STAMUKHI SHOALS OF THE ARCTIC - SOME OBSERVATIONS FROM THE BEAUFORT SEA

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INTRODUCTION

A number of linear shoals, representing pronounced topographic anomalies on the surface of the Arctic shelf, have been studied in the Prudhoe Bay area. These shoals have been referred to in several previous studies. Based on seismic reflection records, Reimnitz et al., (1972a), stated that the shoals are constructional features younger than the post-Wisconsin transgression. Large chunks of grounded ice have frequently been seen on the linear shoals of the inner shelf. These ice chunks form barriers parallel to the shore (Reimnitz, et al. 1972b). Reimnitz and Barnes (1974) considered the lack of gravel concentrations on the shoals to be evidence that the stream of pack ice drifting past northern Alaska carries very little gravel today. Lewellen (1977) referred to the linear shoals as submerged barrier islands, while Reimnitz, et al., (1977b) pointed out that, although similar in shape to barrier islands, the linear shoals are very different in composition and do not appear to represent drowned barrier islands. They show that the shoals localize the formation of major shear and pressure events in the ice, which in turn cause the formation of linear belts of deformed and grounded ice. Today the shoals appear to be migrating under the influence of ice-bottom interaction, and indeed may have formed in response to ice-bottom interaction within the "stamukhi zone". The shoals migrate rather slowly and retain their shapes over periods of 25 years, yet control the location and stabilize the outer edge of the floating fast ice zone, and provide shelter for the inner shelf and coast. Reimnitz et al. (1977b) surmised that similar artificial structures might be used to modify the ice environment on the arctic shelf.

Linear shoals occuring along the eastern seaboard of the United States (Field and Duane, 1976) are similar to those in the Prudhoe Bay region in their general shape, size, and orientation with respect to the coast. Their origin is still under question, but regardless of whether these shoals originated as barrier islands or as nearshore shoals, the processes affecting them today are very different from those found on the Beaufort Sea Shelf.

Understanding the nature and behavior of Beaufort Sea shoals and their interaction with the ice regime is fundamental to understanding ice zonation on the Beaufort Sea Shelf. A similar interaction between linear shoals, stamukhi, and grounded ridges, may control ice zonation along the Siberian shelf. Thus, the shoals are of regional rather than local significance and warrant closer study.

Modern barrier islands along the Beaufort Sea are composed of sand and gravel, a natural resource in high demand for offshore petroleum development. If the shoals under consideration were indeed drowned barrier islands, as suggested by Lewellen (1977), they might also contain valuable materials for offshore construction.

For the reasons stated above we have made special efforts during the last few years to learn more about the linear shoals of the Arctic shelf, and in this report we present some of our data.

REGIONAL SETTING AND MARINE PROCESSES OF THE LINEAR SHOALS

Figure 1 is a contour map of the area of linear shoals under investigation. The outer shoal, which we surveyed for the first time in 1977, is by far the largest - 17 km long. We will refer to this hereafter as the Stamukhi Shoal. Cat Shoals, a 12 km long, broad, and ill-defined set of

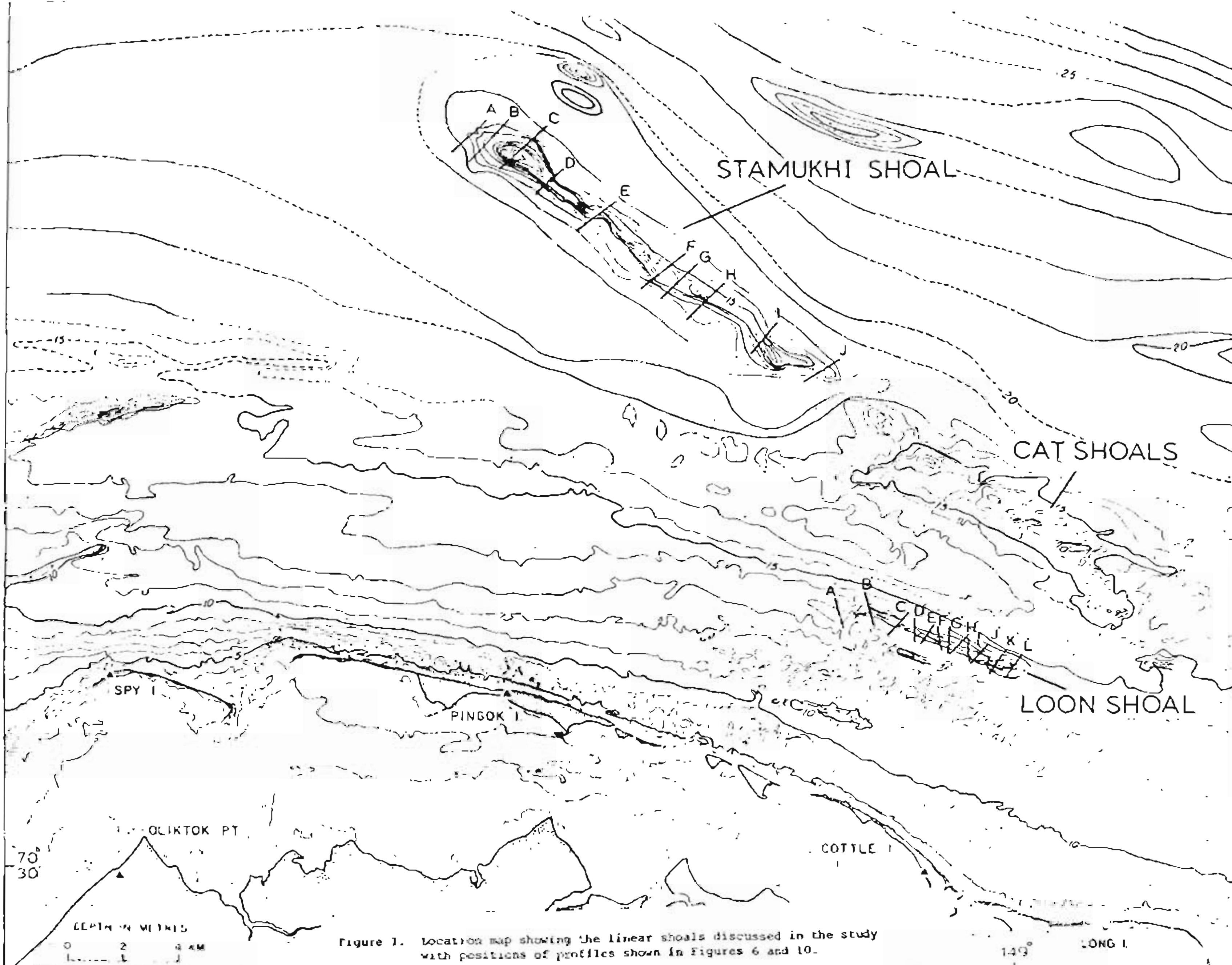


Figure 1. Location map showing the linear shoals discussed in the study with positions of profiles shown in Figures 6 and 10.

discontiuous shoals, forms a southeastward extension of Stamukhi Shoal. Several smaller shoals inshore range in length from 1 to 7 km. The shoals are on the average about 6 m above the surrouding sea floor and are typically steeper on the landward side than on the seaward side.

The frequency and intensity of ice interaction with the shoals has been referred to by Reimnitz, et al. (1972b), Reimnitz and Barnes (1974), and Reimnitz, et al. (1977). Within the area of figure 1, linear ice ridge elements formed by ice pressure and shearing during the winter were shown to have a striking correlation with the linear shoals. This correlation was used as evidence that both ice dynamics and ice zonation in this region are perhaps controlled by grounding during ridge formation. Analagous conditions apparently exist on the Siberian shelf, where "heaps of ice" (stamukhi) form on shoals along the outer edge of the fast ice and shelter the fast ice. These relationships, noted in geographically widely separted regions, were recognized as having fundamental significance for ice zonation, and the term "stamukhi zone" was introduced (Reimnitz, et al. 1977b). But when making their analysis those authors did not know of the existence of a major shoal which serves as a strong point between Cross Island and Stringer's (1974) "ring of grounded ice" off Harrison Bay, which also is marked by shoals. The newly surveyed shoal serves as this missing link. The Landsat image of early July, 1973, (Fig. 2) taken from Reimnitz, et al. (1977b), shows that the newly discovered Stamukhi Shoal correlates with a major ice boundary. This shoal sets the stage for the ice shear events across Harrison Bay. It causes further ice grounding there, and also provides shelter for the formation of a second sheet of undeformed ice in Harrison Bay. This process has been discussed by Reimnitz et al. (1977b). The northern tip of the region of white-appearing ice in figure 2, identified by Stringer (1974) as a hummock field, coincides with

