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NEARSHORE ICE CONDITIONS AND HAZARDS
IN THE BEAUFORT, CHUKCHI, AND BERING SEAS

by

William J. Stringer
Stephen A. Barrett
Linda K. Schreurs

SCIENTIFIC REPORT

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William J. Stringer
Assistant Professor
of Applied Science


Juan G. Roederer
Director
Geophysical Institute

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I. Summary of Objectives, Conclusions and Implications with Respect to Oil and Gas Development on the Outer Continental Shelf

The objective of this research unit is to develop a description of nearshore ice along the Beaufort, **Chukchi** and Bering coasts of Alaska, and identify those features which may represent hazards imposed by ice conditions on oil and gas development on the outer continental shelf (**OCS**).

Winter and spring Beaufort, **Chukchi**, and Bering Sea nearshore ice conditions have been analyzed for 1973, 1974, 1975, 1976, and 1977. The chief objective of this analysis was to assess hazards related to activities associated with offshore petroleum developments.

Landsat imagery has been utilized to map major ice features related to regional ice morphology. Following this, significant features from individual Landsat image maps have been combined to yield regional maps of major ice ridge systems for each year of study and maps of **flaw** lead systems for representative seasons during each year of study. These regional maps have, in turn, been used to prepare seasonal ice morphology maps.

The seasonal ice morphology maps show, in terms of a **zonal** analysis, regions of statistically uniform ice behavior. The behavioral characteristics of each zone have been described in terms of coastal processes and bathymetric configuration.

Based on the combined seasonal **morphologies**, a **zonal** analysis of potential hazards related to offshore petroleum development has been made for the study area. The hazards addressed are: safety of **field** personnel performing offshore geologic reconnaissance, large-scale displacement or deformation of fast ice sheet, the probability of formation of large ice ridge systems which could bring large forces to bear on offshore structures, and the possible fate of an under-ice oil spill.

The general conclusion is that nearshore sea ice behavioral patterns are similar from year to year, thereby yielding some predictability in terms of offshore sea ice hazards to oil and gas development.

The implications are that geographical zones of different design and construction criteria can be established in the offshore areas

- 2) difficulty in detection and delineation of the extent of the spill
- 3) possible transport of petroleum beneath the ice or with ice during dynamic events
- 4) clean-up difficulties caused by combinations of 1 thru 3
- 5) possible danger to personnel and equipment during dynamic ice events.

Ice conditions vary significantly depending on season and geographic location. Although the morphology presented later will be more complex, for the sake of this introduction two major zones of ice in **nearshore** areas need to be considered. These are:

- 1) The "fast ice zone", the area generally **shoreward** of the 20-meter **isobath** with quite stable ice much of the ice year. (December through June.)
- 2) The "shear zone", the area generally extending some distance beyond the 20-meter **isobath**. In this zone, the ice has the potential for undergoing shear to the point of failure and movement with respect to the fast ice at any time.

Within each zone the year can be broken into several behavioral periods. These are:

<u>Month</u>	<u>East_Zone</u> Period	<u>Shear_Zone</u> Period
Oct.	<u>Freeze-up:</u> Ice freezes in place or is driven into near shore areas and piled. Grounded ridges form out to the 20-meter isobath . The result is a stable sheet of fast ice.	<u>Freeze-up:</u> Complex process with periods possibly including pack ice, new ice pans, open water, etc. Result is nearly complete covering of ocean with ice not stable and subject to motion.
Nov.	<u>Stable:</u> Ice within zone is stable with few leads resulting from shear.	<u>Semi-stable:</u> Static ice can extend several tens of km seaward beyond fast ice for several weeks at a time. Ice can fail in shear at any time.
Dec.		
Jan.		
Feb.	occur resulting from temperature-related tension and tidal processes. Opening	

a. Exploration I. This activity is **mainly** geologic mapping by seismic crews. Currently seismic mapping is being carried out in the Beaufort Sea **using** fast ice as an operational platform **rather** than using boats during the relatively short and undependable open water season. Although few, if any, environmental hazards are created by this activity, hazards are imposed on the crews performing such work. The ice morphology developed here has been interpreted in terms of persistence **of** various ice zones and the period (if any) that exploration activities can be carried out from the ice within these zones.

b. Exploration II. **During** this phase, test wells are drilled--very **likely** from temporary structures including man-made gravel islands, anchored drill ships, movable platforms, etc. The choice of temporary structure used **will** depend **in part** on the morphological **behavior** of the ice in the location where a test well is desired. For instance, areas with a high incidence of hummock fields and shear ridging **would** be poor locations for anchored **drill** ships and might require artificial islands. A poor choice here might result in higher exploration costs and possibly environmental risk resulting from petroleum products spilled by damaged exploration equipment.

c. Development. During this phase, permanent structures are constructed for drilling of permanent wells and extraction facilities. Collector pipelines are laid and other permanent facilities are constructed. The considerations involved in the placement of these structures include the probability of ice **piling** around **and** upon man-made islands, ridge keel gouging of pipelines and also the effect of the facility on the morphology of nearshore ice and this, in turn on, the quality and nature of habitats.

This **report will** obviously yield information about ice piling and the probability of bottom plowing. Through the morphology of nearshore ice, including the dynamics of ice behavior near natural obstructions to ice motions, descriptive models of the impact of man-made islands on the morphology of nearshore ice can be developed. This can then in turn be related to impact on nearshore habitats.

d. Production. This phase of petroleum-related activities would take **place** over a span of many years. Consideration has to be

longitude and 69° 30' to 71° 30' north latitude. The coastline is irregular in shape, consisting of numerous bays, **points, capes,** and lagoons. The lagoons are bordered on the seaward side **by** long, narrow islands less than 4 meters in elevation.

There is little human habitation in this region. There is one native village **along** the Beaufort Sea coast located east of Barrow, in the **Colville** Delta. The only other permanent human habitation **along** this coast are three military **Distant-Early-Warning** stations at Lonely, **Oliktok** Point, and Barter Island and the oil fields at Prudhoe Bay.

In the **Chukchi** region, there is approximately 1750 kilometers of coastline, extending from 169° west longitude and 157° west longitude, and from 65° 40' **to** 71° 30' north latitude. The coastline is irregular in shape, consisting of numerous bays, point, capes, and lagoons. **Nome, Kotzebue,** and Barrow are the major population centers with populations of 3,000, 4,000, and 1,000 respectively. There are several native villages **along** the coast between Barrow and **Nome,** most having populations **less** than 100 persons.

The Bering region encompasses approximately 2,500 kilometers of coast line, extending from approximately 157° **to** 168° 30' west longitude and 53° 30' to 65° 40' north latitude. The coast line is very irregular in shape and consists of numerous bays, points, and capes as well as several large islands, notably **Nunivak** and St. Lawrence Island. Several **large** rivers empty into the Bering Sea, including the Yukon, **Kuskokwim,** and **Kuichak** Rivers.

Major settlements in the region consist of Nome, **Unalakleet, Bethel,** Cape Newenham, **Dillingham,** King Salmon, **Naknek,** and Cape **Sarichef.** There are numerous other villages and encampments in the region, having populations less than 100 persons.

B. Physical Setting

The **bathymetry** varies significantly in the area of study. **In** the Beaufort Sea the 80-meter **isobath** is approximately 70 kilometers offshore from Barrow **to** Demarcation Point and is the approximate edge of the continental shelf. The sea **floor** drops off very sharply there to depths of 4000 meters.

The bathymetry of the **Chukchi** Sea is quite different from that of the Beaufort Sea. The maximum depth of the **Chukchi** Sea is approximately

The tidal fluctuations in the Bering Sea are even greater than in the Beaufort and **Chukchi** regions. The diurnal tide fluctuations vary from 36.6 centimeters on St. Lawrence Island to 689 centimeters at the mouth of the Naknek River. These fluctuations are sufficient to significantly affect the winter ice conditions along the coast.

The amount of daylight, i.e., the period from sunrise to sunset, undergoes large seasonal variations at high latitudes. **At** Barrow, the northern most point of **land** in the Beaufort area, the sun does not set during the summer months from late May to late July, while the sun is below **the** horizon from approximately **late** November to late January. The conditions at Nome, the most southerly point. in the **Chukchi** study area, are similar although not as extreme.

The annual variations in daylight hours are less extreme in the Bering region than in the Beaufort or **Chukchi** regions. At the Bering Strait, the amount of daylight varies from continuous from 12 June through 30 June **to** approximately three hours on December 22. However, in the southern part of the Bering Sea, the daylight hours vary from seventeen hours on June 20 to seven hours on December 22.

c. Climate

The climatic conditions **along** the Beaufort Sea coast are relatively uniform from Barrow to Barter Island. The mean annual temperature at Barrow is -12.6°C with a record maximum of **$+26^{\circ}\text{C}$** and a record minimum of **-49°C** . The normal yearly water equivalent precipitation at Barrow is 12.4 centimeters with an average yearly humidity of 80 percent. The mean yearly snowfall is 72.6 centimeters. The average windspeed at Barrow is 18.9 **km/hr** from the east; the maximum wind velocity was 93 **km/hr** from the west. The prevailing wind directions are from the east-northeast to east-southeast.

The weather conditions **at** Barter Island are similar to those **at** Barrow. The Barter Island mean annual temperature is -12°C with a maximum of **$+26^{\circ}\text{C}$** and a record low of **-51°C** . The normal yearly water equivalent precipitation is 17.9 centimeters with a normal **yearly** snowfall of 113 centimeters. The humidity at Barter Island averages 80 percent.

The higher temperatures are generally to the south. The mean annual total water equivalent precipitation along the Bering Sea coast ranges between approximately 50 to 100 centimeters. The snowfall ranges from 70 to 200 centimeters annually. The wind speeds average 20 km/hr along the coast with some areas recording windspeeds in excess of 100 km/hr. The predominant wind directions vary from due north to southeast.

were **used**. First, there needed to be enough coastline showing on the image to match a coastline overlay to the image. Generally, if even a small section of the coastline or coastal river was visible on the image, the image could be lined up with the overlay, using the latitude and longitude marks on the image. The latitude and longitude marks were not usable by themselves due to the difference in projections of the Landsat image and the Lambert conic **conformal** map overlay. The second criteria **required** that significant ice detail be visible through the **cloud** cover. "Significant" ice **detail** varied from scene to scene. For example, a low-contrast scene with moderate cloud cover but showing open **leads** in the ice has informational value whereas a scene with the same **cloud** conditions but not showing open leads may be useless for ice mapping. Generally, Landsat cycles with fewer than five **usable** scenes were not considered for detailed analysis. Exceptions included scenes used in stationary ice and open water maps (see below).

B. Mapping Technique

The images chosen for analysis were obtained at a scale of **1:500,000** from the EROS Data Center, Sioux Falls, South Dakota. The EROS Data Center produces **1:1,000,000** scale, **1:500,000** scale and **1:250,000** scale black and white prints of available Landsat imagery as standard products. The **1:1,000,000** scale images were too small to accurately map details while the **1:250,000** scale imagery was too expensive. Therefore, the **1:500,000** scale imagery was chosen as a compromise between cost and resolution of detail.

General overlays of the Beaufort Sea, **Chukchi** Sea and Bering Sea coastlines including the major rivers were drawn in ink on clear acetate. The base maps used for the overlays were the **1:500,000** scale sectional aeronautical charts. These maps are published by the U.S. Department of Commerce using the Lambert **conformal** conic projection (standard parallels 49°20' and 54°40'). This projection is the closest to the Landsat projection found. The error in locating points on the Landsat image using the base map overlay is approximately a kilometer,

The technique used in mapping the ice on each Landsat image is as follows. First, the base map overlay **was** placed onto the image and the

average was made for each season. From these, a third generation map was constructed showing the averages of the three seasons combined onto one map to illustrate the seasonal migration of **the** ice edge. The above maps are discussed in Section VI.

Yearly composite maps of the ridge systems visible on the Landsat imagery were made using the same method used for making the contiguous ice edge maps. One composite map was made for each **ice** year. Then **all** composite maps were compiled into one map of "all-time" ridge systems. These maps are discussed in Section VI.

The second phase of products utilizing the **preliminary** and composite ice maps consists of ridge density maps, sea ice morphology maps and ice hazard maps for the Beaufort, Chukchi, and Bering Seas. The ridge density maps were prepared from the compiled ridge system maps by visually delineating the areas of differing **ridge** density. The sea ice morphology maps were prepared from various sources including contiguous ice edge composite maps, ice ridge density maps and other data listed below. Morphology maps were prepared for the late **fall** to early winter ice season (approximately October to early March) and the midwinter **to** late spring ice season (approximately mid-March to late May - early June). The morphology maps contain information on the various ice conditions such as average edge of ice, contiguous ice, ridge occurrences, areas of smooth ice, fast-moving ice, hummock fields, etc. The ice hazard maps used **all** of the above sources of data for determining the type and location of ice conditions that may be hazardous to offshore structures and ship traffic. The hazards include areas of heavy ridging, continuously changing ice conditions, ice islands, etc. The ice hazard maps are discussed in detail in Section VIII of this report.

Other data products, compiled directly from Landsat imagery, **included** maps of stationary ice and open water for the Beaufort Sea. The term "stationary ice" as used here defines ice that was observed to have remained unmoved by wind and currents during breakup of the nearshore ice from one Landsat cycle to the next. Stationary ice is either grounded or attached to grounded ice. The stationary ice maps were prepared by superimposing two images of the same location, but acquired

this only became apparent upon inspection of two overlapping images from successive days.

Perhaps the most **useful** ground truth information was obtained in June of 1974 when we obtained **1:20,000 scale** panchromatic photography **along** a several hundred km flight line in the Beaufort Sea, followed a few days later by a NASA U-2 flight **obtaining 1:120,000** scale color infrared photography and the acquisition of a good quality Landsat image a few days **later**. On this data, it was possible **to** conclusively relate measurable ice features with patterns identified on Landsat imagery.

E. Applicability of Developed Techniques to Other Places Where **Nearshore** Ice **is** a Hazard

The chief utility of Landsat data was found to be the detection of large ridge systems and lead openings by direct observation and observation of ice piling and shearing events largely by inference. The analysis of the ice hazards depends on the gathering of sufficient data **to** make possible the development of a synoptic picture of ice conditions. This, in turn, depends on two factors: the commitment of the spacecraft for data acquisition and a sufficiently adequate number of cloud and haze free occasions when data could be obtained.

Other than data availability two other factors need be considered: the nature of the hazard and the size of the area under consideration. The techniques used here have been developed to determine rather **large** zones of somewhat broad hazard description.

off the **Beaufort** coast where the edge of contiguous ice has been observed to range from the 20-meter **isobath** to a point 30 to 40 km seaward. The cause **of** these extensions appears to be an absence of sufficient winds, currents, and internal forces within the ice sheet to keep individual pans within the pack ice from freezing together. This condition can persist for several weeks before sufficient forces exist for failure to take place along lines considerably closer to shore.

When describing conditions similar to these, some observers define the "fast ice" identically to the ice **called** "contiguous" here. Others insist that the true "fast ice" is defined by the ice which would remain adjacent to shore after a major shearing event and subsequent failure of the ice sheet. Those who **use** the latter definition **generally** associate well-grounded ridge systems and other ice features with this stable edge of ice. Our results have shown sufficient exceptions to this association to dissuade the use of this definition except in the most general sense and develop ice descriptions for each zone which can be identified to have uniform ice behavior.

Maps showing the edge of contiguous ice have been made showing ice edges for different dates in 1974, 1974, 1975, **1976**, and for the Beaufort Sea in **1977**. These data have then been combined from each year showing late winter, early spring, and late spring average ice edge maps, and where appropriate, these average seasonal maps have been combined to show the seasonal migration of the average ice edge.

3. Ridge system maps. Ridge system maps were useful in several ways in the development of a nearshore ice morphology. Ridges located within the existing contiguous ice sheet observed on the earliest available Landsat images each year, serve as a record of earlier, unobserved, ice events. **Where** they are grounded, ridges often--but not always--serve as anchoring points for the **nearshore** ice sheet. By mapping ridges created for each year and comparing year to year, it is possible to determine variability of dynamic ice events from one year to the next. Compilation of several years' ridge data onto one map shows the persistent locations of this type of feature, at the same time implying year to year persistence of the conditions responsible for ridge creation.

Beaufort - Results

20 April - 8 May - Indicated by alternating dots and dashes, contiguous ice was well offshore during this period and only the shoreward **limit** is shown here for much of the Beaufort Sea.

13-30 June - Shown by a line consisting of **two** dashes followed by a single dot, the edge of ice shows some agreement with earlier ice edges but also indicates the advanced season and decay of ice in Harrison Bay.

3. 1975 Contiguous Ice Edge

20 February - 10 March - **Only** one acceptable Landsat cycle was found for this year showing the edge of contiguous ice. During this time there is an indication that the edge of ice has been considerably farther offshore until just recently and is now nearly coincident with the 20-meter **isobath** for much of the Beaufort coast.

4. 1976 Contiguous Ice Edge

22 October - 8 November - This ice edge, shown by a dashed **line**, **is** the only extensive ice edge data obtained in the fall season during the entire study. It shows the edge of contiguous ice roughly coincident with the 20-meter **isobath** along the western Beaufort and significantly seaward of that line east of Harrison Bay.

6-23 February - This ice edge is indicated by a dotted **line**. For most of the Beaufort Coast, the edge of contiguous ice is beyond the area mapped by the individual Landsat images. Only in the vicinity of Barrow is the actual ice edge mapped.

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Beaufort - Results

14 April - 1 May- Data for this Landsat cycle begins opposite the Canning River and continues beyond Barrow. The edge of contiguous ice is nearly coincident with the 20-meter **isobath along** the entire coast.

2 May - 30 June - The edge of contiguous ice was observed during this period across the central Beaufort coast. During this time, **it** was again located significantly seaward of the **20-meter isobath**.

25 June - **15 July** - Data **for** this Landsat cycle exists between July 6 and July 8. During this time the ice edge was observed off the Beaufort coast between the Canning River and the **Colville** River. On the 6th, the ice edge was located along the 20-meter **isobath**, while on July 7th, it was found far offshore.

31 March - **17 April** - The observed edge of contiguous ice for this date is shown by a **line** consisting of a dash followed by two dots. The data indicate that during this Landsat **cycle**, the edge of contiguous ice moved considerably shoreward. The earlier images obtained in the eastern Beaufort show the edge of contiguous ice far offshore while the later images show the ice edge much closer to its normal position. Comparison of data obtained on March 12 and 14 show this to actually be the case in the central portion of the **Beaufort** Sea.

Seasonal Ice Edge Maps: The data representing the various edges of contiguous ice have been recompiled for each season yielding sufficient

This location is somewhat landward of the **bulk** of other ice edge data in this region, but it does not represent a highly significant deviation. East of Harrison Bay, the 1973 data strike significantly seaward. However, this is not considered to be a seasonal morphological feature; other data have shown that this phenomenon can occur in any season. What this does show, however, is that this can occur even this **late** in the ice season.

The mid-June **1974** data are the only ice edge **information** representing contiguous ice which show the decay of nearshore ice to points **well** within the 20-meter **isobath**. This is only true to mid-Harrison Bay where the edge of contiguous ice is again located roughly along the 20-meter **isobath**.

Ridge System Maps

Yearly Ridge System Maps: For each year of study a **single** map of the **Beaufort** coast has been prepared from the individual Landsat image maps showing the ridges observed during that year. No attempt has been made here to identify the date of formation of each ridge. The object of this mapping exercise was to identify those locations where ridging does occur in order to **relate** this phenomenon with bathymetric features including depth and **isobath** configuration. Mapping on a yearly basis was performed in order to provide information regarding year to year persistence in location and severity.

1. 1973 Ridge System

This map shows a cluster of **major** ridges offshore between **Prudhoe** Bay and Harrison Bay and a few ridges very close to shore in the western Canadian Beaufort. The ridges mapped well inside Harrison Bay are located in shallow waters and were very **likely created at** the time of freeze-up.

