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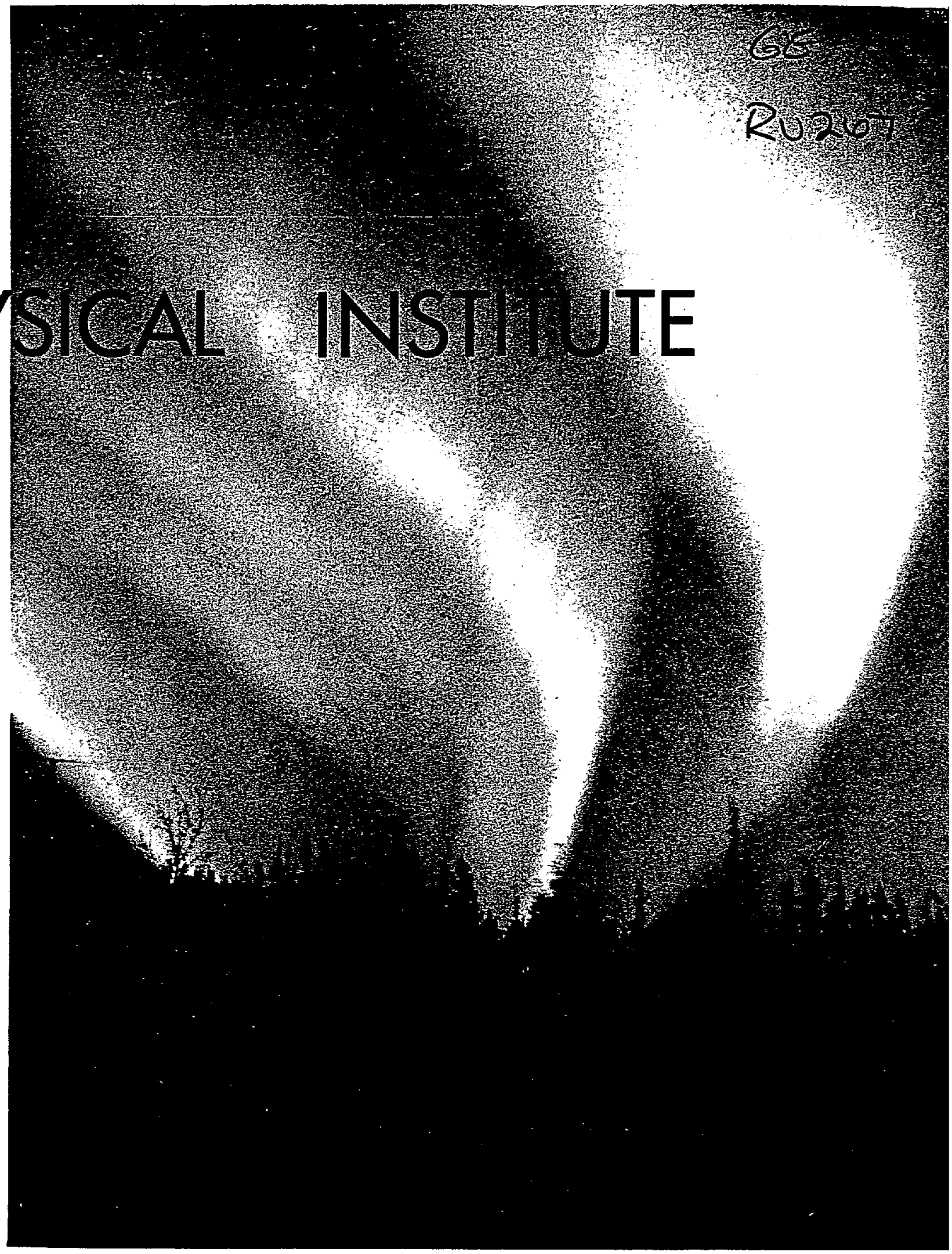

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UAG R-235

A PRELIMINARY STUDY OF THE FORMATION OF LANDFAST ICE AT BARROW, ALASKA

Winter 1973-74

by

Lewis H. Shapiro

SCIENTIFIC REPORT

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Sea Grant Report No. 75-7

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Report Approved By

Keith B. Mather
Director

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ABSTRACT

During late December 1973, the landfast ice sheet at Barrow broke loose and drifted offshore, following which an intense storm drove the pack ice into the nearshore zone. As a result, a new landfast ice mass was formed, which included a complex array of pressure ridges, shear ridges and hummock fields. The entire process was monitored by radar, and study of the imagery provides information on the velocity vector of the pack ice during this time, and on the sequence of events which lead to the formation of the landfast ice. This data, in conjunction with field observations, gives some insight into the mechanisms by which some of the structural features of the landfast ice mass were formed.

An important feature of the landfast ice was a linear hummock field about 4 km long, 135 m wide, and with an average elevation of about 3 m. This feature, termed here as “ice pile”, was approximately aligned along a shoal 4-5 m deep which is oriented at an angle of about 10 degrees to the drift vector of the pack ice, On its offshore side, the ice pile was bounded by a shear ridge which built shortly after the pile under the same conditions of ice drift. The formation of both these features took less than 1.5 hours, and the transition between them is hypothesized to have resulted from the change in water depth along the outer boundary of the shoal.

Measurements of the size and shape of blocks in the pressure ridges and hummock fields suggest that the ice failed in bending during the formation of these features. This may serve to put an upper limit on the forces involved in these processes, but the possibility remains that stresses approaching the crushing strength of the ice are attained during the growth of shear ridges.

INTRODUCTION

The morphology of landfast ice varies from year to year depending upon the mode of formation of the ice. Simple freezing in place with no significant movement forms relatively smooth, flat ice, while rougher surfaces develop as the result of deformation of the ice due to storms or the impact of the drifting pack ice. The landfast ice at Barrow in the winter of 1973-1974 represents an extreme example of the latter case. The first landfast ice sheet to form along this part of the coast was broken loose from the shore and drifted off to sea. Then, seasonal pack ice about 0.5 to 0.6 meters thick was driven into the area by strong winds, forming a landfast ice mass out to the 20 meter depth contour which remained in place. with no detectable movement until break-up. Within the landfast ice, a complex array of structural features was formed, which reflects the manner in which the ice was emplaced in various part of the are-a.

Figure 1 is a location map of the study area showing the near shore bathymetry. A single frame of the radar data, acquired after the landfast ice mass was in place, is shown in Figure 2. Images such as this are acquired at about 2-1/2 minute intervals and are studied as time-lapse movies or on individual microfilm copies.

The radar system operated continuously throughout the time the landfast ice mass was forming and provided a record of the velocity and direction o’f movement of the ice. In addition, oblique air photographs of the area were obtained by the author using a hand-held 35 mm camera, and vertical air photos covering part of the area were acquired by the U. S. Geological Survey using a KA-62 camera system. These, unfortunately, were too distorted to be used for mapping, but do give information about ice characteristics. Ground observations were made in a limited part of

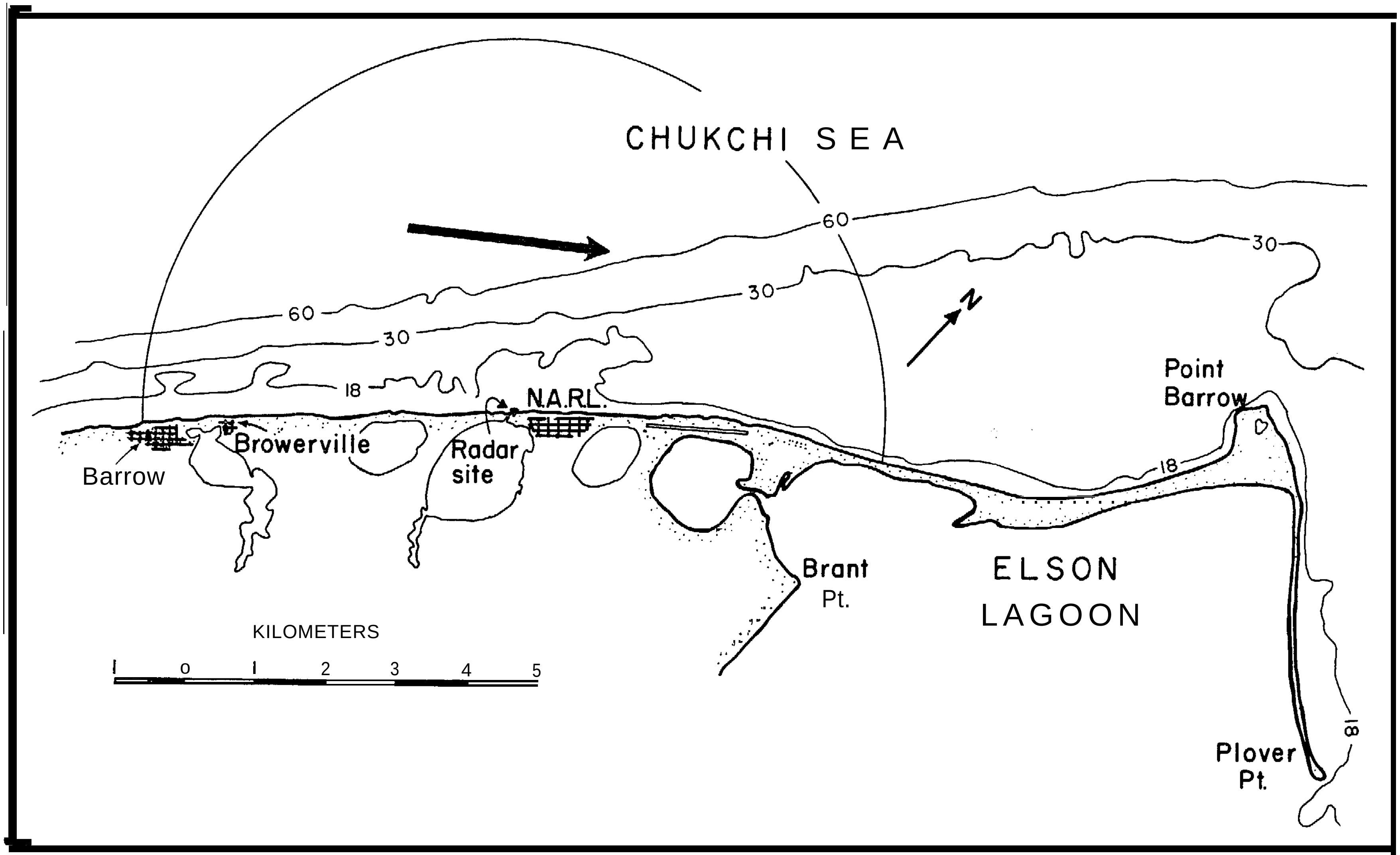


Figure 1. Map of the Barrow area showing location of the radar unit, with the radar field of view indicated by the semicircle. Bathymetry from U.S. Geological Survey 1:63360 map of the Barrow (B-4) Quadrangle (1955). Depths in feet. The arrow shows the direction of ice drift as the landfast ice mass was emplaced.