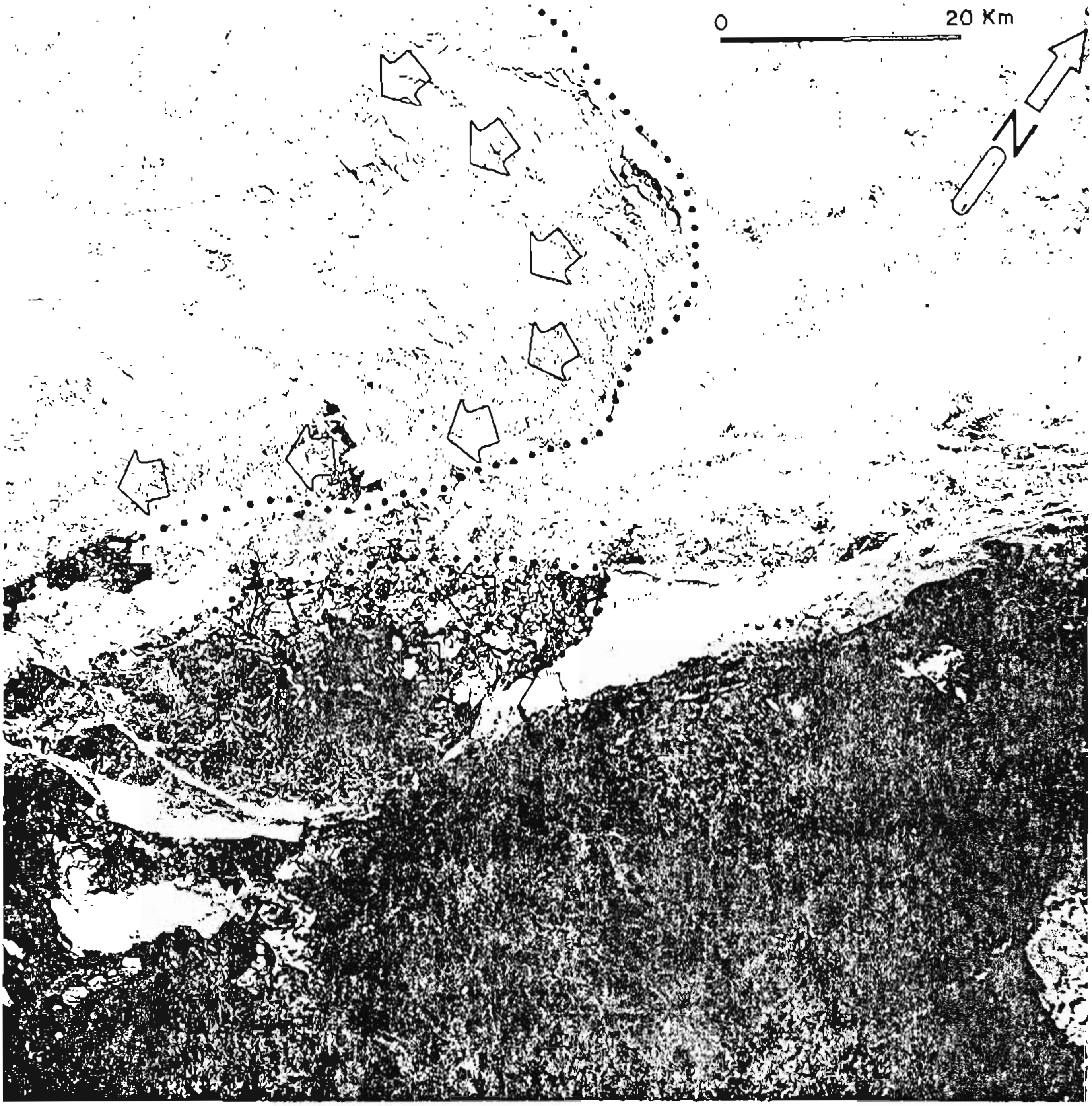
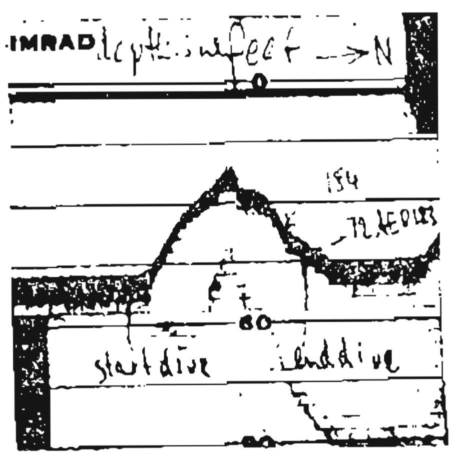


Figure 2. Landsat image of early July,1973,ice conditions. Stamukhi Shoal corresponds with the northeast boundary of the white appearing ice near the center of photo.

the northeastern tip of Stamukhi Shoal. Summer ice distribution is controlled by ice grounding on the shoals as well. We commonly observed this during the navigation season. Figure 4 is a Landsat image of July 25, 1977, showing how Stamukhi Shoal acts as a controlling element in the distribution of summer ice. Figure 3 is another example representing a photograph of the radar screen of the R/V Karluk showing Cottle Island close on the right and a linear accumulation of ice along Loon Shoal (described in the next section), and smaller shoals inshore.

As expected, the ridges are marked by intense and frequent reworking and gouging caused by physical action of ice. An abbreviated list of observations taken from a 1972 dive on Loon Shoal will serve to demonstrate the importance of ice-related processes. The diving traverse started in the flat trough landward of the ridge, at a water depth of 14.5 m (see ridge cross-section taken on Simrad depth recorder after the dive). The bottom was sand, covered



A 1972 Simrad record along diving traverse on Loon Shoal

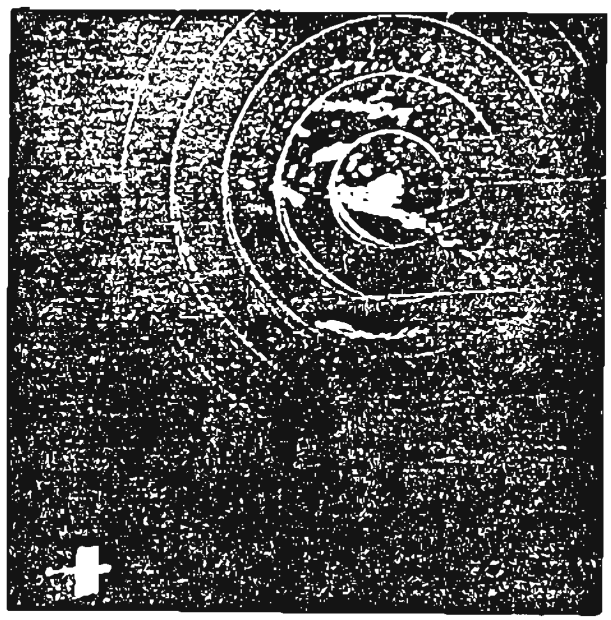


Figure 3. A photograph of radar screen on the R/V KARLUK as it passes just offshore of Cottle Island. Towards the bottom is ice free Simpson Lagoon with Beechy Point being the bottom-most target. Loon Shoal appears as a linear series of targets uppermost in the photo.These targets are stamukhi grounded along the crest of the shoal.