Beaufort - Results

Composite Ridge System Map: This map shows the combined ridge systems from 1973 through 1977. Here ridge density trends noted on the yearly ridge maps become more apparent.

- a. The greatest density along the **Beaufort** coast is found far offshore between Harrison and Prudhoe Bay.
- b. A secondary maximum ridge density occurs in a **fan-shaped** pattern in eastern Camden Bay.
- c. There is an indented area across inner Harrison Bay with a moderate tendency toward ridging.
- d. A cluster of ridges occurs seaward of Midway and Cross Islands with a tendency toward greater density between the islands and the 20-meter **isobath**.
- e. **The focus of** the fan-shaped ridge cluster in eastern Camden Bay is located significantly **landward** from the 20-meter **isobath**.

Stationary Ice Maps

A Note on Stationary Ice vs. Contiguous Ice:

During winter **along** the Beaufort sea coast, large ridges form in a zone parallel to the shore. These ridges have keel depths sufficient to cause grounding out to approximately the 20-meter bathymetric contour. This zone **of** grounded ridges varies between a few kilometers and many tens of kilometers in width and effectively shields the smoother ice inshore from the effects of pack ice motion. The zone of immobile ice is usually referred to as stationary ice.

When summer breakup occurs, these grounded ridges are often the last ice forms to dislodge. These areas were not mapped in terms of edge of contiguous ice because they are not contiguous with the shore, yet the ice does remain bottom-fast and is an important part of the nearshore ice regime. Three questions need to be answered regarding these stationary ice areas. 1) Where are these areas located? 2) Do they occur in the same locations each year? and 3) How long do they last in the summer?

Beaufort - Results

- a. Stationary ice is generally located inshore of the 20-meter bathymetric contour. Inshore areas that are generally clear of stationary ice include the majority of Harrison Bay and the immediate river mouth vicinities.
- b. Areas where stationary ice recurs were difficult to determine because of insufficient data. One area where it does recur and seems to last most of the summer is along the 20-meter contour north of the Colville River in Harrison Bay. Each year a large hummock field forms, causing a seaward bulge in the edge of the fast ice that persists until late summer. Another area where stationary ice was seen to recur was between Oliktok Point and the Sagavanirktok River, extending from shore to the 20-meter contour.
- c. In 1976, stationary ice was last seen to exist on 2 August only in a small area west of Harrison Bay. The next image of the area was not obtained until 20 August (one Landsat cycle later). By then, the stationary ice had disappeared completely. Therefore, it can be concluded that stationary ice is generally gone by mid-August. One exception to this was seen in 1974. A large piece of a ridge system north of Oliktok point was observed to remain throughout the summer of 1974 and was still there in the spring of 1975. However, it did not remain as stationary ice in 1975.

Open Water Maps

Maps of open water of the Beaufort Sea were prepared at 1:500,000 scale from Landsat imagery. They were prepared in three sections extending from Point Barrow to Demarcation Point for the years 1973 through 1977. The open water was mapped from the Landsat image by overlaying a prepared mylar base map onto the image and drawing the boundaries of the open water on the mylar. A different symbol was used for each Landsat scene for which open water was mapped. In addition, the date of the image was indicated on the mylar with a line drawn to the open water area.

Results of Analysis of Imagery for Ice Island Data

Because of the potential value of determining statistical information concerning ice islands, each Landsat image used was examined explicitly for evidence of ice islands. It was thought that even if no ice islands could be observed directly, large ice islands would drift differentially from pack ice because of their deep draft and leave an identifying wake in their trail.

Unfortunately, no ice islands were observed directly or indirectly on the Landsat imagery. On two occasions stranded and broken-up ice "islands" were observed along the Beaufort coast during aerial reconnaissance operations. In both cases the broken-up island was approximately 300 meters in diameter.

Attempts were made to identify these ice features on Landsat imagery. Positive identification could not be made in either case. In the first case, the ice island was observed well inside the contiguous ice between Admiralty and Smith Bays (1974). The exact position was difficult to determine, however, because of inadequate navigation equipment on the aircraft used. The second ice island was observed during a 1976 photographic reconnaissance trip. It was well located by navigational equipment on board the aircraft and also by its location with respect to other ice features in the vicinity. Both grounded ice islands were located in water on the order of 20 meters in depth.

Chukchi - Results

2-19 April - Ice edge data for these dates are shown as a series of dots. Generally closer to shore, the ice edge for this date follows the shoreline configuration more closely than did the earlier ice edge. Note that at Cape Lisburne this ice edge does meet the coast.

26 May-12 June - Represented by alternating dots and dashes, the ice edge on this date is generally closer to shore than the dotted line representing the April ice edge. In some places, however, the contiguous ice edge even for this late date can be found seaward of the earlier edge, indicating that the edge of ice does not merely retreat with advancing season.

13-30 June - Contiguous ice edge data for this date are represented by a sequence consisting of two dots and a dash. Note that this ice edge is the most seaward of the four plotted for this year in the region just southeast of Point Hope. This ice is most likely pans which have been driven into this location and compacted. Farther north, the ice edge for this date can be seen to be quite close to shore except at Pt. Franklin where the April ice edge was actually closer to shore.

3. 1975 Contiguous Ice Edge

Note: The ice edges shown for this year are unusually similar.

20 February-9 March - Data for this period are represented by a series of dashes. Again, as in previous years, this earliest ice edge extends farthest seaward in outer Kotzebue Sound and off Cape Lisburne.

28 March-14 April - The contiguous ice edge for this Landsat cycle is indicated by a line of two dots followed by two dashes. Note

for this period in the vicinity of the Seward Peninsula and Kotzebue Sound, it differs somewhat to the north where it is unusually distant from the shore in the vicinity of Cape Thompson and Cape Lisburne. Farther north, between Icy Cape and Pt. Franklin, the ice edge advances unusually seaward, followed by a sharp coastward transect. North of Pt. Franklin this behavior is repeated somewhat.

19 April-6 May - Shown by a series of dots, the contiguous ice edge data for this date are as unusual as the data shown for 6-23 February: Here, instead of indenting toward and into Kotzebue Sound, this ice edge actually bridges across outer Kotzebue Sound. It would seem that the winter and spring data were interchanged. Farther to the north, the springtime data continues to exhibit this unusual behavior, remaining far seaward.

Seasonal Ice Edge Maps: The data representing the various edges of contiguous ice have been recompiled for each season yielding sufficient information to warrant analysis: late winter (February-March), early spring (April-May), and late spring-early summer (June-July). The reason for these groupings is to determine whether each season can be characterized by a single, generalized ice edge representing that season. The result of this analysis will be discussed in order of season.

1. Late Winter Ice Edge

Shown here are the ice edge data for late winter (February-March) Landsat cycles, 1973 through 1976. These data indicate some interesting trends showing areas tending toward a high degree of variability in ice edge location. While one might expect a focusing of ice edge locations at exposed headlands (Wales, Point Hope, Cape Lisburne, Pt. Franklin, and Barrow), Pt. Lay is not similarly exposed yet the ice edge data there also exhibit this behavior pattern.

the average ice edge follows the coastline **at** some distance **until** reaching Pt. Franklin, where again the average edge is quite **close** to **shore**. The average edge bridges across the coastal indentation between Pt. Franklin and Barrow, passing that point at a distance of approximately **10** km.

2. Average Mid-Spring Ice Edge

The average ice edge for this period does not differ a great deal from the average ice edge for late winter except for a tendency to lie closer to shore in some locations. It is interesting to note that the envelope **of** variability is much smaller during this season than during late winter, indicating perhaps a steady-state condition during this period. However, the variability in outer **Kotzebue** Sound is **still** quite large during this season.

3. Average Late Spring-Early Summer Ice Edge

The average ice edge **for this** season is generally closer to shore than the previous season's average ice edge. **The** envelope of variability of contiguous ice edges during this period is generally narrow except for the vicinities of large embayments. For instance, in **Kotzebue** Sound the variation envelope is large just as it has been in other seasons, only now it is located even farther inshore.

Migration of Average Seasonal Edge of Contiguous Ice

This map shows the three seasonal average ice edges plotted together so that the possibility of a systematic change in **ice** edge location can be investigated. When considering the relationship between these ice edges, the envelope of ice edge variability must be borne in mind. For instance, both in **Kotzebue** Sound and north of Cape Lisburne, there is a wide seasonal spatial variation in ice edge location and the immediate conclusion might be to consider any apparent seasonal motion of ice edge more significant here than opposite Icy Cape where the spatial variation is smaller. However, in **Kotzebue** Sound the variation envelopes are all quite **large** so that seasonal ice edges located relatively close together

Chukchi Sea Ice Ridge Systems

Yearly Ridge System: These maps show the locations of **ridge** systems which could be recognized on Landsat imagery clearly as ridge systems. The ridges identified are generally shear **ridges** which are several km long.

1. 1973 Ridge System

Ridges were mapped in **only** a few locations this year. It is interesting to note that they were found in locations adjacent to headlands in all cases. These headlands were: the tip **of the** Seward Peninsula at **Wales**, Point Lay and Point Franklin.

2. 1974 Ridge System

The ridge pattern mapped for 1974 is significantly different from the 1973 pattern. There appears to be a tendency for ridges to be located on the south side of major embayments. The large "V" shaped ridge northeast of Cape **Lisburne** was formed when ice was driven southward toward the coast. **It** is interesting to note that although the forces creating this ridge system were **compressional**, the ridges formed under shear failure.

3. 1975 Ridge System

Ridge systems mapped for 1975 were even fewer than previous years. **No** particular pattern was observed. In the embayment between Barrow and Pt. Franklin, a ridge was observed to follow the coast in a way resembling the pattern found between Point Franklin and Icy Cape the previous year. Off Cape **Lisburne** a long ridge system was found in a position indicating flow of ice across Cape **Lisburne**. Ridges in this location were not seen previously.

4. 1976 Ridge System

Three ridge systems were observed this year north of Bering Strait. They have an interesting similarity in that they all lie "north" of the three major headlands: Seward Peninsula, Cape Lisburne, and Icy Cape.

D. Bering Sea Results

This section describes ice edge maps constructed for the **Bering Sea**. It should be emphasized that very little field checking was possible in this region. Hence, many of the conclusions drawn are based on knowledge gained in constructing the Beaufort and **Chukchi Sea morphologies**.

As described in earlier sections, a principal distinguishing physical parameter in this region is the large tidal range which should act as a destabilizing factor in the behavior of contiguous ice. A second physical parameter distinguishing the Bering Sea from the Beaufort and **Chukchi** regions is the open ocean to the south which allows ice mobility not found in the other areas. Both of these factors tend to produce an unstable contiguous ice zone.

The morphology and hazards described in section VIII C depict the central period of the ice season when the ice should be most stable. Because of the large tidal range and open ocean to the south, freeze-up and breakup ice conditions along this area of the Alaskan coast are probably quite dynamic and warrant a specialized study.

Contiguous Ice Edge Maps

Yearly Ice Edge Maps: The following maps were constructed to show the instantaneous edge of contiguous ice in the Bering Sea at times when good satellite coverage of a large area of coast could be obtained. For that reason, it should be borne in mind that this selection principle could influence the data presented. In some locations, particularly in dynamic areas, cloudy weather may preclude satellite viewing of dynamic ice events.

1. 1973 Contiguous Ice Edge

Ice edge data was obtained from the 12-29 March and 5-22 May Landsat cycles. It is interesting to note that although these ice edges are generally coincident, where they do differ, the March edge is the more seaward of the two.

Bering - Results

of the area: North of Sledge Island, for instance, the two ice edges recorded are several kilometers apart, indicating a wide variability. **Just** east of Sledge **Island**, a **low** variability is indicated. The magnitude of variation of the average location must be considered when determining whether seasonal trends are **indi-**cated by a systematic change in ice edge location.

2. Late Winter - Early Spring Ice Edge

Data from March, 1973 and 1974 have been compared on this map. In addition, an "average" ice edge has been drawn upon inspection of these data. Here, as with the mid-winter data, great variability **is** shown in some locations **while in** others stability of ice edge location **is** indicated. Comparison with the mid-winter ice edge map **will** show agreement between these two seasons concerning areas of ice edge variation or stability.

3. Mid - Late Spring Ice Edge

Data from May, 1973, 1974, and 1975 and April, 1976 have been compared on this map. In addition, an "average" ice edge has been drawn based on **inspection** of these data. Notice that here, as in the mid-winter and **late** winter - early spring maps, ice edge variability changes from location to location **along** the coast. In general, as in the earlier two maps, there is agreement regarding locations of great variability and locations with a marked tendency toward ice edge stability.

4. Seasonal Average Edge of Contiguous Ice

On this map the winter, **late** winter - early spring, and mid-to late spring average ice edges are compared with respect to the 20-meter **isobath**.

Starting at Wales, there appears to be close seasonal ice edge coincidence down to Sledge Island. Reference to the individual

with advancing season. It would be tempting to conclude that this is a consistent trend and mechanisms can **be** constructed to account for this behavior. However, the great variation in ice edge locations seen on the late winter - early spring and late spring maps indicates that the trend shown here **is** not as systematic as the plot of average ice edges alone would lead one to believe. **It** appears safe to conclude that in this region the ice edge advances well into the sound **during** mid-winter and becomes quite variable as the season advances. A possible mechanism responsible for this behavior is that during the colder periods the ice can quickly grow to a thickness offering sufficient tensile strength to resist breaking well into this **embayment**. **Kotzebue** Sound to the north tends **to** behave in a similar fashion.

From Stuart Island to the entrance of Norton Sound, there is great variability in both the average edge location and in the variation on the individual maps. Hence, the statistical validity of the trend indicated is weak. The trend indicated does, however, agree with observations of ice behavior in this vicinity on individual **Landsat** scenes. Note that according to the location of the average ice edges, the mid-winter edge is shoreward of the late winter - early spring ice edge. On the other hand, the late spring ice edge is well inshore from both of these ice edges. Although **evidence** supporting the phenomenon is weak, the proposed mechanism is as follows: There is ice motion out Norton Sound into the Bering Sea nearly all winter and spring, usually to the southwest. Few **large** ridge systems were identified along the Bering Sea coast. Most of those observed were located in this region, apparently formed by ice moving seaward out of Norton Sound. It is proposed that through this ridging process, there is a mechanism that widens the contiguous ice zone in this location. **With** advance of season, ice removal mechanisms (tides, etc.) present a stronger influence and dominate, causing the shoreward retreat.

Bering Results

Locations are all well inshore from the 20-meter isobath.

Along the east side of Bristol Bay contiguous ice is found very close to shore, bridging embayments. This behavior along the north and east sides of Bristol Bay is for the most part explained by the apparently constant motion of ice to the southwest out of Bristol Bay. Very little ice motion takes place which would result in grounded ridge construction that would, in turn, lead to extensive areas of contiguous ice.

Proceeding along the Alaska Peninsula, a point is reached where the southwestward motion of ice out of the bay could lead to ridge construction. This was in fact observed during 1974, yielding the simple observation of contiguous ice along this region of coast. During this event contiguous ice was formed even beyond the 20-meter isobath in the Port Moller area.

In addition, even if the models **do** represent the long-term average conditions, there is **little** hint of what variability in conditions should be expected over a span of twenty to thirty years. Hence, it **is** not certain what range of ice conditions **to** anticipate during the active life of an offshore oil field.

For instance, during this period of observation the melt season weather conditions have been reasonably mild, Nearshore ice has broken up and melted in place. Grounded ridge systems have **slowly** broken contact with the sea floor and drifted away. We have not had the opportunity to assess the potential hazard created if a major storm were to occur during this period when great quantities of **highly mobile** ice are present in the **nearshore** areas.

Finally, the model developed here is only semi-dynamic in that only a few processes involved in nearshore ice morphology have been identified. **To** develop a dynamic morphology, a more extensive analysis would be necessary.

c. A Discussion of the Detectability of Ice Islands by Landsat Imagery

At the outset of this analysis it was anticipated that ice islands in the pack ice during winter and spring would be detectable because their deep draft would make them susceptible to oceanic currents and, to a certain extent, drive them through the pack leaving a wake behind. Only on one occasion was anything like this observed and it was not possible to verify the ice island possibility. (Actual **ly**, the **image** was acquired before the initiation of this project.)

As stated earlier in this report, on two occasions small ice islands were observed apparently grounded in the contiguous ice zone. Both times an attempt was made to locate the **islands** on Landsat imagery. Neither time could they be found. In both cases, the islands had broken into several fragments.

VIII. Conclusions

A. Beaufort Sea

In this section, the results described in Section VI are interpreted in terms of seasonal **morphologies** of the Beaufort Sea near-shore ice regime. Based on these **morphologies**, an assessment of relative hazards has been made for the Beaufort nearshore area.

The development of a complete **nearshore** morphology should be based on an analysis of statistical data from several years where average conditions and deviations from average conditions have been determined, followed by detailed analysis of specific individual events to test the validity of the conclusions drawn on the basis of **the** statistical analysis. Here, five years' statistical data has been compiled and related to specific ice events observed during the period of study. Rather than being considered a completed **product**, this analysis should be considered a starting point for further study.

The ice year has been broken into two periods: Late fall to **early** winter, and mid-winter to late spring. A map has been prepared for each season showing areas of relatively uniform behavioral characteristics which can then be described for each area. These two periods include the times when ice hazards appear to be greatest: The division was based on splitting the period of formation of the most **stable** ice from the later period when this ice is essentially static.

Beaufort Sea Nearshore Ice Morphology

1. Late Fall to Early Winter Morphology Map

This period includes the time of freeze-up to the establishment of stable ice within the nearshore area. This period roughly corresponds to early November through late January. Unfortunately, very few direct observations of ice conditions during this period are available; in late fall cloudy conditions prevail and between late November and early February no Landsat data is normally obtained because solar depression angles less than 6° generally do not

- a) the relative safety of field crews operating on the ice
- b) possible ice motion endangering drilling operations from temporary structures (anchored **drill** ships, **ice** structures, pile structures, etc.)
- c) the probability of ice **piling** events posing obstruction to rapid surface evacuation from potentially hazardous situations
- d) the potential for ice piling events and subsequent damage to undersea structures from the subsurface structure of the piled ice
- e) the potential for increased bearing load against **bottom-**founded structures as a result of **piled** ice

The Beaufort Ice Hazard Map shows the coast with several major hazard zones delineated. The hazard zones have been chosen on the basis of a rather uniform hazard potential within each zone. The zones have been grouped into 5 major zones based largely on probability of ice edge occurrence and subdivided further largely on the basis of ridging probability. Each major zone is described, followed by descriptions of the subzones.

and stationary ice, shear-ridges are formed. This ridging activity appears to be greater in some areas than in others. Details of ridging activity are given in the following subsections.

- IIa.** This rather large area stretching from Cape **Halkett** to Barrow has rather low ridging activity, although lead formation appears to be rather frequent. This would suggest a relative absence of compressive forces along this portion of the coast.
- IIb.** Moderate ridging occurs in this area early in the ice year as a result of ice being driven into Harrison Bay from the east. This activity soon ceases as a result of the increased strength created in the ice. Thereafter, coastal ice motions are deflected along zone **IIc**.
- IIc.** This zone of moderate ridging is created after the increased strength of ice in zone **IIb** halts motions into Harrison Bay from the east. Because of shoals just shoreward of the 20-meter isobath, large draft multiyear floes act as anchoring mechanisms for the sheet of ice to the shoreward (Zone **III**). Ridges created in this zone during early winter have a high probability of remaining in place the entire ice year.
- IId.** This zone of high ridging frequency begins approximately at the 20-meter isobath and extends seaward to the vicinity of the 40-meter isobath. Ridges in this zone are not well grounded and can be severed by lead formation. However, following such an event, there is a high probability of new shear-ridge formation along the boundary of the opened lead. All along this zone, from **Mikkelson** Bay to a point off Cape **Halkett**, long, highly identifiable shear-ridges can be formed by the combination of motion of pack ice toward the west and by compressive forces as it is held against the fast ice.
- IIE.** This is a zone of moderate ridge formation extending from the west side of Camden Bay to **Mikkelson** Bay. It is presumed that, although westward slippage of seaward ice takes place here, similar to Zones **IIc** and **IId**, compressive forces are not as great along this section of coast. As a result, shear-ridging is less pronounced.

