PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

THE UNDERWATER SHAPE OF A GROUNDED ICE ISLAND OFF PRUDHOE BAY, ALASKA

By

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ABSTRACT

The underwater geometry of an ice island grounded off Prudhoe Bay, Alaska was mapped using a narrow beam sonar. Vertical section profiles of the submerged portion of the ice island were obtained by lowering a sonar transducer through the pack ice at eleven sites surrounding the ice island.

The ice island studied had previously been ballasted by freezing sea water on its upper surface in an attempt to ground it more firmly. This was part of a research effort to investigate the feasibility of using grounded ice islands as offshore platforms.

The results of the sonar investigation showed that the ice island was sharply undercut in some places. At a later date, the ice island broke into a few fragments and was partially abandoned.

INTRODUCTION

Ice islands, as they are known in the Arctic, are tabular (flat) - icebergs (Figure 1); their origins are quite different from the more common pinnacled iceberg shown in most photographs and more commonly associated with Arctic waters. The ice islands calve (break off) from a few glaciers which float out over the water; the resultant buoyancy allows the pieces to be quite large before breaking off. In contrast, the pinnacled bergs (most of which come from western Greenland and float down Davis Strait and into the North Atlantic) break off from glaciers that end on land; the abrupt fall of the shore at the water's edge and the height of the underlying land does not allow the tongue of the glacier to float. It breaks off into smaller vertically oriented pieces which usually fall a good way to float in equilibrium. Ice islands have been used for scientific stations; among these were an Arliss II, which broke up in early 1965 in the North Atlantic, and T-3, which is still occupied.

Occasionally these islands ground and then, because of resulting stresses break up. Recently, in 1968, an island estimated to be a few miles in extent, grounded off the north coast of Alaska, scattering fragments approximately on the 15 fathom depth line along a distance of over a hundred miles (Figure 2). Most of the pieces were about 120 feet thick, and averaged an acre in extent.

These islands, massive and strong as they are, can withstand the action of pack ice and resist its forces. Often impelled by subsurface currents (their 100-200 foot thickness is an order of magnitude greater than most pack ice) they can and do move at a different direction from pack ice, munching it up in a malevolent fashion (Figure 3). Pack ice appears to move as a result of forces generated by wind, surface currents, barometric pressure, shore contour and the rotation of the earth.

The massiveness and strength of these islands makes them ideal for stable platforms in the Arctic. Grounded, they are hard points, resistant to most pack ice action, and could be used for moorings, offshore platforms and the like.

The ice islands off Prudhoe Bay, Alaska were the subject of several scientific efforts. One rather novel effort was an attempt to effect a permanent "capture" of two of the islands.

The islands selected, each roughly the size of a football field, were about 100 yards apart and located 35 miles offshore at about the 15 fathom line, the minimum safe draft for jumbo tankers in the poorly charted waters of the Arctic. A University of Alaska team (under contract to Humble Oil & Refining Co.), sprayed sea water on the surface of the islands and increased the thickness from 100 feet to 110 feet, thereby adding approximately 10,000 tons of weight on to each island. This additional topside weight (approximately 10 percent of the ice island's original weight when grounded) caused the base of these ice islands to bear more heavily on the sea floor, and more firmly ground them. At the completion of the ice addition, a topographic survey was made of the above water portion of these ice islands (contours referenced to sea level were drawn) in order to determine the resulting shape of these ice islands. Subsequently, questions arose as to the underwater shape of these ice island, and a joint U.S. Coast Guard and University of Alaska field study was conducted to investigate this. The remainder of this present paper will discuss the field study of the underwater shape of one of these ice islands.

TECHNIQUES AND INSTRUMENTATION

The underwater shape of the ice island was determined by an acoustic echo-ranging technique. This technique is based upon the principle of generating an acoustic wave in the water, bouncing it off an object, and recording the echo from the object hit by the acoustic wave. The time it takes for the echo to return is a measure of the distance from where the acoustic wave is generated, to the object which produces the echo.

The device which generates the acoustic wave as well as receives the echo is known as a transducer. In this application, the transducer was attached to a long pipe which was lowered through a hole in the sea ice adjacent to the ice island. By orienting the transducer so that the acoustic wave traveled horizontally, it was possible to obtain a measurement of the distance from the transducer to the nearest point of the submerged portion of the ice island, within a given plane. By lowering the transducer from the sea surface to the sea floor and thereby obtaining distance measurements in each horizontal plane so traversed, a vertical profile of the submerged portion of the ice island in the vicinity of the transducer site can be obtained. By repeating this measurement process at many separate transducer sites, it is possible to obtain a sufficient number of vertical profiles to draw contours of the submerged portion of the ice island and thereby determine its underwater shape.

The sonar used to make the echo ranging measurements was the Kelvin Hughes Transit Sonar (Ref. 1). This commercially obtainable instrument was designed by the manufacturer for shipboard use as a side scan sonar system to observe the sea floor. It was used in the present application without any alteration other than mechanically attaching the transducer to a long aluminim pipe, and increasing the length of the electrical cable between the transducer and console to a length of 100 feet.

The sonar consists of a "shipboard" console and underwater transducer. The shipboard console measures 12x16x7 inches and weighs 40 pounds. It includes the transmitter, receiver, and recorder. Power input is 40 watts at 24 volts D.C. The sonar output is a 1 millisecond pulse at 48 KC, with a transmission rate of either 160 pulses per minute or 80 pulses per minute, for the 300 yard or 600 yard range scales respectively. The receiver provides the option of using stepped gain or time swept gain. The recorder is of the stylus and dry recording paper type, which provides a rectilinear display of echo arrival time versus paper transport. Paper speeds are 1.5 or 3.0 inches per minute for the 300 yard range scale, and 0.75 or 1.5 inches per minute for the 600 yard range scale. The 6 inch chart paper used by the recorder is available in 50 foot rolls.

The magnetostrictive transducer measures 6x4x44 inches and weighs 53 pounds. It is used for both transmitting and receiving. The beam directivity pattern is fan-shaped and measures 1.5 degrees between the 3 DB points in the wide beam narrow beam direction and 51 degrees between the 3 DB points in the wide beam direction. Some physical feeling for this extremely asymmetrical directivity pattern can be obtained by thinking of the acoustic energy as confined to a thin sheet which is perpendicular to the long axis of the transducer. When the long axis of the transducer is parallel to the long axis of the long aluminum pipe used for mechanical support, the beam directivity pattern is in the horizontal sheet configuration (51 degrees horizontal plane, 1.5 degrees vertical plane).

The "long aluminum pipe" previously referred to in this paper was actually composed of a string of eight-foot long, three-inch diameter aluminum pipes which were assembled and disassembled as the transducer was lowered and raised through the water. This pipe string was designed and fabricated at the Cold Regions Research Laboratory of the U.S. Army. Each length of pipe incorporated a sealed off air space within it so that the pipe would be neutrally buoyant in water. The sealed off internal spaces utilized "O" ring seals. The end couplings of the pipes were all universally interchangeable and uniformly keyed so that the orientation of the assembled pipe string was known and fixed.

A portable steel tripod was used to support the pipe string and transducer head during raising and lowering. A heavy-duty winch, of the type used on outboard boat trailers, with a 200 foot 3/16 inch diameter stainless steel cable rove through a ball bearing swivel block at the apex of the tripod, was attached to one of the legs. This winch had a brake and two reduction gear ratios. The tripod, the legs of which were demountable for easier portability, stood about ten feet high, and the base of the legs was on a circle approximately 6 feet in diameter.

A gasoline powered ice auger was used to make access holes through the sea ice cover surrounding the ice island. This apparatus consisted of a power head, a detachable eight-inch auger, and extension shafts. The gasoline driven power head incorporated a centrifugal clutch, which enabled starting and idling of the engine under load. Because it was anticipated that some fairly thick ice would be encountered, a number of augers had 4 and 8 foot extensions welded on. Bolted strings of extensions are very unsatisfactory; they are unsteady, break easily, and are usually very exasperating to assemble and disassemble.

FIELD WORK

The field operation was conducted during April 8-16, 1969. During this period the ice island was completely surrounded by a full cover of ridged and hummocked sea ice with a slight snow cover (Figure 4). Personnel and equipment had to contend with air temperatures which ranged down to minus twenty-five degrees farenheit. Personnel were lodged at the Atlantic Richfield base camp at Prudhoe Bay and transportation of personnel and equipment to the offshore island was accomplished by Bell Jet Ranger Helicopter. A shack on top of the ice island was used for lodging during periods when the Helicopter was grounded due to white-out conditions.