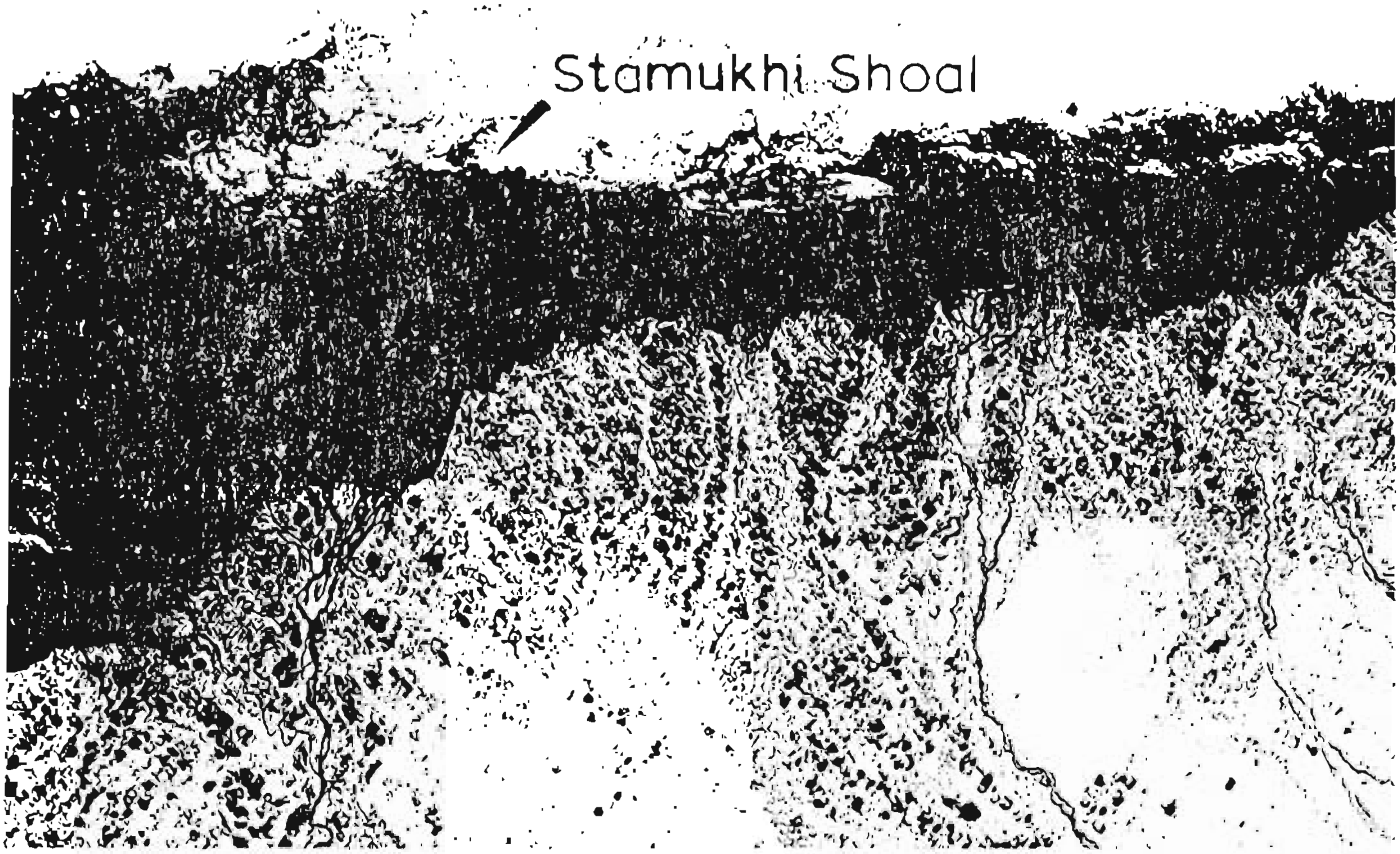


Figure 4. Landsat image of July 25,1977. Northwest end of Stamukhi Shoal is located by leader. The trend of the shoal is closely followed by the landward edge of ice.

by a thin layer of organic ooze, and there were several obscure, east-west trending gouges. As we swam up the lee side of the shoal, we noted that the ooze disappeared. A surface of clean sand was exposed which had been extremely disturbed by gouging. The trend of the gouges was dominantly parallel to the trend of the ridge, but they were criss-crossing in irregular patterns, and some trended upslope. Some of the gouges were multiple types, and many gouges terminated within the field of view, showing that gouges on steep slopes are short. Vertical relief of gouges measured up to 2 m, width up to 10 m, and flanks generally sloped at the angle of repose of the sand. Wave- or current-produced bedforms were scarce and ill-defined, and ripple structures generally were restricted to particular gouges, often transverse to the gouge trend. We have observed this in dives on other ridges. Only a few bottom-dwelling organisms, including isopods and coelenterates, were seen. Shortly after we crossed the ridge crest the layer of organic ooze reappeared. At first the ooze covered only the gouge troughs, but as we descended further it blanketed the entire surface, including the crests of flanking ridges. We felt a shelly, gravelly sand at about 10 cm below the sea floor. The number of gouges decreased with water depth. At a depth of 13 m, irregular, blocky outcrops of dark, stiff, slightly sandy mud protruded from the sediment blanket.

The above observations (including the clean sand bottom) generally apply to all of the shoals landward of the Stamukhi Shoal. Due to currents, summer accumulation of fine sediment on the upper part of the shoals is less than the accumulation on the lower flanks and adjacent flat bottom. Bottom-dwelling organisms are scarce on the sandy shoals, therefore ice gouging is the dominant factor in reworking the bottom. This can often be observed in progress. However, the gouges are short and irregular and are criss-crossing. Non-cohesive sand lies at the angle of repose, and the gouges are difficult to record with side-scan sonar. Also, the absolute rate of bottom reworking by ice is not easily monitored with side-scan sonar due to the presence of stamukhi on the shoals which force the ship to veer from the comparison base line. However, the linear shoal north of Spy Island (Fig. 1) appears to be well marked by an entirely new set of gouges from year to year, (Barnes et al., 1978). The dominant trends of the gouges reflect the steering effects of the shoals on ice drift. North of the linear shoal seaward of Spy Island, the dominant gouge tend is WNW, while south of the shoal it is WSW.

A summary of processes acting on the linear shoals cannot be complete without considering ice-rafting as a means of supplying new materials. Retarded drift of melting ice provides an optimum condition for the concentration of ice-rafted sediments (Reimnitz and Barnes, 1974). This condition prevails on the shoals during summer as shown schematically in figure 5. The ridge crests which attract ice-rafted debris, should also be sites of enhanced winnowing of sediments by ice contact and currents, as compared to the surrounding sea floor. The presence of clean sand, rather than gravel, capping the inner shoals, would seem to rule out ice-rafting as an important contributor of sediment to the shoals since ice-rafting generally deposits a wide range of particle sizes including gravel and cobbles.

BATHYMETRY

Loon Shoal The long shoal about 8 km north of Cottle Island in water 13 m deep is called Loon Shoal, after the U.S.G.S. R/V Loon from which the first studies of the shoal were made since 1971.

Methods- Bathymetric data for Loon Shoal obtained by the U.S. Coast and Geodetic Survey in 1950-51 and compiled onto C. & G. S. Hydrographic Sheet

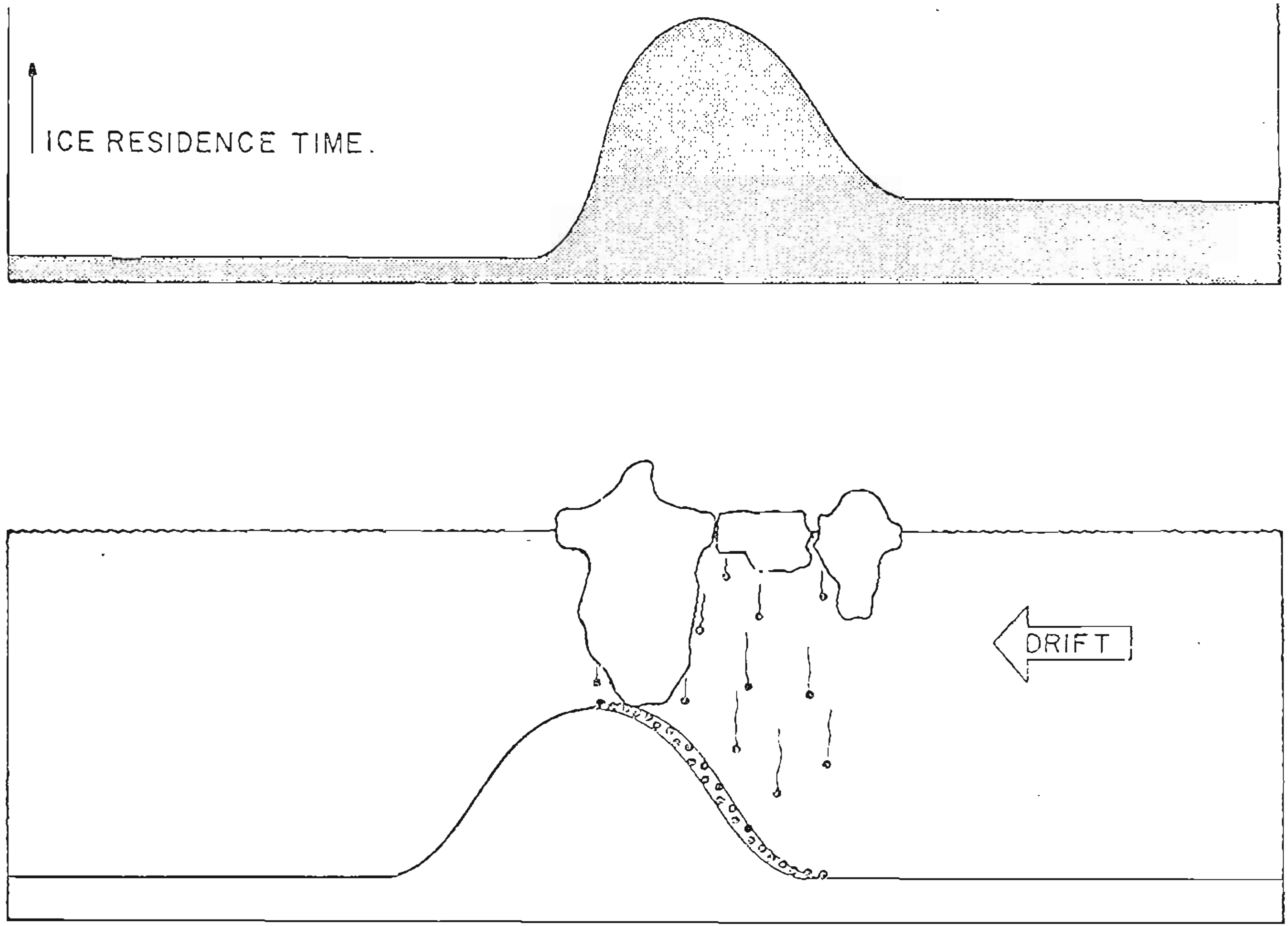


Figure 5. Conceptual diagram showing prefered deposition of ice-rafted materials on shoal during summer conditions.

#7856, were compared with data obtained in 1976 by the R/V Karluk. The 1950 data were controlled using a combination of Shoran and sextant fixes on shore objects; accurate to ± 100 m. The 1976 data were controlled with a Del Norte range-range navigation system accurate to ± 5 m. Bathymetry was obtained with a 100 kHz narrow beam transducer coupled with a Raytheon RTT 1000 depth recorder. Both Del Norte ranges and bathymetry were recorded on magnetic tape simultaneously at 10 to 30 second intervals. The data was then plotted by computer at the same scale and projection as C. & G. S.- Hydrographic sheet #7856. Where 1976 tracklines coincided with 1950 lines the original 1950 fathograms were used to construct profiles for comparison with the 1976 paper Raytheon records.