Legend - Beaufort Mid-Winter to Late Spring Morphology Map

- I. Stable fast ice. The ice within this classification is usually well formed by the beginning of February. **With** one possible exception (denoted Ib), the ice in this category is sufficiently stable that flaw **leads** form to the seaward throughout this period (somewhere within category II). Hence, except for opening and closing of tidal and tension cracks, the ice within this zone is static during this period. The following subdivisions within this zone are based on statistical occurrence of major ridges.
- Ia. Zone of light ridging. Generally overlying shallow waters, this ice is free from major ridges. Often large expanses of very smooth ice **can be found**.
- Ib. Zone of moderate ridging. A variety of conditions can be encountered reflecting conditions during time of freeze-up. **Multi-**year floes may be encased in a matrix of new ice. Large floes of worked, first year ice may be broken by smooth, frozen-over lead systems. Pressure ridges can be expected in these areas. There is also a moderate probability of encountering a Shear-ridge created some time during freeze-up.
- Ic. Zone of intermediate ridging. Ice conditions are similar to those described for zone Id. However, the probability of large shear-ridges is considerably increased.
- Id. Zone of severe ridging. The ice in these areas **is** likely to be first year pack ice and **multiyear** floes - obviously not formed in their present location. A great deal of ridging and pressuring has taken place, creating large grounded hummock fields in some areas. Note that these areas occur along the seaward boundary of **stable** fast ice and often **at** points of inflection of this boundary. These areas are the main anchors of the fast ice system.
- II. Zone of mid-winter to late spring flaw lead formation. The areas within this classification are prone to flaw lead formation at any time during this period. Following flaw lead formation, **shear-ridging** may occur, the lead may freeze over and remain static

Legend - Beaufort Sea Ice Hazard Map

I. This **zone** represents the most stable ice along the **Beaufort coast**. After December it is extremely safe for surface travel (with one possible exception noted later). It has not been observed to fail in shear between December and June, therefore, deformations are generally small, and ice **piling** is at a minimum.

Actually, this zone contains two **subzones** not shown here, determined **almost** entirely by depth of water. The first subzone consists of water less than two meters in depth. The significance of this zone is that by late winter, the ocean freezes to this depth hence after that date this subzone should be very stable. The **second** subzone consists of the balance of Zone I and contains depths as great as **10** meters. These two **subzones** have not been distinguished because the difference of hazards between the two has not been considered here.

The greatest source of hazard observed to occur in this zone was the mid-winter formation of thermal tension cracks. These cracks occur generally during very cold temperatures in December and open to a width of 2 to 3 meters. Often the new ice formed in the crack is drifted over with snow with the result that it does not equal the thickness of the surrounding ice. On one occasion in **Prudhoe Bay**, a **large** piece of equipment and its driver were lost when an attempt was made to drive across a frozen-over tension crack. There appears to be some repetition of these cracks: one major tension crack appears annually between **Thetis Island** and **Oliktok Point**.

Ridging only occurs within this zone early within the ice season with the participating floes generally on the order of 30-40 centimeters in thickness. Major ocean floor plowing should not be expected from these events. After December and January the active edge of ice is **well** seaward of this zone. No ice failure events which indicate deformation have been observed to occur within this zone between the end of January and the end of May. It is estimated that an event resulting in a 20 meter lead would have been observable by the techniques utilized here.

ridge density was observed to be greater than in Zone I and consequently ice piling events by older and thicker ice than in Zone I are likely.

Oil spilled in this zone would encounter a somewhat rough under ice surface and therefore would spread less than in Zone I. Similarly, however, clean-up operations would be hampered by the ice surface roughness.

I Ib. This has been designated a separate hazard area from Zone **I Ia** because of one lead-forming event occurring along the dotted line distinguishing these two zones. It is interesting to note that were zone **I Ib** not recognized, this would be the only significant area in Zone **I Ia** seaward of the 20-meter isobath. However, the one lead-forming event observed indicates that this area is not as stable as the balance of Zone **I Ia** and should be distinguished. Within this zone then, there is greater hazard to surface parties through the possibility of ice failure.

I Ic. This is an area of relatively smooth ice surrounded by ice which is rougher in terms of the number of major ridge systems. It has often been found to contain floes of varying ages surrounded by younger ice. Generally, however, both are annual ice. This has been determined to be a zone of relatively low hazard to surface travel. Dynamic ice events appear to be at a local minimum. Deformation and lead formation have not been observed during winter and spring. Oil spilled under this ice might spread and could be channeled by the smooth undersurface of the newer ice surrounding the older floes.

I Id, I Ie. These are areas of heavy and moderate ridging respectively, located inshore from the average location of flaw leads. These areas are stable and often contain large areas of grounded ridge systems. The chief hazard to personnel performing surface operations comes from the probability of lead formation, compounded by the difficulty imposed on attempts at rapid escape by the large ridges. Clearly in late fall, massive ridge-forming events occur here, and at least once, an ice island fragment was observed grounded in this vicinity. It would appear, then, that structures

An oil spill would tend to pool under this ice and thus be contained.

IIh. This zone is the east end of an area of severe ridging. This portion lies shoreward of the flaw lead zone. Hazards in this zone are essentially the same as those described for Zone IIg.

IIi. This is a rather large zone of moderate ridge density lying shoreward of the shoreward edge of winter and spring contiguous ice. In two places this zone is shoreward of areas of more severe ridging, between it and the shoreward edge of contiguous ice, while a large area actually borders this edge. A good portion of this zone lies seaward of the 20-meter isobath. This circumstance might raise a question concerning the stability of that portion. Certainly there is very little reason to believe that ridge systems in these rather deep waters are grounded. However, this ice is stable. The apparent reason is coastline geometry.

This area is statistically safe for surface travel. However, considering the above observation, escape precautions should be made when operating beyond the 20-meter isobath.

Structures placed in this zone could encounter major ridging events. Deformation could take place in the exposed region and dislocation is a serious possibility in the region beyond the 20-meter isobath. Oil spilled under this ice could be expected to pool somewhat because of the moderately rough undersurface.

An additional hazard in this subzone not encountered by other subzones in the II group, is the possibility of ice island occurrences because of the large area with water depths greater than 20 meters.

IIj. This is a zone of severe ridging located shoreward of the flaw lead zone. Because this zone lies seaward of the 20-meter isobath, its stability should be held in question. However, the flaw lead has consistently been observed along its seaward edge. Hence, while surface operations might be performed, precautions should be made to make certain that evacuation could be made quickly.

Major ice displacements are possible in this zone at any time associated with **lead-forming** events and ice deformation. This possibility is found throughout this zone and should be kept in mind in terms of the subzones defined below.

- IIIa. This zone rounds Pt. Barrow joining the Beaufort and Chukchi Seas. It represents an area of moderate ridging and a very narrow focus of flaw lead location. It **should** be considered extremely hazardous for surface operations. Structures placed **in** this zone **would** be confronted by **almost** constant ridge-building events. An oil spill located here would be **pooled** significantly by the ice bottom topography but would **also** face a high probability of exposure to the water surface and incorporation within the ice over a **large** area through lead and ridge activity.
- IIIb. This is an area of high probability of flaw lead formation with a **low** probability of ridging. During winter and spring there is often new ice being formed **in** this vicinity. It should be considered extremely hazardous for surface operations. Structures **placed** in this zone may have a low probability of encountering major ridge-building events. However, their interaction with the often newly created ice within this zone should be considered carefully. Further, the probability of ice island visits may be enhanced by coastal configuration here. Oil spilled within this zone would have a high probability of incorporation into new ice and transport with pack ice motion.
- IIIc. This is a large area of low probability of major ridging, oriented parallel to the coast and located far beyond the 20-meter **isobath**. It should be considered significantly hazardous for surface operations. A structure placed in this zone would have a low probability of encountering a major ridging event but ice island visits would be quite possible. Oil spilled under this zone would not be pooled by major ridges and would have a high **probability** of incorporation into the pack ice through lead formation.
- IIId. This zone runs parallel to the coast for much of the length of the Alaskan Beaufort Sea. It possesses a moderate probability

probability of a flaw **lead** formation between a point located **in** this zone and shore is very great. **During** lead-forming events, there is a good chance that field crews could flee dangerous situations **to** nearby points but not escape **to** shore by surface transportation. Structures, while largely free from major **ridge-**building events could be confronted **by ice** islands. An under-ice **oil** spill would probably spread significantly and soon be introduced into the pack ice.

IIIj. This zone possesses a low ridging probability and a high probability that flaw leads are located to the shoreward. Hazards are essentially the same as Zone **IIIh**.

IV. This zone contains **ice** with a moderate probability of major ridge formation as a result of ice interaction with the shore, yet there is a high probability that flaw **leads** will be found **shoreward** of this zone. Because of the shore-linked aspect of its morphology and hazards, it has been differentiated from Zone **V** which is essentially pack ice.

Surface operations in this zone **should** not be performed without provisions for non-surface evacuation. Structures placed in this zone will be subject to the possibility of major ridge formation, **while** ice island and **floeberg** visitations are entirely possible. Oil spilled under this zone would tend to be pooled significantly **by major** ridges but **would also** be subject to introduction to the ocean surface during lead-forming events.

v. This zone is essentially the pack ice zone. Here, influence of shore on ice morphology and hazards **has** been reduced to regional influences. **In** the region north of the Beaufort Sea, there are periods of stable ice extending up to six weeks duration. During that time, **field** operations could be carried out here subject to the provision for non-surface evacuation. The relative danger is actually diminished from that in Zones III and IV because of the smaller chance for major shear deformation in this zone. An **under-**ice oil spill would essentially be a spill into pack ice.

Chukchi - Conclusions

winter and spring period, ice-moving events take place **along the Chukchi** coast, often creating shear ridges along shoals jutting seaward from the string of prominent capes and headlands along the coast. Farther **south**, the edge of contiguous ice between headlands is more poorly defined and the ice contained is prone to seaward motion, leaving areas of open water behind. In general, there is often a lead system extending the length of the coast from Barrow to Cape **Lisburne**. **Just south of Cape Lisburne** and north of Point Hope is an area with a constantly reformed **polynya**.

South of Point Hope the effect of ice motion out Bering Strait is even more prominent. Another recurring **polynya** formed by southward ice motion occurs just southeast of Point Hope. **Kotzebue** Sound is generally covered by stable ice during much of the ice year, but the presence of a zone of weak and often moving ice just seaward hints that this sheet of ice is potentially unstable.

At the southern end of the **Chukchi** Sea is Bering Strait. Just north of the strait is a **large** system of **shoals** where large extensive shear ridges are built during ice motion out the strait.

Chukchi Ice Hazards

Based on the **Chukchi** Sea morphology described in the previous section, the question of hazards related to offshore petroleum development has been addressed. The **Chukchi** hazard map shows a number of hazard descriptor areas having relatively uniform conditions within each area.

The points addressed include: the safety of crews and equipment used to perform surface exploratory operations, an assessment of the possible load-bearing ice surface imposed on structures resulting from ice piling events, the possible plowing of the ocean floor by ice piling events, and the possible fate of petroleum spilled in each descriptor area.

The following table describes the hazards related to each of the descriptor areas defined on the Chukchi hazard map.

4. This is an area subject to moderate ridging activity at any time during the ice season. Since lead formation is frequent as well, surface travel is extremely dangerous here at any time and is actually less hazardous farther offshore. Surface and subsurface structures are subject to damage by ice piling and plowing during the entire ice season. Oil spilled in this region during the ice season would soon become subject to lead pumping and incorporation into ice piles and ridges. There would be a high probability of transport within one week of the spill. Cleanup attempts would be made difficult by the possibility of ice motion.

5. An area of severe ridging seaward of the normal edge of stable ice, this is an extremely hazardous area for exploration activities anytime during the ice season. In addition, surface structures would be constantly subjected to piling events and damage by ice keel plowing. Oil spilled in this region would very likely be incorporated into piled ice, pumped onto the surface by lead activity and incorporated into newly forming ice within leads.

6. An area of severe ridging just shoreward of the mid-winter edge of fast ice, this region should not be considered stable. However, during mid-winter, ice here might remain in place two to three weeks at a time. By mid-spring, the boundary of fast ice is located along the shoreward edge of this zone.

The safety of surface operations in this zone is similar to that of Zone 4 except that the increased ridging in Zone 6 would make retreats to safer ice more difficult in case of dangerous ice conditions. The increased piling in this area increases the probability of parties being caught in truly hazardous situations. Camps should not be established in this area.

Surface and subsurface structures would be subjected to damage by ice piling and plowing, perhaps as severe as any place along the Beaufort/Chukchi coast. Oil spills generally would be located under mobile ice that is subject to piling events most of the ice year. During mid-winter, spills might be trapped under stationary ice for as long as six weeks. Lead formation is a possibility at any time during the ice year.

plowing. Fall and early winter oil spills would probably be transported away with any ice motion. Later spills are likely to be trapped under the ice and pooled between ridge keels until spring.

10. This is an area generally free from major ridges running from south of Barrow to near Pt. Franklin and is located seaward of the late spring ice edge but shoreward of the early spring ice edge. Because of the wide variation of the ice edge in this region, the description of this area and Zone 11 should not be considered entirely accurate. One reason for the wide variation of behavior here is the location of these areas in waters considerably deeper than 20 meters, and hence, the absence of significant grounded ice features to provide anchoring mechanisms for fast ice. This situation is reversed on headlands (Pt. Barrow, Pt. Franklin, Icy Cape, etc.) where many of the identified nearshore zones are located within the 20-meter isobath.

This area tends to be free of lead activity from mid-winter until mid-spring. However, surface travel should be considered hazardous even at those times because of the wide variation in behavior mentioned above. Surface and subsurface structures are relatively free from hazards due to major piling and plowing events. Subsurface oil spills may be pooled under stationary ice for up to a month at a time but lead activity and ice motion would eventually result in the pools of oil breaking up and being redistributed.

11. This area, which is generally free from major ridges, runs from south of Pt. Barrow to north of Pt. Franklin and is located seaward of the early spring ice edge but shoreward of the mid-winter ice edge. For the same reasons described for Zone 10, the boundaries of this zone are not well defined. The hazards described for Zone 10 also apply to this zone. However, the probability of stationary ice here is even less than in Zone 10 and the possibility is generally restricted to the period December-February.
12. This is a broad zone subject to moderate ridging, extending from Barrow to Pt. Franklin and located shoreward of the late spring ice

14. This zone adjacent to Pt. Franklin appears to exhibit ice behavioral characteristics somewhat different from **ice** zones adjacent to other headlands. Very **little** major ridging appears to occur here and the edge of contiguous ice varies little from season to season. This behavior is apparently due to the fact that the ocean floor profile drops off rapidly to 20 meters along this section of coast and the same profile is maintained much of the length of this region. Hence, ridging resulting from differential motion under compression ("shear ridging") is confined to a very narrow zone and may not be of sufficient width **to** be detected on a Landsat image. This zone may be quite narrow and may consist of a single shear ridge perhaps 50 meters wide.

This zone is hazardous for surface travel because of the high degree of activity within it and structures would be endangered by the constant ice motion.

15. This is a broad zone of moderate ridging located **seaward** of the late spring edge of contiguous ice but **shoreward** of the mid-winter ice edge. The variation of the edge of this zone is relatively small, hence, the boundaries of this zone should be considered fairly well defined.

Surface travel in this zone **should** be relatively safe from December through late March, with increasing risk toward the seaward side. Structures **placed** here would be exposed to moderate ridging before December and after March. Underwater oil spills would be contained under the ice from December through March and subject to transport at other times.

16. This is a zone of moderate ridging inshore of the late **spring** edge of ice and located between Pt. Franklin and Icy Cape. This zone is generally stable from December through late March and **could** be used for surface exploration with a reasonable degree of safety during this period. Structures are subject to ice motion, piling and plowing before December and after April. Under-ice oil spills could be expected to be trapped under the ice.

Zone 19. The hazards to surface travel in **this** zone are considerably less than in Zone 19, although the ridging might make travel difficult.

- 21, 22. This is a region of moderate ridging with an adjacent zone of severe ridging located between the mid-winter and early **spring** edges of ice. This is an active area during the entire ice year with perhaps the exception of a few weeks between December and March. The variation in the limits of these zones is sufficiently **large** to prevent precise determination of their location. Also, depending on ice activity, ridges created in these two areas may be broken away to drift with the pack ice.

Generally, these two areas are extremely hazardous for surface travel. Also, structures located within these zones would be subject to nearly constant piling and plowing except for perhaps one or two periods of several weeks in mid-winter. Oil spilled under these two regions would soon be transported into the pack ice.

23. A zone of moderate ridging located between the early spring and late spring edges of fast ice, this zone is similar to the adjacent Zone 19 except for ridge density.

24. A zone of mid-winter contiguous ice extending from Icy Cape to Point Lay, this zone **lies** between the mid-winter and early spring edges of fast ice. Along this section of the coast the variation of the mid-winter edge of ice is large and the width of this region can vary considerably. For this reason, the existence of this zone should not be depended upon for surface travel.

Structures located in this region **would** generally be free from ice piling and plowing events. Oil deposited under this area would soon be transported into the pack ice region.

25. This is a zone of reasonably stable contiguous **ice** located between the early and late spring boundaries of contiguous ice. The statistical variation of the positions of these boundaries is on the order of the width of the zone. Hence, its width and precise location can vary from year to year. The ice within this zone

increasing significantly after early spring **and** with distance from shore. Structures placed in this **zone** would be subjected to relatively small ridging and plowing events. However, **it** is very likely that one or more small shear ridges may become frozen into the zone during the time of formation. **Oil** spilled under this zone **is likely to** remain until May or June.

27. This is a zone of moderate ridging located between the early and late spring edges of ice. The early and late spring edges of ice converge along this section of coast off Pt. Lay. The mid-winter edge of ice remains much farther offshore. The shoreward variation of the mid-winter edge of ice is quite high here, **generally** coinciding with the combined edge of **early** and late spring fast ice. This small zone is reasonably safe for surface **travel** until early spring, but is increasingly hazardous after that time. Structures would be exposed to a moderate amount of ridging and plowing. Underwater oil **spills** would most likely be trapped under ice here until mid-spring when lead-forming activity would **introduce** the oil into the pack ice.

28. This zone of moderate ridging is located inshore **from** the combined early and late spring edges of contiguous ice. (See description for Zone 27.) This zone is formed during November and December and usually lasts until mid-spring. Early and **late** spring data show a wide variation in the boundaries of this zone, It can be very narrow with **flaw leads quite** close to shore.

This area should **be** safe for surface **travel** from December through early March but with increasing probability of **lead** formation following that date. Structures placed in this zone are exposed to ice piling and plowing events during November and December. **Oil** spilled under the surface in this zone **would normally** remain in **place** until May when it would be introduced into the pack ice due to breakup of the ice.

29. This is a zone of moderate ridging just seaward of the combined edge of early and **late** spring contiguous ice. This zone is subject to lead formation generally after early March but the data show that lead formation has occurred at earlier dates. For this

Because of water depths in this zone, it is unlikely that structures attached to the bottom would be constructed. Any structure located within this area would rarely be free from ice motion for more than two to three weeks. Similarly, oil deposited under the ice in this zone would soon be incorporated into the moving pack ice.