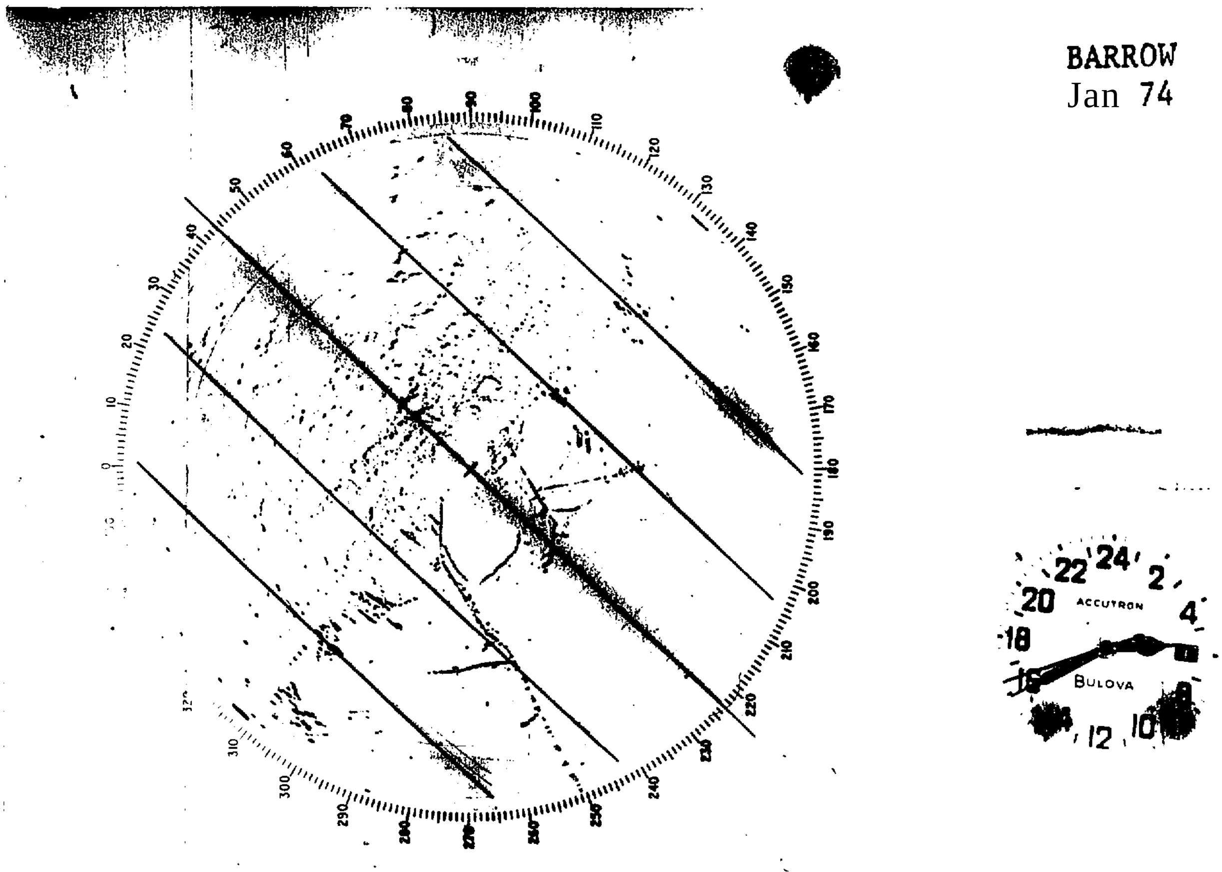


Figure 2. Sample frame of radar data. North is at 90° on the ring. Coastline trends (approximately) from 310° to 130°, landward side is to the southeast. Scale lines are 1 nautical mile apart, circular range lines at 1/2 nautical mile.

the area, and a representative topographic profile was measured over the first kilometer of the landfast ice zone on a line normal to the shore opposite the radar site. Some ice samples were collected for laboratory study, but unfortunately these, and the laboratory equipment, were destroyed during a fire at N.A.R.L. before any work could be done on them, but after the melt season had begun.

The data available are adequate for a rather detailed descriptive analysis of the processes involved in the formation of the landfast ice mass to be made. In addition, some speculations about the nature of the variables which govern these are also given. However, more study is required before details of the mechanics involved are sufficiently well known for realistic models to be prepared. The present study tends to indicate areas where such work is needed, and it is anticipated that some progress will be made towards that goal during the coming field season.

The term "ice pile" is used throughout this report to refer to a specific feature of the landfast ice. This was a roughly linear zone (i.e., length much greater than width) of hummocked ice which occurred offshore, and was grounded over most of its areal extent. The use of this term serves to distinguish this feature from other hummock zones, and also has the genetic connotation that the bulk of the ice was driven up the pile by the force of the incoming pack, with only minimal assistance from buoyant forces.

SEQUENCE OF EVENTS AND RELATIONSHIP TO WEATHER CONDITIONS

Landfast ice was in place out to the 20 meter depth contour off the coast at Barrow by early December. After December 16, the radar pictures indicate no movement of the ice within 3 km of the shore (well outside the 20 meter contour) and only some slow drift to the southwest offshore from the ice edge. This situation was maintained until 0545 Z, 26 December, when a large part of the ice sheet was rafted away (Figure 3) and drifted out of radar range at a velocity of about 0.7 km/hr. For 15 hours prior to the movement, the wind at the Barrow airport was from the east at velocities ranging from 7 to 13 knots (13 to 24 km/hr), and reached 16 knots (30 km/hr) at the time the ice velocity was measured.

Following this movement, the remaining ice was stable for about 3 days. During this time, winds were generally from the east to southeast at 10 to 20 knots (18.5 to 37 km/hr), and only scattered reflectors were observed drifting into the area. The first of these came from the north, drifted around the edge of the remaining fast ice, reversed direction and came to rest against the southwest side of the fast ice. Its track is shown in Figure 4. The remaining floes drifted in from the southwest, and their tracks were clearly deflected offshore as they approached the ice edge.

Figure 5 shows the wind velocity and direction recorded at the Barrow airport from 28 December 1973 to 2 January 1974, duirng which the events described below occurred. Note that the coastline in the radar field of view trends almost northeast-southwest, as indicated in the figure.

At 1930 Z, 29 December, the remaining fast ice sheet broke loose from shore and drifted off to the northeast at the end of a period of offshore winds of moderate strength (Figure 5). It is of interest that the wind direction during the day prior to movement was turning gradually from offshore to parallel to shore, and the movement occurred just after

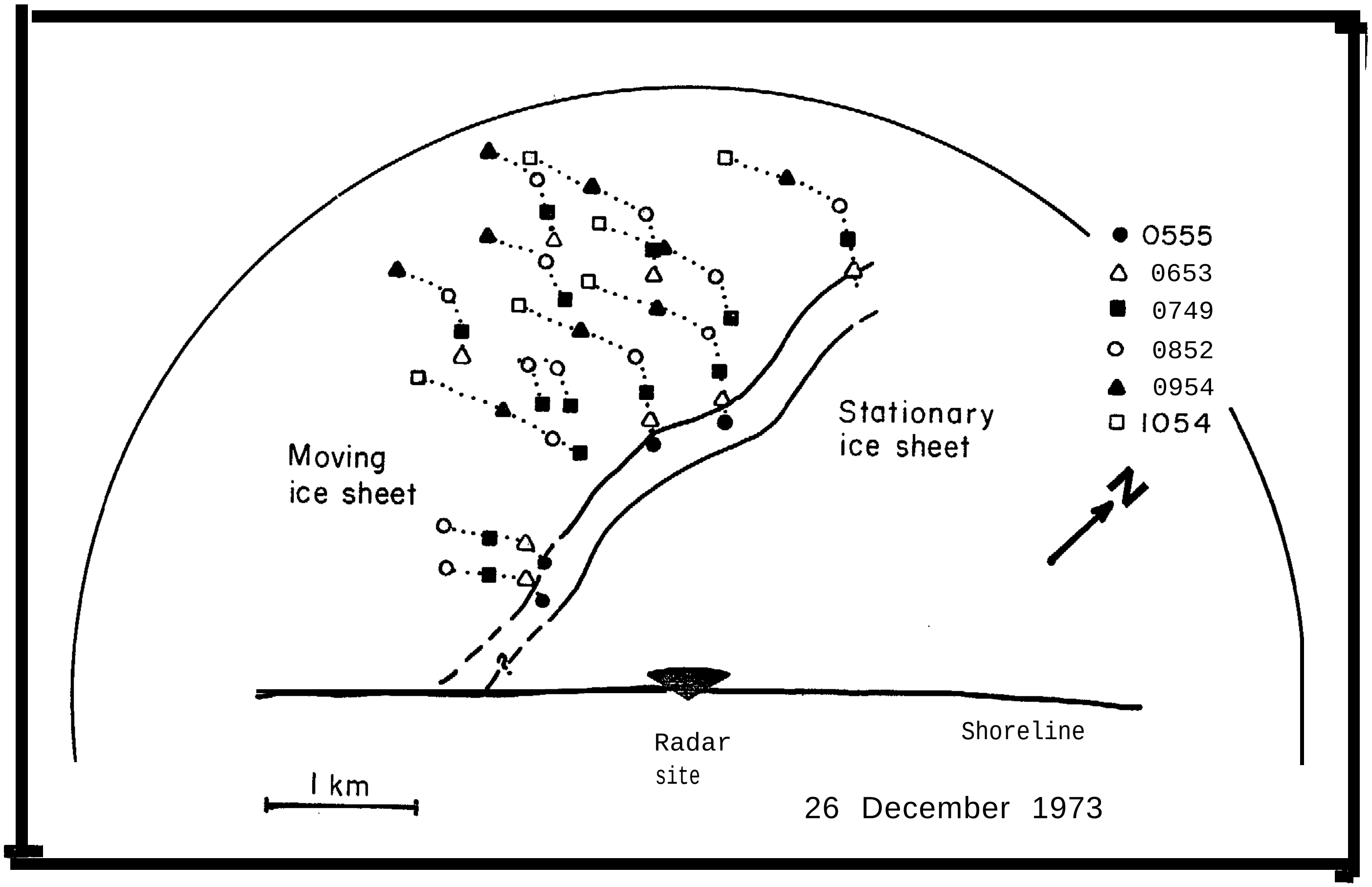


Figure 3. Breakaway of part of the landfast ice sheet on December 26, 1973. The symbols, and dotted lines connecting them, indicate the positions of identifiable reflectors at the times indicated.

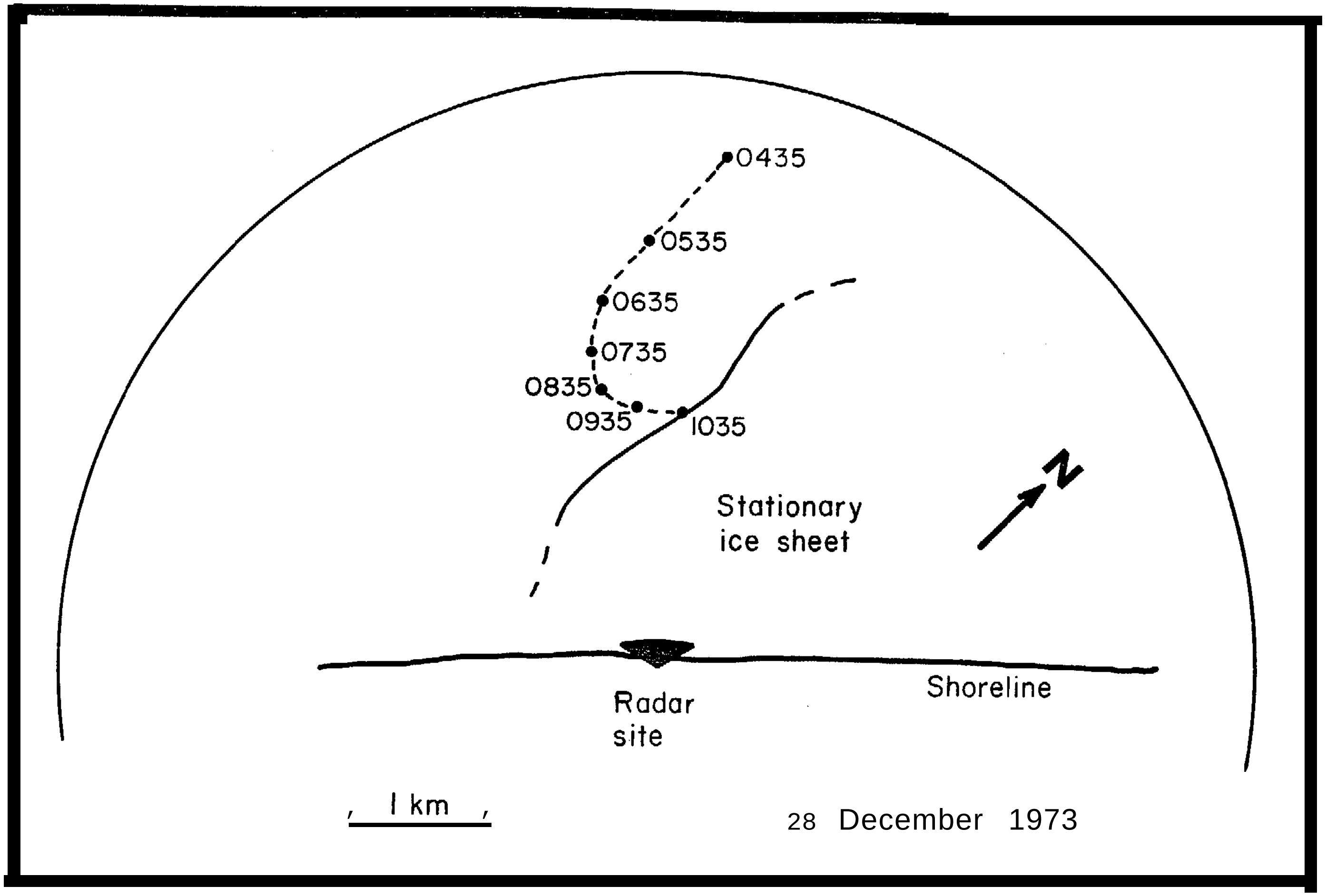


Figure 4. Drift track of a single floe on December 28, 1973. Dots and numbers indicate position of the floe and time of observations. Winds over this time period were from the ESE at an average of 15 km/hr.