The sea ice cover in the vicinity of the ice island was irregular and variable in thickness from place to place. It was considerably more irregular and much thicker on the "windward" (north) side of the ice island. Obviously, the sea ice had drifted against the "windward" side of the island and had crumbled and buckled to form this rubble-line area. Figure 4 does not adequately display the gross irregularity of the sea ice cover since this photograph was taken in haze conditions and the subject is of very low contrast.

Access holes through the sea ice cover were derived and attempted around the entire perimeter of the ice island, but the only ones completed are shown in Figure 4 where they are labeled as Sites "A" through "K". About an equal number of access holes as were completed were attempted and abandoned. One prospective access hole reached 18 feet before it was abandoned. Several augers and extension rods became permanently stuck in the ice. Sea ice thicknesses at access holes completed ranged from approximately 4 to 8 feet.

Sites "A" through "K" were subsequently surveyed using an optical transit and their locations were determined with reference to a marker post on top of the ice island.

The gasoline powered head was satisfactory for holes in ice less than 6 or 8 feet thick, but could not develop enough torgue to drive the auger through thick old ice. Chips would jam on top of the auger, stalling the engine, and often causing loss of the auger, even when it was heaved on with the tripod and winch. Conceivably this problem could be solved by a water supply, either from a pilot hole or hose, which would float the chips away. Additionally, the two stroke gasoline engines showed the usual contrariness often experienced with that type of machine, and could not be reversed to back out the auger. Future users would do well to consider a reversible electric drive, with battery pack or portable generator.

The sonar, batteries, ice augers, tripod, and pipe sections were transported from work site to work site by man powered sled. Upon arrival at a work site (location where access hole had previously been completed), the tripod would be assembled and the sonar console set up on an oil drum (an ubiquitous feature in the Arctic). The aluminum pipe string would be assembled in twenty-four foot sections for ease of handling. The 3/16 inch cable of the hand winch on the tripod would be connected directly to the transducer for mechanical support. The pipe stem was not used to support a load but only to provide vertical stability and precise horizontal orientation to the transducer.

The procedure to make a sonar profile consisted of lowering the transducer to the sea floor and then cranking it up to the surface at a constant speed, while continuously pinging at and recording echoes from the ice island. The pipe stem had distance markings on it and the transducer depth was noted and marked on the sonar record at five-foot intervals as the transducer was raised. An annotated photograph showing the sonar profiling operation is presented as Figure 5.

The sonar profiling operation ran rather smoothly. The twenty-four foot sections of pipe string were connected together as the transducer was lowered to the sea floor by slacking the wire away under control of the winch brake. The transducer was then raised by cranking on the hand winch using the low-speed gear ratio. Most of the time the twenty-four foot segments could be disconnected as they emerged from the access hole without stopping the cranking of the winch. This procedure required three men: one to monitor and mark the sonar recorder; one to crank the winch; and one to disconnect the sections of pipe string. Actually, two men could perform the sonar profiling operation by stopping the winch to disconnect the pipe string sections.

The tripod and winch rig was very satisfactory for the purpose and worked well. Future users might make the tripod so that the legs folded together, for easier portability. The tripod could be easily slung beneath a helicopter; it was a well behaved load when slung vertically by its apex. The winch gave a satisfactory uniform motion to the wire and attached apparatus when heaving in; due to the nature of the brake, its motion was not so good when slacking away.

The sonar system was adequate for the job. Some mechanical trouble was experienced with the sonar recorder, however. Occasionally, the paper would tear or the chart paper drive would stop. This was attributed to excessive friction in the chart paper transport mechanism, which was caused by the extreme cold. A satisfactory field solution to this problem was achieved by lubricating some of the moving parts with butter and by manually applying a slight continuous tension on the chart paper. Needless to say, future users should have the sonar winterized.

RESULTS

The results of this field experiment consist of the vertical profiles of the underwater portion of the ice island that were obtained in the vicinity of the sample sites shown in Figure 4. The original recordings of these profiles are presented in Figures 6 and 7; and rescaled graphs of the same profiles are presented in Figures 8 and 9.

Perhaps a word of guidance is appropriate concerning the interpretation of the original recordings and rescaled graphs of the ice island profiles. The original recordings of the profiles do not give a true impression of what the true ice island profile really looks like because the horizontal and vertical scales of the original records are not equal to each other. A consequence of the inequality of the horizontal and vertical scales in the original recordings is the fact that one dimension is exaggerated with respect to the other dimension and shapes are not preserved. These shortcomings can be overcome by using the data contained in the original recordings to construct equal scale graphs.

The reason for the inequality of horizontal and vertical scales in the original recordings is because each of these scales is generated independently in any echo ranging profiling device in which transducer motion creates the profiling traverse. A common example of this is a depth recording chart produced by a fathometer aboard a ship. With regard to our echo ranging system used for the ice island experiment, the horizontal scale indicates the distance from the transducer to the ice island. This scale is developed by the fixed sweep rate of the sonar stylus which records the arrival time of the acoustic echo from the ice island. This scale is simply a function of sonar setting and was kept constant for all the profiles obtained in the present field experiment. The vertical scale indicates the depth that the transducer is below the sea surface. This scale is developed by the constant movement of the strip chart through the sonar recorder while the transducer makes its traverse from the sea floor to sea surface. This scale varied from profile to profile (it even varied a bit within each individual profile) since the winch cranking rate, which produced the transducer movement, was not always the same during the field experiment.

The original recordings of the ice island profiles contain both relevant and extraneous information. These recordings contain echo returns from the ice island, sea ice hummocks, calved ice blocks (all these are considered relevant) as well as extraneous information such as recordings of echo returns from the sea floor below the access hole, side reflection from the previously mentioned relevant features, and scattered echo returns following specular reflections. The recording of extraneous information is caused by the fact that the beam pattern function of the sonar transducer is not sharply defined at its nominal boundaries as is that of a flashlight beam. All sonar transducers have some degree of transmitting and receiving response at any angle. In addition, it should be noted that only the leading edge of the echo return is due to specular reflection, and only this portion of the echo return contains the echo ranging information that we desire.

The previous discussion concerning horizontal and vertical scales, and the various echo arrivals on the original recordings, was presented to give the reader who is not familiar with sonar systems, some feeling for what must be considered when reading the original recordings. Consideration of the various echo arrivals has been done by the authors in the formulation of line tracings of the original profiles, and these line tracings represent processed data which include all the relevant information present in the original recordings.

Figures 6 and 7 display both original recordings and line tracings of original recordings of the ice island profiles. Figure 6 contains profiles A through E, and Figure 7 contains profiles F through K. The line tracings of the original recordings are presented alongside of the respective original recordings to allow the reader to see what has been picked off the original recordings. These line tracings contain all the relevant information and have been annotated to indicate significant features responsible for producing various portions of the echo ranging profiles. The reader's attention is called to the fact that all these profiles have a large vertical exaggeration (the vertical exaggerations range from 2.9 in profile E to 5.6 in profile A) and consequently the shape of these profiles is misleading.

Figures8 and Figure 9 display equal scale graphs of the island profiles. Figure 8 contains profiles A through F, and Figure 9 contains profiles G through K. The equal scale graphs have been made using data picked off the line tracings of the original recordings. These equal scale graphs present the profiles of the ice island in their true shape.

Examination of the profiles contained in Figures 6 through 9 reveals some interesting characteristics.

Hummocked sea ice obscures the topmost portion of the ice island to a depth of twenty feet or so. Below that depth, all the profiles with the exception of profile K, have a tendency to flare out with depth. This tendency to flare out is very pronounced in profiles H and D, and least pronounced in profile F. Profile K is nearly vertical.

The flaring out does not in all cases continue to the bottom. Perhaps it is noteworthy that, profiles A, B, D, and E all seem to undergo a significant change in slope at approximately the forty-foot depth level. Some profiles show that the lower portion of the ice island is undercut in some places. This undercutting is most pronounced in the vicinity of site B, but it also exists in the vicinities of sites A and K.

The presence of a large calved ice block was detected in profile J. The lower surface appeared to extend to a depth of 65 feet.

