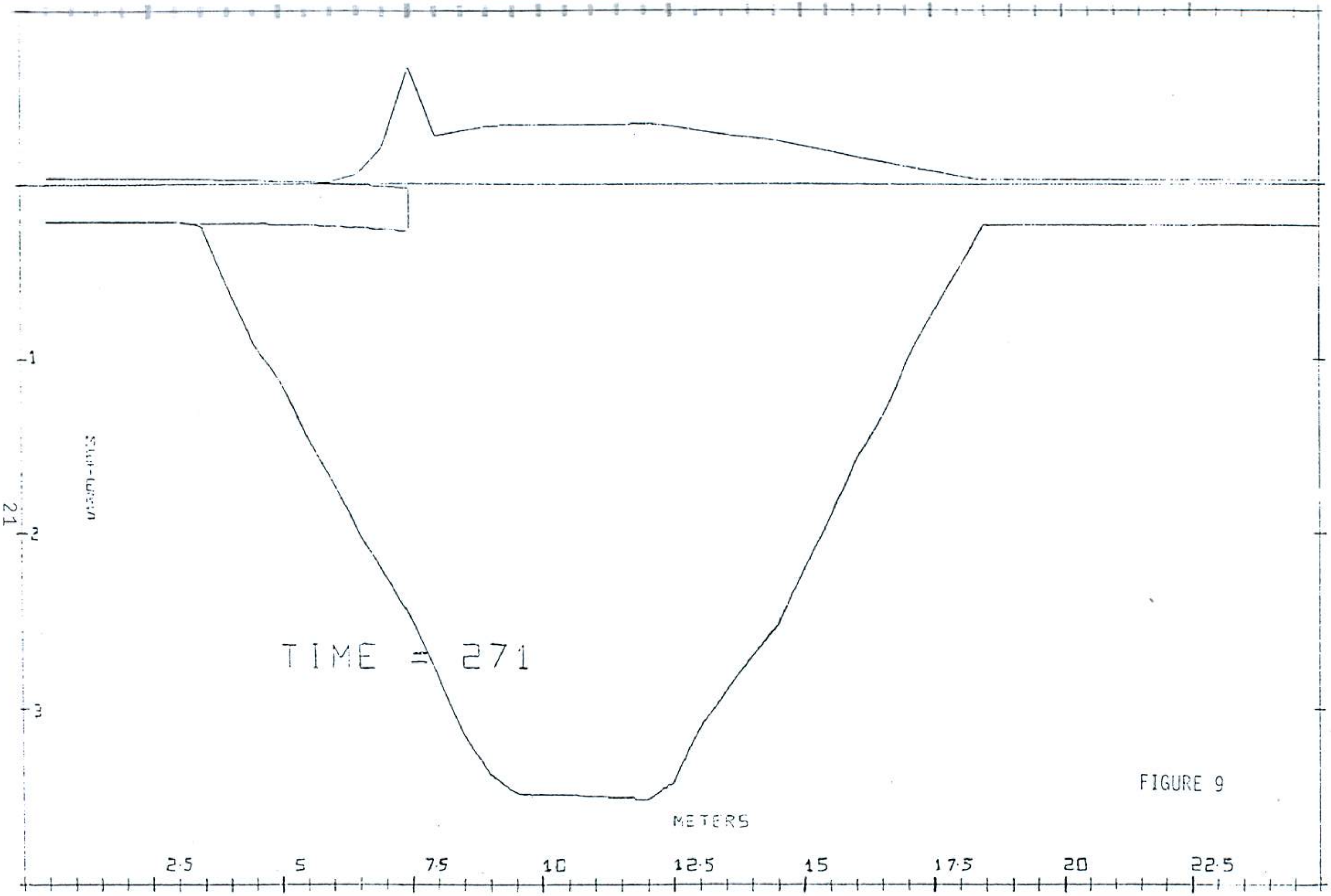


FIGURE 9

MODEL PROFILE - ICE THICKNESS 0.3 m

DISCUSSION

Professor R. Parmerter, AIDJEX, University of Washington, Seattle, Washington, U.S.A.:

The ridging you observe in Lake Melville seems to be quite different from ridging in arctic sea ice, since you state that most of the ridging occurrs before freeze up, when the lake is filled with broken pieces of ice. It is not clear that the kinematic model assumptions are valid in this case.

Professor D.A. Mills, Memorial University of Newfoundland, St. John's, Newfoundland, Canada:

At the time of ridge formation ice sheets with thickness of about 0.25 m and ranging beyond one hundred meters in lateral extent were observed. The characteristic length in bending of such a floating ice sheet is less than five meters. Thus, the bending and breaking response to transverse edge loads would be as predicted for the semiinfinite sheet in the kinematic model.

The process of ridge formation may well be initiated by successive rafting and fracturing events at the edges of large floes. In this case the "rubble" components and the "parent ice sheet" both have the same thickness.