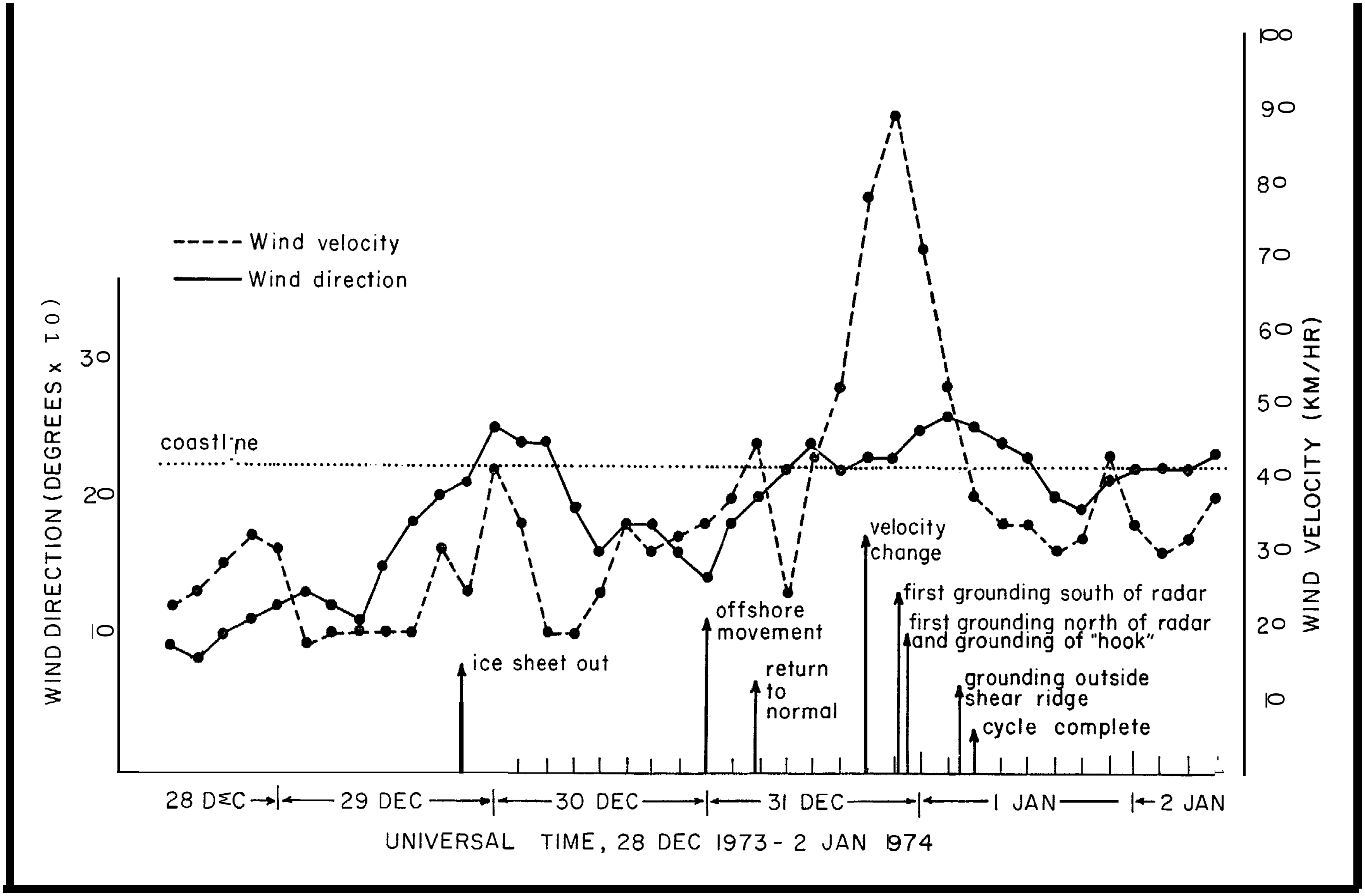


Figure 5. Wind velocity and direction as recorded at the Barrow airport during the time of emplacement of the landfast ice. Times of particular events described in the text are indicated by arrows. The average azimuth of the coastline within the radar field of view is shown by the dotted line.

a peak in the wind velocity. However, there appears to be no extraordinary feature of either curve which would indicate that such a major event was about to occur. Examination of the radar films showed a jog in the drift track which probably resulted from impact of the ice sheet with some obstruction to the northeast.

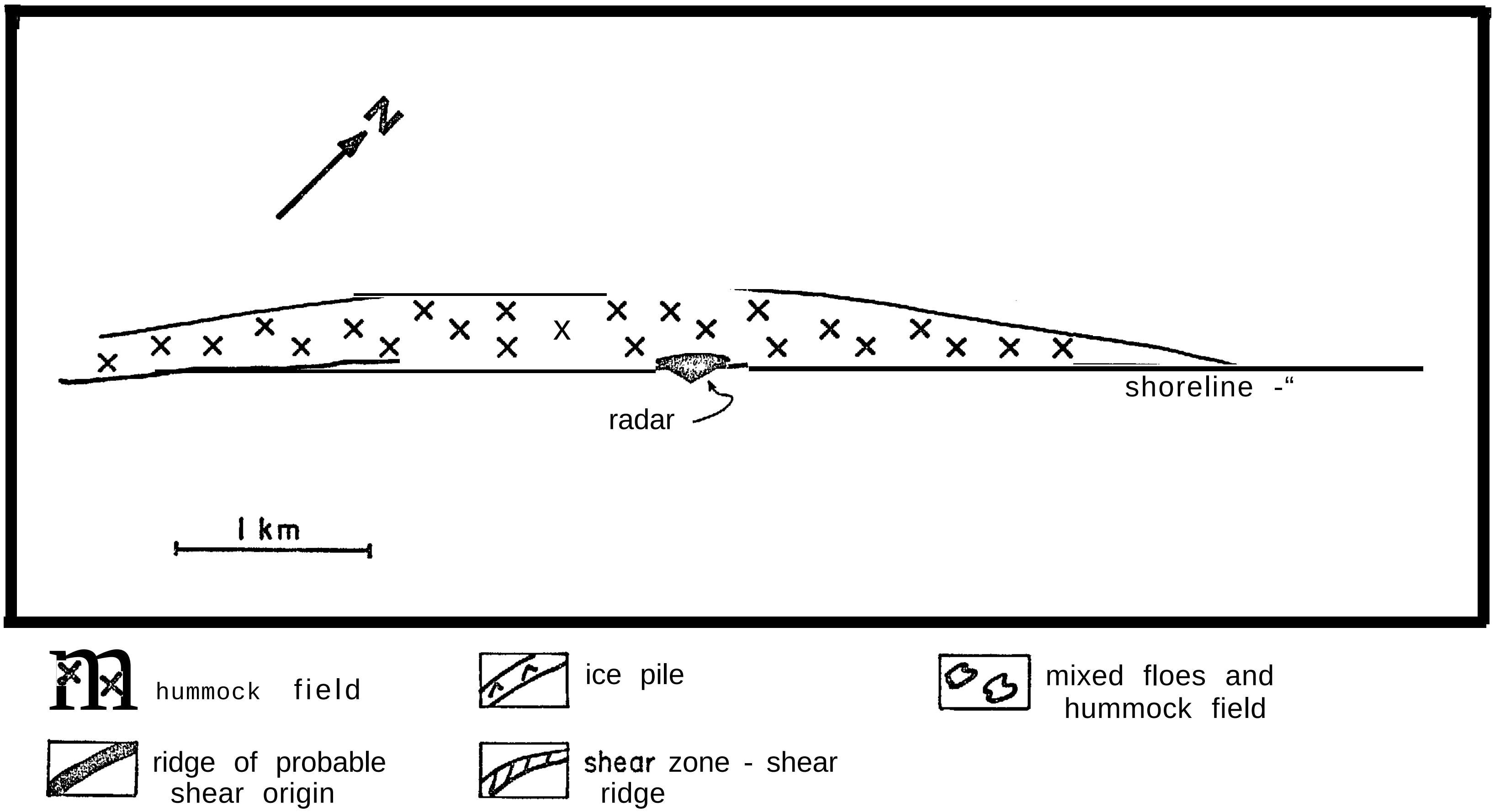
Immediately after the ice sheet went out, drifting ice appeared moving up the coast from the southwest at about 3.7 km/hr. Several reflectors were observed to stop along the crest of a shoal which originates close to shore near Browerville, and extends northeast to a point opposite N.A.R.L. where it terminates about 1 km offshore (Figure 1). Water depth over the crest is about 4 to 5 meters. This shoal also controlled the position of the major ice pile-shear ridge complex which developed at a later time as described below.

Observations by Dr. T. Hanley, who was present at N.A.R.L. during this time, indicate that one floe grounded just offshore from the radar site at about 2305 Z, 29 December. This served to block additional movements locally so that an area of stationary ice, consisting of pans with slush ice between them, was formed. No apparent movements occurred in this near shore ice through observations at 0240 Z and 2300 Z, 30 December. However, the radar imagery shows that the stationary ice extended only about 0.5 km offshore, and that the pack ice further out was continuing to drift northeast at about 3.5 km/hr throughout this time interval.

The next ground observation was made at 2257 Z, 31 December, at which time it appeared that a large mass of blue, seasonal pack ice had replaced or been rafted in over, the pans and slush ice. Darkness and storm conditions prevented the observer from seeing what had transpired in the time between observations, but the radar data show that between the observations at 2300 Z, 30 December, and 2257 Z, 31 December, all of the ice near shore had been driven out, and the main episode of ridging and piling was in progress, as described below.

At about 2245 Z, 30 December, the drifting ice, which had been moving parallel to the coast, changed direction and began to drift offshore. Over the next four hours, the ice inshore also drifted out, until the only stationary ice masses in the area were the grounded ice piles along the shoal noted above. However, by 0200 Z, 31 December, drift parallel to the coast at a velocity of about 3.7 km/hr had been reestablished. The offshore movement appears to correlate well with the wind direction, since it occurred when the wind was blowing at 80° to 85° to the coastline in an offshore sense (Figure 5). In addition, some threshold in wind velocity may also have been important because of the increasing wind velocity which is shown in the figure for approximately 15 hours prior to the time the change in direction of movement occurred.

A rapid increase in ice drift velocity occurred at about 1645 Z, 31 December, which is clearly associated with an increase in wind velocity (Figure 5). It should also be noted that wind gusts up to almost double the peak winds shown in the figure were also observed at this time. The ice drift velocity increased to 8.3 km/hr, following which all the grounded ice along the shoal was driven out by force of impact of the drifting ice. (Note that the direction of ice drift was parallel to the coast at this time, and remained so during all subsequent events described in this paper.) For the next 3 to 4 hours, the ice continued to move through the radar field of view without stopping, until just before 2054 Z, 31 December. At that time numerous small, stationary reflectors were identified close to shore which later field work showed to be within a hummock field in the area shown in Figure 6a. (Note: in this section

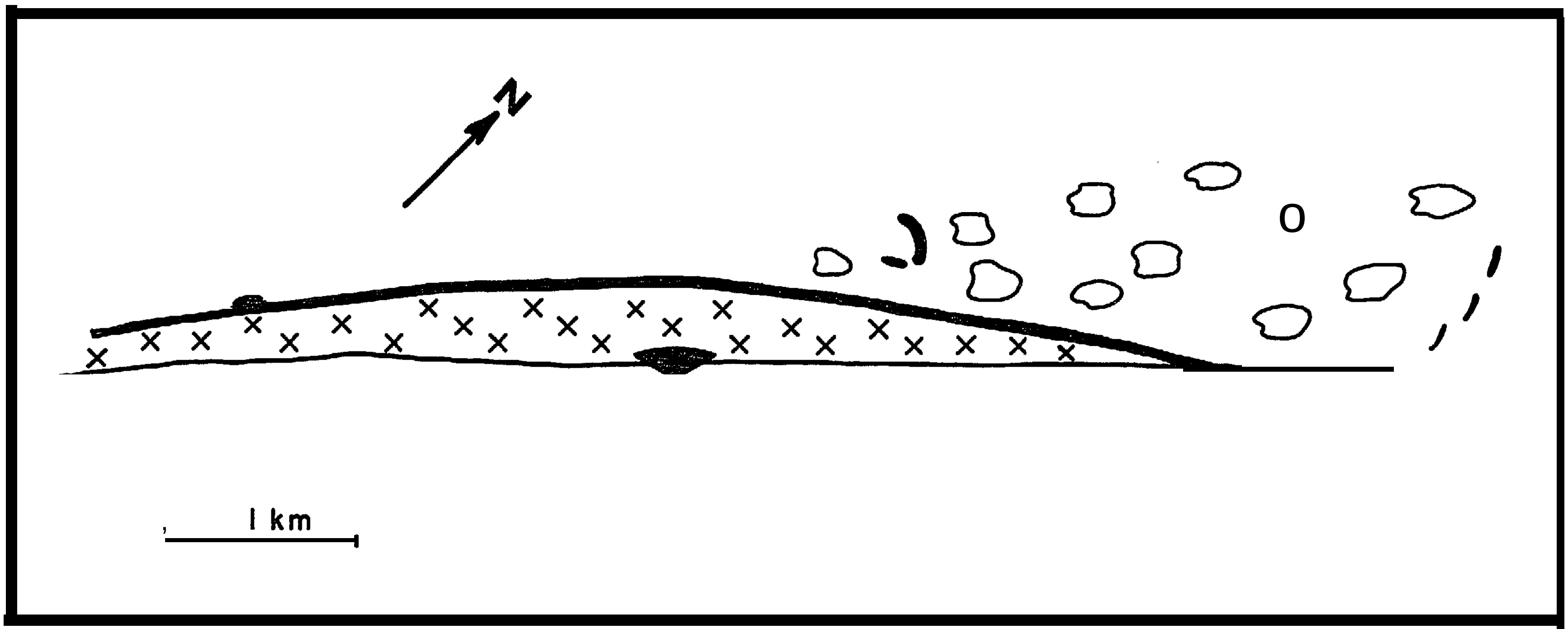


"Figure 6a. Map of the near shore hummock field emplaced prior to 2054 Z, December 31, 1973. Symbols apply to figures 6a-6f.

the sequence of emplacement of various ice zones within the radar field of view is given and the zones are identified. Detailed descriptions appear in the next section of the report.) The first large reflector to stop was emplaced at 2054 Z, 31 December , and 2 km southwest of the radar and 0,3 km offshore (Figure 6b). At 2116 Z, 31 December, a second reflector stopped at the northeastern end of the radar field of view, followed quickly by several others in the same area. These reflectors were probably part of a pressure ridge rimming a single floe , which may have been broken by impact with other floes already stopped in its path to the northeast. The area behind these reflectors was quickly filled by floes and hummock fields.