Topography

Figure 6 shows 1976 profiles of Loon Shoal, keyed to figure 1 by letters A' through L'. Profiles G' and K' coincide with 1950 survey lines and for these the 1950 profiles are shown as dashed lines. Figures 7 and 8 compare 1950 and 1976 bathymetry contoured at 1 m intervals.

Loon Shoal is a 6.5 km long linear ridge, trending approximately 120°T. It rises 7 m above the sea floor near its eastern end, and gradually diminishes in height toward the west. It is also asymmetyrical in cross section with the landward side characteristically steeper than the seaward side. Profiles D' through K' also show slightly deeper water landward of the shoal than that present at an equal distance seaward of the shoal. These characteristics are opposite to the configuration of present day barrier islands which are steeper and deeper on their seaward sides.

The sea floor landward of the shoal is generally smoother than it is seaward of the shoal and major relief features occur along its crest. This relief is the result of grounding ice.

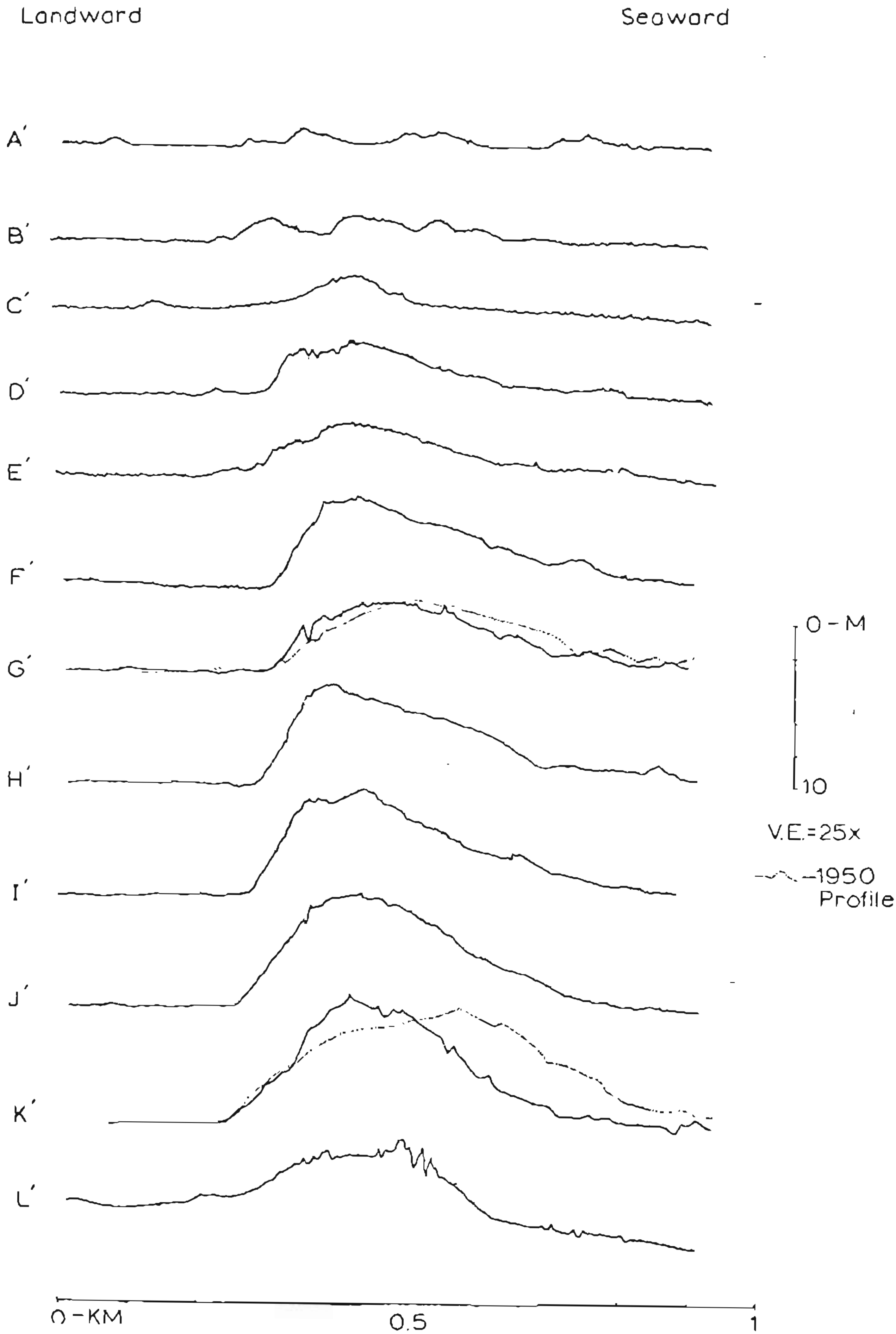


Figure 6. Profiles of Loon Shoal. All profiles were run on calm days so that micro-relief seen is real. Profiles G' and K' are superimposed with [illegible]

A comparison of the two bathymetric contour maps (Figs. 7 and 8) shows that during the last 25 years changes in the shoal's position and configuration have been minor. The flanks of the shoal coincide almost exactly along its length and the asymmetry of its longitudinal and axial cross section has been preserved. The crest of the shoal has moved landward at various points along its length and the isolated highs near the western end of the shoal have changed position slightly. The 8 m and 9 m contour along the crest of the shoal, just to the west of the shoal's high point, have been extended to the west about 1 km, suggesting significant depositional modification.

Migration of the shoal's crest is shown in figure 9. At all points except at the extreme west end of the shoal, the crest has either remained stationary or migrated landward. Profile K' shows how the shoal cross section has changed at the point of maximum migration - approximately 200 m.

Stamukhi Shoal

Methods- The rather rare opportunity to survey the region of Stamukhi Shoal presented itself in 1977, when the area became ice free. Navigation was controlled by Del Norte range-range navigation, and bathymetry was recorded with the same system used for Loon Shoal. The Raytheon RTT 1000 was used with a 7 kHz transducer as a sub-bottom profiler. Since no comparative study with older data could be made, positions and depths were plotted directly on 1:80,000 scale charts.

Results- Stamukhi Shoal (Fig. 1) is the most striking feature on the shelf between Prudhoe Bay and Barrow. Its shape is somewhat different from that of Loon Shoal in that its highest part is on the western, rather than on the eastern, end. Here it stands about 10 m above the surrounding sea floor. Inshore of Stamukhi Shoal is a broad, lagoon-like depression, that extends