CONCLUSIONS

An engineering conclusion of this paper is that the side scan sonar technique is effective in defining underwater ice shapes. The acoustic impedance contrast between sea water and natural ice is sufficient to produce a discernable echo. No evidence of a mushy surface layer capable of absorbing acoustic energy without significant acoustic reflection was encountered.

The profiles were used to generate a contour chart (Figure 10). There were not enough profiles (they were not close enough together) to draw a really good set of contours, but the contour chart does give a fairly good general idea of part of the underwater shape of the island, particularly on the south side.

On Figure 10, the known and inferred contours are shown as solid and dotted lines, respectively. Where a contour is undercut, it is crosshatched.

There are certain consistencies which corroborate the profiles and contours. In the traverse for profile C, the transducer struck a solid obstruction at 38 feet of depth; a plateau can be discerned on profile B. Hole C is almost in a direct line toward the island from hole B. A somewhat similar situation occurred at holes G and H. At hole G, the transducer was stopped at 20 feet (incidentally the bottom of the transducer is about two feet lower than the center of the acoustic beam to which depth measurements are related). Profile H shows a rather shallow slope. By tilting the top of the pipe string toward the island, it was possible to lower the transducer a little below the depth at which it was first stopped. The existence of the calved ice block (Figure 10) was not obvious at the time the field work was done. Holes L and M were stopped at 12 and 18 feet respectively; due to clogging of dry chips. The chips recovered were fresh water ice; the hole did not have any communication with the sea. It was not until the equal scale profiles were plotted, that the existence of this block was suspected. The photograph in Figure 11 was taken about 3 months after the field work was performed. In this picture the camera is looking almost due east. A crack can be seen in the island, running toward the North, starting just about in line with where hole F was. Because of excess buoyancy, the northwest corner of this piece has tilted up; the slope shown in the countours near G and H can be partly seen. Also, part of the hummocked ice and the calved ice block (Figure 10) can be seen.

No physical process is apparent to the authors that is capable of undercutting the base of the ice island after it had grounded. Drifting pack ice might impinge on the upper portion of the island and erode or accrete it, but the lower portion of the island should not be exposed to drifting pack ice. Nevertheless, the island is undercut in some sections. Perhaps this happened as a result of pack ice drift against a glacial tongue before calving produced the ice island, or perhaps the bottom surface of the ice island was fractured in this pattern during the grounding process.

The question as to whether the ice island was undercut subsequent to grounding has important ramifications concerning the utility of ice islands for fixed platforms. If the undercut surface was an original feature, it might be possible to sonar survey a number of grounded ice islands and then make use of one which is found not to be severely undercut.

ACKNOWLEDGEMENTS

The support for this experiment was provided through a contract by Humble Oil and Refining Company to the University of Alaska.

Ronald L. Morris, a Humble Oil Photographer, took the picture from which Figures 4 and 5 were made, and helped far beyond the call of duty in many tasks associated with the experiment.

Professor Ronald Mackay, Department of Engineering, University of Alaska, took the photograph from which Figure 11 was made. Other photographs he took of the island in its later condition revealed some aspects of its underwater shape off the northwest corner.

Mr. Marvin L. Messer provided excellent logistical support in the purchase of special equipment used. John Corpi and Richard Huitt assisted in many ways; their determination and resourcefulness in drilling holes through often thick pack ice were outstanding.

Mr. Austin Kovacs, through the U. S. Army Cold Regions Research and Engineering Laboratory designed, fabricated and loaned the pipe stem, while Mr. Leo Fisher of NAVOCEANO provided the sonar equipment.

Through the kindness of Dr. Max Brewer, Naval Arctic Research Laboratory, Barrow, an adapter to mount the sonar transducer to the pipe stem was fabricated.

Mr. Edward Miller of ERA Helicopters was the skilled and cooperative helicopter pilot without whose services in passenger and cargo transportation (with his delicate touch with sling load) under often difficult conditions, this operation would not have been possible.

Mr. Frank Love, the superintendent at Atlantic Richfield's Camp at Prudhoe Bay, made superb facilities available for food and lodging.

Master Chief Quartermaster John W. Fuller, U. S. Coast Guard did the drafting of the figures. Chief Yeoman Kenneth A. Pence, U. S. Coast Guard typed the manuscripts.

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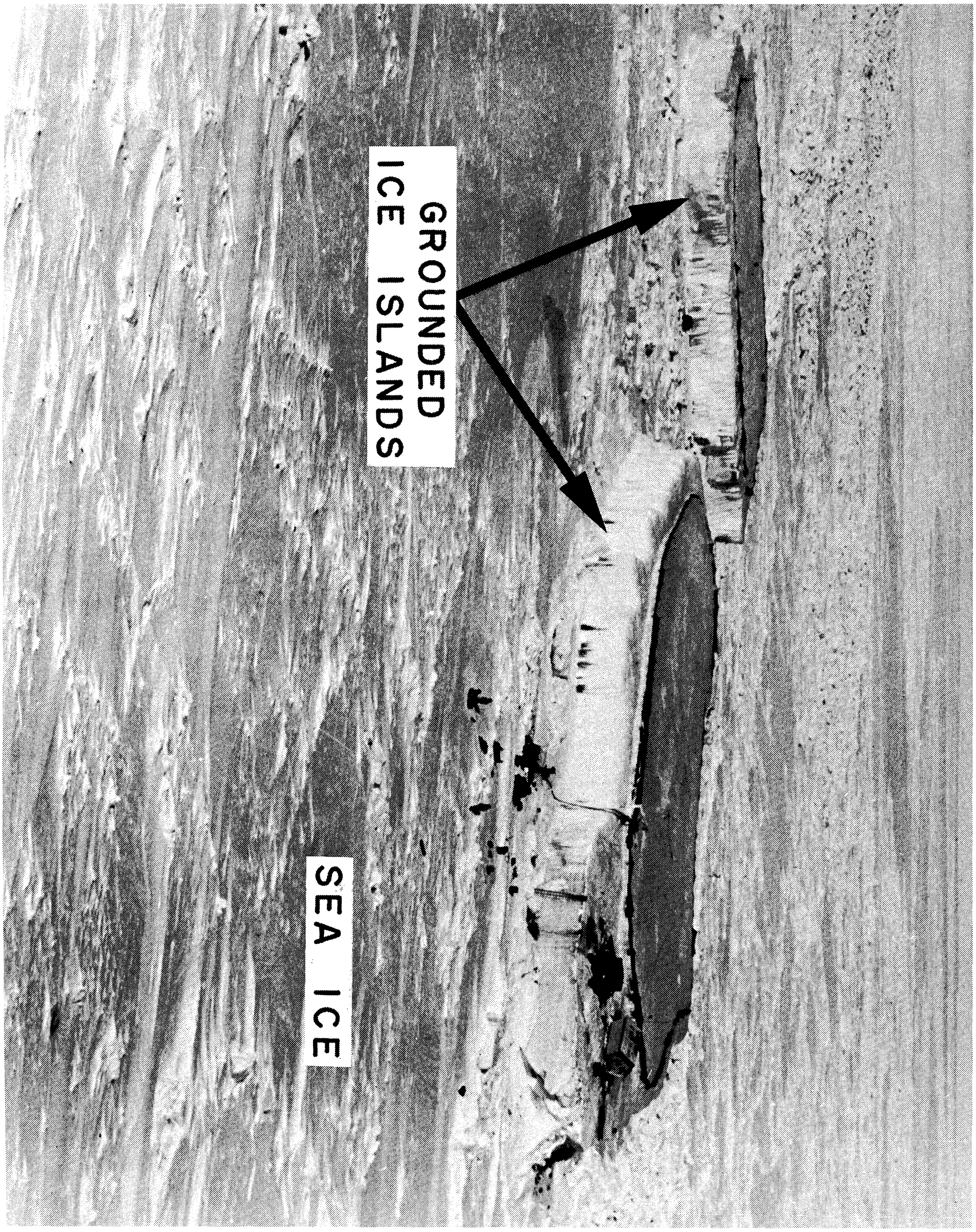
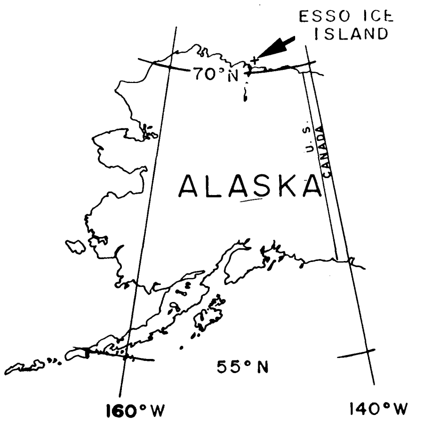