At about 2202 Z, 31 December, a large pan, bounded by a distinctive "hook''-shaped reflector, grounded on the shoal about 1.5 km north of the radar site and 0.7 km offshore, ii's location, along with those of the reflectors at the northeast end of the radar field of view and the zone of floes and hummocks emplaced at. this time, are shown in Figure 6b.

The line of reflectors which defines the position of the main ice pile formed within five minutes after emplacement of the "hook''-shaped reflector, and the pile then grew in an offshore direction for some additional time. Unfortunately, it is not possible to determine how long this process continued, because the growth occurred in a shadow zone behind the pile. When the pile stopped growing in width, the drifting pack ice began to shear by its outer edge, forming a shear ridge. The transition from piling (or pressure riding) to shear ridging occurred with no change in the drift vector of the moving pack ice, indicating that other variables controlled the process.



·Figure 6b. Map of the landfast ice shortly after 2202 Z, December 31, following emplacement of the first zone of floes and hummock fields. Note probable shear ridge separating this zone from the near shore hummock field. First reflector to stop (2054 Z) is indicated by black mark outside shear ridge at left of drawing. Black lines at right are the reflectors which stopped at 2116 Z. "Hook" shaped reflector referred to in text (2202 Z) is shown near the center of the picture. Symbols indicated on figure 6a.

Following the growth of the pile and the transition to shearing, the configuration of the ice remained as shown in Figure 6c until 2330 Z, 31 December, when the shear zone changed trend as indicated in Figure 6d, probably as the result of the emplacement of the zone of pans and hummock fields indicated in the figure. The next important change to occur was the emplacement of the three ridges and the small zone of floes and hummock fields outside of the shear zone between 0413 Z and 0445 Z, 1 January, as shown in Figure 6e. This created a bight between these ridges and the main shear zone which was quickly filled by floes and hummock fields. By 0520 Z, 1 January, the outermost shear ridge had been defined, approximately at the 20 meter depth contour, and the area appeared as shown in Figure 6f.

A summary of the position of the most prominent linear zones of reflectors and the time at which they were identified, is given in Figure 7.

The emplacement of ice out to the 20 meter depth contour occurred during a period of decreasing wind velocities, while the ice movement did not have a large onshore component, but instead was almost parallel to the coast at the radar site as shown in Figure 1. Further, all of the ice masses which were grounded on the shoal had been driven away by impact of the moving pack following the velocity change at 1645 Z, 31 December. Thus, it is difficult to hypothesize that grounding of the drifting ice was responsible for the initiation of the extensive hummocking and ridging which occurred during emplacement of the ice. Instead, from the relationship between the ice drift direction and the coastline shown in Figure 1, it appears likely that the movement of the ice was stopped by the coast south of Pt. Barrow, where the shoreline is turned

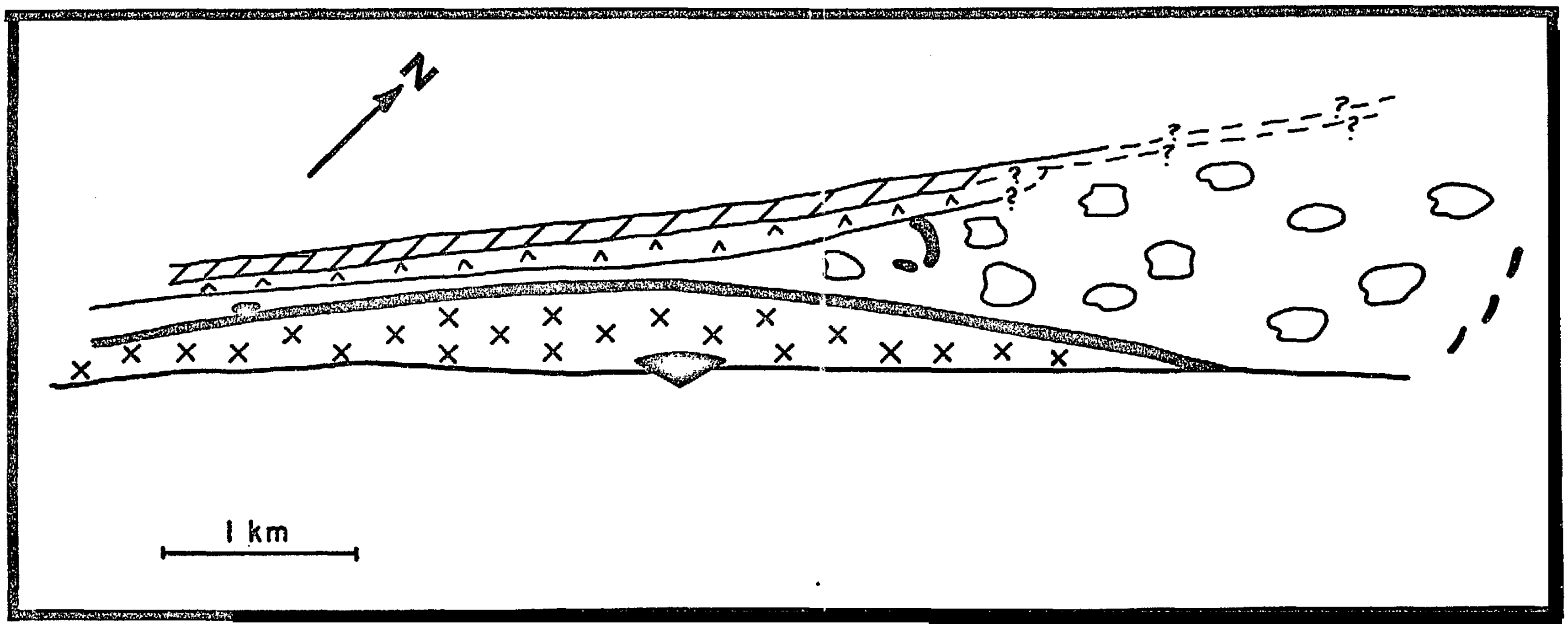


Figure 6c. Map of the landfast ice just before 2330 Z, December 31, following building of the main ice pile, and the transition to shearing. Symbols as in figure 6a.

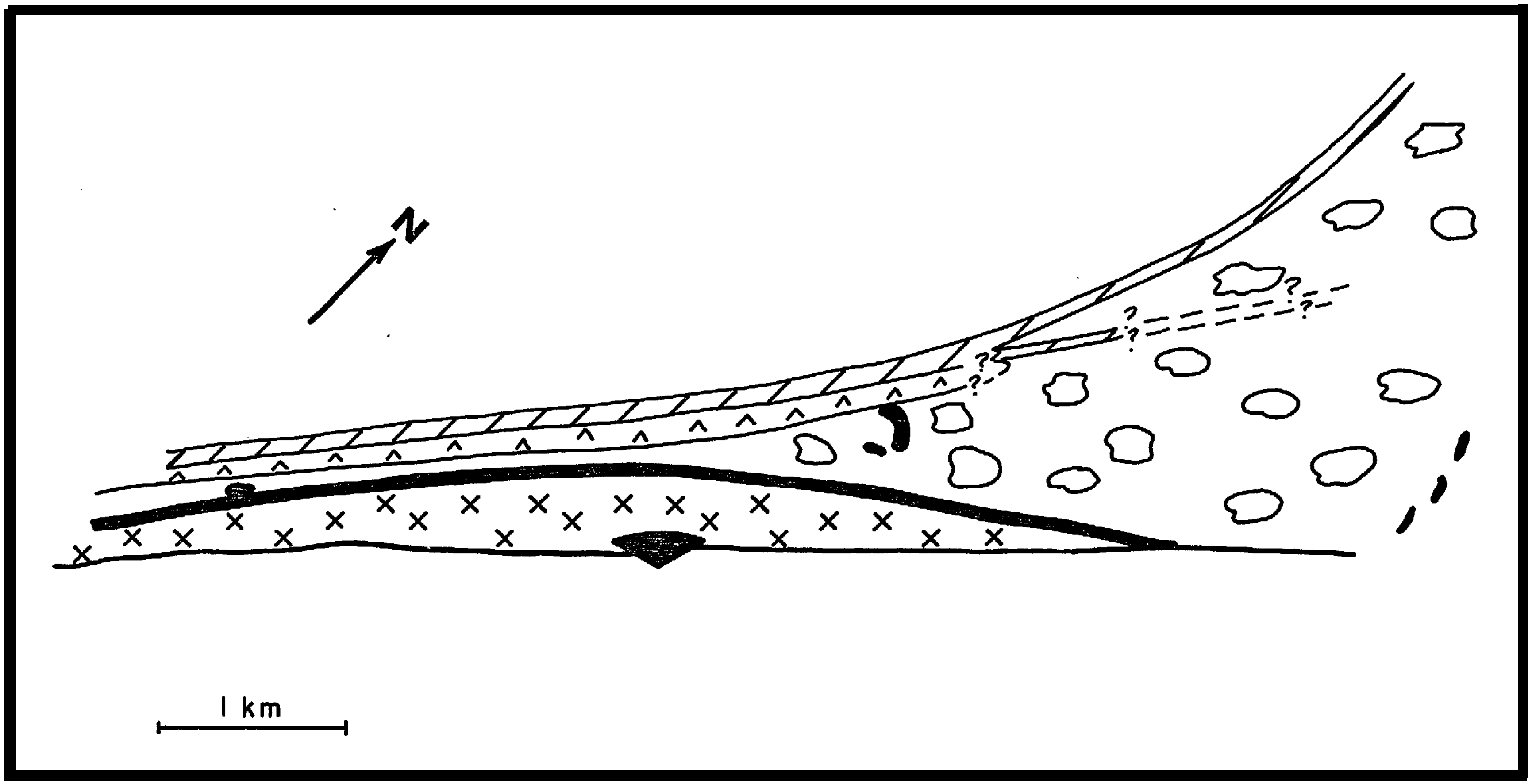
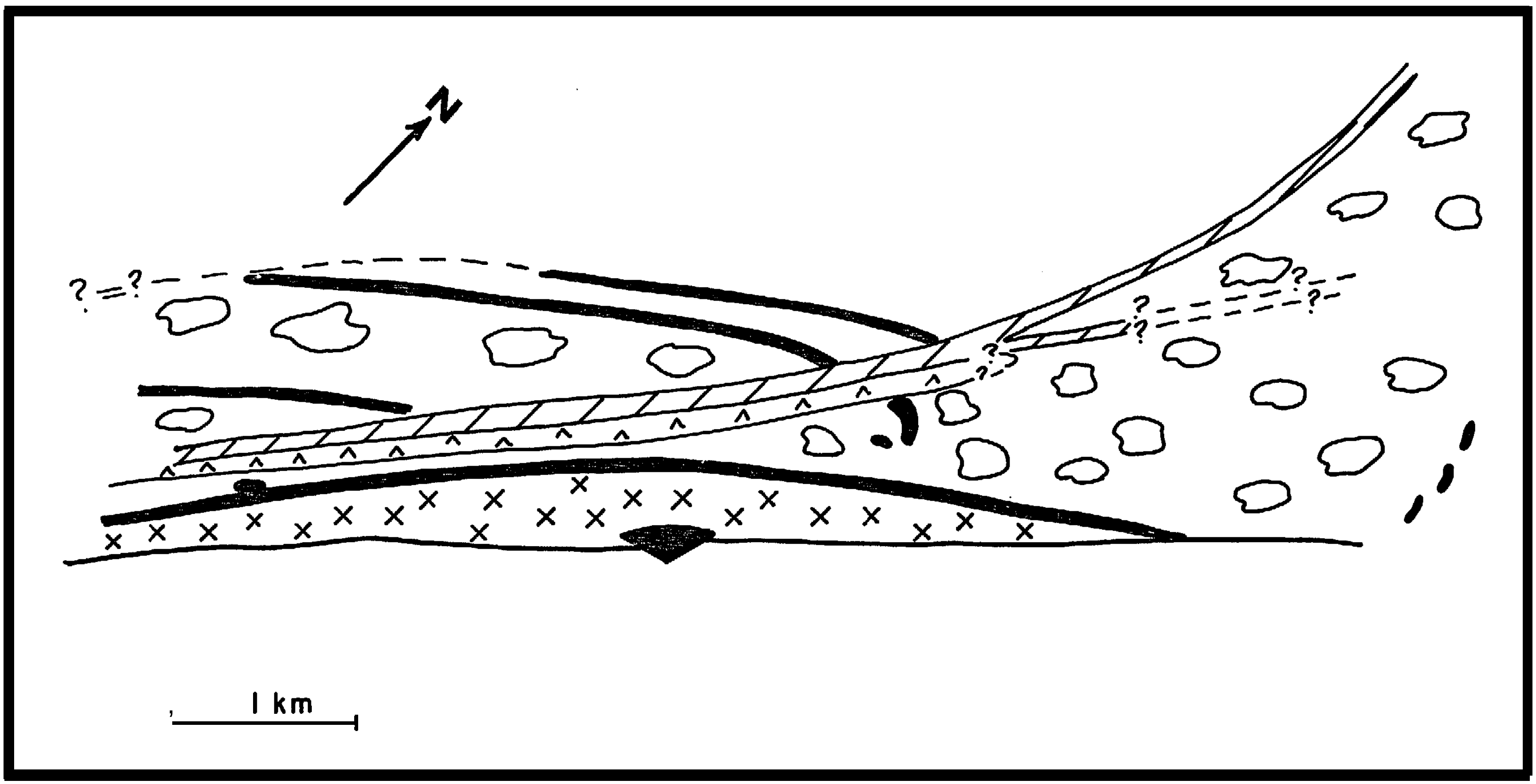