34. This two-part zone **of ice**, which is relatively free from ridging, is located between the early and late spring **edges of** contiguous ice. The zone is broken into two subzones by Zone 35. The variation of both boundaries is low. Hence, between December and March this area should be reasonably safe for surface travel with the hazard increasing after that time. Structures located in this area **should** be relatively free from the effects of ice motion from December through March and subject only to flaw lead activity after that time. Oil deposited under the ice in this zone would spread due to the absence of major ridges and be incorporated into flaw **leads** after March.
- 35, 36. These two zones are basically the same with moderate ridging intruding into Zones 30 and 34. The formation of Zones 35 and 36 decrease the utility of zones 30 and 34 as avenues for surface travel. The mechanism for the creation of this zone is somewhat different from the mechanism **responsible** for other **nearshore** areas of ridging: while most other ridges in the nearshore area are shear ridges, the ridges in this area are better classified as "pressure" ridges which are due to ice moving down the **Chukchi** coast and being driven into the nearshore ice blocking that path.
37. This is an area of severe ridging located in the vicinity **of** shoals off Cape **Lisburne**. This zone is inshore from the average edge of mid-winter contiguous ice but within the range of boundary variation of that zone. **Hence**, this area should be considered the location of early winter ridging with moderate stability from mid-winter to early spring. After that date, the edge of contiguous ice generally moves shoreward.

be subject to a minimum of ice hazards. Oil spilled here would quickly be incorporated into new ice and be transported seaward into the pack ice.

43. This zone of moderately stable ice is located just north of Point Hope, over relatively shallow water and within a reasonably stable portion of the late spring edge of contiguous ice. This area should be safe from ridging events and significant bottom plowing. Oil spilled under this zone **could** be expected to spread and then remain between December and May.
44. A zone of intermediately safe ice located between the early spring and **late** spring edges of contiguous ice. Because of **the** variation of the boundaries, this is an area of transition between the relatively stable Zone 43 and the unstable Zone 45 described next.
45. This is a small zone located within the average edge of mid-winter contiguous ice and adjacent to the recurring **polynya** (41 and 42). Generally, this zone does exist in this vicinity but its precise location changes frequently. This is an area where newly formed ice from the adjacent **polynya** is sometimes compacted and at other times, broken away. It **is** generally unsafe for surface travel. Structures placed within this zone would be subject to minor piling events but probably very **little** bottom plowing. **Oil** spilled under this zone during December through May will very likely become incorporated into compacted new ice and subsequently enter the pack ice region.
46. In this zone the edge of contiguous ice remains constant throughout the ice season. An apron of ice generally extends seaward from the shore. Pack ice rounding Pt. Hope occasionally results in **flaw** lead activity at the west end of this zone. Statistically the zone varies significantly, with **the** seaward **edge** of the zone migrating occasionally very **close** to shore. This zone should be moderately safe for surface travel as long as quick access to the shore is maintained. Structures placed in this zone would be subject to a minimum of ridging activity. An oil leak

- spills of this nature would probably **be** retained **in the** vicinity for the balance **of** the ice season.
50. This zone of ice is shoreward of the late spring ice **edge**. Landsat imagery of this area reveals linear features which are probably shear ridges running close to and parallel with the shore. Because of these shear ridges, this zone was separated from Zone 46. These ridges are most likely formed during November and December and remain with the ice in this zone until May. During this period, surface travel within this zone is relatively safe. Structures placed here may be subject **to** some ridge-building activity in November and December and some bottom plowing might occur during these events. Oil spilled under the ice could be expected to spread somewhat as a result of the relatively smooth undersurface of the ice in most of this zone. It would then remain in place until April-May.
51. This large zone of relatively stable ice is located inshore of the late spring ice edge including inner Kotzebue Sound. During the period of formation in November-December, dynamic ice events may take place in this zone; pressure and shear ridges may form, particularly in Kotzebue Sound, creating conditions hazardous to structures. Following that period and until April, this surface should be fairly safe for surface travel. Oil spilled here during November-December would most likely be incorporated into the ice somewhere within the zone - depending on the nature of the dynamic ice events during that period. After that time, oil **would** spread out under the relatively smooth surface of the ice and remain **until** breakup around May.
52. This zone of ice within Kotzebue Sound is located between the **early** and late spring edges of fast ice. Analysis of contiguous ice edge variations shows that the ice within this zone is broken up sometime between early and late spring. From December until the ice breaks up, this area should be safe for surface travel. Structures placed within this zone would be subject to ridging activity during November-December but generally not after that date. Oil

dangerous area for surface travel. Structures placed within this zone would be subject to **almost** constant ridging processes and, **in** locations less than 20 meters in depth, bottom **plowing** could be expected to take place. Oil spilled under the **ice** in this zone **would** temporarily become trapped. Since the ice in this zone is frequently broken free, such trapped oil would soon be introduced into the pack ice.

56. This area of severe ridging is located offshore from the average edge of mid-winter contiguous ice. This zone is similar to Zone 55 except that the density of ridging and the relative stability is increased, (see description of Zone 55) but not sufficiently **to** consider this zone safe for surface operations.

57, 58. These are zones of moderate and severe ridging respectively, located inshore from the average edge of early spring contiguous ice and offshore from the average edge of mid-winter contiguous ice. This situation is reversed from the relationship of these two average edges elsewhere along the coast. The variation of the early spring contiguous ice edge is **also** less than the variation of the mid-winter ice edge. These data support the concept of a building up of stable ice in this area during the winter and early spring portions of the ice season, while elsewhere **along** the coast, maximum buildup generally occurs by mid-winter. Presumably this effect is a result of the nearly constant motion of ice out Bering Strait, creating many parallel, shear ridges **along** this area of the coast.

This area should be considered for surface travel only in **early** spring. However, the surface roughness at that time would impede evacuation attempts from dangerous ice conditions. Structures placed **in** these zones would be subject to pressured ice events throughout the ice season. Bottom plowing **is also** a **distinct** possibility **at** all times. Oil spilled under this zone has a high probability of entrapment in pressured ice.

59. This is an area of severe ridging located inshore from the average edges of contiguous ice for mid-winter, early spring and

This zone is, therefore, not entirely safe for surface travel with the relative danger increasing significantly with distance beyond well grounded ridges. Ice conditions imposed on structures would vary considerably across this zone. Oil spilled under the ice in this zone would be subject to pooling as a result of the rough undersurface and introduction into the pack ice during the occasional break-off events.

61. This is a zone of relatively smooth, stable ice formed early in the ice year and remaining in place until late spring. It is moderately safe for surface travel from December through May. Structures placed in this zone would be relatively free from ice piling events and bottom plowing. Oil spilled under this zone would be subject to considerable spreading because of the relatively smooth undersurface.
62. This is a zone of moderate ridging and variable stability throughout the ice season. It is generally unsafe for extensive surface travel, although brief excursions could be safely carried out if ice conditions were monitored carefully. Structures in this zone would generally be subject to ice piling conditions at any time. Oil spilled under this zone would tend to become trapped under the relatively rough undersurface and be introduced into the pack ice during the occasional ice breaking events.
63. This is a broad zone of unstable ice located in relatively shallow waters running from Cape **Espenberg** to Males. This zone has some unusual characteristics: the edges of contiguous ice run adjacent to the shore. The area is highly variable: it can be relatively broad when the ice edge is far from shore and quite narrow when close to shore. This area should be considered unsafe for surface travel. Structures placed within this zone would probably not be exempt from ice piling events for very long periods of time. Oil spilled under this zone would soon become incorporated into broken and refreezing pack ice.

flaw leads can open at almost **any** time. Oil spilled under this ice **would at** those times find pathways to the surface. Surface operations would be hazardous.

3. These are areas where ice may occasionally become temporarily attached to the contiguous ice. Because this area **lies** mostly within the 20-meter **isobath**, grounded ice features could exist **at** any time, particularly if man-made artificial islands were to be constructed, thereby trapping an under-ice **oil** spill. Generally, however, **oil** spilled in these regions would be spilled into mobile pack ice.
- 4* These are regions generally similar to the regions denoted by "2" except that ridging as well as flaw lead openings apparently occur during the entire season. Oil spilled in these areas **could** be subject to either lead opening transport or semi-permanent incorporation into ice through ridge-forming processes. In terms of the consequences of oil spills, this is a quite hazardous zone.
5. These are areas of **nearly** constant new ice formation. One is located at the head of Norton Sound and the other on the north side of Bristol Bay. Hazards in these areas include the **almost** certain incorporation of spilled **oil** into new ice and its transport with that ice to other areas. Surface operations in these areas during freezing conditions would also be hazardous. The open water in these areas **would** certainly **be** prone to pack ice invasions should winds reverse from their normal direction. Surface structures near these zones would be subject to rime ice formation much of the time.
6. These are areas adjacent to the areas of new ice formation. These areas are similar except that this zone often contains compacting new ice which recently formed in the adjacent

exposed to opening and closing leads and ice **piling** events. Surface recovery operations would be quite hazardous.

The third zone shown here lies in **the** outer mouth of the **Kuskokwim** River and the extensive mud flats to the west. Here, **tidal** activity results in ice motion with hazards similar to those described above.

The fourth of these zones is located in the estuary off **Dillingham**. As in the **Kuskokwim** region, tide-driven ice results in hazards similar to the other areas given this designation.

9. This region has been separately defined because it represents in many ways a transition between the "3" designated area to the west and the "6" designated area to the south. Newly forming ice often mixed with pack ice from the west is found over waters less than 20 meters deep. Large **tidal** ranges exist here. Oil spilled in this area **could** encounter a variety of conditions or combinations of conditions **all** of which are unstable. Hence, oil spilled in this area would almost certainly be **lead-pumped** to the surface, spread by tidal activity, and transported toward the Bering Sea. Surface activities would be hazardous.

10. This unit includes the nearshore area between the contiguous ice **zone** along the Alaska Peninsula and the "6" zone beyond the 20-meter **isobath**. Normally ice withdraws from this shore as part of a general movement into the Bering Sea. Contiguous ice is generally limited to the narrow zones designated "1". However, there is the possibility that Bering Sea **ice** can be driven in this direction and cause ridging and pile-ups in this **zone**. (see zone 11)

IX. List of References

No direct references to other publications are made in this report. This is largely because of the original nature of this statistical analysis. However, use was made of the following publications:

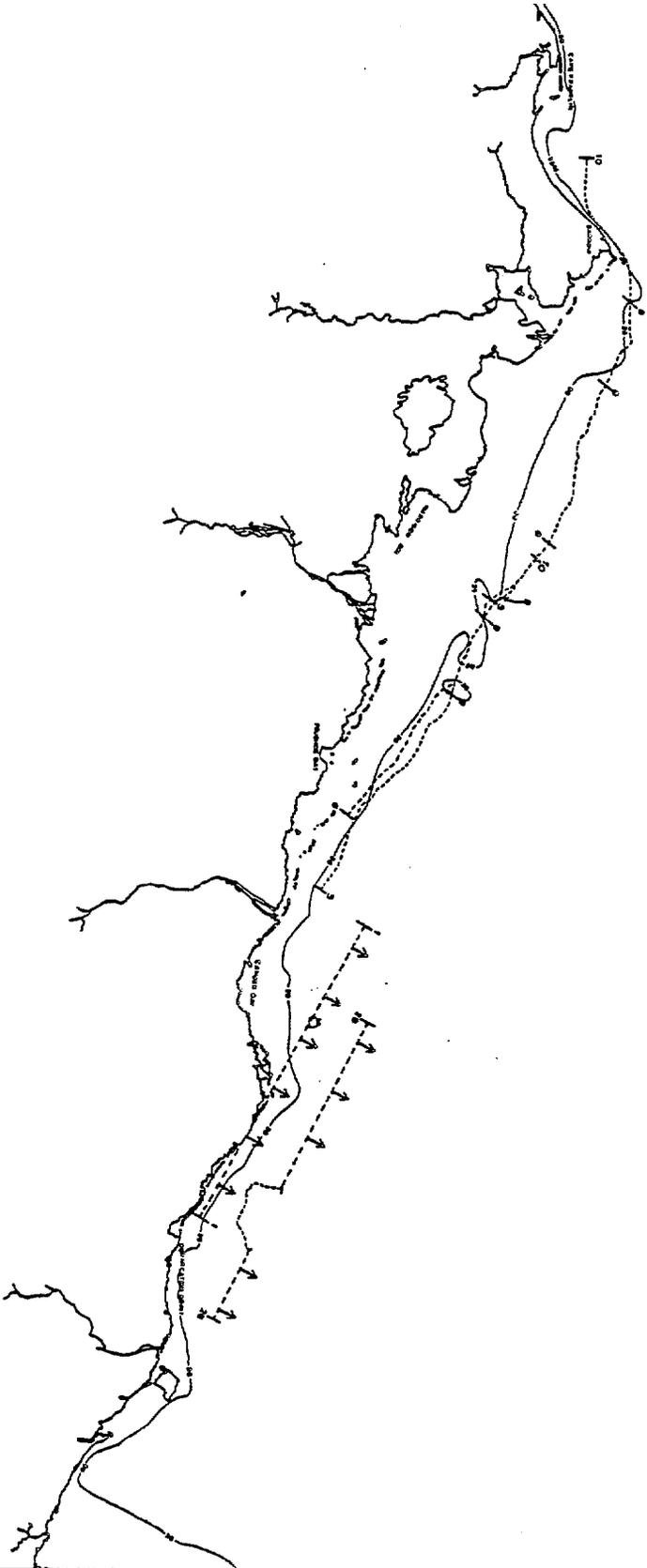
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- Fryer, M., Planning marine structures for Alaska's arctic regions, Northern Engineer, 2, p. 17, 1970.
- Kovacs, A., and M. Mellor, Sea ice morphology and ice as a geologic agent in the southern Beaufort Sea, Proceedings of the Symposium on Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, 1974.
- Kovacs, Austin, and Anthony J. Gow, Some characteristics of grounded floebergs near Prudhoe Bay, Alaska, CRREL Report 76-34, prepared for NOAA, Sept. 1976.
- Kovacs, Austin, Grounded ice in the fast ice zone along the Beaufort Sea coast of Alaska, CRREL Report 76-32, prepared for NOAA, September 1976.
- Kovacs, A., A. J. Gow, and W. F. Dehn, Islands of grounded sea ice, CRREL Report 76-4.
- Kovacs, Austin, Sea ice thickness profiling and under ice oil entrapment, 9th Annual Offshore Technology Conference, Houston, Texas, May 1977.
- Nelson, Richard K., Hunters of the Northern Ice, University of Chicago, Press, 1969.
- Reimnitz, E., and P. W. Barnes, Studies of the inner shelf and coastal sedimentation environment of the Beaufort Sea from ERTS-1, NASA Report no. NASA-CR-132240, p. 3, 1973.
- Reimnitz, Erk, Larry Toimil, and Peter Barnes, Development of the Stamukhi zone and its relationship to arctic shelf processes and morphology, Beaufort Sea, Alaska, U. S. Geological Survey, Menlo Park, California, 1976.
- Searby, Harold W., and Marcelle Hunter, Climate of the north slope Alaska, U. S. Department of Commerce, NOAA, National Weather Service, February 1971.
- Seifert, Richard D., The structure of shorefast ice off the north slope of Alaska, M. S. Thesis, University of Alaska, May 1973.

BEAUFORT SEA
1979 ICE EDGE

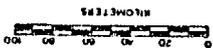
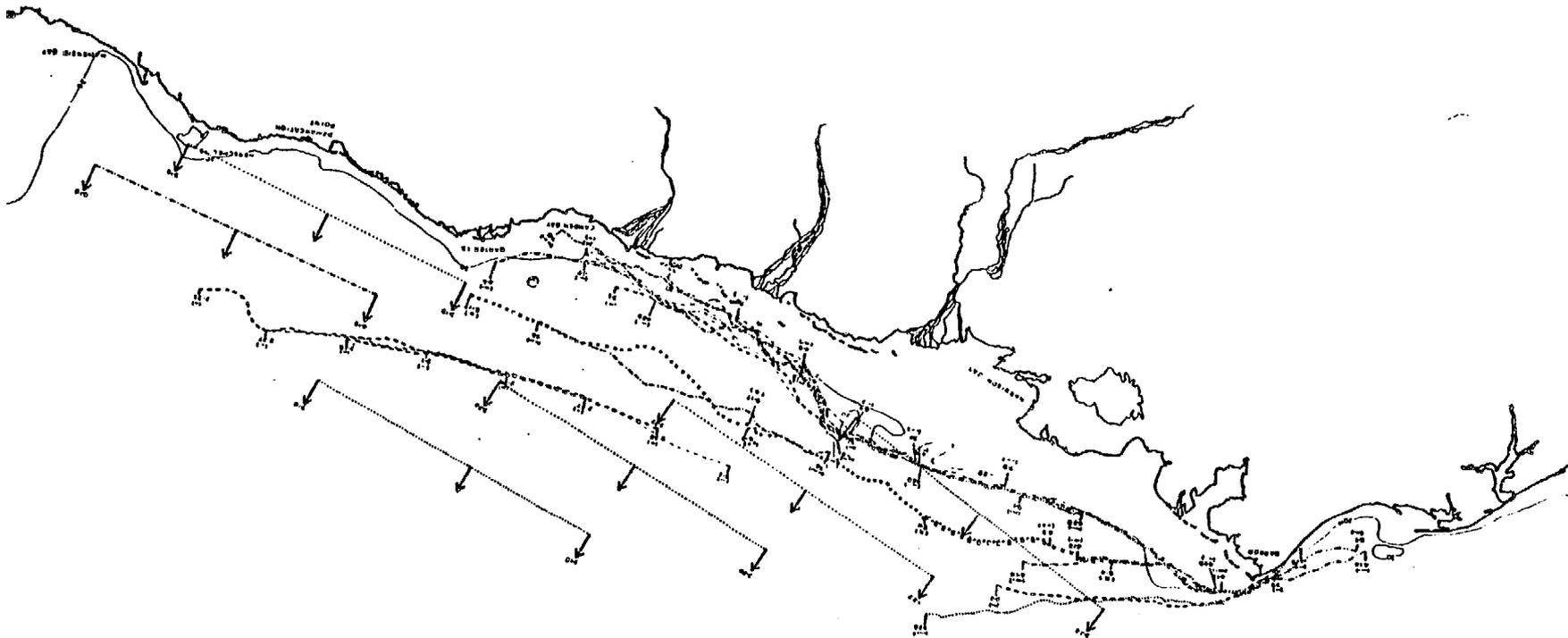
----- 20 February - 10 March

— Limit of data for date indicated

↔ Indicates contiguous ice
sewns beyond edge of
sonar scans.