FIG. 1


ESSO ICE
ISLAND
70°N
ALASKA
U.S.
CANADA
55°N
160°W
140°W

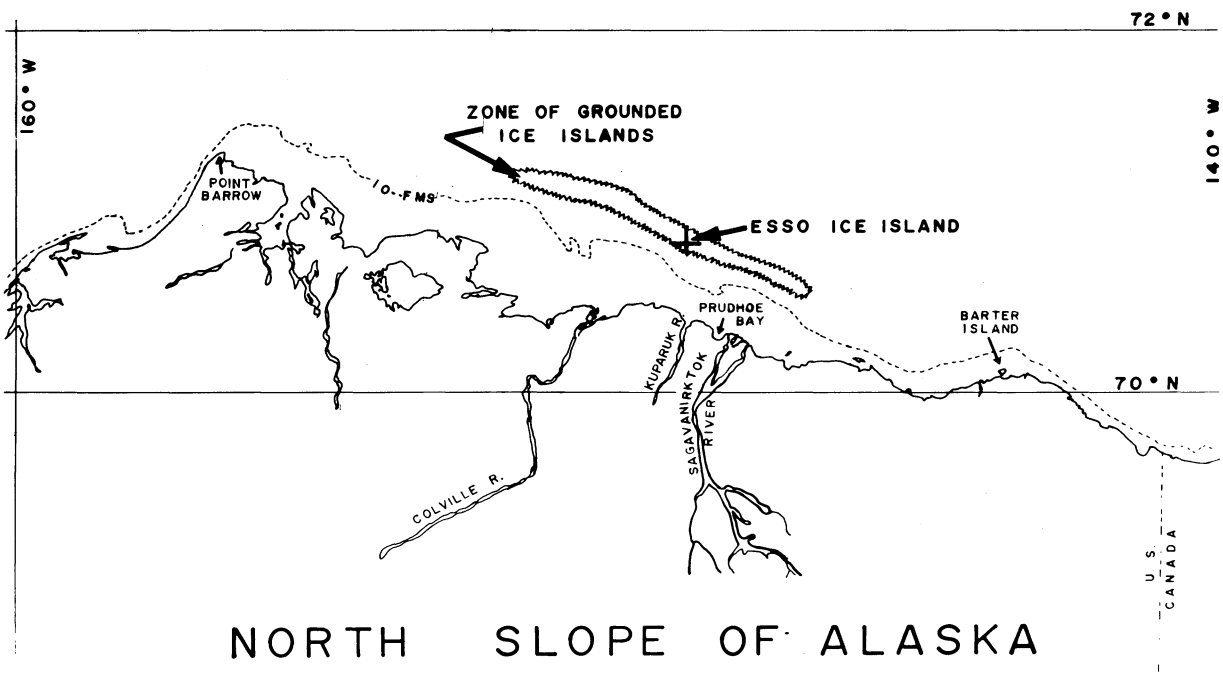

72°N
160°W
140°W
ZONE OF GROUNDED
ICE ISLANDS
POINT
BARROW
10 FMS
ESSO ICE ISLAND
PRUDHOE
BAY
BARTER
ISLAND
KUPARUK R.
SAGAVANIRKTOK
RIVER
70°N
COLVILLE R.
U.S.
CANADA
NORTH SLOPE OF ALASKA