Figure 6d. Map of the landfast ice following the change in trend of the shear zone and emplacement of the second zone of floes and hummock fields at 2330 Z, December 31. Symbols as shown in figure 6a.



'Figure 6e. Map of the landfast ice at 0445 Z, January 1, 1974, following emplacement of the three probable shear ridges. Note the bight between the main shear zo'ne and the new ridge. Symbols as shown in figure 6a.

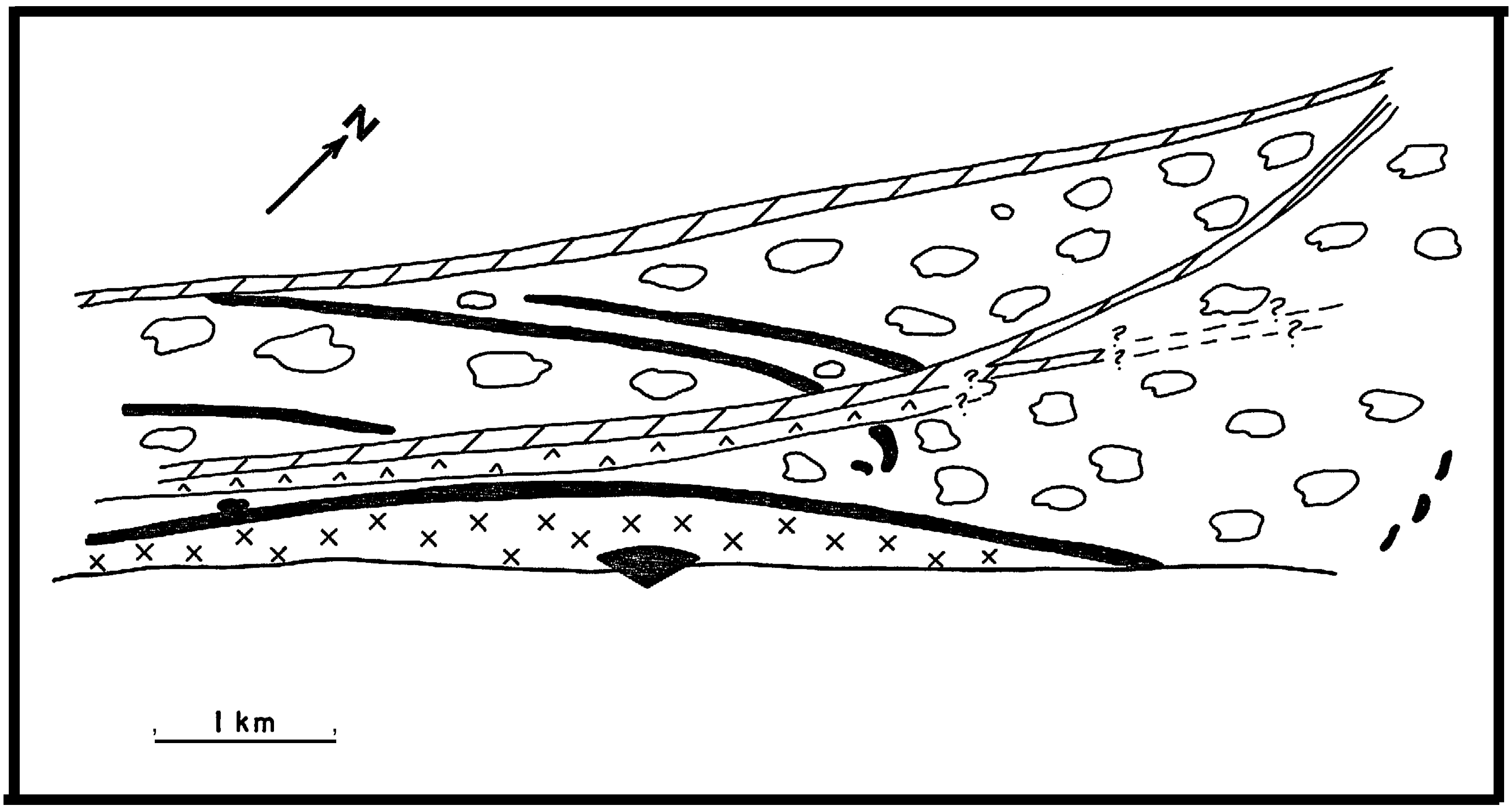
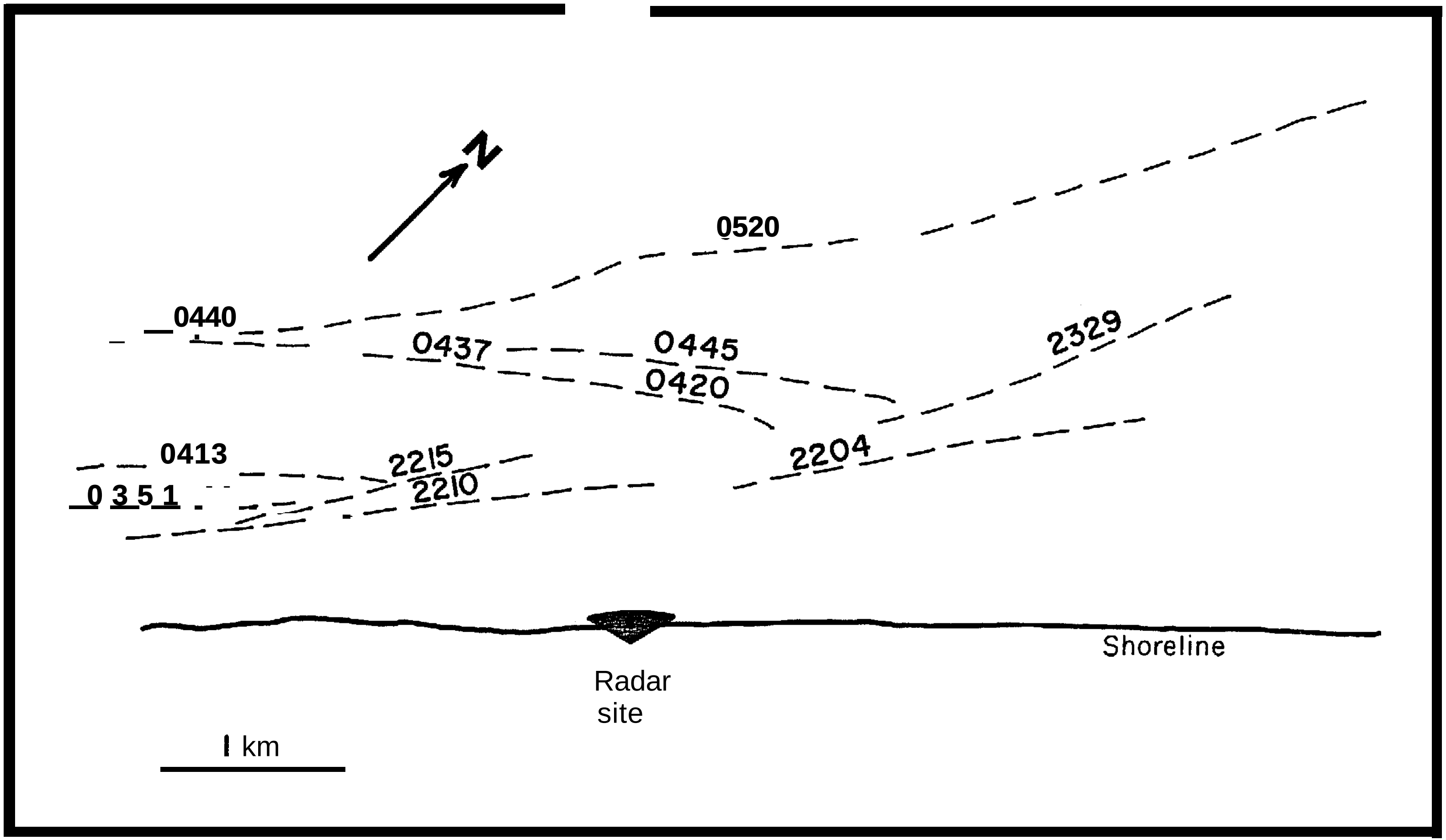


Figure 6f. Map of the landfast ice at 0520 Z, January 1, after emplacement of the zone of floes and hummock fields in the bight shown in figure 6e, and definition of the outer shear zone. Symbols as shown in figure 6a.