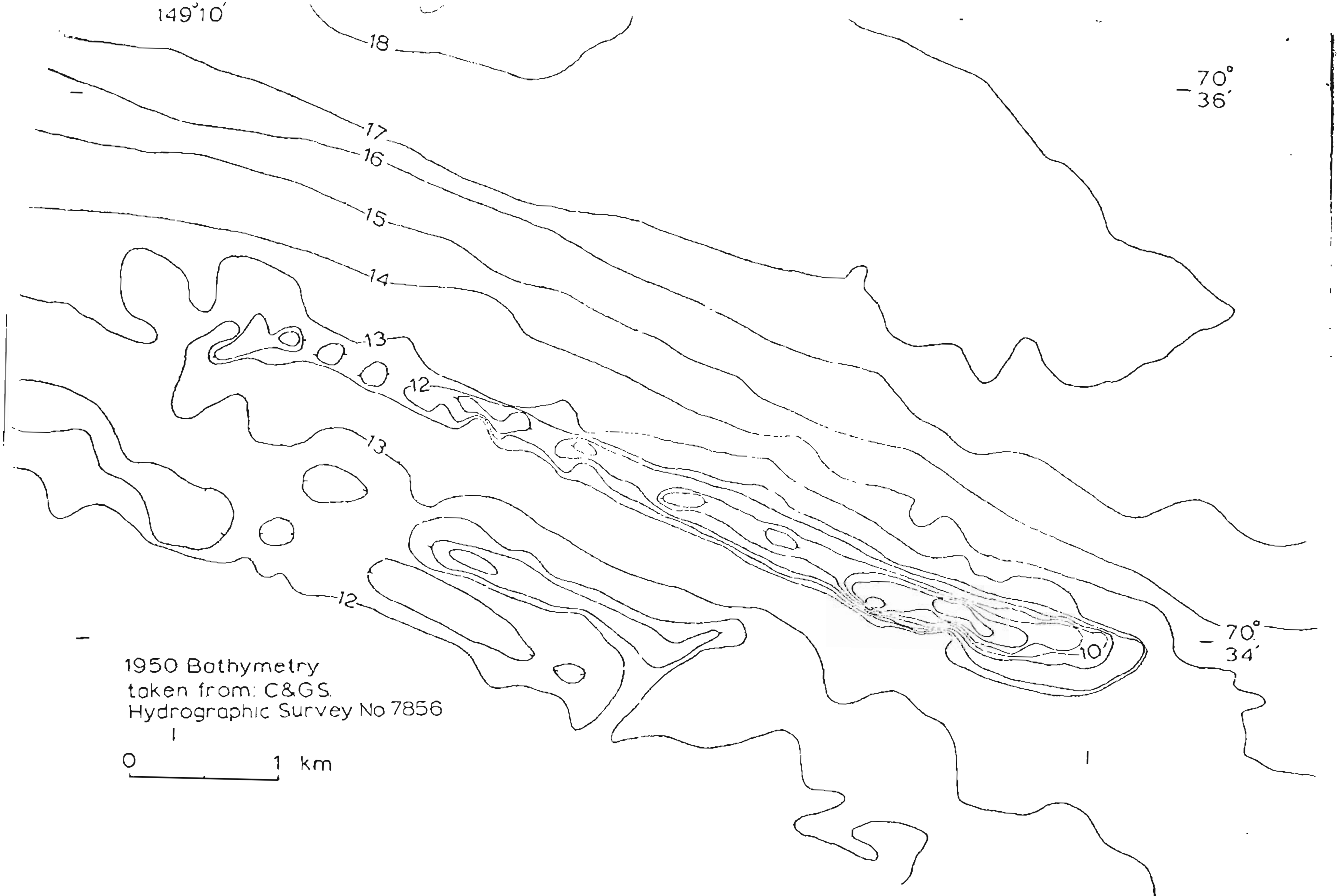


Figure 7. Bathymetry of Loon Shoal as surveyed in 1950, contoured in meters.

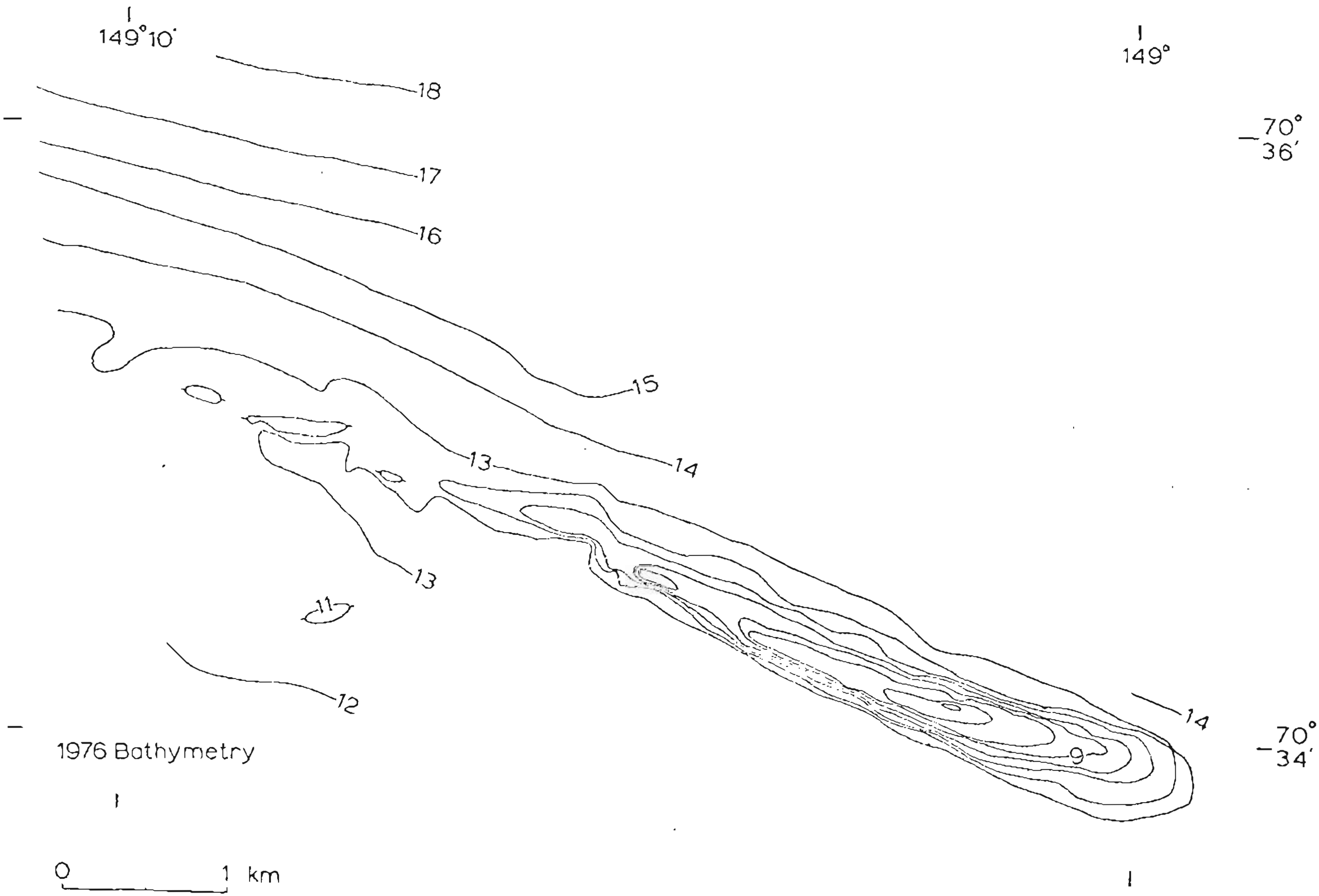


Figure 8. Bathymetry of Loon Shoal as surveyed in 1976, contoured in meters.

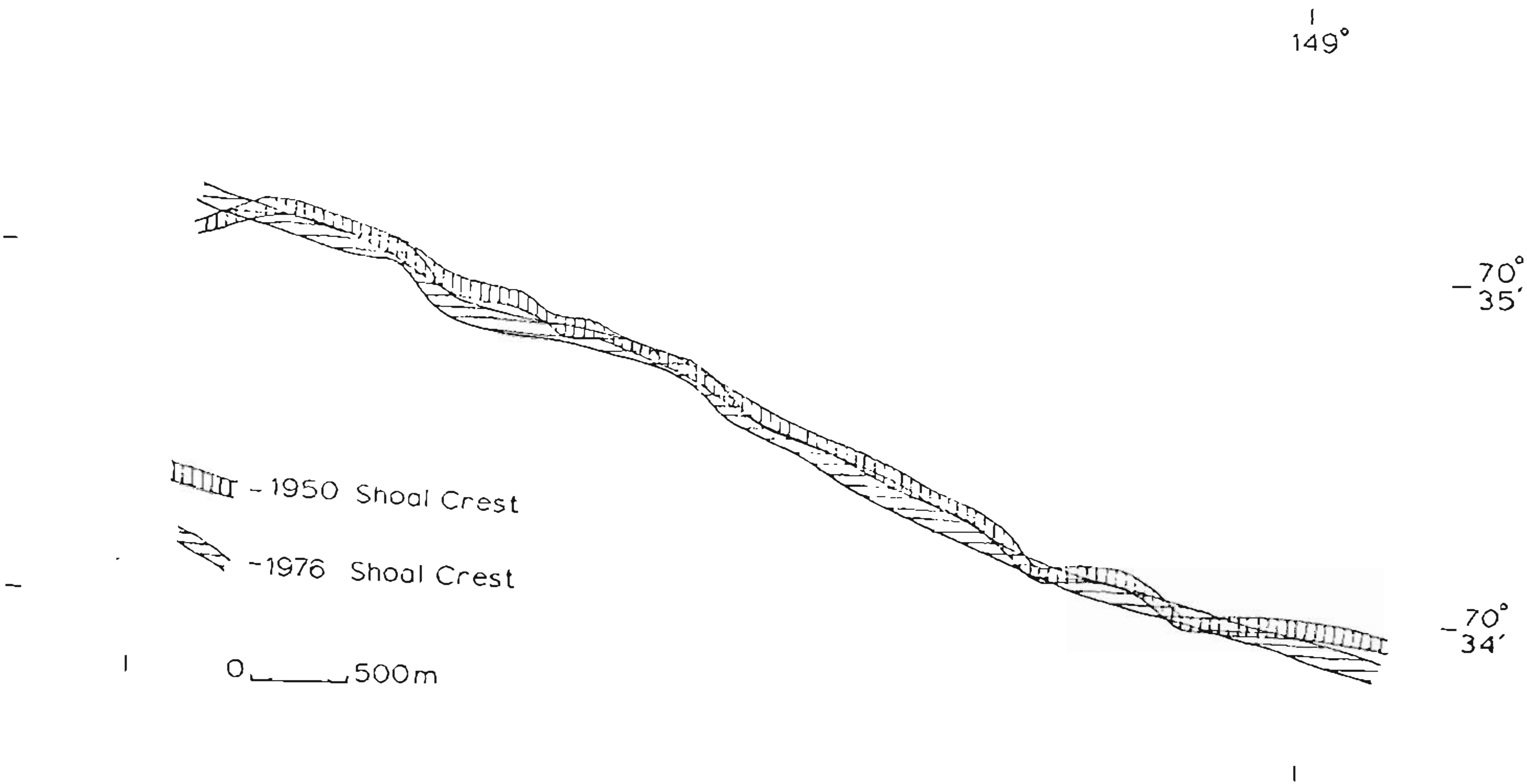


Figure 9. Superimposed ridge crest from Figures 7 and 8 showing landward migration.

seaward as a narrow arm through the gap between Stamukhi Shoal and Cat Shoals. Plotting of additional bathymetry surrounding Stamukhi Shoal will be completed at a later date.