FIG. 2

10

130

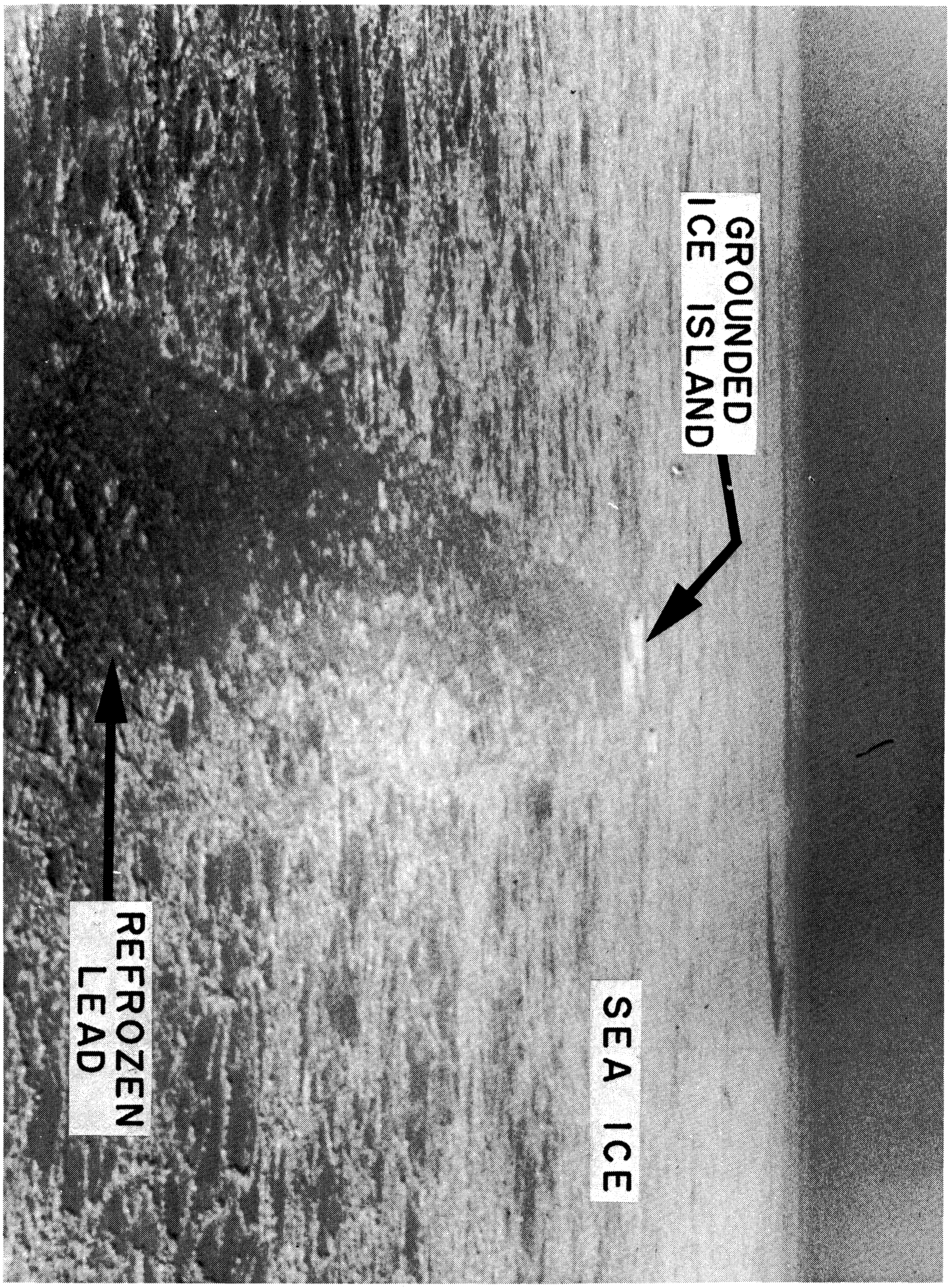


FIG. 3

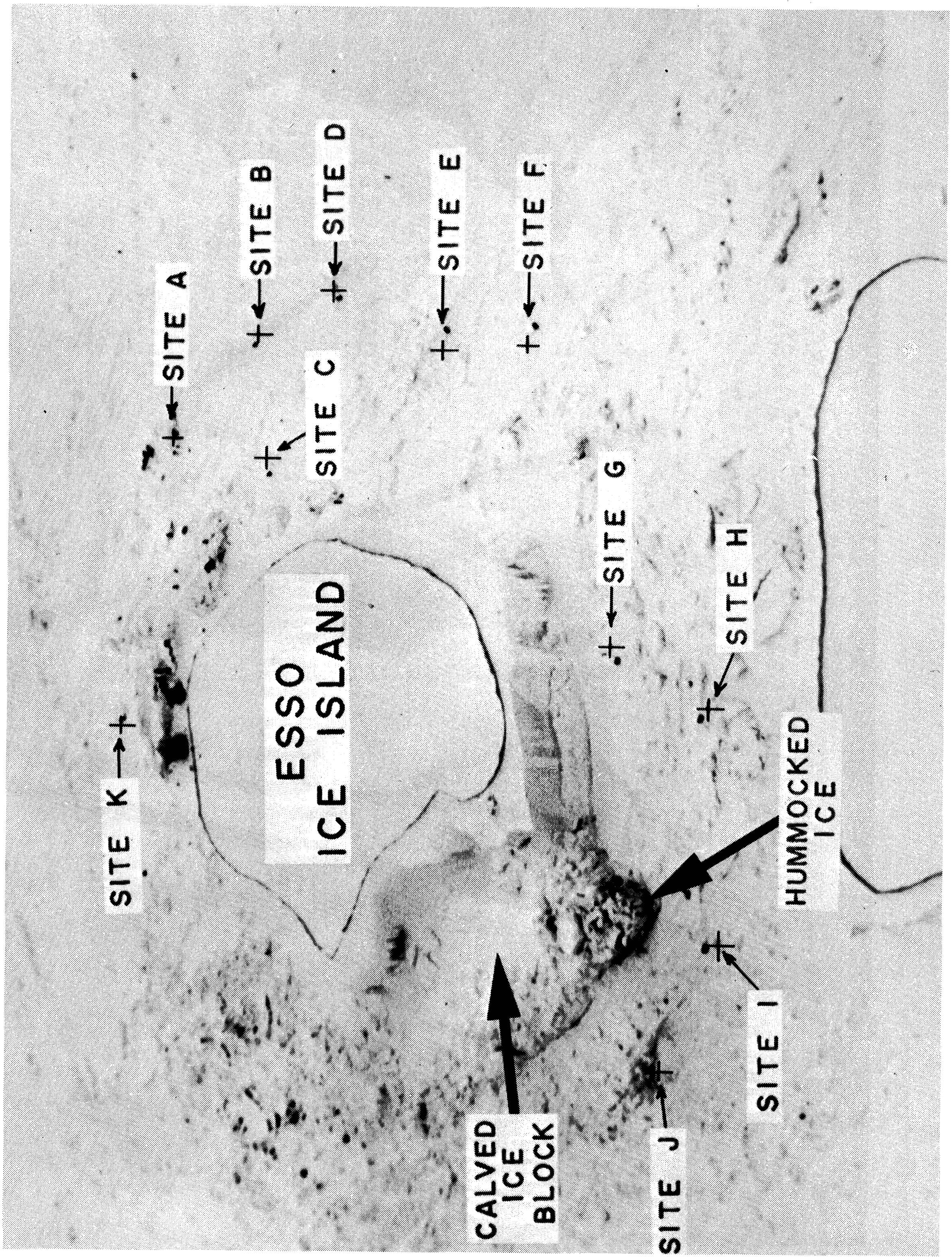

SITE A
SITE B
SITE C
SITE D
SITE E
SITE F
SITE G
SITE H
SITE I
SITE J
SITE K
ESSO
ICE ISLAND
CALVED
ICE
BLOCK
HUMMOCKED
ICE

FIG. 4

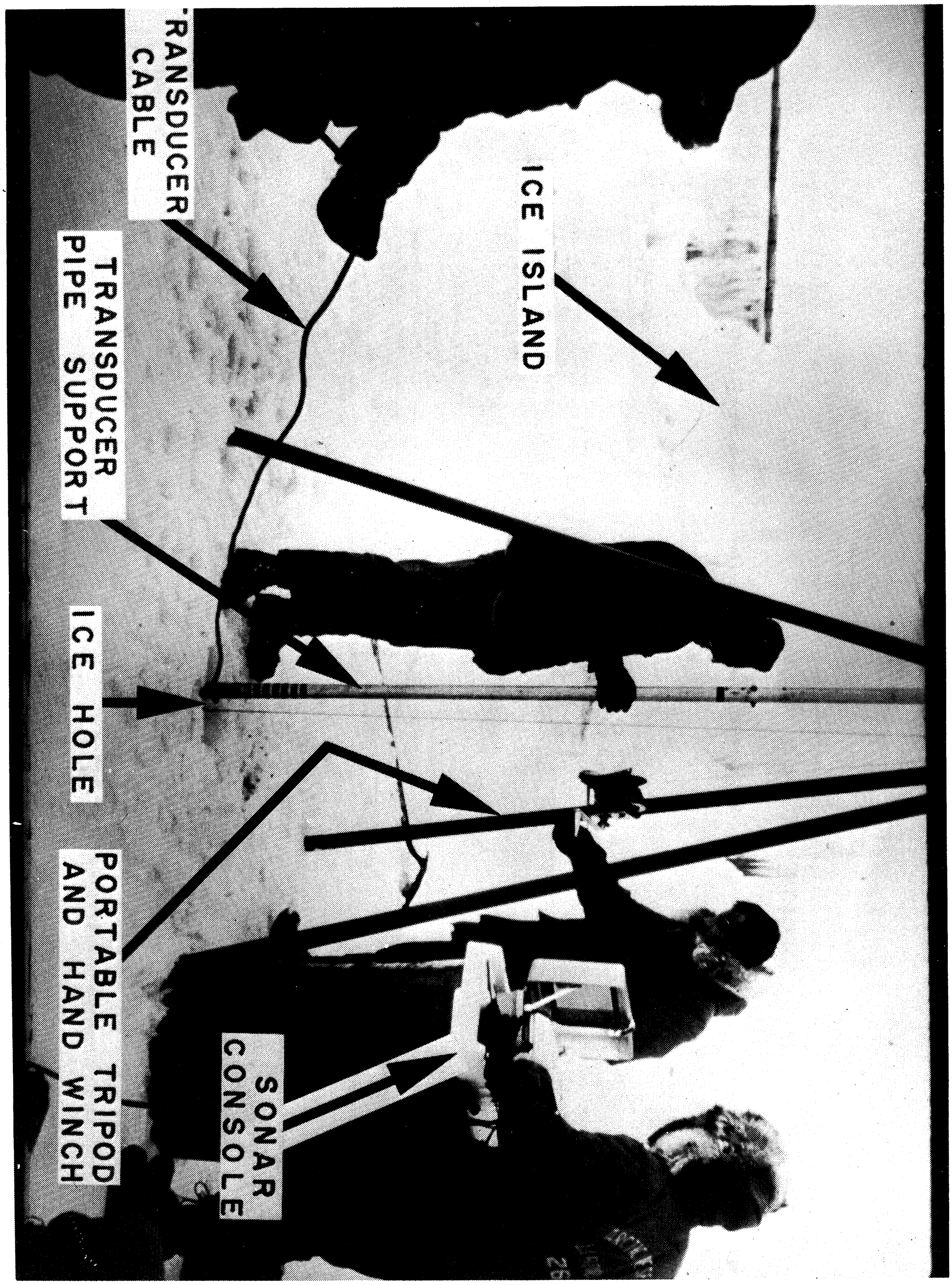
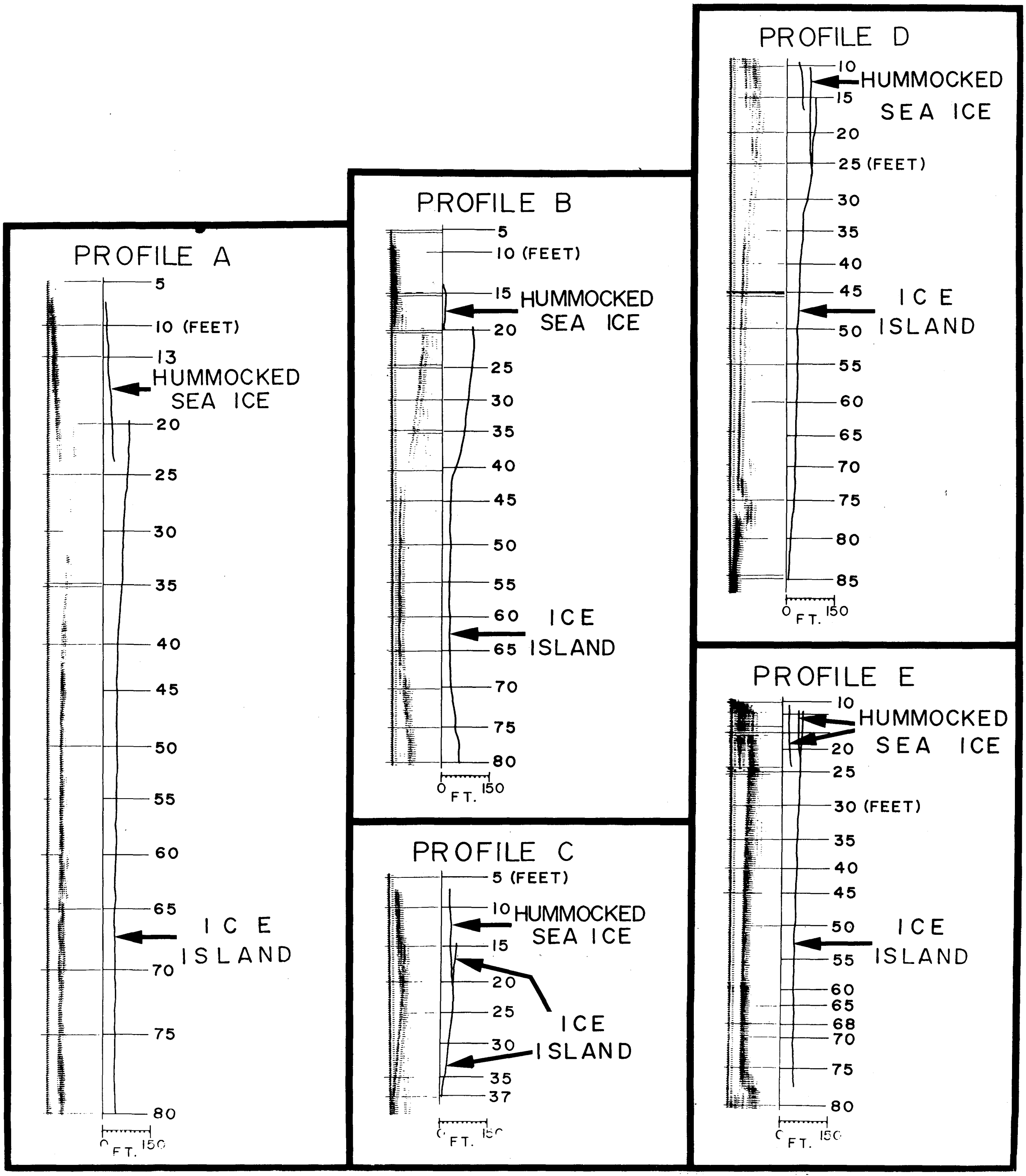