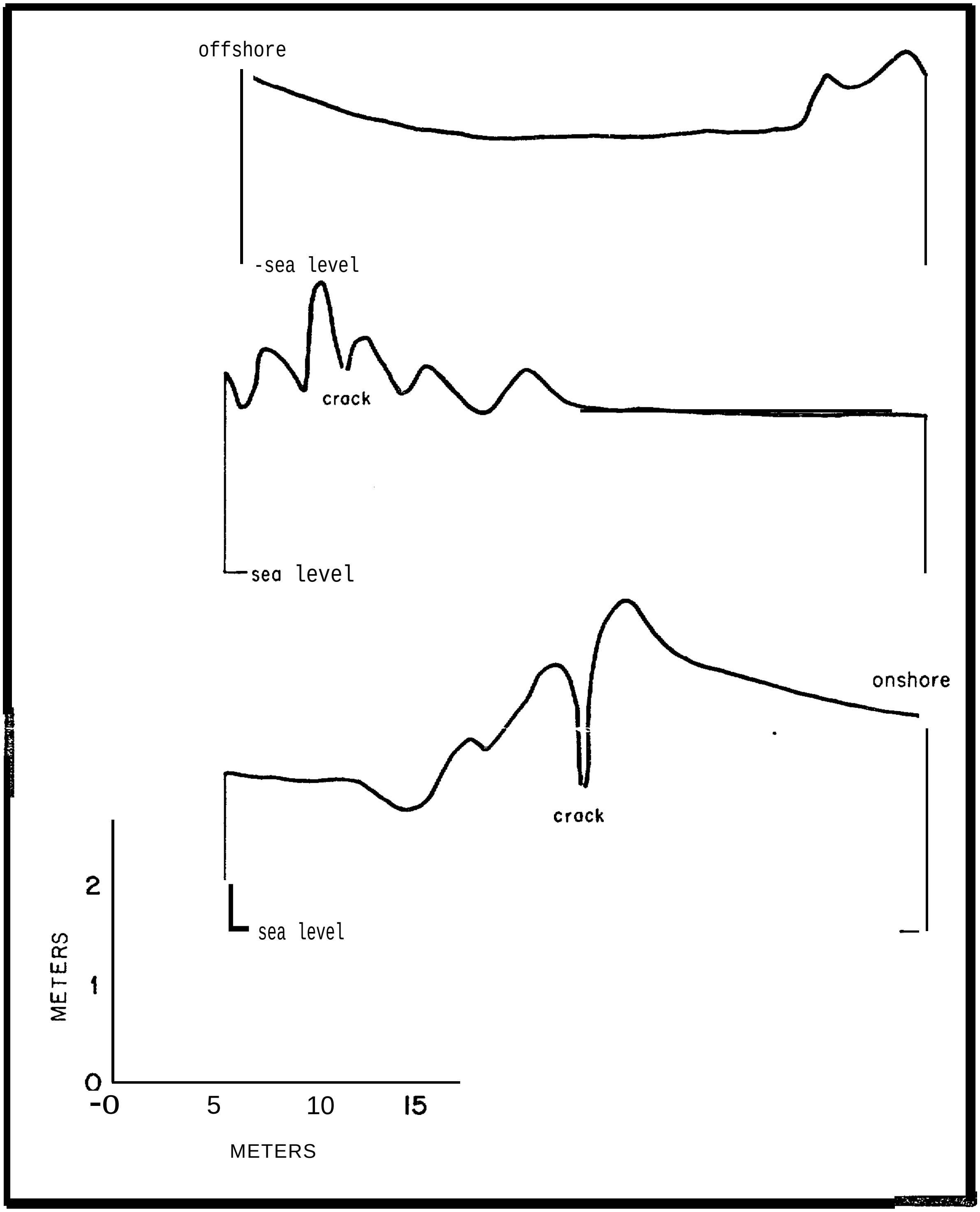
'Figure 7. Summary of the positions of prominent linear zones of reflectors. and times at which they were identified.

about 20 degrees further north than that near the radar. As a result, the drifting pack was simply compressed against the ice already stopped in its path, with accompanying ridging and hummocking. Locally, the formation of ridges, piles and hummock fields was caused by grounding, but these were secondary to the emplacement of the entire fast ice mass.

DESCRIPTION OF THE LANDFAST ICE

The ice field emplaced during the events described above extended up to 2.5 km offshore in the field of view of the radar. Included within this area is a complex array of ice structures including hummock fields, ice piles, shear ridges and grounded pressure ridges of generally limited extent. As noted, all of these features developed in less than 9 hours, during which time the velocity and direction of drift of the pack ice appear to have been constant.

The most striking morphologic feature of the ice was-the shear zone which trends generally northeast-southwest across the map area (Figure 6d). A topographic profile across this zone, measured directly offshore from the radar site, is shown in Figure 8. Along this profile the shear zone was bounded on its inshore side by a shear ridge with a relief of about two meters, while the offshore margin had been overridden by incoming pack ice. The total width of the zone was about 90 meters in addition to that part which was buried by the pack. A few small shear ridges were also present within the shear zone. These were sinuous in plan view and tended to intersect within distances of up to a few hundred meters.



'Figure 8. Topographic profile across the shear zone of figure 6c and 6d directly offshore from the radar site. Profile is continuous from upper left (offshore) to lower right (onshore). Zero on the vertical scale is sea level.

Over its entire width, the ice within the shear zone consisted of rounded fragments of pack ice, ranging in diameter from a few centimeters to about 0.5 meter, in a matrix of loosely bonded, fine-grained ice fragments. In general, it resembled a loosely cemented conglomerate and was easily disaggregated by hand, and the rounding of fragments and fine crushing of the ice clearly show the effect of pack ice grinding past the fast ice. The Eskimo term for ice of this type is "flour" ice.

Scattered through the shear zone were occasional small "sink" holes. These were circular depressions one to two meters in diameter and about one meter deep. There is no direct evidence available as to their origin, but it seems likely that they were formed as collapse features. An an example, it can be assumed that both the sea surface and the ice in the shear zone were raised during the time the zone was active, due to the force exerted by the combination of onshore winds and the incoming pack. Then, when these driving forces relaxed, some settling of the ice in the shear zone would be expected, and local differential settling could account for the formation of the sink holes.

The shear ridge proper was generally of low relief on its inshore side, and was prominent for two reasons. First, because of the rapid drop on the offshore side of the ridge to the level of the flour ice surface, and second, a low pile of partially rounded ice blocks was present at its crest (Figure 9). The rounding indicates that these were pushed up out of the zone of active shearing, and their presence some two meters above the surface of the flour ice can be interpreted as implying a higher stand of the ice surface in the zone during shearing.

A prominent crack was also present in the offshore side of the ridge (Figure 9). Its origin is uncertain, but the shape and position of the ice adjacent to and offshore from the crack, suggest some rotation

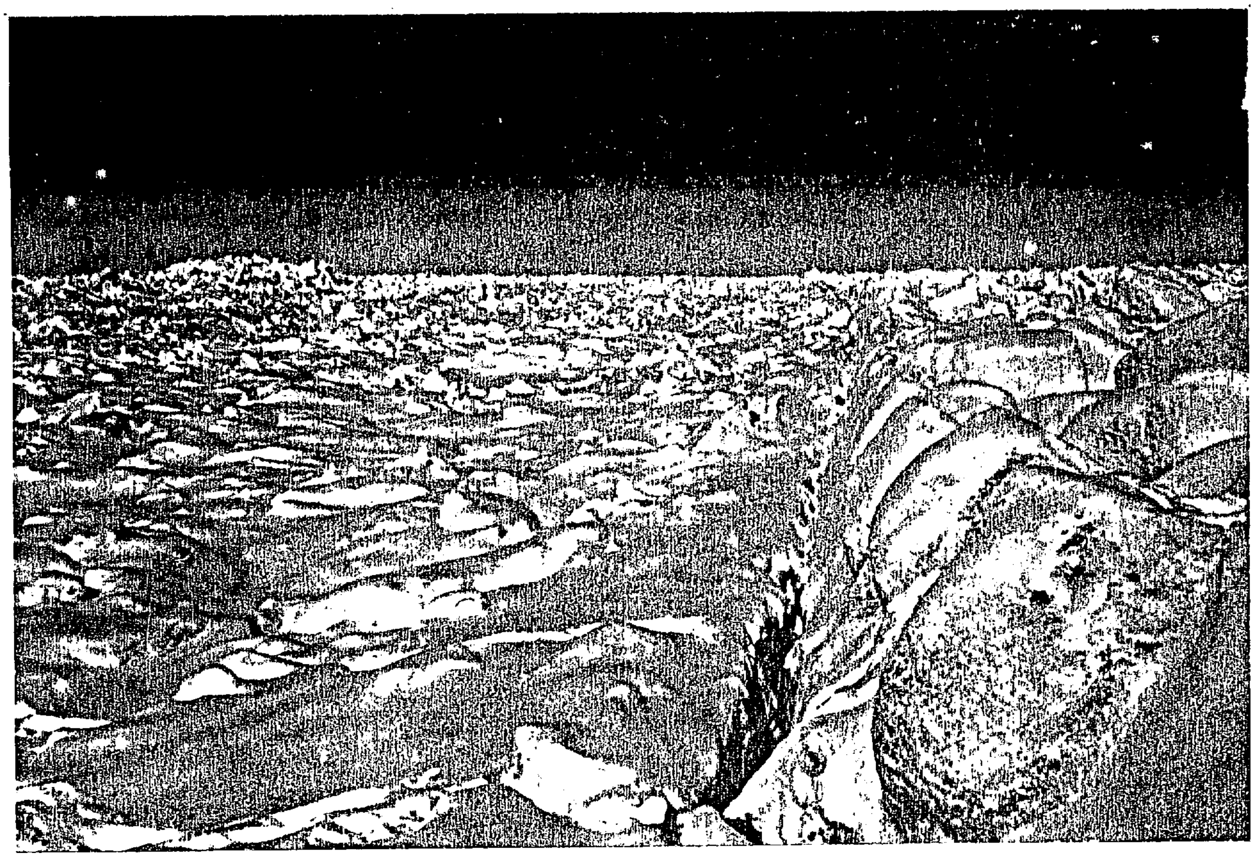


Figure 9. Crack on offshore side of shear ridge of figure 8. Relief is about 2 meters. Note rounding of ice block in right foreground.

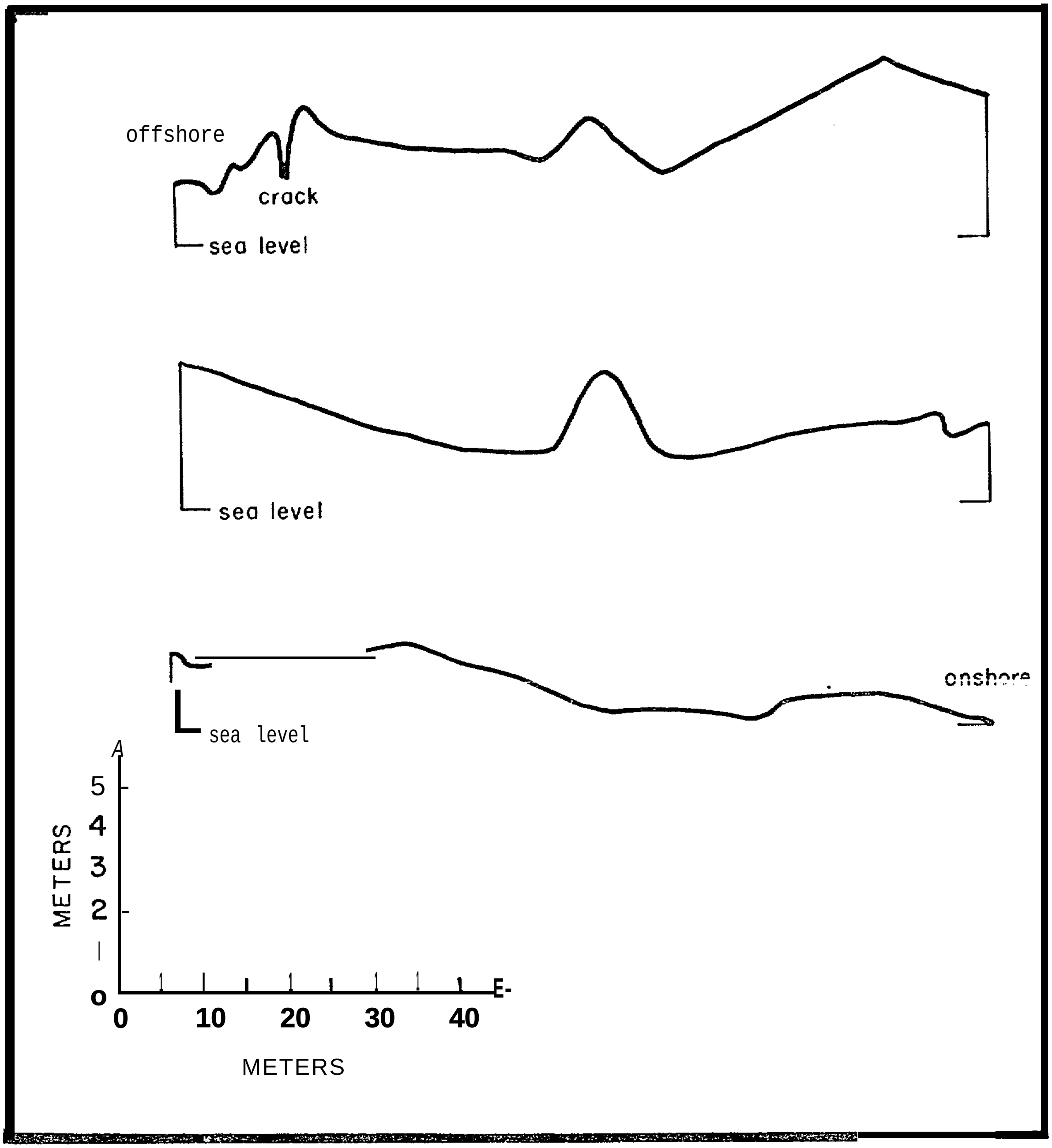
away from the ridge, This implies that this ice fell away from the ridge along the crack, which in turn indicates that the crack was the boundary between the moving and stationary ice during shearing. Cracks such as this may be genetic to shear ridges, as suggested by the presence of similar cracks elsewhere in the shear zone (Figure 8) and in the shear ridge which formed at the outer edge of the fast ice at the 20 meter depth contour (Figure 10).