A series of bathymetric and sub-bottom profiles (vertical hatch marks) of Stamukhi Shoal is shown in figure 10. As at Loon Shoal, these profiles are keyed to figure 1 by letters. It should be noted that profiles I' and J' were run on a day with rough seas and therefore the apparent microrelief is due partly to vertical motion of the ship.

The highest and steepest relief is seen in profile C', where the leeward side is much steeper than the seaward side. Such steep landward asymmetry is seen in several other profiles, but in other cases it is less pronounced, and in still other profiles a seaward asymmetry is noted. Both ends of the shoal terminate rather abruptly. At the northwestern end, the shoal suddenly bifurcates into three distinct arms. It is noteworthy that along the length of the shoal marked differences in profiles occur over short distances, and when viewed as a whole it appears to be rather irregular and winding.

Profiles A' through H' were taken in a calm sea and show very pronounced ice gouging with extremely jagged microrelief seaward of the crest and a rather smooth bottom on the landward side.

SEDIMENTS

Certain textural parameters of surficial sediments from the region under study have been mapped by Barnes and Reimnitz, 1974. However, these patterns show only regional trends, and do not adequately portray details of sediment distribution around the shoals. Also, additional data has been collected in the shoal area since that time. Sampling and observation stations in the study area are shown in figure 11. The stations represent surface grabs, vibrocores, and sediment observations from dive traverses. Details of one

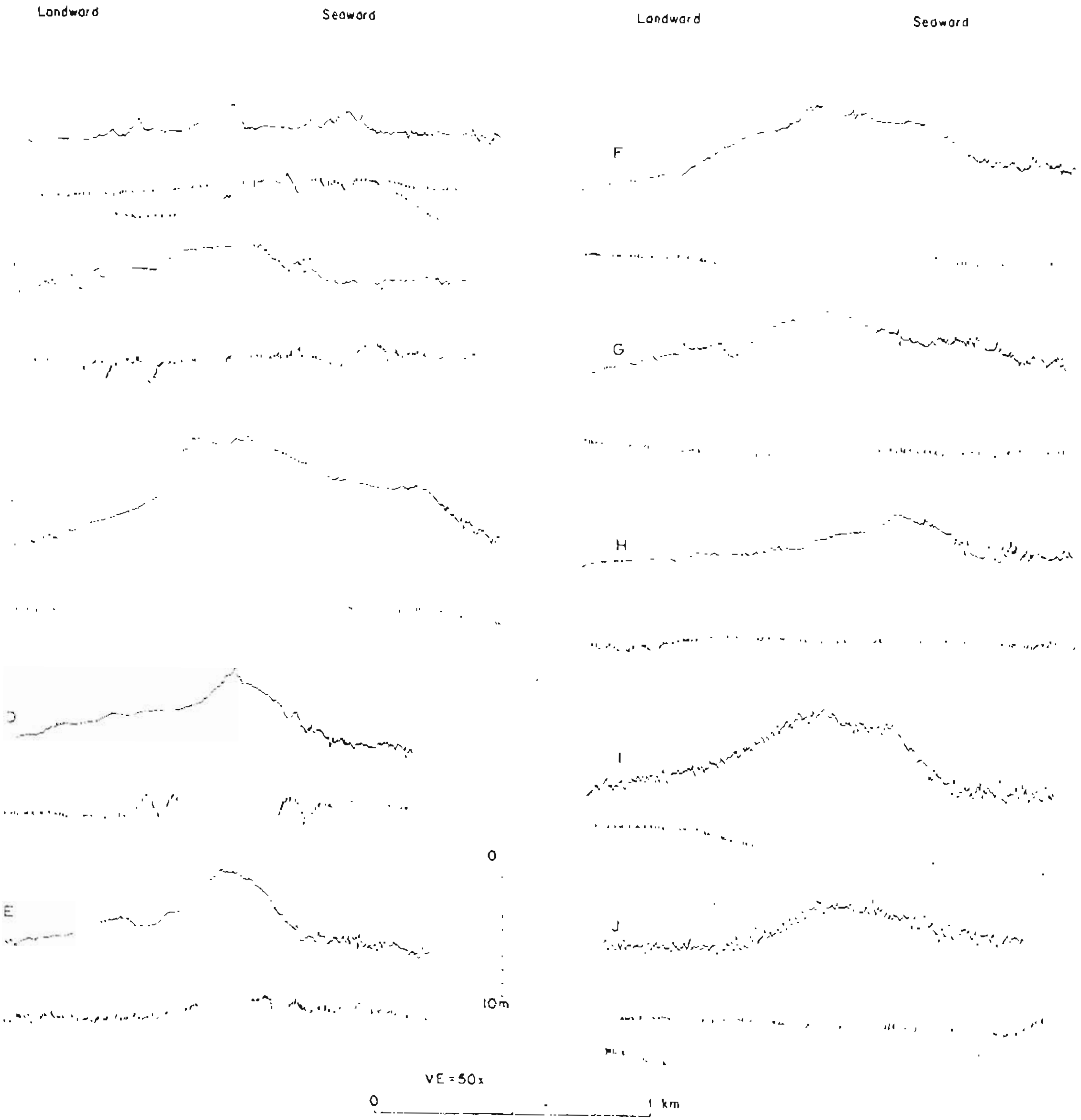
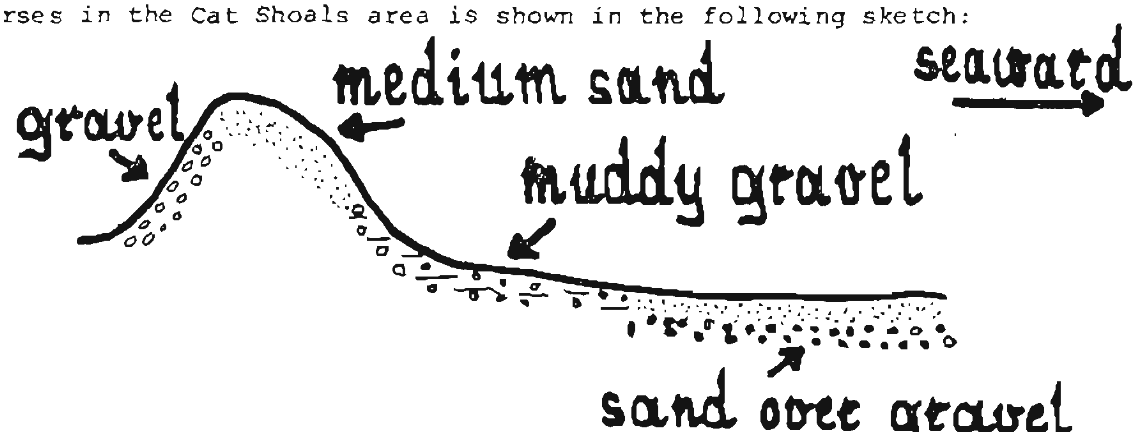


Figure 10. Profiles of Stamuhki Shoal with sub-bottom shown as vertical hatches. Profiles I and J were run with rough seas giving apparent micro-relief. The other profiles show ice gouging ,and show the shoal as a boundary for ice processes.

dive (Dive site #76-18)were given by Reimnitz and Toimil (1977). The diving investigations demonstrate that over much of the area generalizations on sediment types cannot be made because of extreme, short-distance variations. The areas where such variations occur are mapped in figure 11 as "variable". This area lies seaward of Loon Shoal and extends out through the region of the Cat Shoals. All the linear shoals landward of Loon Shoal are made up of well sorted, medium-grained sand. This sand seems to cover the intervening areas, except for a narrow band of mud along the leeward side of Loon Shoal. The seaward toe of Loon Shoal, below a depth of 11.5 m, is underlain by pebbly sand with shells, as seen at three locations along the length of the shoal. Landward of the 10 m isobath, the bottom deposits consist of clayey, sandy silt, shown here as sandy mud.

An attempt to compile a generalized sediment profile from two diving traverses in the Cat Shoals area is shown in the following sketch:



Two diving traverses cover small portions of Stamukhi Shoal and our knowledge of this shoal is therefore very sketchy. We found highly differing sediment types on these dives: near the center of the shoal the crest was capped with clean gravel, but near the eastern end we found both sand and gravel.