Division of E.S. Parsons
S.A. Roberts
Bartlett of E.S. Parsons

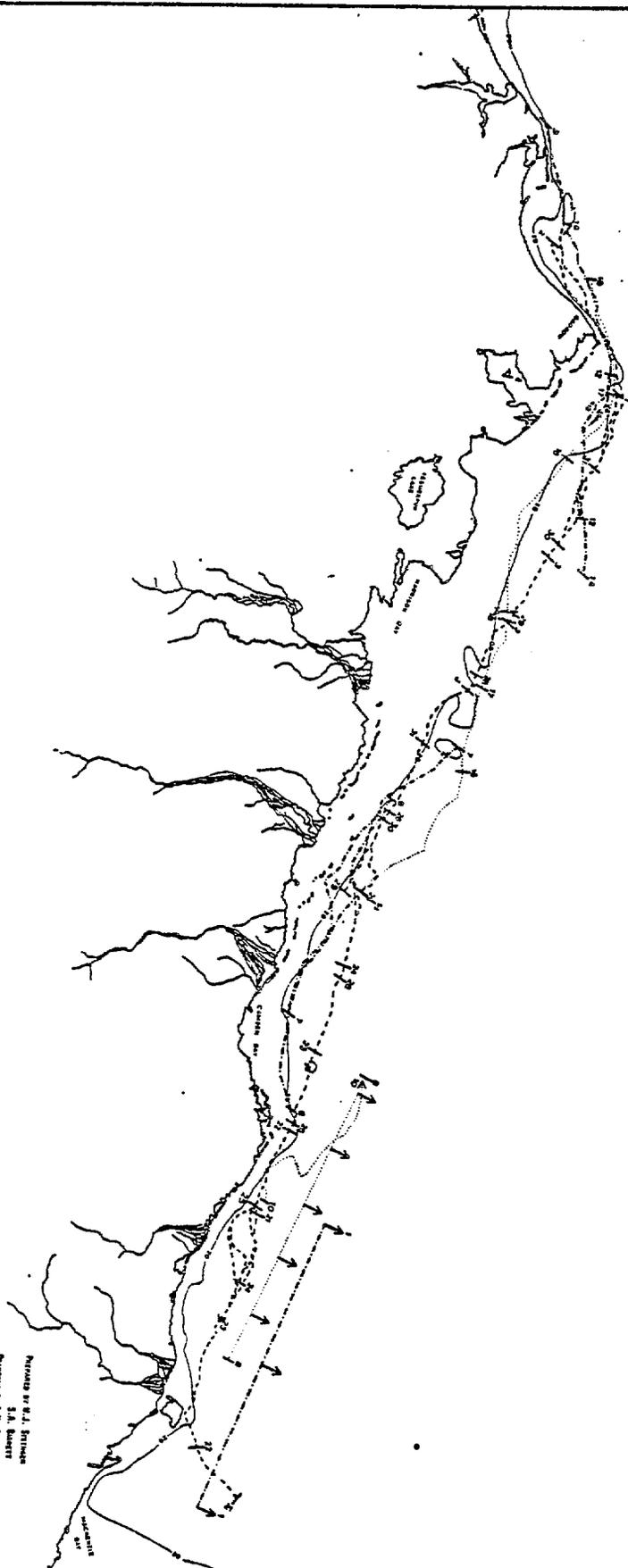


BEAUFORT SEA
1977 ICE EDGE
..... 12, 19 FEBRUARY - 9 MARCH
- - - 9-26 MARCH
- - - 27 MARCH - 14 APRIL
- - - 14 APRIL - 01 MAY
- - - 29 JUNE - 19 JULY
- - - 2 MAY - 30 JUNE
- - - LIMIT OF DATA
→ LIMIT OF DISTINGUISHABILITY
..... ICE 3003 IS BEYOND LIMIT OF DATA

Map showing the 1977 ice edge in the Beaufort Sea and Chukchi Sea, with various data points and limits of distinguishability and data.

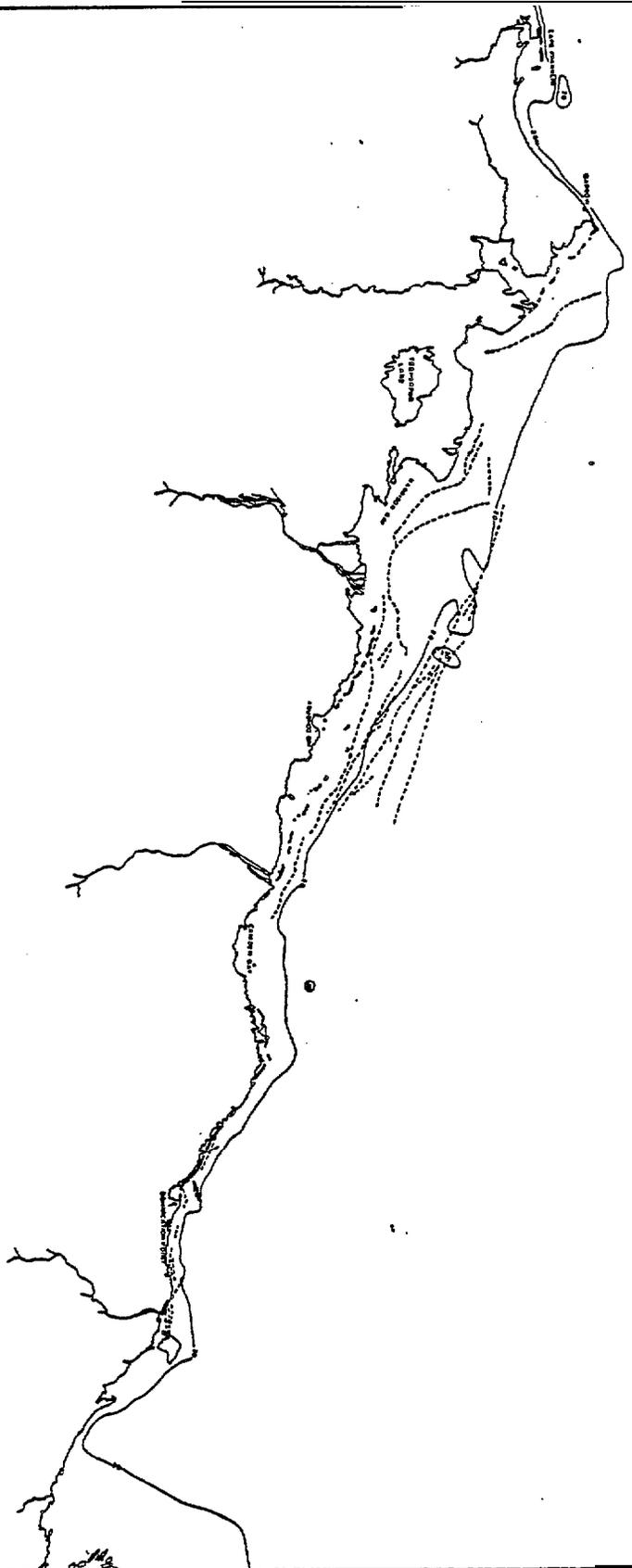
BEAUFORT SEA
EARLY SPRING ICE EDGE
1974, 1976, 1977

- 15 March - 3 April 1974
- 31 March - 17 April 1976
- - - - 27 March - 14 April 1977
- Limit of distinguishability
- ↔ Arrows indicate contiguous ice extended beyond edge of Landsat scene.
- ↔ Limit now edge of scene

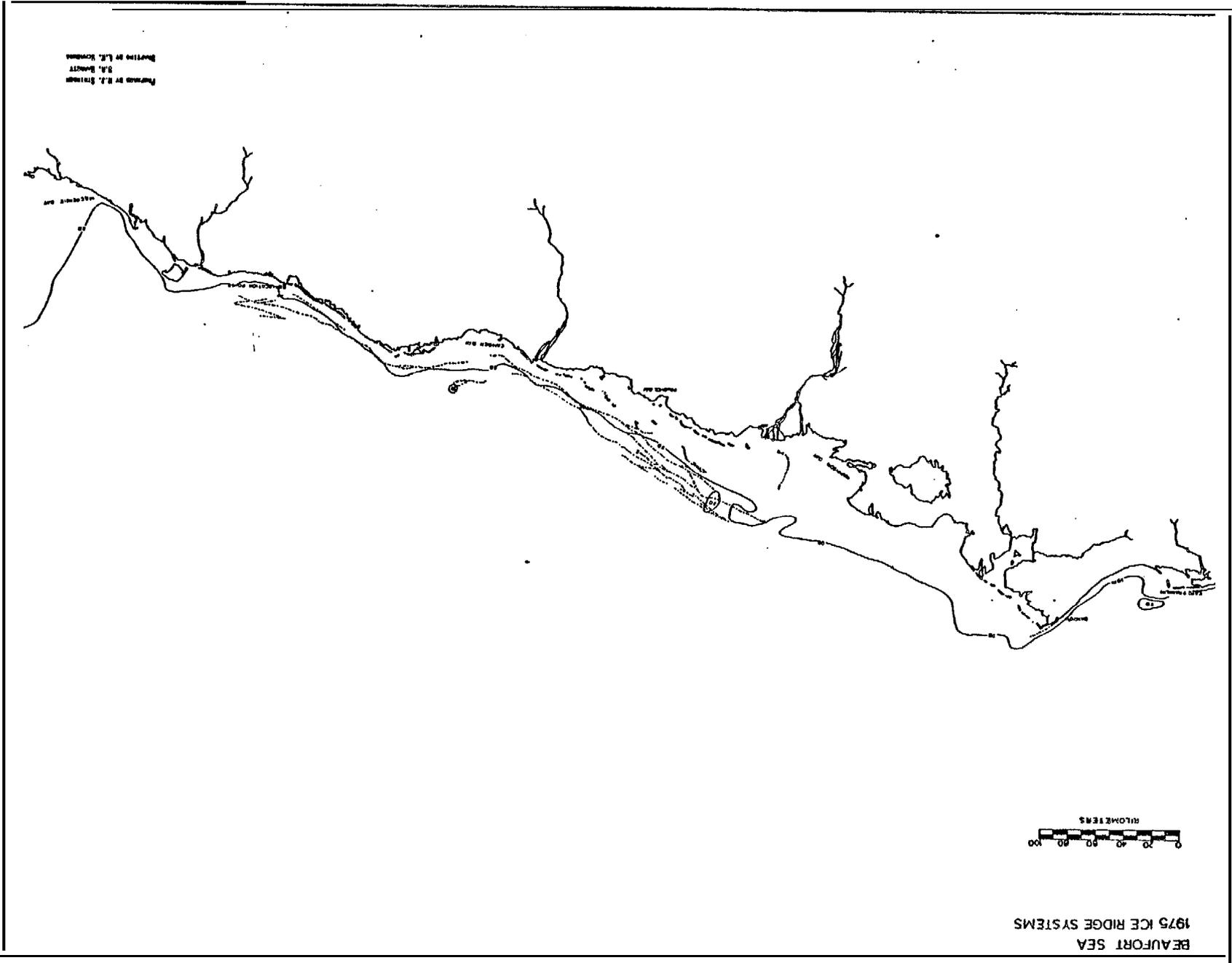


REVISED BY W.A. ERTTER
S.A. BERRY
DARTON BY L.E. SCHWAB

BEAUFORT SEA
1973 ICE RIDGE SYSTEMS



Revised by E.A. Sorenson
S.A. Jansen
Revised by L.K. Senneker

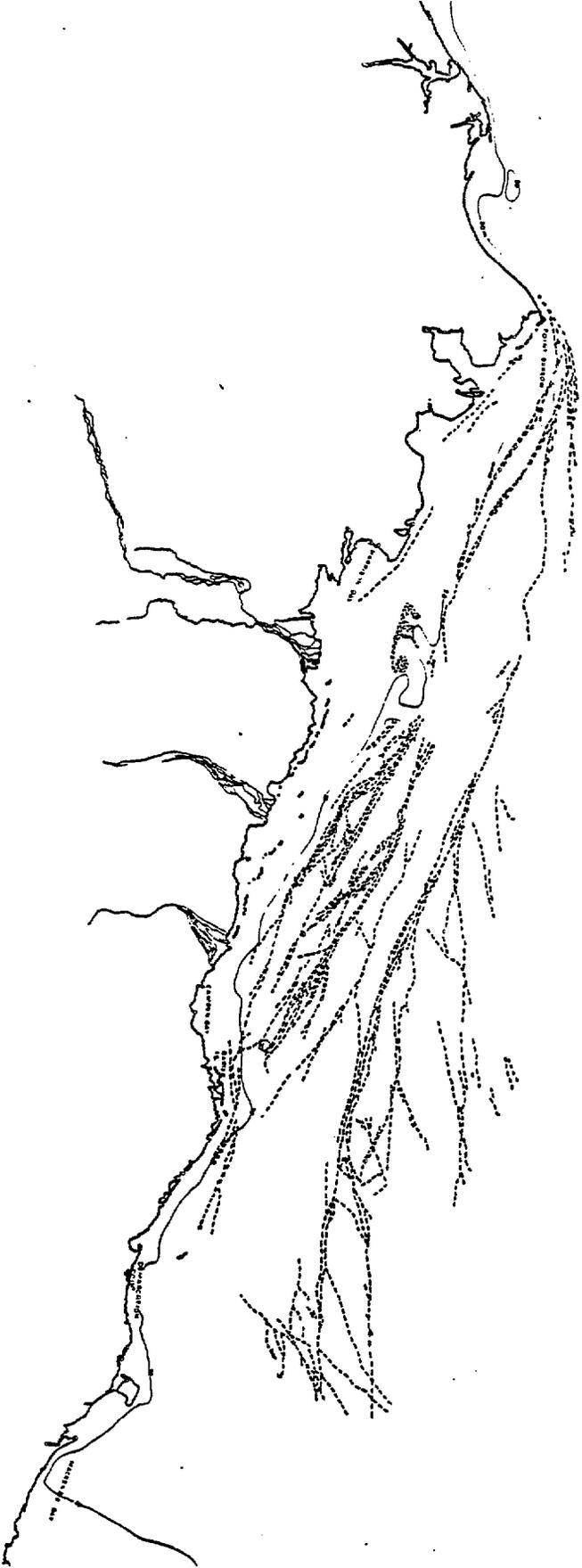


BEAUFORT SEA
1975 ICE RIDGE SYSTEMS

KILOMETERS
0 20 40 60 80 100

Prepared by R.L. Shinn
S.A. Bouché
Bouffon & L.L. Schmitt

BEAUFORT SEA
1977 ICE RIDGE SYSTEM



Acquired by R.A. Stillman
R.L. Stewart
Mapping by A.L. Schaner

BEAUFORT SEA ICE RIDGE DENSITY MAP

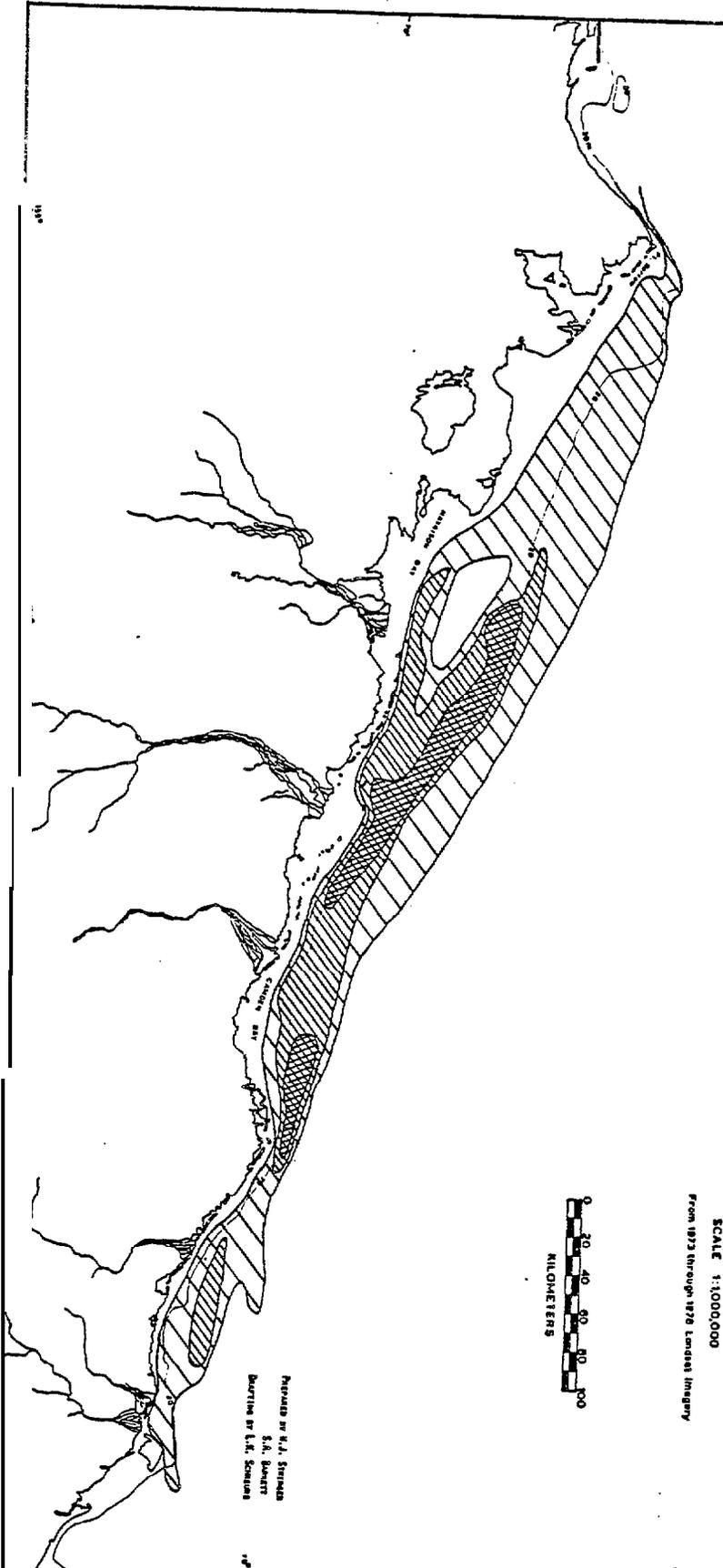
- Little or no ridging
- Light ridging
- Medium ridging
- Heavy ridging

SCALE 1:1,000,000

From 1973 through 1978 Landfast Inventory

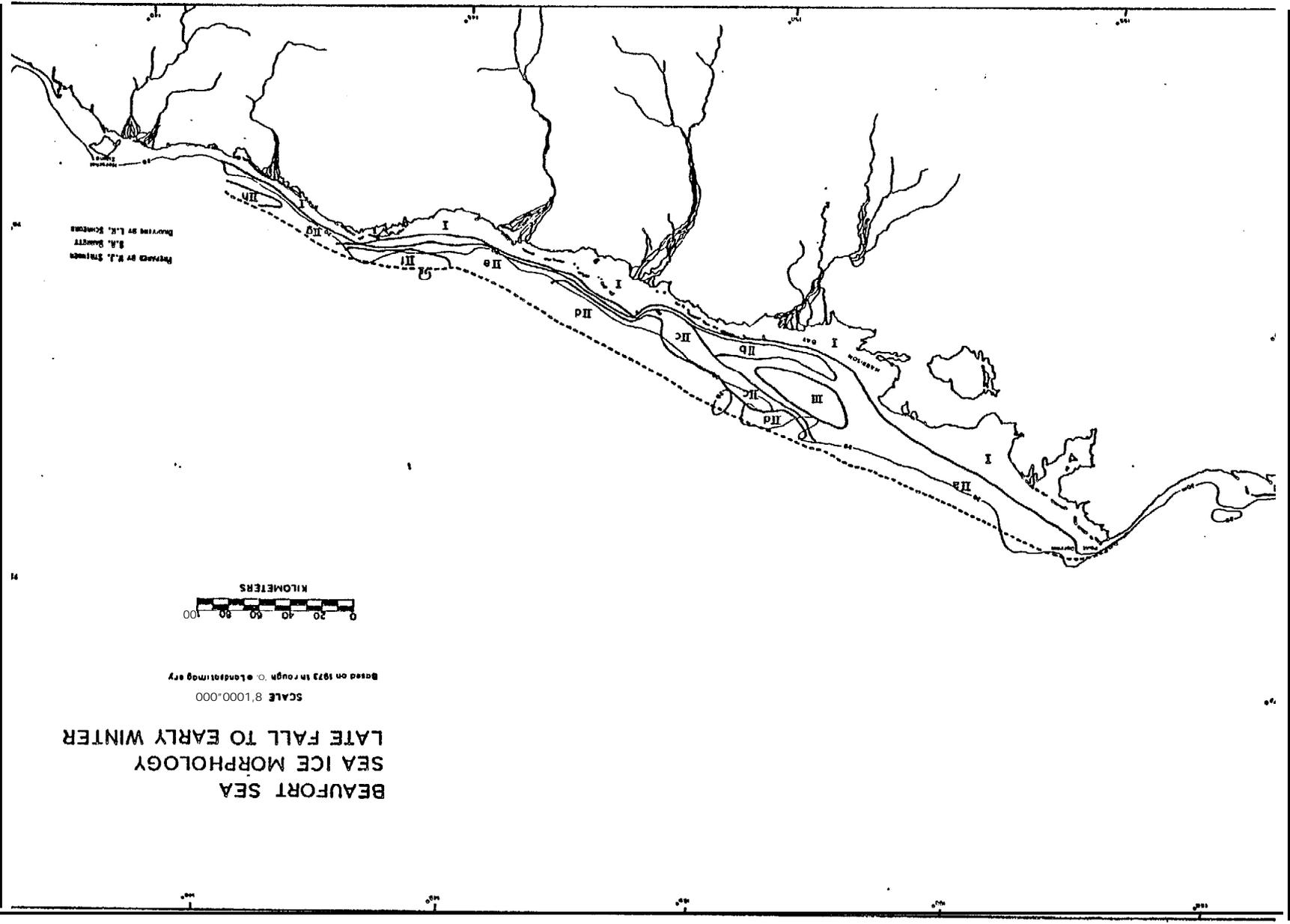
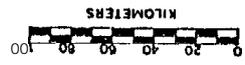


Prepared by W.A. Sturges
S.A. Benson
Directed by L.K. Stouffer



BEAUFORT SEA
SEA ICE MORPHOLOGY
LATE FALL TO EARLY WINTER

SCALE 8 1000:000
Based on 1973 rough \odot Landström et al.