RANSDUCER CABLE
ICE ISLAND
TRANSDUCER PIPE SUPPORT
ICE HOLE
PORTABLE TRIPOD AND HAND WINCH
SONAR CONSOLE

FIG. 5



PROFILE A
5
10 (FEET)
13
HUMMOCKED SEA ICE
20
25
30
35
40
45
50
55
60
65
70
ICE ISLAND
75
80
0 FT. 150
PROFILE B
5
10 (FEET)
15
HUMMOCKED SEA ICE
20
25
30
35
40
45
50
55
60
65
ICE ISLAND
70
75
80
0 FT. 150
PROFILE C
5 (FEET)
10
HUMMOCKED SEA ICE
15
20
25
30
ICE ISLAND
35
37
PROFILE D
10
HUMMOCKED SEA ICE
15
20
25 (FEET)
30
35
40
45
50
ICE ISLAND
55
60
65
70
75
80
85
0 FT. 150
PROFILE E
10
HUMMOCKED SEA ICE
20
25
30 (FEET)
35
40
45
50
ICE ISLAND
55
60
65
68
70
75
80

FIG. 6

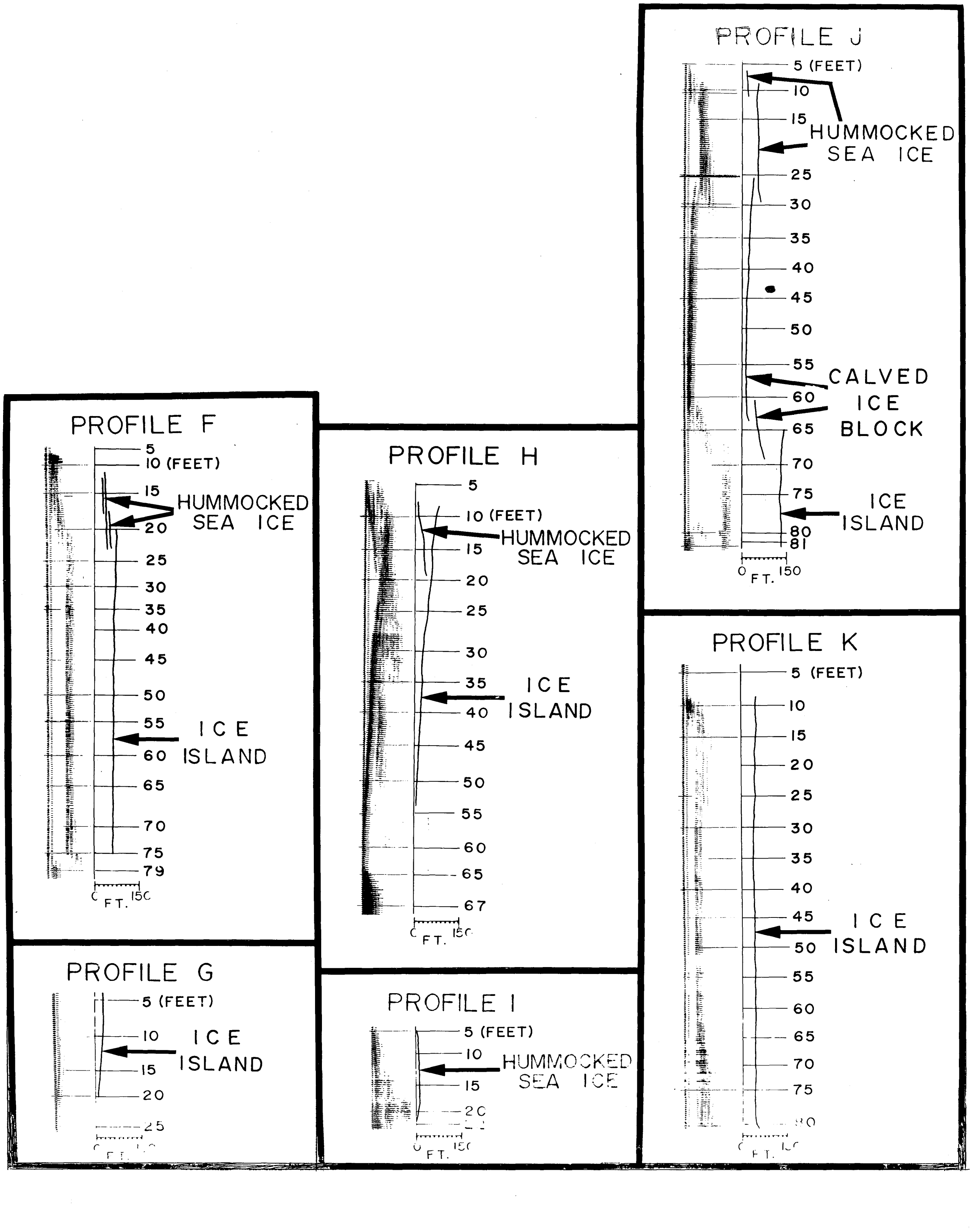

PROFILE F
5
10 (FEET)
15
20
25
30
35
40
45
50
55
60
65
70
75
79
HUMMOCKED SEA ICE
ICE ISLAND
FT. 150
PROFILE G
5 (FEET)
10
15
20
25
ICE ISLAND
PROFILE H
5
10 (FEET)
15
20
25
30
35
40
45
50
55
60
65
67
HUMMOCKED SEA ICE
ICE ISLAND
FT.
PROFILE I
5 (FEET)
10
15
HUMMOCKED SEA ICE
FT.
PROFILE J
5 (FEET)
10
15
25
30
35
40
45
50
55
60
65
70
75
80
81
HUMMOCKED SEA ICE
CALVED ICE BLOCK
ICE ISLAND
0 FT. 150
PROFILE K
5 (FEET)
10
15
20
25
30
35
40
45
50
55
60
65
70
75
ICE ISLAND