The possibility exists that stresses in the ice on the inshore side of a growing shear ridge may become large, approaching the crushing strength of the ice at the boundary. However, it should be noted that it is not necessary for high compressive stresses to exist throughout the shear zones in order to accomplish the crushing and grinding of the ice which characterizes the zone. It is apparent that such stress fields are not present while sand grains are rounded in streams, or during crushing in ball or rod mills, Thus, impact between ice fragments during movement may form sufficiently high dynamic stresses at contact points to cause the observed crushing, without a superimposed high compressive stress field.

The data presently available are not adequate to resolve this question. However, a planned program of installing stress transducer arrays along the outer shear ridge at Barrow may provide the necessary information.

Just inshore from the shear ridge was the main ice pile which formed behind the “hook”. It was about 135 meters wide with an average elevation of about 3 meters and was aligned along the crest of the shoal, though it extended a few hundred meters further to the northeast. The topographic profile (Figure 11) shows three distinct crests on the

Figure 10. Crack in outer shear ridge. Offshore side is to the left.



'Figure 11. Topographic profile across main ice pile directly offshore from radar site. Profile is continuous from upper left (offshore) to lower right (onshore). Shear ridge of figure 8 is at upper left.

pile, but examination of air photos indicates that these were local highs rather than identifiable ridges which could be traced for any significant distance.

No statistical studies of the sizes and shapes of blocks in this ice pile were made because snow cover prevented any statistically valid sample from being identified and properly measured. In particular, the smaller blocks tend to be most easily buried and thus, any sample would be expected to be strongly skewed toward the larger size blocks. However, because the size and shape of these blocks does give information regarding fracture mechanisms which operated during the piling episode, some attempt was made to qualitatively evaluate these parameters, and a few measurements were made.

In general, there appeared to be few blocks in the pile with linear dimensions smaller than the ice thickness (0.5 to 0.6 meters) which probably implies that crushing and failure in shear were not important mechanisms in the fracture processes operating during piling, Instead, the smallest dimension of many of the blocks was no less than 1.5 to 2 times the block thickness with the larger dimension about *twice* the smaller (i.e., about 3 to 4 times the thickness). However, a large variation in size was noted with blocks ranging in area up to several meters square being present and often tilted at high angles. That is, they were not simply rafted onto the pile, but were actively pushed and rotated away from the horizontal. Several pans ranging up to tens of square meters in area were also present within the pile, and these did seem to have been rafted into the positions where they were observed. They were only slightly tilted away from the horizontal, and their surfaces tended to be undulatory with numerous tension cracks, so that they gave the appearance of having settled to conform to the configuration of the surface on which they came to rest.

A conspicuous feature of the blocks in the pile (and of other areas noted below) was the presence of numerous blocks of approximately triangular shape. In general, these had two smooth sides which defined the vertex angle of the triangle, while the third side was irregular. The vertex angles of 12 blocks were measured in the field, and these ranged from 58 to 75 degrees, with an average value of 67 degrees. The shape of these blocks suggests failure of an ice sheet along radial cracks which results from rafting up on an inclined pier. Similar stress fields could be expected to be generated during the development of the pile as the ice was rafted up on the irregular leading edge of the growing pile.

Based upon the discussion above, it is reasonable to conclude that during the piling episode, fracture of the ice was predominately in bending so that forces greater than required to cause failure in this mode probably did not develop in the pile. It is possible that if a structure had been present in the area, a pile of significant height might have been built adjacent to it so that the weight of the ice would have been sufficient to generate forces in excess of the bending strength. However, it appears that the moving ice itself did not do so.

The area inshore from the shear ridge-ice pile complex was earlier shown to be divided into two zones. The innermost zone was a hummock field (Figure 6a) which consisted of a chaotic mixture of blocks of varying sizes and orientations including many of triangular shape as described above. Pans larger than a few square meters in size were rare in this zone, and where present, were generally tilted or fractured and warped from having been rafted over the underlying surface of irregular blocks . A general view of the area is shown in Figure 12. A few discrete linear ice piles aligned approximately parallel to the shore line, also were found in this zone, but these were low and poorly defined.

The outer boundary of the hummock field was defined by a ridge about two meters high. Air photos show that it had a relatively straight trace (Figure 13) , and a large pan on its inshore side was truncated against it, suggesting a shear origin. However, no flour ice was found near the ridge and the offshore side was not vertical as were the faces of other shear ridges in the area. As noted, this hummock field was in place prior to the emplacement of the next zone further offshore. Thus , it is likely that shearing did occur along this ridge in the time just after grounding of the hummock field. Then. at the time of emplacement of the ice outside the ridge, some overthrusting may have occurred, which would serve to enhance the height of the ridge, perserve its linear aspect, and simultaneously bury any other evidence of shear origin.

The area between this ridge and the main shear zone-ice pile complex was, as noted above, a zone of mixed floes and hummock fields (Figure 6b). The floes were of variable sizes, ranging up to about 400 meters in diameter. Pressure ridges, which probably predated the grounding episode, cut across some of these in irregular directions. Locally, however, relatively short, high ridges occurred along the boundaries of some of the floes, and judging from the height of these ridges, it is likely that they were grounded. This zone of floes and hummock fields originated as the result of the development of a block to the movement of the pack ice out of the field of view of the radar to the northeast, as discussed at the end of the

Figure 12. View of the near shore hummock field from the radar site.

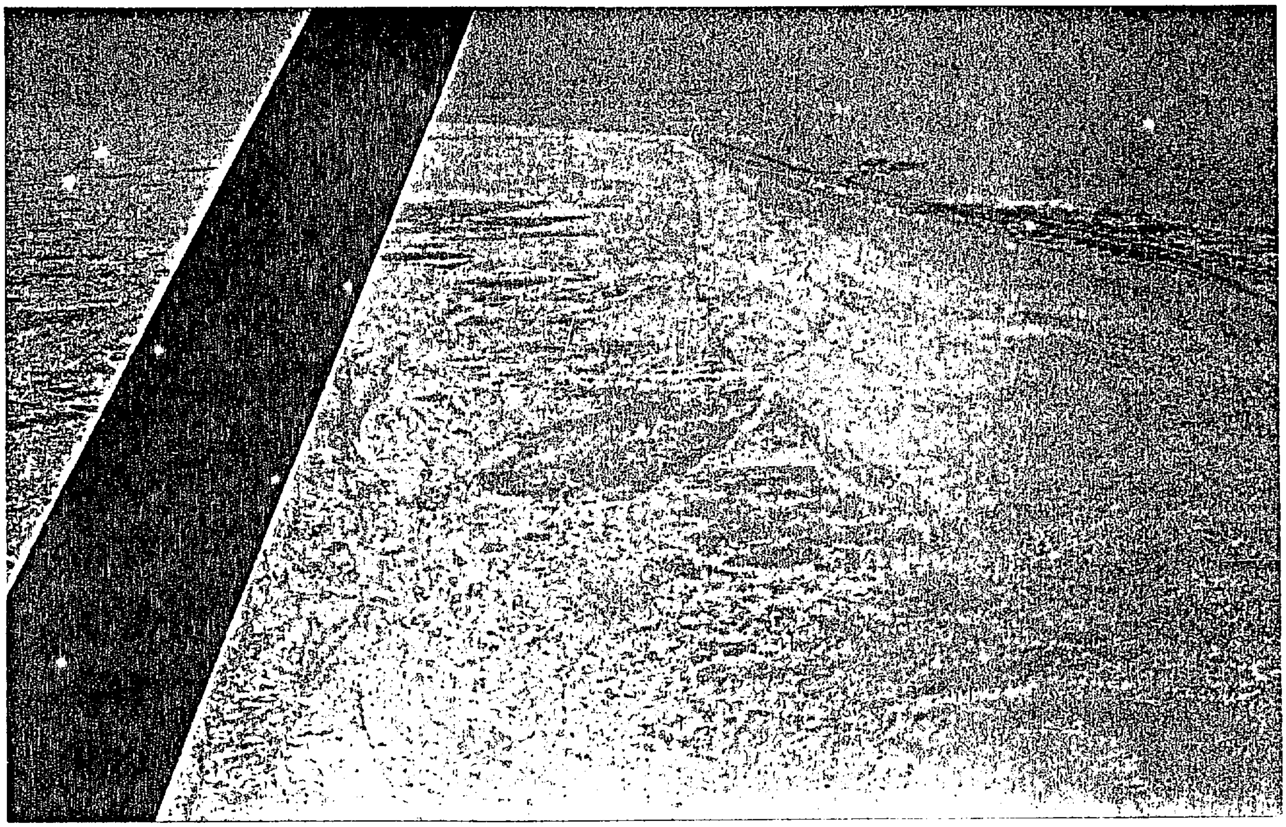


Figure 13. Oblique air photo showing the boundary of the near shore hummock field, view is northeast. The boundary shows as a faint gray line just to the right of the center of the photo. N.A.R.L. is on the right. The main shear zone and the ice pile just inshore appear at lower left. Width of the nearshore hummock zone is about .5 km opposite the south end of N.A.R.L.

last section of this paper. As noted above, the first reflectors observed to stop in this field were those which do so at 2116 Z, 31 December (Figure 6b), and movements observed on the radar imagery indicated that they were probably part of a large pan which was jostled and broken upon impact with ice already stopped further northeast. The remaining ice in the zone appears to have slowly come to a halt as it came up against the ice already stopped ahead. The stress environment must have been compressive as evidenced by the ridging which occurred throughout the zone.

The first reflectors to become stationary outside the shear zone were those associated with the three linear zones of reflectors, of questionable origin, shown in Figure 6e. Note that these extended away from the main shear zone at angles of about 20 degrees, but projected back into the direction of flow of the ice. These lines are identifiable on air photographs, but they were not examined in the field, Their traces were straight, again implying a shear origin. The introduction of these ridges created a bight bounded on the opposite side by the main shear zone (Figure 6e), and the moving ice quickly filled this area with floes and hummock fields. A general view of the area is shown in Figure 14.

When the bight noted above had filled out to the 20 meter depth contour, shearing began again and continued for several days until the storm subsided. However, the shear ridge marking this line had been defined by a line of reflectors by 0520 Z, 1 January. This ridge was not examined in the field until March, so that the morphologic aspects which can definitely be attributed to the initial formation of the ridge

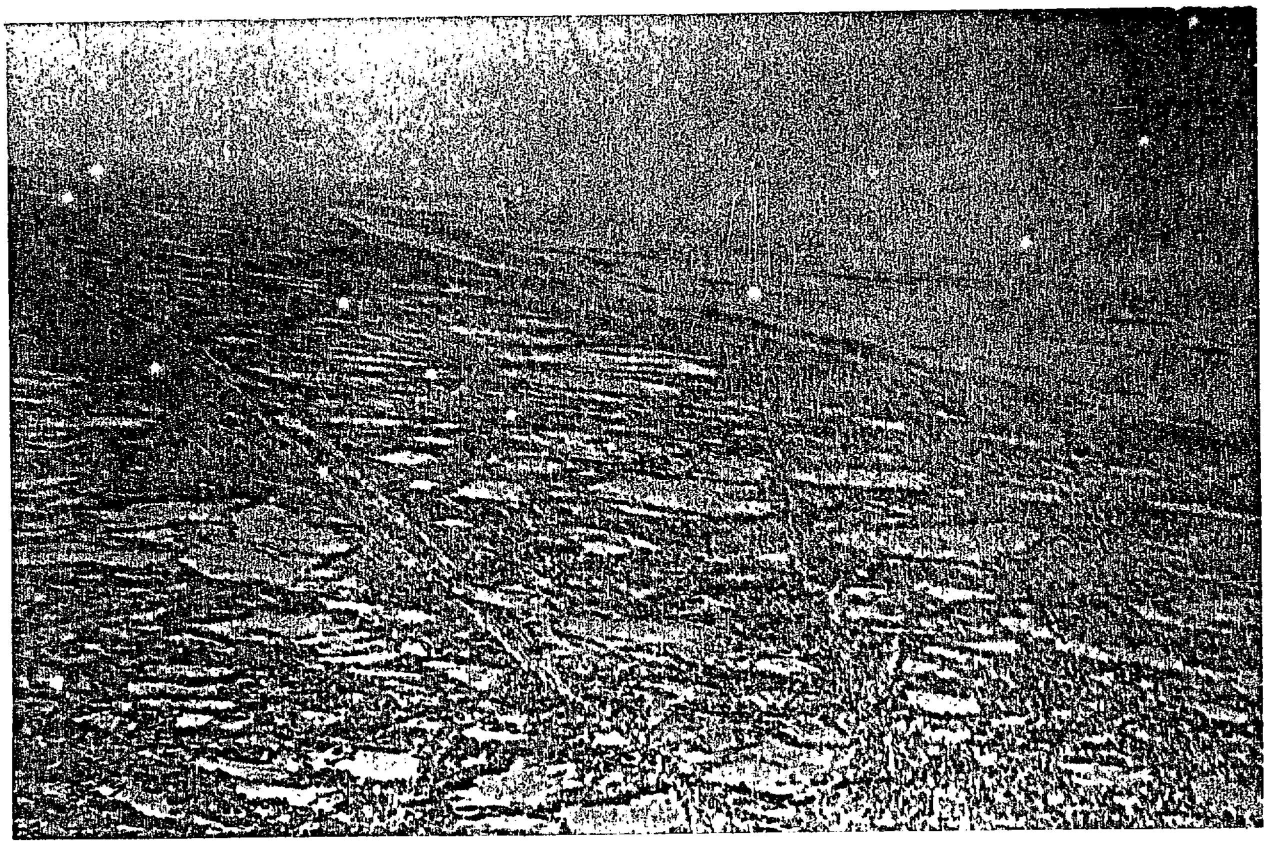


Figure 14. Oblique air photo of the outer zone of floes and hummock fields. View is to the southwest. The width of the landfast ice in foreground is about 1 km. The main shear zone and ice pile transect the left half of the picture, and a probable shear ridge appears just to the right of the center.

are uncertain. However, it is apparent from the radar data that the movement of the ice was such as to produce a shear ridge. In fact, the ridge was composed almost entirely of flour ice, and a prominent crack similar to that described from the inner shear zone, was also present in the outer ridge in an analogous position (Figure 10), as noted above.