PREPARED BY W. J. STRAIN
S. A. BARNETT
DRAWING BY L. J. SCHWENK

BEAUFORT SEA ICE HAZARD MAP

Based on 1973 1978 LANDIS imagery



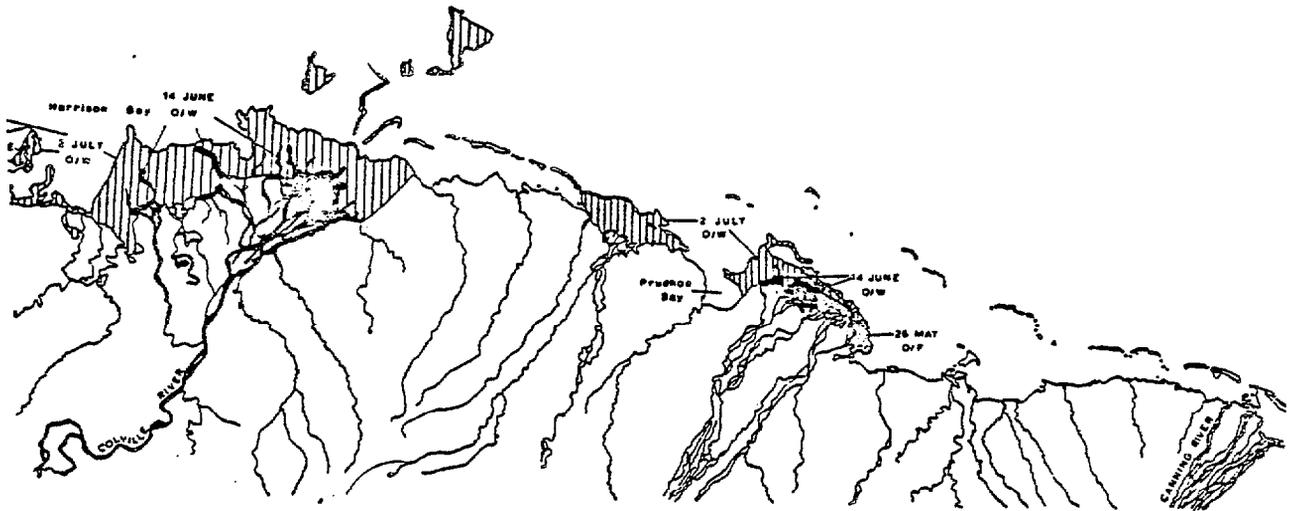
Produced by R.L. Stimpson
S.A. Lambert
Revised by R.L. Stimpson

BEAUFORT SEA 1973 OPEN WATER

Harrison Bay to Canning River

O/F - Overflow

O/W - Open water

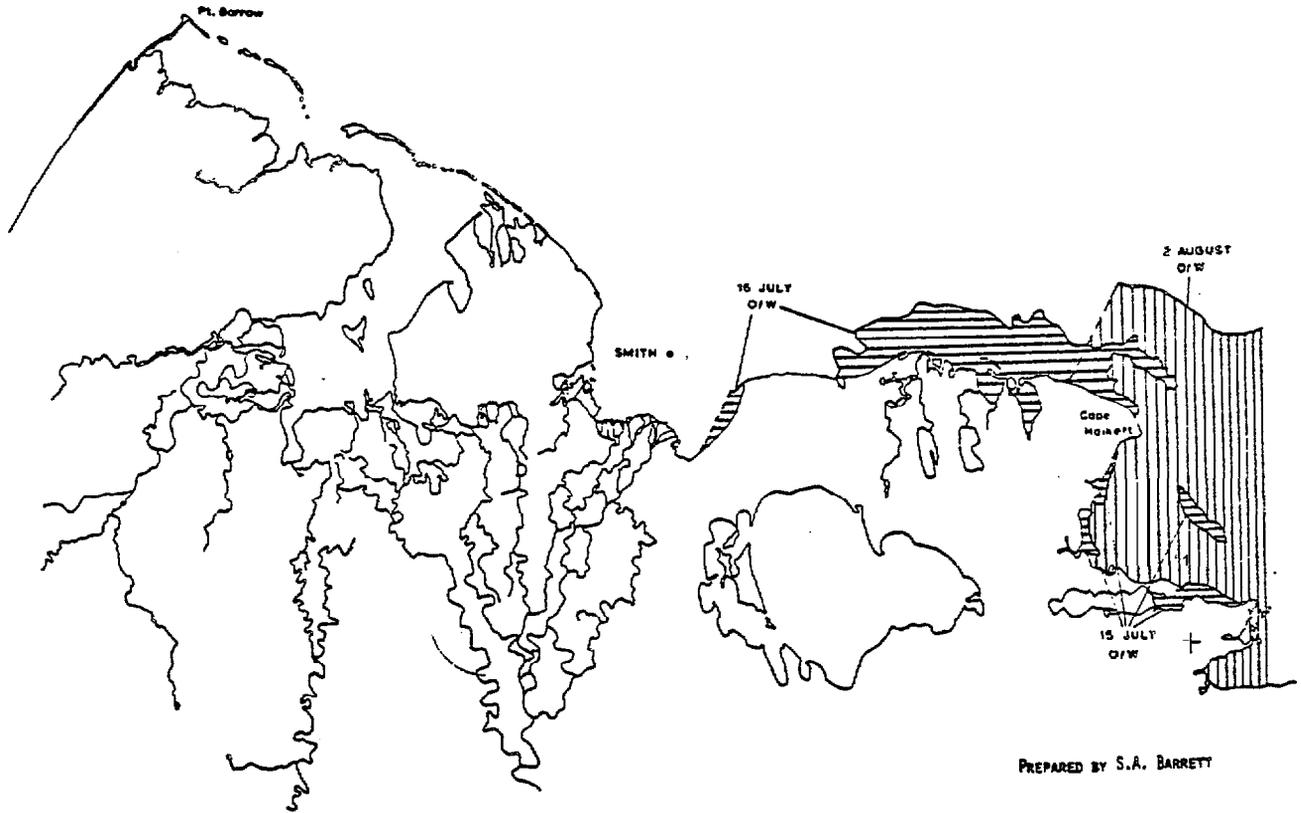
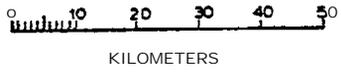


PREPARED BY S.A. BARRETT

+

BEAUFORT SEA 1974 . OPEN WATER

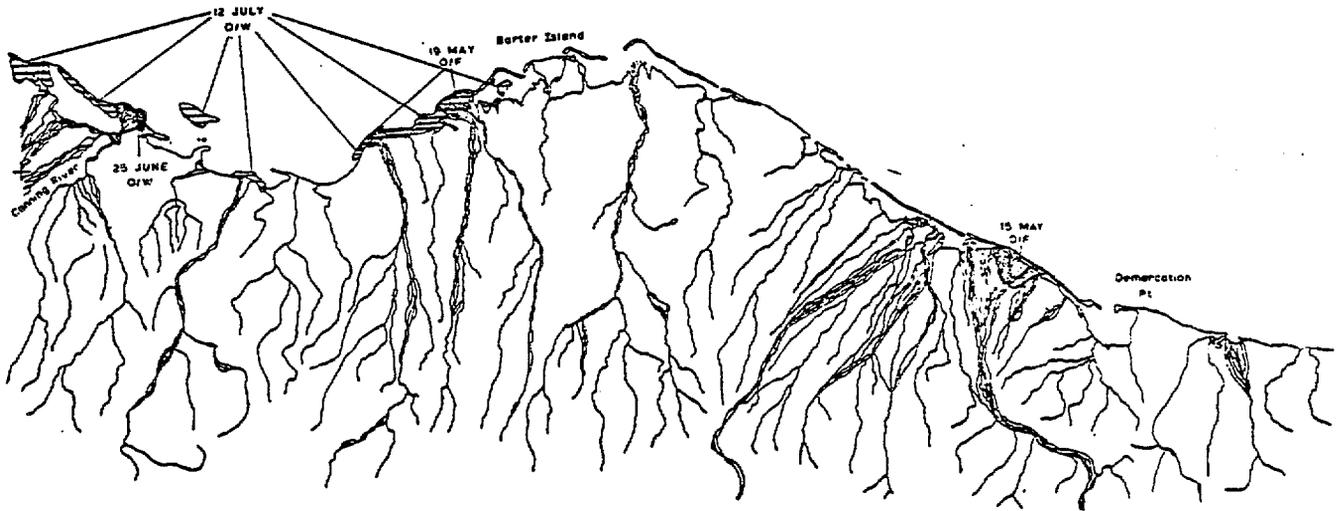
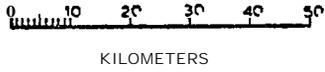
Pt. Barrow to Cape Hallett
O/W Open water



PREPARED BY S.A. BARRETT

BEAUFORT SEA 1974 . OPEN WATER

Canning River to Demarcation Pt.
O/F—Overflow
O/W—Open water

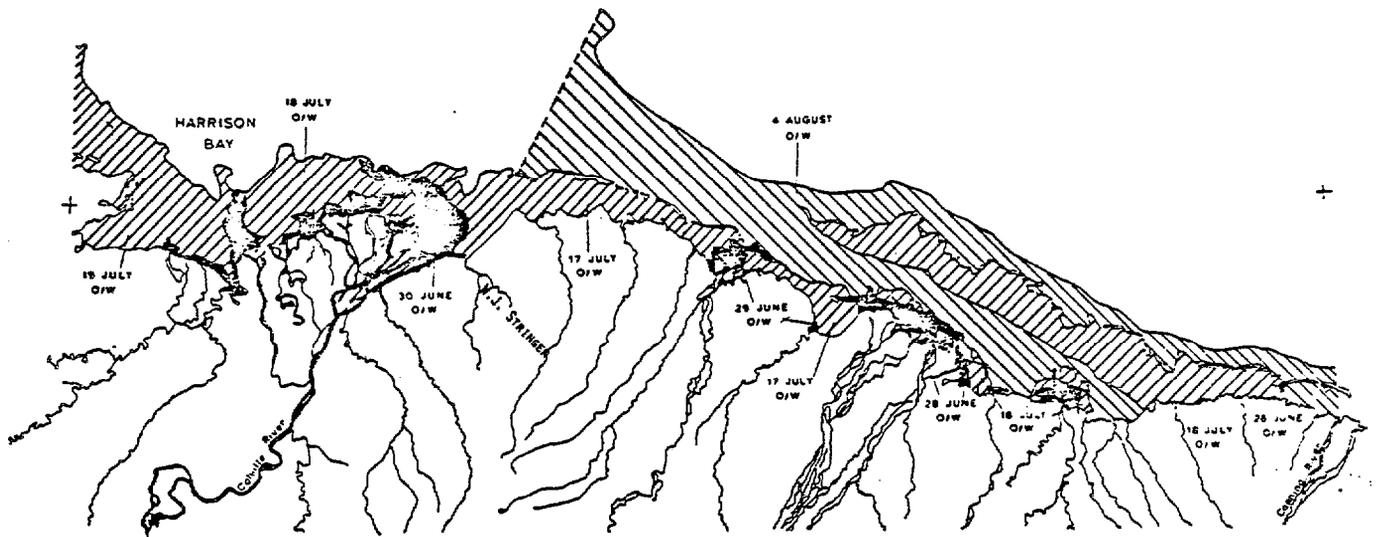


PREPARED BY S.A. BARRETT

BEAUFORT SEA 1975
OPEN WATER

Harrison Bay to Canning River

O/W — Open water

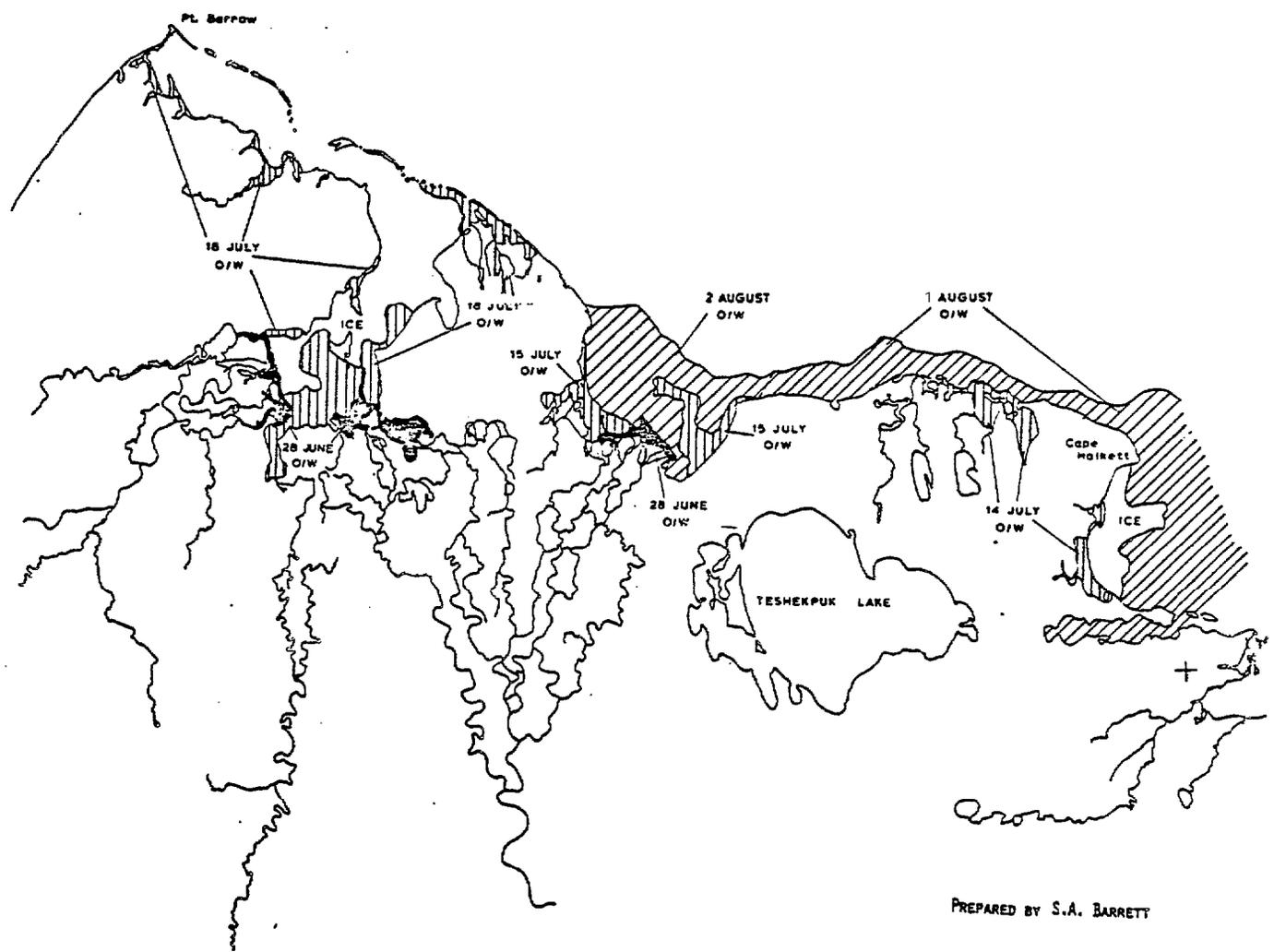
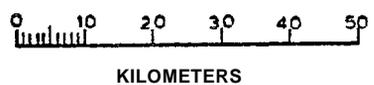


PREPARED BY S.A. BARRETT



BEAUFORT SEA 1976 OPEN WATER

Pt. Barrow to Cape Halkett
O/W — Open water

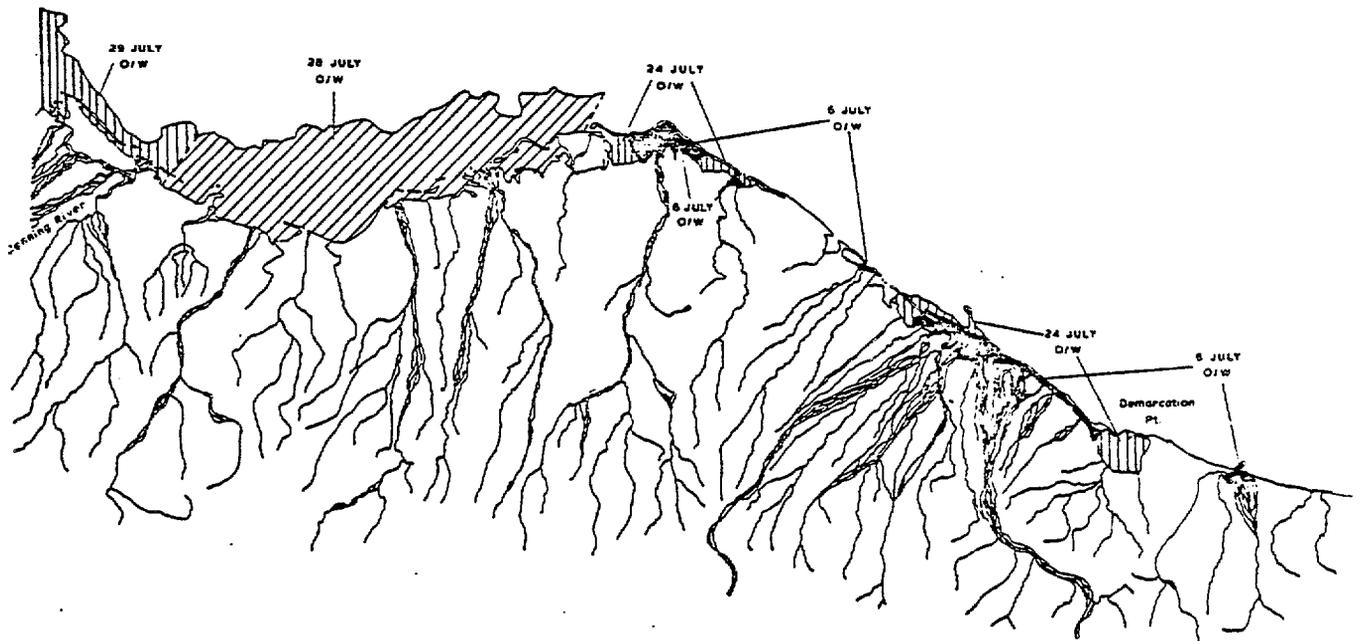
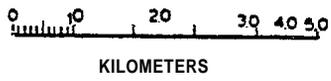


PREPARED BY S.A. BARRETT

BEAUFORT SEA 1976
OPEN WATER

Canning River to Demarcation Pt.