FIG. 7

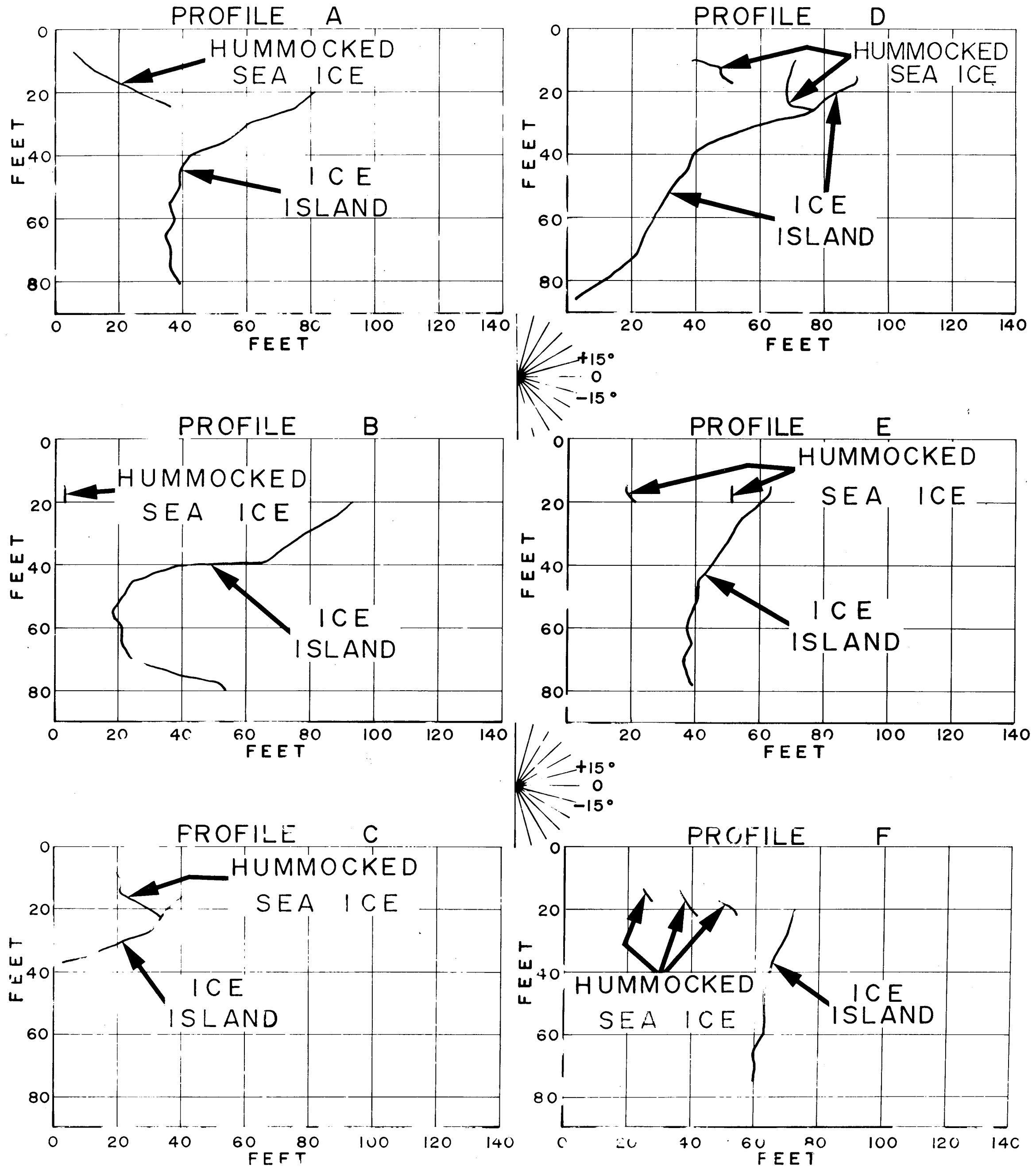

PROFILE A
HUMMOCKED SEA ICE
ICE ISLAND
PROFILE B
HUMMOCKED SEA ICE
ICE ISLAND
PROFILE C
HUMMOCKED SEA ICE
ICE ISLAND
PROFILE D
HUMMOCKED SEA ICE
ICE ISLAND
PROFILE E
HUMMOCKED SEA ICE
ICE ISLAND
PROFILE F
HUMMOCKED SEA ICE
ICE ISLAND
FEET
+15°
0
-15°

FIG. 8

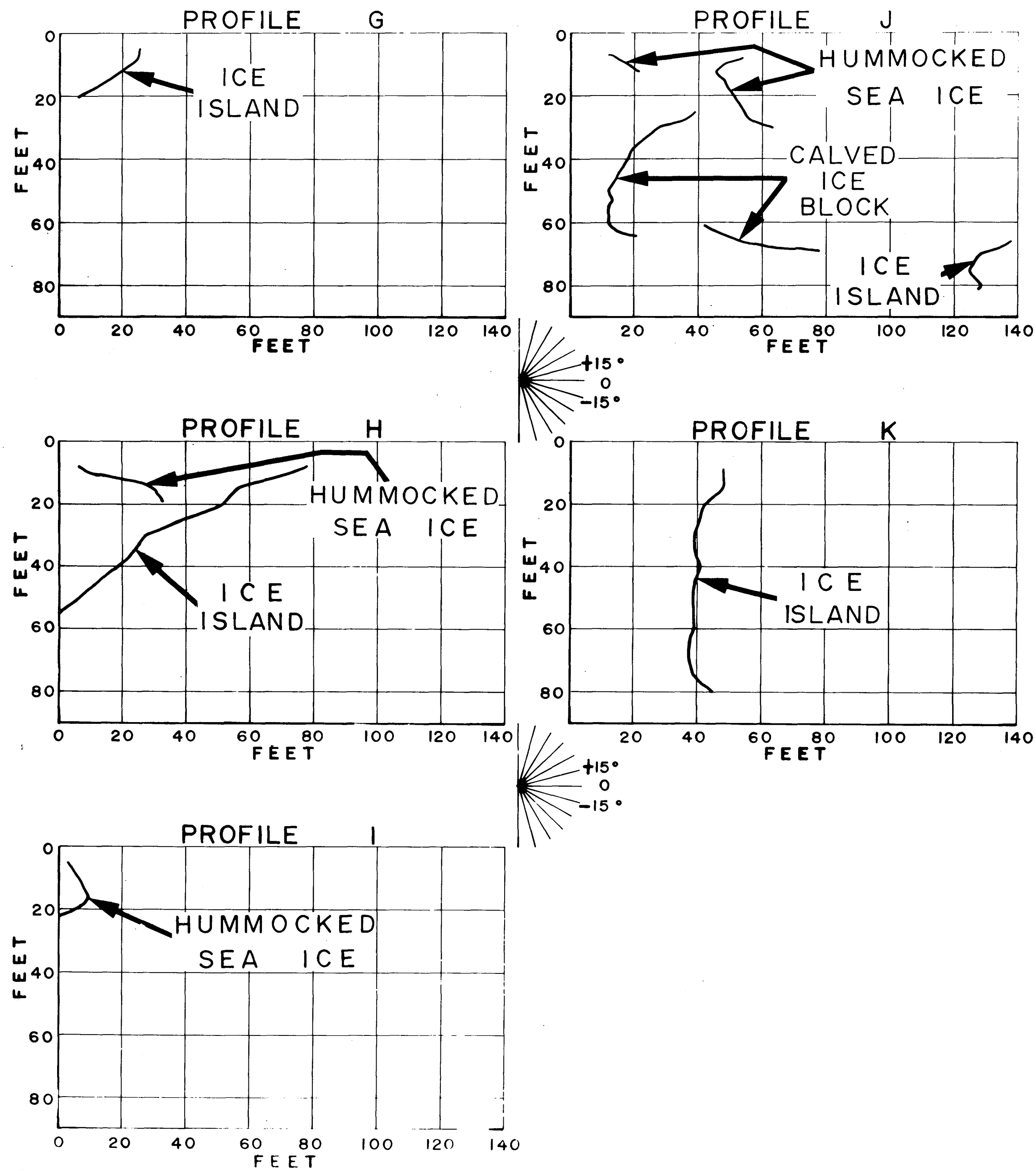

PROFILE G
ICE ISLAND
PROFILE J
HUMMOCKED SEA ICE
CALVED ICE BLOCK
ICE ISLAND
PROFILE H
HUMMOCKED SEA ICE
ICE ISLAND
PROFILE K
ICE ISLAND
PROFILE I
HUMMOCKED SEA ICE
FEET
+15°
0
−15°