Outcrops of older sediments were seen on two dives in the area of highly variable sediments (Fig. 11). One of these outcrops, at the seaward toe of Loon Shoal, consisted of angular blocky outcrops of very dark, over-

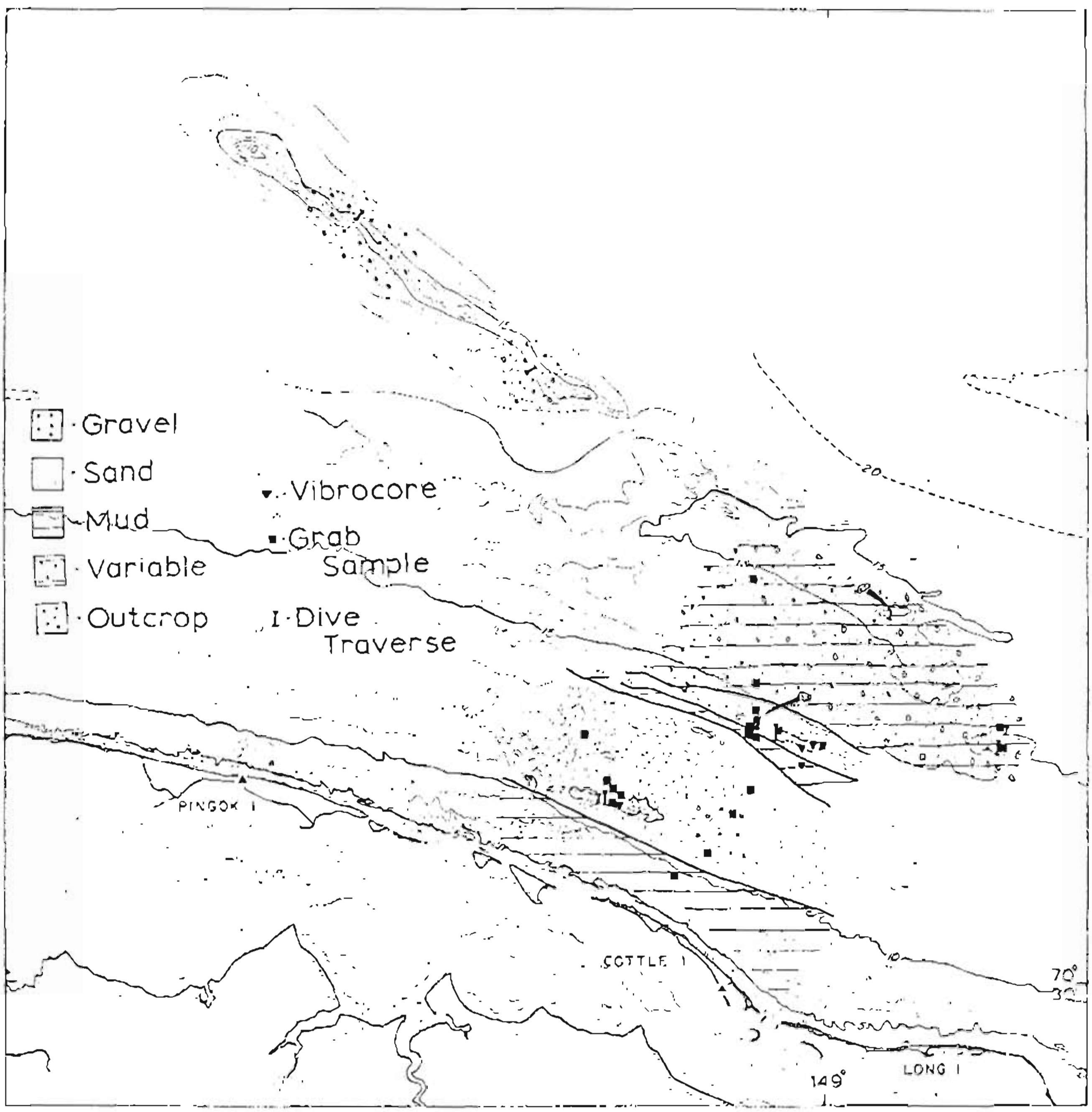


Figure 11. Location of stations in the shoal area and inferred sediment distribution.

consolidated, slightly sandy mud in various stages of disintegration due to burrowing. This material contained marine pelecypods (Serripes Groenlandicus and Astarte), and has a C_{14} age of 11,280 years ±280 years B.P. (whole sample date). On the lee slope of Cat Shoals, (marked by a dive traverse symbol in Fig. 11), we found a partly cemented, rust-colored, slightly sandy gravel cropping out in small patches which were elongated in the north-south direction. These patches were about '.5 m across and one to several meters long. Beating on the surface with a lead weight produced a sharp sound but did not dent the material.

SEISMIC REFLECTION PROFILES

Over the years a variety of sub-bottom profiling systems have been used in the study area. In this study the RTT 1000, operated at a frequency of 7 kHz, provided penetration sufficient to trace the shallowest sub-bottom reflectors through the area of the shoals. The general area is mantled by only 5 to 10 m of Holocene marine sediments with some "windows" which expose underlying deposits of the Quaternary Gubic Formation (Reimnitz, et al., 1972a). The fact that the linear shoals are marked by an upward thickening of the surficial unit resting on a flat-lying base is of importance to this sudy. In the case of Loon Shoal and shoals landward of Loon Shoal, this base is probably an old land surface marked with channel-like features. The sub-bottom profiles for Stamukhi Shoal (Fig. 10) show that a flat surface extends below the shoal for its entire length. Last year's records extend far out onto the shelf and indicate that Stamukhi Shoal and Cat Shoals sit on a different unit than Loon Shoal and shoals landward of Loon Shoal. More work is required to understand the details of this relationship.

INTERPRETATION AND CONCLUSIONS

The initial thoughts of a marine geologist contemplating the origin of the linear shoals would be attempts to link pertinent data to a history of submergence of barrier islands or offshore bars during the last transgression. But scientists familiar with the tremendous forces involved in moving fields of pack ice, and the bulldozing and scraping action of such ice, will find it incomprehensible that a linear topographic high could survive under these conditions for thousands of years.

Figure 12 shows a profile across Simpson Lagoon and a barrier island and seaward across Loon Shoal, to compare a typical modern barrier island with one of the linear shoals. Here, Loon Shoal stands nearly twice as high above the landward shelf surface than the barrier island stands above the adjacent lagoon. Another difference is seen in the detailed profiles of Loon Shoal in figure 6. These profiles are generally skewed landward, whereas the modern barrier islands are skewed seaward. The three-dimensional aspects also show considerable differences. The crest of Stamukhi Shoal is sinuous and discontinuous, unlike the linear arched shapes of typical modern barrier islands.

These differences could be explained by the modern ice processes which are now acting on the shoals. Profiles in figure 6, G' and K' show that the tendency through time may be toward steepening the landward side of the shoal. This process is accomplished by removal of sediment from the seaward side of the shoal and deposition of the sediment on the landward side. The shoal, when viewed as a whole, has not measurably migrated landward in the last 25 years but appears to have only been steepened on its landward side. This indicates that the difference in symmetry between the present day barriers and

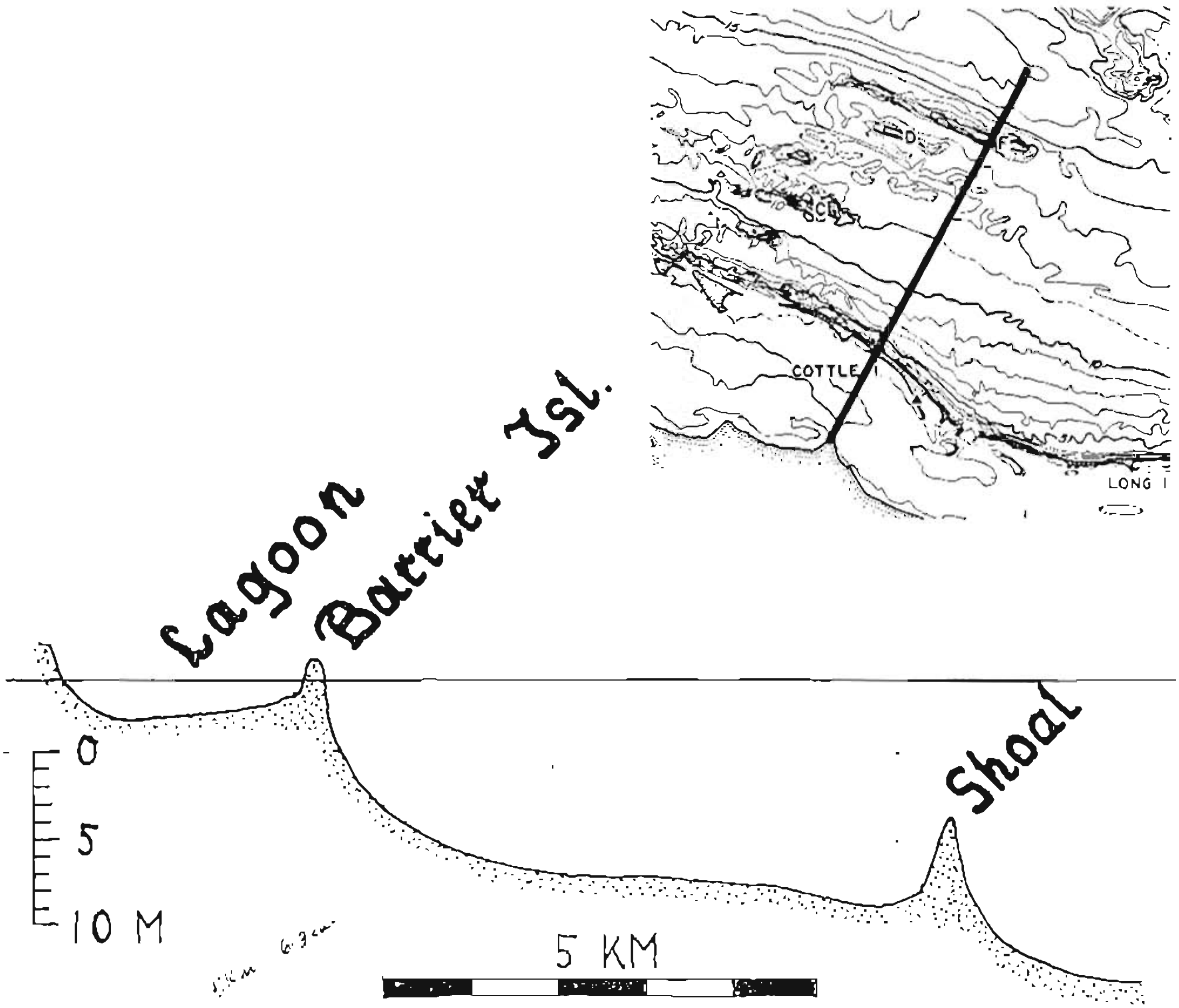


Figure 12.- Comparative profiel of a modern barrier island and lagoon and one of the linear shoals. The greater height of the shoal, which should be under the levelling action of ice, is notable.