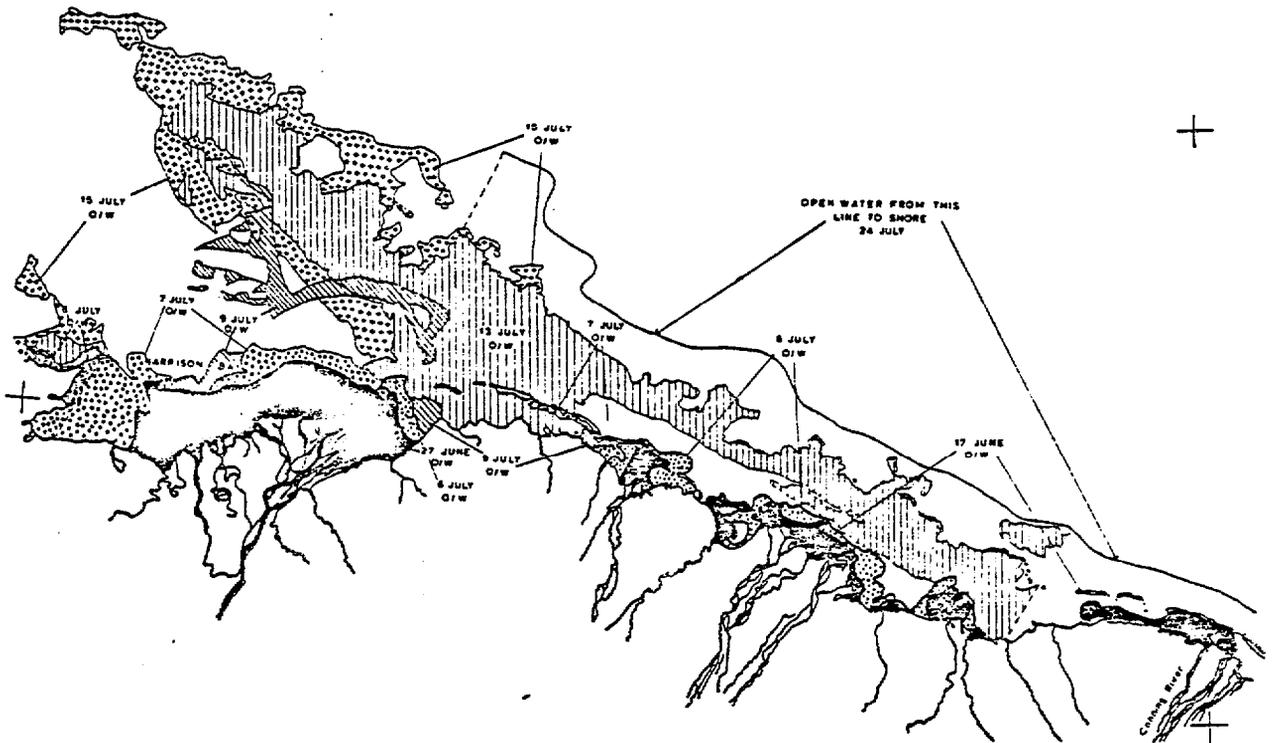
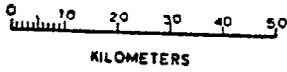
O/W—Open water



PREPARED BY S.A. BARRETT

BEAUFORT SEA 1977 OPEN WATER

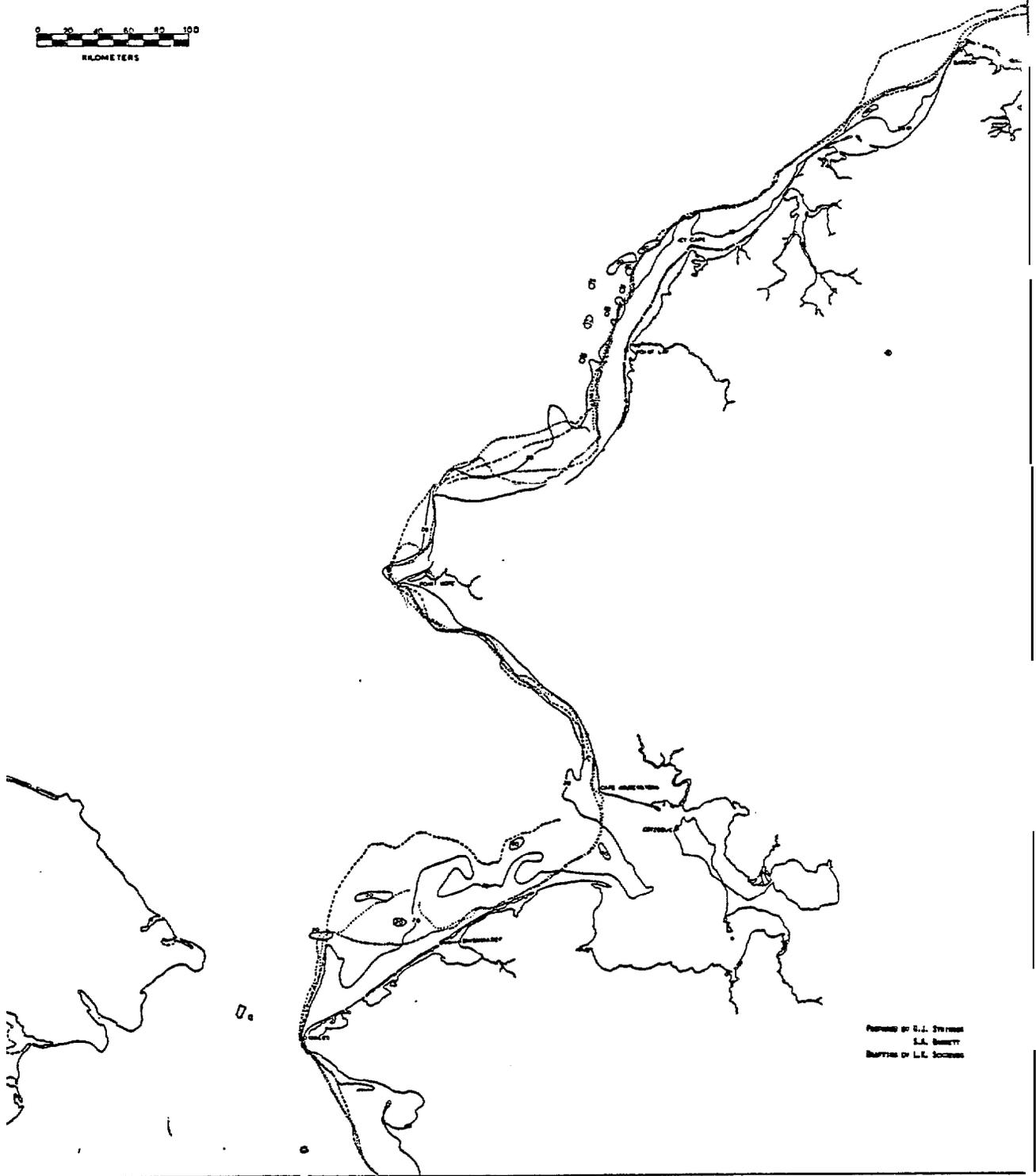
Harrison Bay to Canning River
+ O/W — Open water



PREPARED BY S.A. BARRETT

CHUKCHI SEA
1975 ICE EDGE

- 20 Feb - 9 March
- 28 March - 14 April
- S-23 April
- 30 May - 18 June

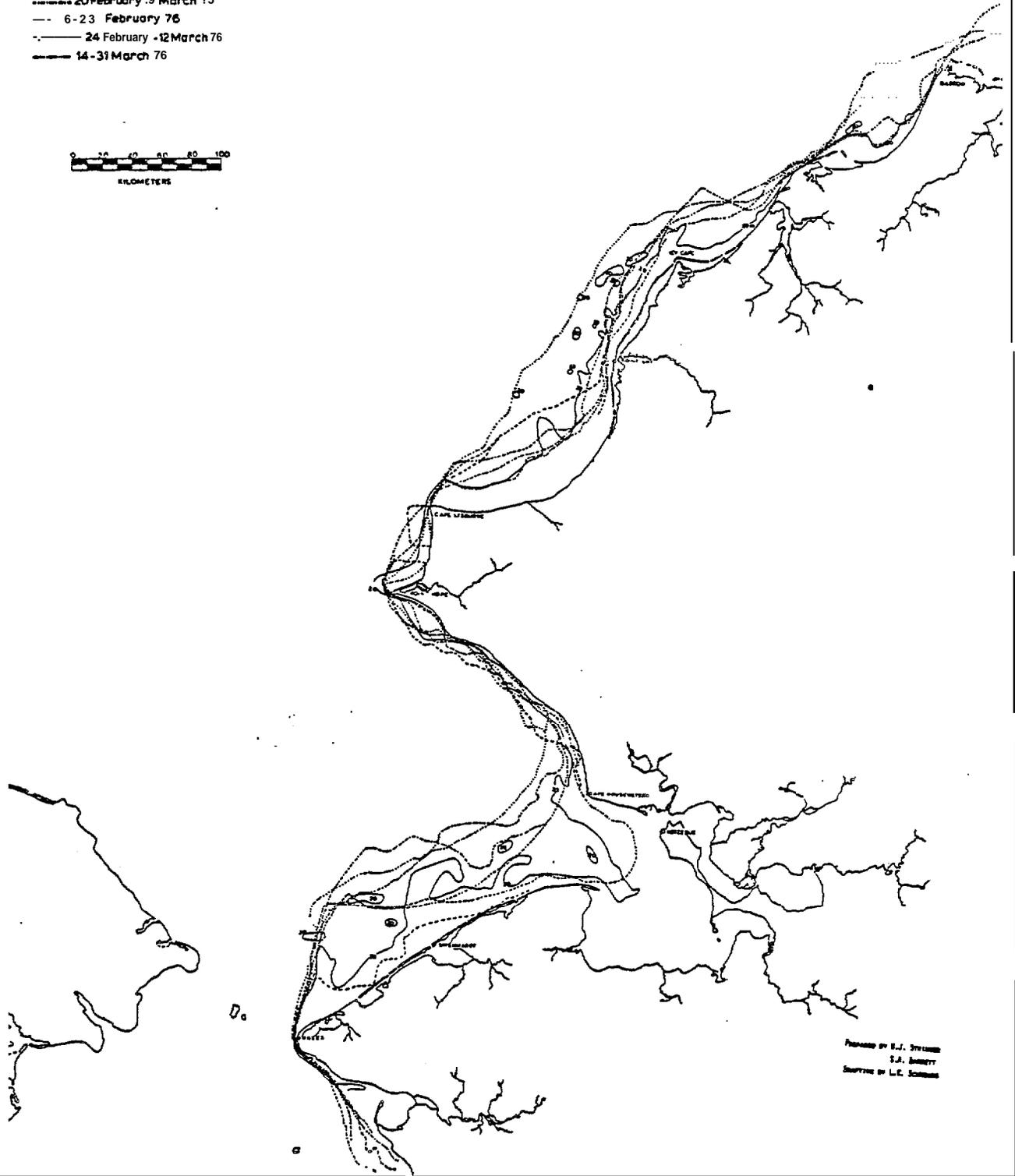
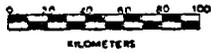


Prepared by R.L. Stevens
S.A. Bennett
Revised by L.E. Sweeney

CHUKCHI SEA

LATE WINTER ICE EDGE 1973-76

-2.17 March 73
- 25 February -14 March 74
- 20 February -9 March 75
- · — · 6-23 February 76
- · - · 24 February -12 March 76
- 14-31 March 76

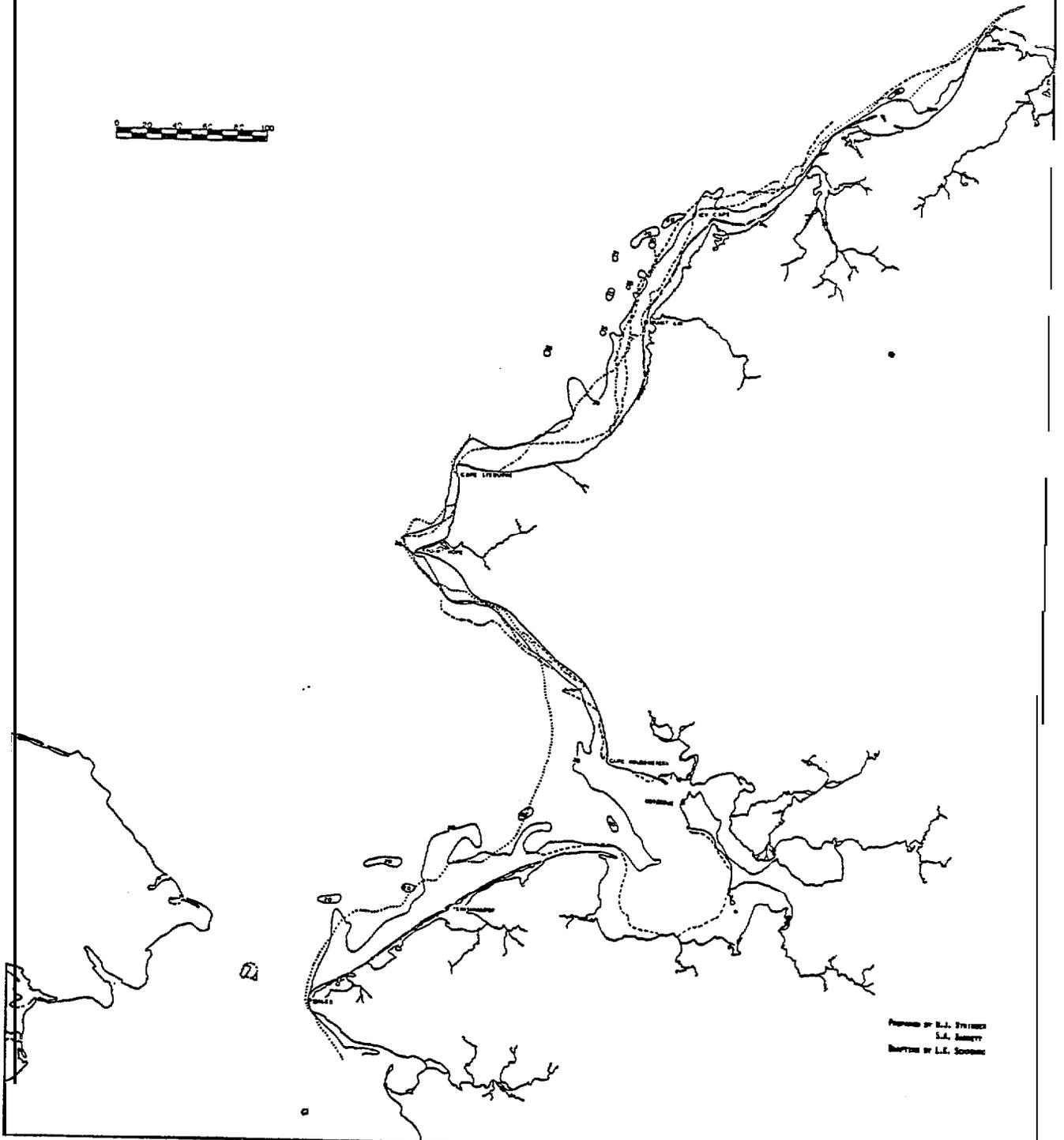


Prepared by R.J. Strickland
S.A. Bennett
Illustrated by L.C. Schmitt

CHUKCHI SEA

LATE SPRING - EARLY SUMMER ICE EDGE 1973-76

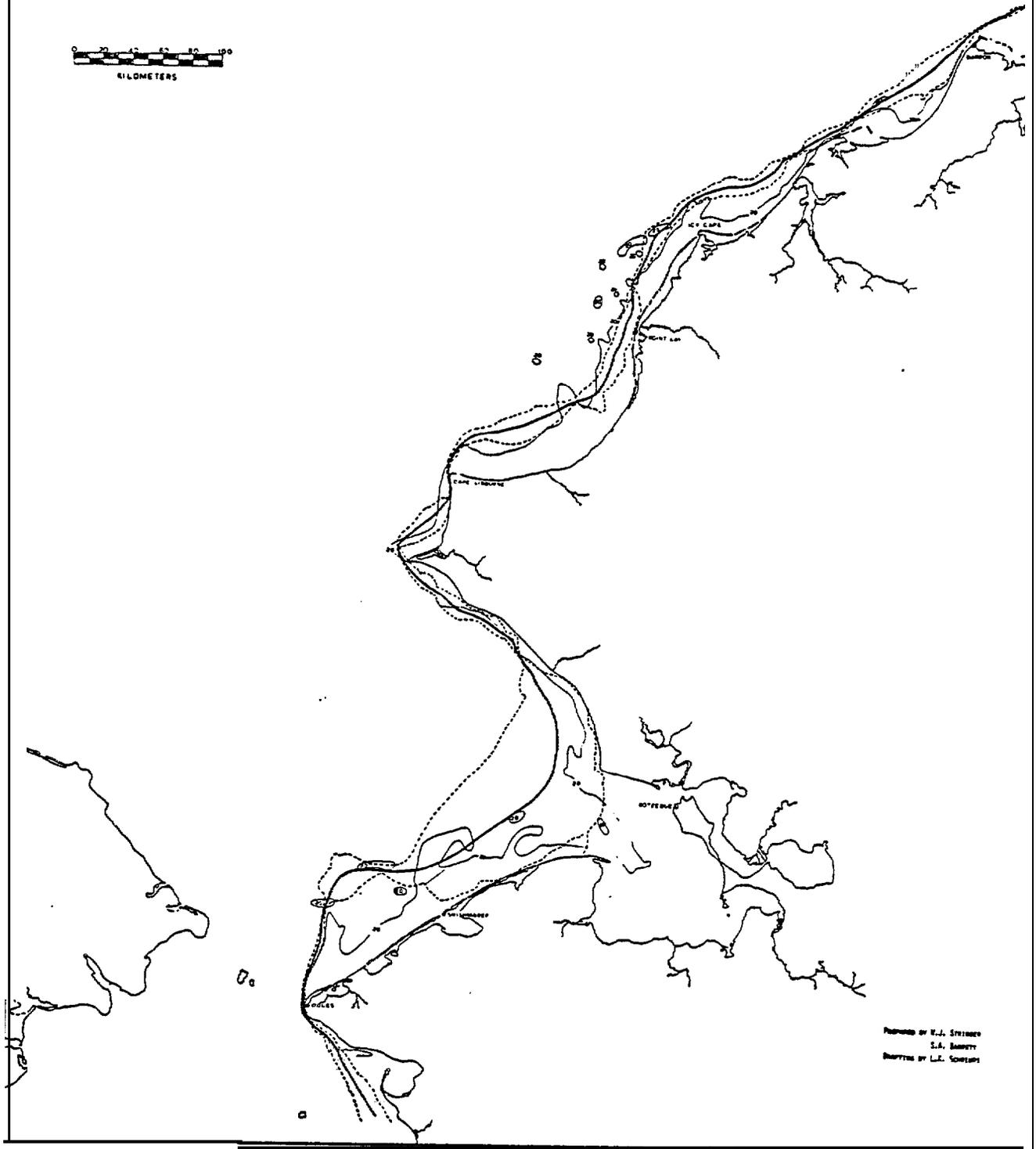
- 31 May - 17 June 73
- - 28 May - 12 June 74
- · · 13-30 June 74
- 30 May - 16 June 75