DISCUSSION

The relationship between the main shear zone and the adjacent massive ice piles is of interest because of the fact that both these features formed under the same flow regime of the ice. The radar data clearly show the initiation of the pile as well as a gradual increase in its width. At some time, however, the ice stopped piling and instead, the moving pack ice began to shear by the stationary piled ice. The exact time at which this transition occurred cannot be determined from the radar imagery, and there is no apparent shift in flow direction or velocity of the moving ice which would indicate that such a transition was in progress. In addition, the exact position of the front of the ice piles at the time the transition occurred also cannot be determined, because it appears from field observations that the interface between the stationary ice and moving pack had been eroded back for some unknown distance, and it is this eroded face which defines the shear ridge.

The transition from piling to shear ridging probably depends upon the mechanisms involved in the piling process, and these are presently unknown. However, based upon the available data, it can be hypothesized that this transition is related to some threshold in water depth, beyond which piles are unstable under the conditions which existed at the time they formed. Comparison of the maps and radar data of the piles with the available bathymetric data shows that, as noted above, the main ice pile was associated with the shoal. In particular, the line of reflectors which defined the pile was aligned parallel to the general trend of the depth contour which marks the offshore side of the shoal. This leads to the inference of depth control on the areal extent of the pile. Regardless of the mechanisms involved in the process, it is necessary that the broken ice can be grounded in order for piling to occur, and the question of whether the ice will ground or not seems to be controlled by two parameters; the depth of the water and, as considered below, the flux of ice into and out of the area, which in turn is partially dependent upon the angle at which the incoming pack ice approaches the pile.

From studies of the radar data and field observations, it can be inferred that the ice broke into small blocks at the contact between the drifting ice and the edge of the growing pile, and that the zone in which the fracturing occurred was no greater than 60 meters wide. This distance was established from the radar data in which discrete reflectors in the moving pack were traced to within this distance from the edge of the pile with no indication of rotation or breaking which could result from interaction with the pile. For the purpose of the following discussion, it is assumed that the zone of breaking would not have been any wider than 60 meters if the pack ice had been approaching the pile at a high angle. Further, it is assumed that an ice pile, breakwater, or other obstruction is already present in the path of the moving ice. The initiation of the pile will be considered below.

Within the fracture zone, a chaotic mixture of blocks will be formed and some over– and underthrusting must inevitably occur. As a result, for the case where the pack ice approaches the obstacle at a high angle, with a corresponding small component of ice transport parallel to the face, the mass of broken blocks will tend to thicken until one of two conditions results. If the water is deep, the ice will form a free-floating pile with an equilibrium thickness analogous to that formed in the limit cycle of the Parmenter and Coon (1973) model for pressure ridge formation. If, however, the water is sufficiently shallow so that grounding occurs before the equilibrium configuration is reached, then piling will continue until the height of the pile reaches some maximum which is a function of the maximum force which the impinging pack ice can exert in lifting the broken ice above sea level. This in turn is a function of the strength of the ice in bending, and its thickness. Once this maximum height is attained, additional ice added to the pile can only cause the pile to grow seaward until the water depth becomes too great for the ice to ground. From this point on, the configuration of the moving and stationary ice is the same as the initial condition assumed above, and the process becomes the same as that noted for deep water. That is, a free floating pile is formed.

In the case where there is a significant component of transport of ice parallel to the interface between the moving pack ice and the growing ice pile, a somewhat different situation may develop. In this case, it is obviously not likely that an ungrounded ice mass will be stable. Thus, the rate at which the ice is driven against the growing pile must be great enough that the mass of broken blocks can thicken sufficiently to ground before it is carried around the end of the pile (assuming, of course, that the pile is of finite length). If this requirement is satisfied, then the pile can continue to grow seaward. However, when the pile has extended over water too deep for grounding to occur, then no configuration analogous to the limit cycle will be stable. Thus, a free floating pile will not form and instead, the ice will be carried along the face of the pile to form a shear zone.

Finally, it should be noted that it is not necessary for the broken blocks to ground simultaneously all along the front of a growing pile. Obviously, if grounding occurs at any single point, it will serve to retard the motion of the ice further "upstream", and thus enhance the possibility of additional grounding and piling. There is some evidence that this did occur during the building of the main ice pile.

It should be noted that these interpretations are purely qualitative, and are based entirely upon study of the radar data and field observations. It would obviously be desirable to construct models of these processes, based upon the ideas outlined above, as a means of checking their validity. However, more data are needed regarding the geometric character of ice piles and the mechanisms important in the process before realistic models can be prepared.

THOUGHTS ON MODELS

As an example of the problems associated with choosing the proper assumptions for construction of a valid model of the piling process, it is instructive to examine the partition of energy during an episode of piling. Following Parmenter and Coon (1973), the most important energy sinks operative during piling are taken as (1) gravitational potential energy of the pile, (2) friction, and (3) energy required to form new surface area during fracture, In addition, grounding of the ice is an important factor in the development of ice piles, Some dissipation of energy must occur through gouging of the sea floor as the blocks are driven downward in the early stages of building the pile.

The simplest possible example of piling is that of the building of a pile by thrusting sheets of ice over each other to form an imbricated structure. In this case, friction and surface energy from new fractures are unimportant relative to the gravitational potential energy. Analysis of the problem should be rather straightforward if the ice approaches the pile at a high angle. If the angle of approach is lowered, then the possibility of shearing is introduced, and the problem is somewhat more complicated.

It is also possible for relatively large sheets of ice to be rafted up onto a growing pile of broken blocks. In this case, the sheet will be supported at a few contact points with the underlying irregular surface. Again, the contribution of friction and new fracture surface is minimal. Reports in the literature (Bruun and Johannesson, 1971) show that large pans can be rafted completely over ice piles and possible examples of this were also noted during field work for this study. such events, however, are probably restricted to cases where the piles are low, or the slope of the leading edge of the pile is gentle enough that a large pan can be rafted up over it without bending sufficiently for failure to occur.

The piles described above, however, developed primarily by a process in which breaking of the ice sheet probably occurred prior to piling. Thus, the pile was built by continuous push of the impinging pack ice against the foot of the existing pile: in effect, “bulldozing” the broken ice up the pile. In this case, it must be assumed that some interface, termed here a “ramp”, can be identified which separates moving from stationary ice in the growing pile. It is apparent that the ramp will be a highly irregular surface, because the blocks on both sides arc irregular in size, shape and orientation. This will cause blocks being pushed up the pile to jam behind other blocks protruding up through the surface of the ramp and stop until those protrusions are broken, or to drop into lows on the surface and possibly be rotated back up again. Thus, the surface of the ramp will be constantly shifting up and down in the pile. In addition, there will be friction between the moving blocks which will further tend to retard the motion up the pile. The effect of these irregular movements of the blocks up the ramp will enter a model as a frictional term, but the difficulties of defining a magnitude for this parameter are apparent.

Rolling of blocks leads to crushing and fracturing, which can further serve as an important energy. sink. Note that in the model of ridging by Parmenter and Coon (1973), it was assumed that the ice broke into blocks about 5 times the linear dimension of the ice thickness, and the energy required to form smooth surfaces of this size were calculated and shown to be insignificant (about 3 orders of magnitude less) than the potential energy of position. However, a simple calculation shows that the contribution of the surface energy is increased by a factor of 15 if it is assumed that the outermost 1 cm of each new surface is fractured to fragments 1 cm on a side during the ridge building process. This takes account of the fact that fracture faces tend not to be smooth surfaces, but instead, usually include a number of closely spaced intersecting fractures of varying lengths. In addition, it can probably be assumed that crushing and grinding of blocks will be significantly more important in piling than in ridging in the open ocean, because of the absence of the bouyancy effect in achieving high elevations in the former process, so that the blocks must be actively pushed to their ultimate height. The contribution to the surface energy from these sources is unknown, but it is certain that the assumption of smooth surfaces to the broken blocks will result in an absolute minimum contribution by surface energy.

A second frictional term enters the problem in another way which is potentially important, and difficult to estimate. If the ice breaks at the base of the pile, then for the case when the ice approaches with a significant component of motion parallel to the face of the pile, there will be a frictional force tending to drag the broken ice in the direction of motion of the moving pack. The two extreme cases of this situation are straightforward. If this frictional force is zero, then there is no motion of the broken blocks parallel to the face of the ramp, and the pile is driven straight up the slope. The ultimate height of the pile would then be independent of the direction of approach of the pack.

At the opposite extreme, consider the case where the friction at the face is very large. This would have the effect of treating the advancing ice sheet as coherent, as it advances up the pile, so that it would simply continue in the same direction as the incoming pack, with some deflection depending upon the slope angle of the ramp. This situation could result if the ice does not fracture at the base of the ramp or if the internal friction of the broken ice mass is so great that the mass retains cohesion as it is driven up the ramp.

The true description of the process probably falls somewhere between these two extremes. It is important to know this reasonably well, because part of the energy loss during the piling process by formation of new fracture surfaces, and by friction between moving and stationary ice depends upon the path length over which the ice is pushed, The shortest path length, and hence the highest piles may be associated with the first case above, while the longer path lengths and lowest piles would result from the second case.

From the above discussion, it is apparent that there is a possibility that the combination of energy losses through friction and the formation of new fracture surfaces may be as large as the gravitational potential energy of the pile, so that these cannot be ignored in analysis of the problem. In addition, the energy loss due to gouging of the sea floor has yet to be estimated. Methods by which these parameters may be determined from field and/or laboratory studies are currently under investigation.

CONCLUSIONS

The results described above represent the first step in a continuing study of ice dynamics in the near shore zone. Because this is the first instance of the availability of radar data for studies of this type, there is little information in the literature for corroboration of the conclusions reached in this investigation. Thus, with the exception noted, the following results should be regarded as preliminary:

1) The utility of the radar data for studies of the near shore ice dynamics can be regarded as established beyond doubt. In fact, without such data, studies such as presented here would be impossible.

2) The correspondence between ice morphology and water depth described above may be a general relationship which, if properly introduced into a valid model of ice drift in the near shore zone, may provide a basis for estimating the worst possible ice conditions at any given site in terms of ice characteristics and movement patterns.

3) No evidence was found to suggest that the stresses associated with the piling of the ice or the emplacement of the zones of floes and hummock fields ever exceeded the bending strength of the ice over any significant area. However, the applicability of this conclusion during the time the shear ridges were being built is uncertain.

4) Many of the blocks in the piles were formed by fracture of the advancing ice sheet as it was driven against the irregular front of the growing pile, Rafting of larger pans onto and over the pile may have occurred, and the dominant mode of piling was probably "bulldozing" of broken blocks up the face of the pile.

5) The transition from piling to shearing was probably controlled by water depth in the example studied, The question of the applicability of this result if the ice had been approaching the pile at a higher angle is still open, because this introduces the question of the flux of ice in the area into the problem which, in turn, requires a quantitative evaluation.

6) In the preparation of a model for ice drift and piling in the near shore zone, it will be necessary to consider the effects of friction in the growing pile, energy loss due to the creation of new fracture surfaces, and energy loss from grounding. It is possible that the combined effect of these will be at least *as* important as gravitational potential energy, although they can safely be neglected in the Parmenter and Coon (1973) model of pressure ridge formation in the open ocean.

7) No movement *was* detected in the landfast ice mass by repeated precise distance and angle measurements until. the onset of break-up. This can probably be attributed to the extensive grounding of the ice.

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