the shoals can be explained by the obliquely landward bulldozing action of modern ice. Bulldozing action of ice along the crest of the shoals can also explain their present-day sinuous, discontinuous crest.

The clean sand of Loon Shoal and other shoals landward of Loon Shoal contrasts sharply with sandy gravels found on adjacent barrier islands and beaches and on Arctic barrier islands in general. The composition of Stamukhi and Cat Shoals, on the other hand, is not dissimilar to that of modern barrier islands and there a case for similar origin could be made. Our new seismic data indicate that the units on which Loon and Stamukhi Shoals sit are different and allow for shoal construction from materials available on the adjacent shelf surface, by similar processes with different results.

All available evidence indicates the linear shoals are depositional features. All observations made regarding modern processes of the Arctic suggest that anything which stands above the general shelf surface will be planed off by the action of ice. Even gently sloping, generally flat surfaces of the inner shelf are reworked by ice at a rate of once every 50 to 80 years. The action of ice is focussed on the high points, so that ice dynamics, and even the overall ice zonation of the shelf, appear to be controlled by the shoals. As Reimnitz, et al., (1977b), pointed out, a large portion of the available marine energy is expended on the sea floor within the stamukhi zone all during the year. Linear shoals, like the newly found Stamukhi Shoal lying within that zone, certainly take the brunt of ice action.

In view of the above, it is difficult to believe that the linear shoals are drowned barrier islands that have survived since submergence. There is not much chance for survival of such sediment piles over thousands of years when subjected to ice processes as we understand them today. However, this possibility has not yet been disproven. As previously reported (Reimnitz, et al., 1977b), and supported by data in this report, the shoals are not stagnant features. The shelly, gravelly sand found at the seaward toe along the length of Loon Shoal, supports onshore migration. We believe that ice-related processes may have caused construction of the linear shoals, but such processes are not understood. We still agree with a previous statement (Reimnitz, et al., 1977b) that future studies will have to show whether such shoals form by: (a) the bulldozing action of ice during one or several major events, (b) the cumulative effects of several thousand years of ice push by grounded ice ridges along the edge of the Pacific Gyre, (c) winter currents being channeled along major ridge systems which tend to concentrate available sediments into sand (or gravel) ridges, or (d) whether several of these processes act together to form the shoals.

Figure 13 presents a regional view of the Beaufort Sea shelf from Prudhoe Bay to Point Barrow. All isolated shoals seaward of the 11 m (6 fm) isobath are circled. The newly surveyed Stamukhi Shoal lies where no major shoal is charted. During the cruises of the Coast Guard Cutter Glacier, several of the shoals indicated on figure 13 were crossed but not found (pers. commun., Peter Barnes). We presently do not suspect that new shoals like Stamukhi Shoal have been formed during historical times, but rather we suspect the accuracy of our charts. Thus the scattering of shoals along the Stamukhi zone from Cross Island to Point Barrow only indicates that numerous shoals occur in the zone but that their true positions and orientations are undetermined in most cases. It may be that many more shoals exist, and we believe that detailed surveys would show the shoals to be more linear, and generally oriented parallel to the coast.

Last summer ice-free conditions allowed us to run surveys far out to sea NE of Cross Island, and we found no shoals. This lack of shoals up-drift of

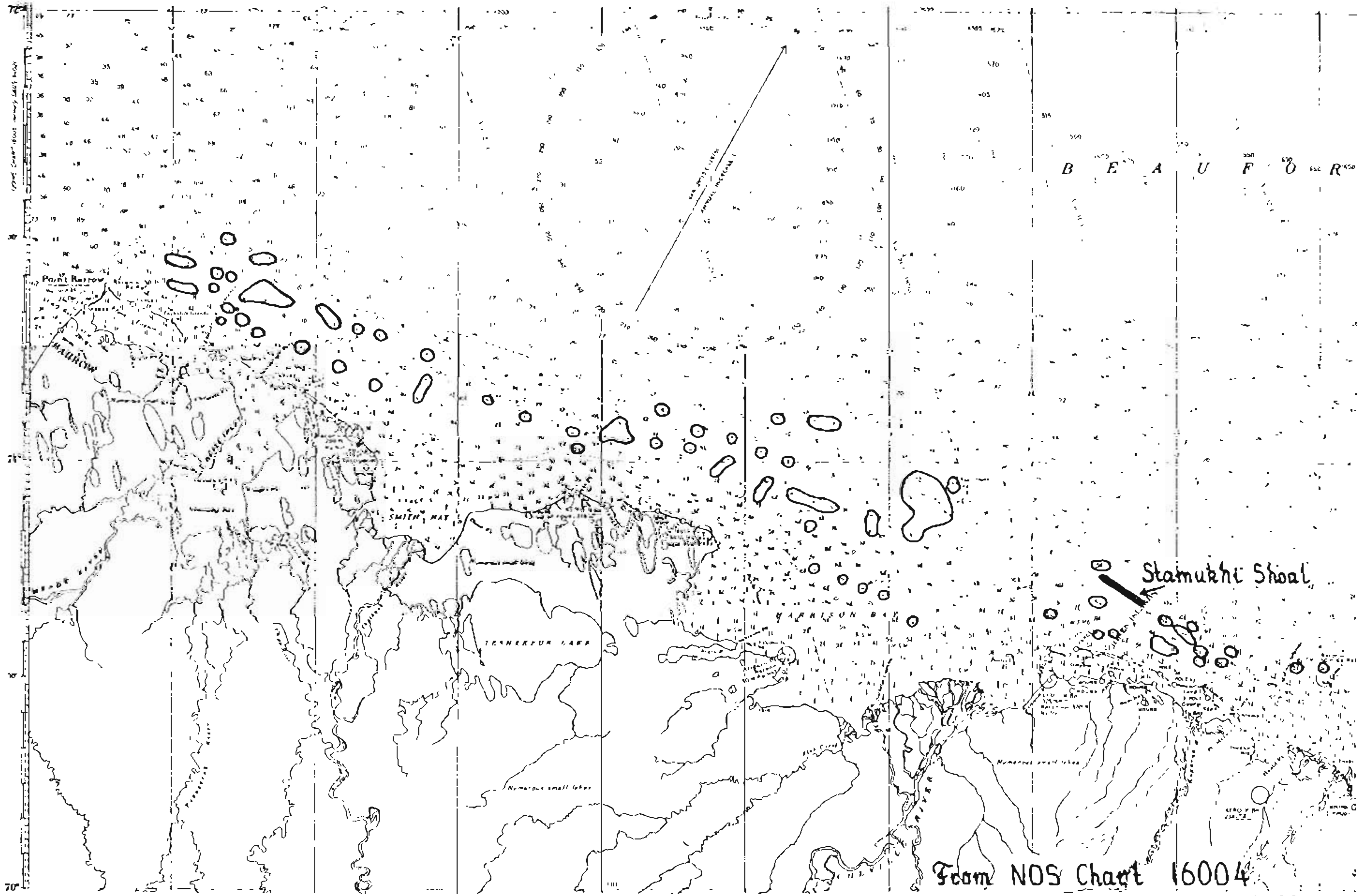


Figure 13.- The Beaufort Sea shelf from Prudhoe Bay to Point Barrow, with all charted shoals cresting shallower than 11 m on the mid shelf circled. Stamukhi Shoal lies where no shoal was indicated, and the two shoals north and south of it apparently do not exist today.

major promontories agrees with the concepts on ice dynamics and zonation proposed previously. We believe that detailed work west of Barter Island and Herschel Island may well show linear shoals, but we do not anticipate the existence of such shoals updrift from these promontories. The concept of linear shoals forming in response to ice-related processes seems to hold for the Alaskan Chukchi coast as well. There the general ice drift direction is southward, and shoals occur, for example, south of the Blossom Shoal region but none are found updrift.

We believe that shoals similar to those investigated here will play an important role in the future offshore development of the Arctic, but we are still far from understanding the details of the interaction of shoals with ice.

ACKNOWLEDGMENT

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