FIG. 9

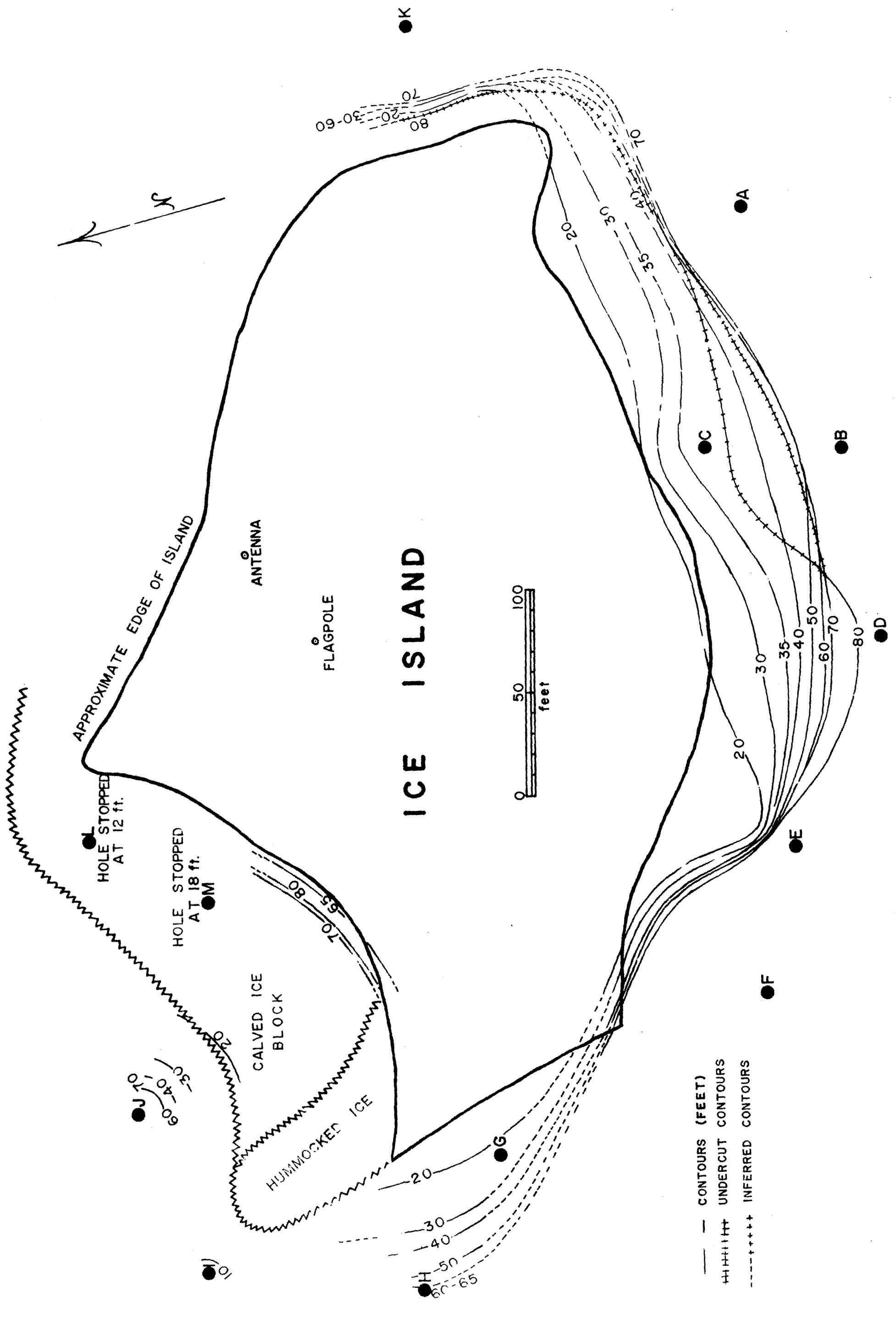

ICE ISLAND
APPROXIMATE EDGE OF ISLAND
ANTENNA
FLAGPOLE
HOLE STOPPED AT 12 ft.
HOLE STOPPED AT 18 ft.
CALVED ICE BLOCK
HUMMOCKED ICE
0 50 100
feet
CONTOURS (FEET)
UNDERCUT CONTOURS
INFERRED CONTOURS

FIG. 10

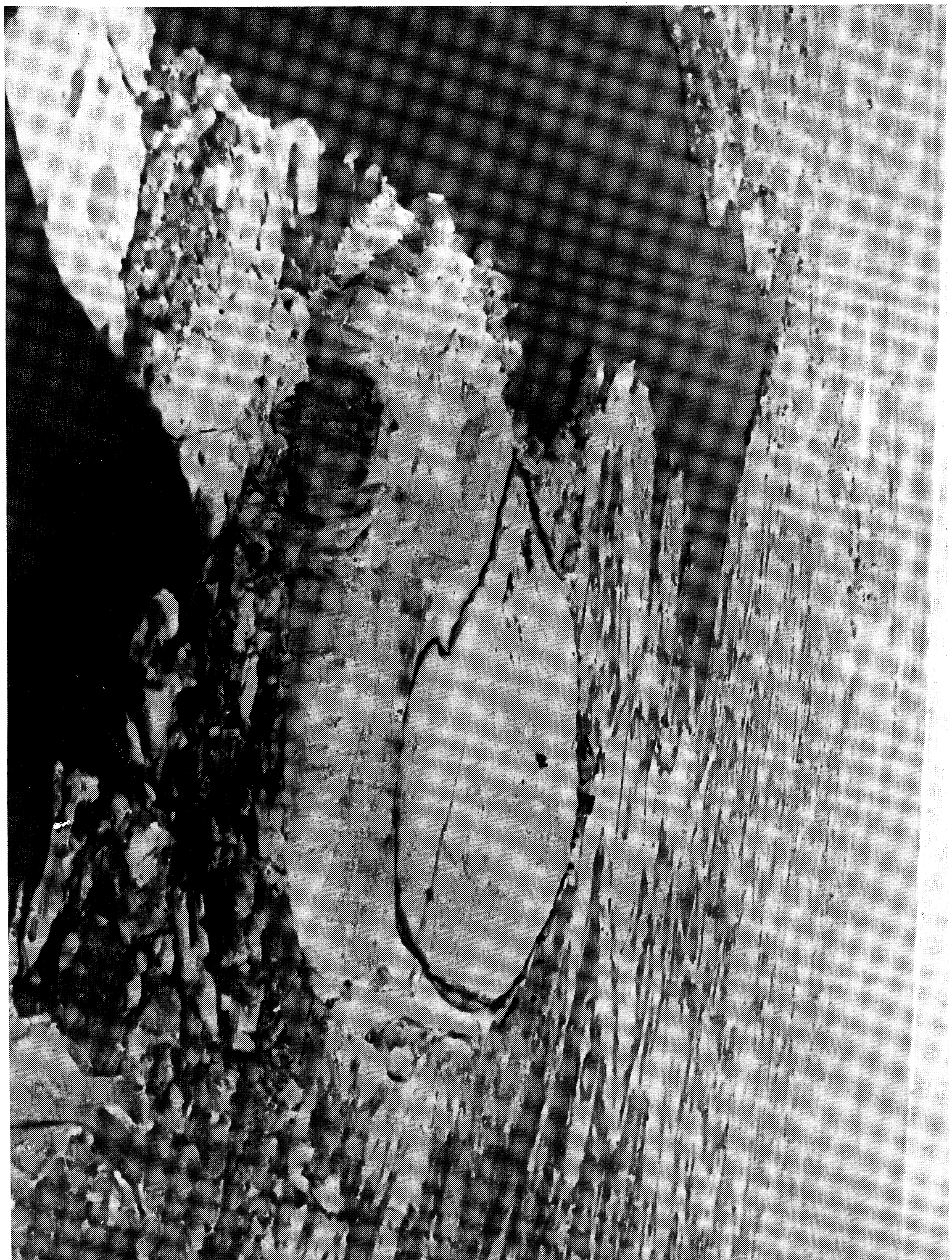


FIG. 11