Prepared by R.J. STINECK
S.A. BARNETT
Revised by L.E. SCOTT

CHUKCHI SEA
AVERAGE SEASONAL MID-SPRING EDGE OF CONTIGUOUS ICE
1973.76

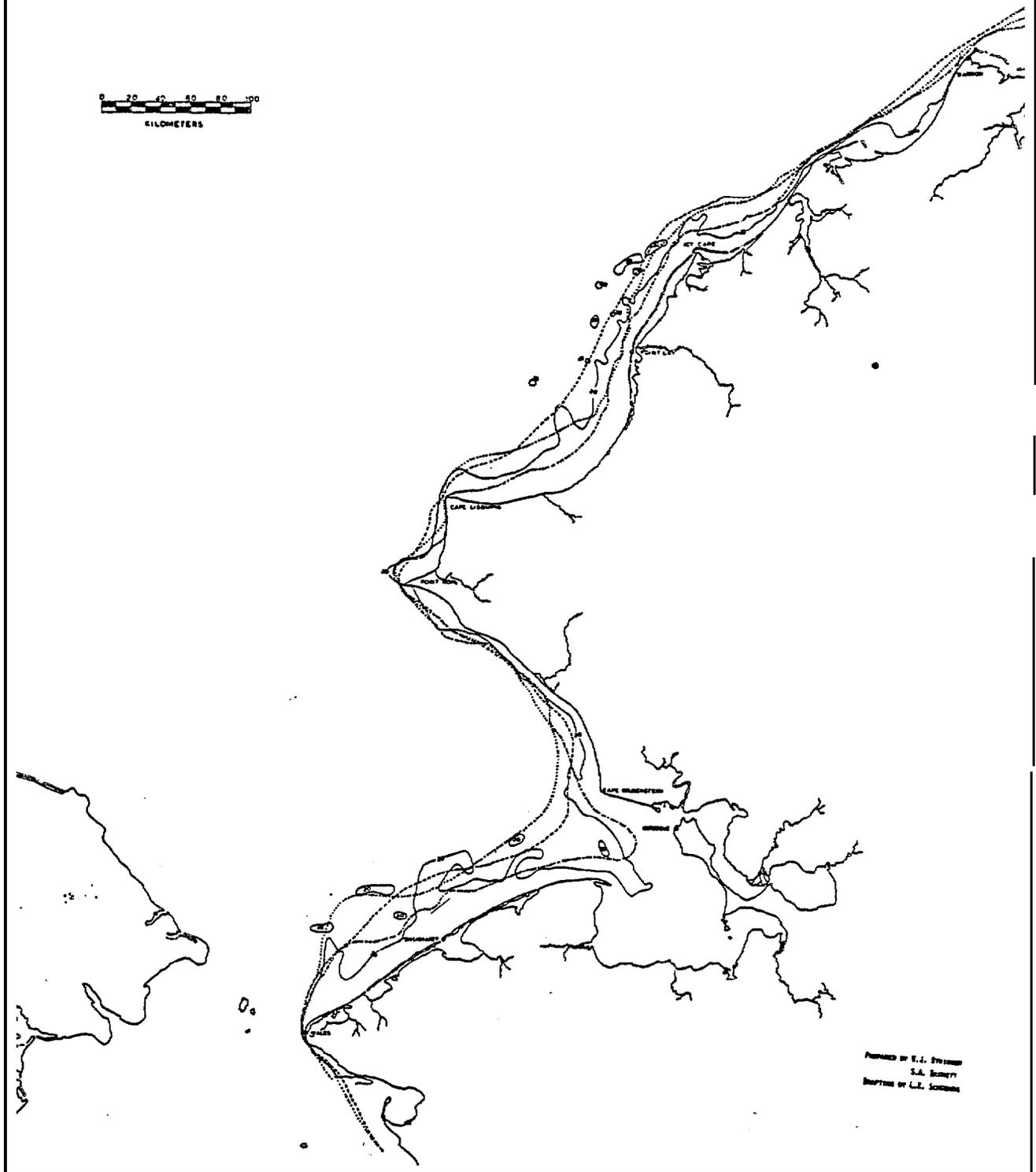
— Average Edge
- - - Maximum Deviation



Prepared by V.J. Stricker
S.A. Sawyer
Checked by L.E. Sawyer

CHUKCHI SEA
MIGRATION OF AVERAGE SEASONAL EDGE OF CONTIGUOUS ICE

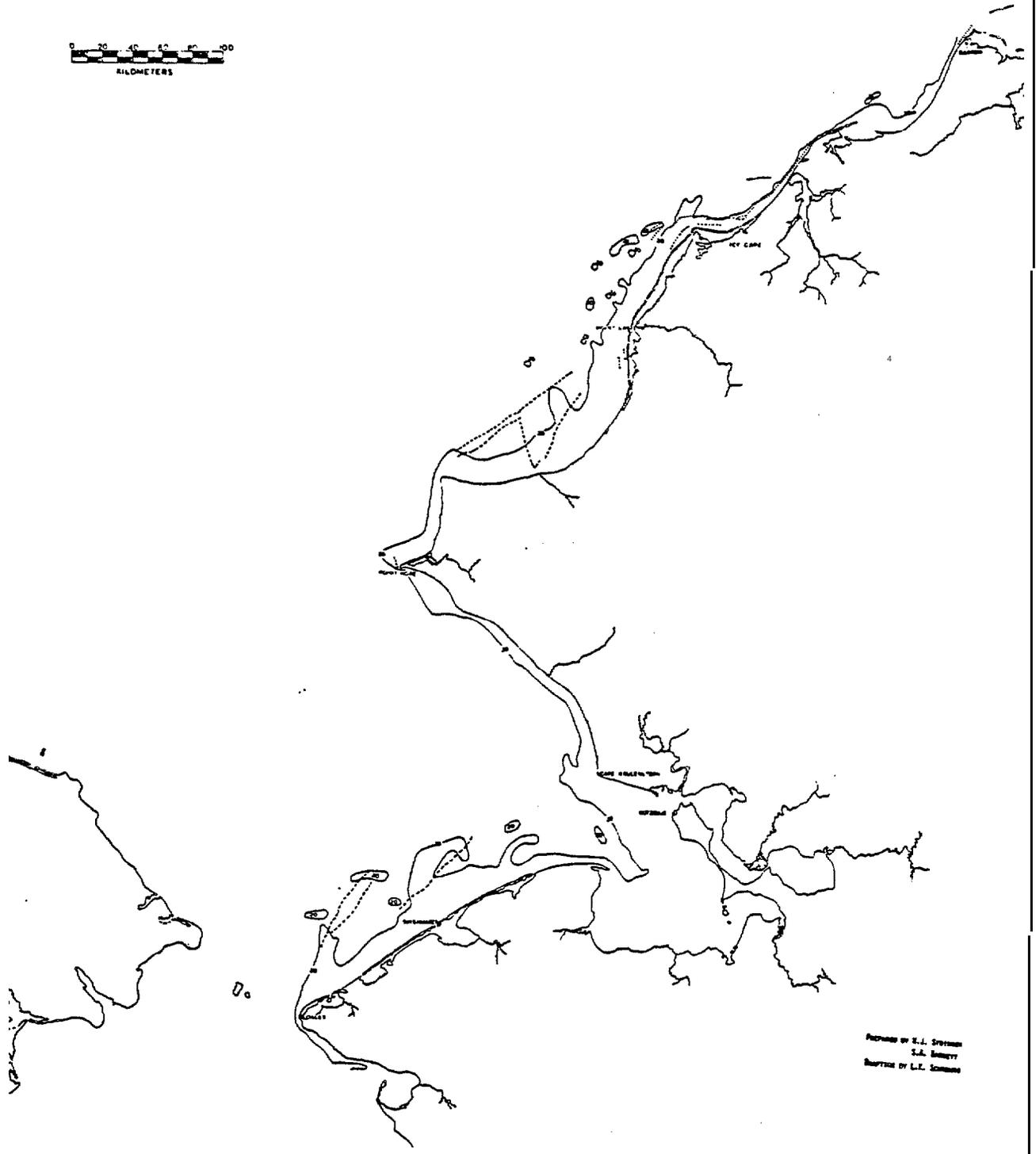
----- Late Winter
----- Mid Spring
- - - - - Late Spring - Early Summer
1973 - 1076



Prepared by R.J. Orvino
S.A. Bennett
Bureau of U.S. Science

CHUKCHI SEA
1974 ICE RIDGE SYSTEM S

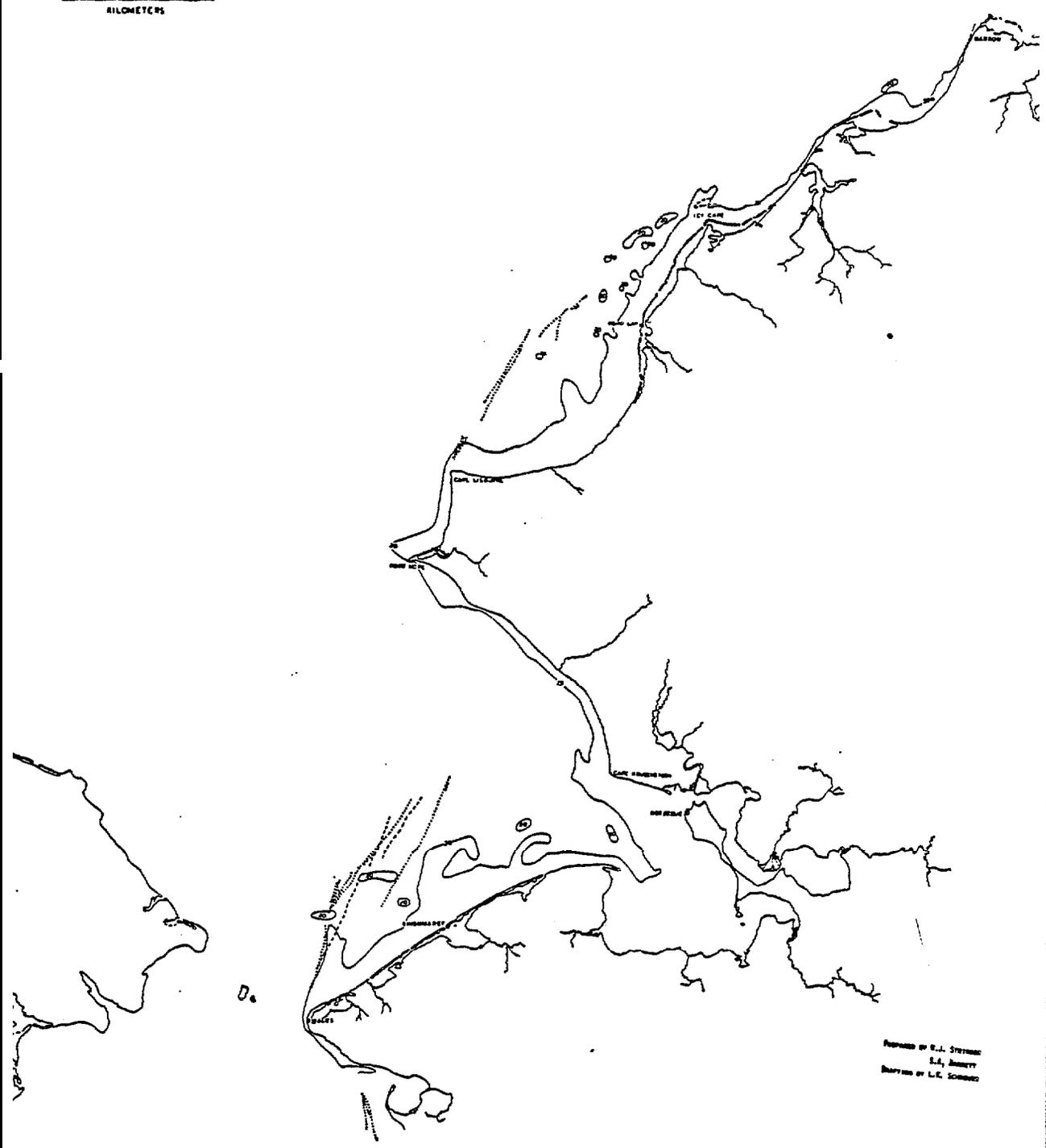
- 25 February-14 March
- 2-19 April
- 26 May-12 June
- 13-20 June



RESEARCH BY U.S. STEAMER
S.S. ELBERT
MAPS BY L.E. SCHMIDT

CHUKCHI SEA
1976 ICE RIDGE SYSTEMS .

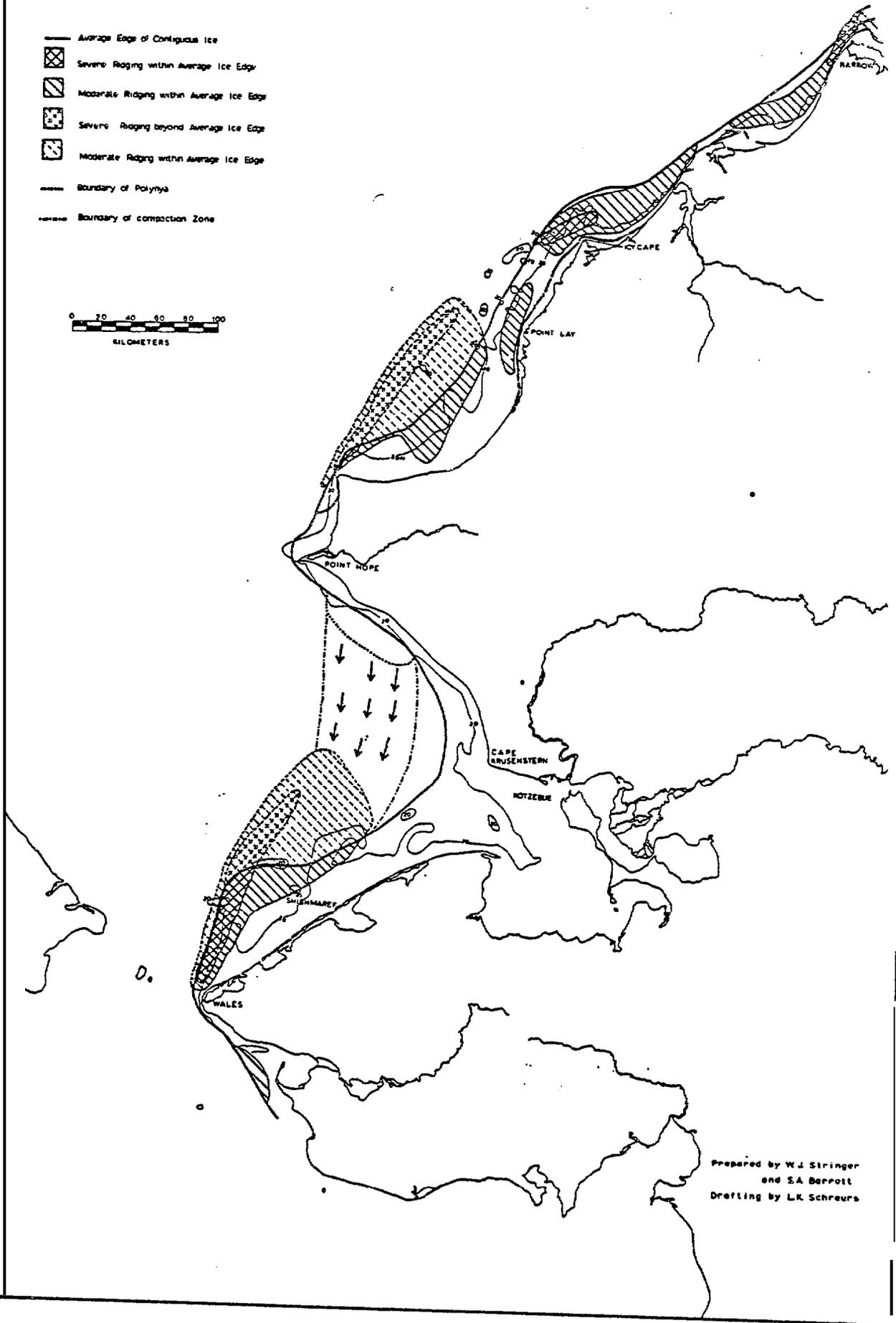
----- 6-23 February
----- 14-31 March



Prepared by R.L. STEVENSON
S.L. JENSEN
Surveyed by L.K. SCHMIDT

CHUKCHI SEA
SEA ICE MORPHOLOGY
MID WINTER

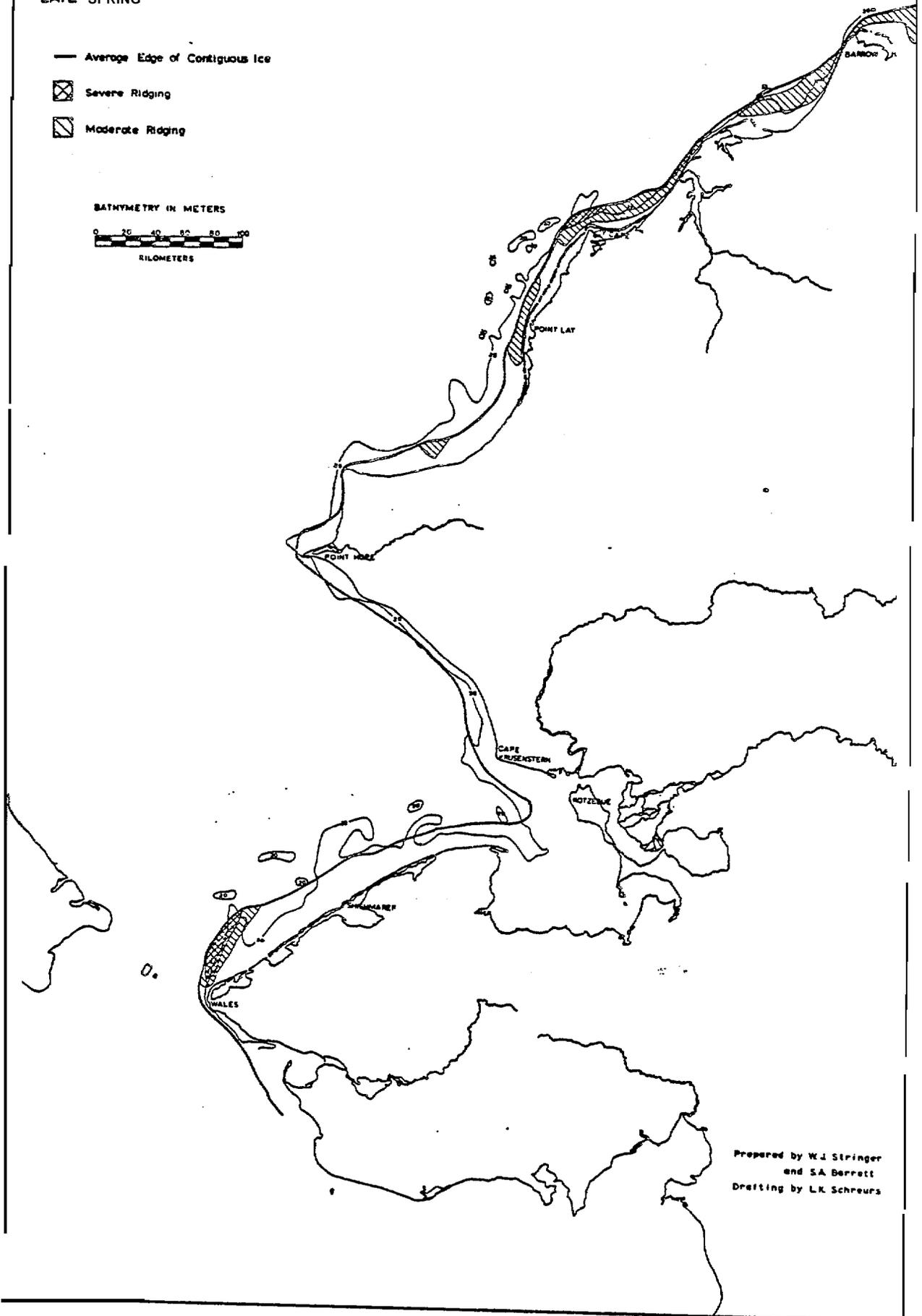
- Average Edge of Contiguous Ice
- ▣ Severe Ridging within Average Ice Edge
- ▤ Moderate Ridging within Average Ice Edge
- ▥ Severe Ridging beyond Average Ice Edge
- ▦ Moderate Ridging within Average Ice Edge
- Boundary of Polynya
- Boundary of compaction Zone



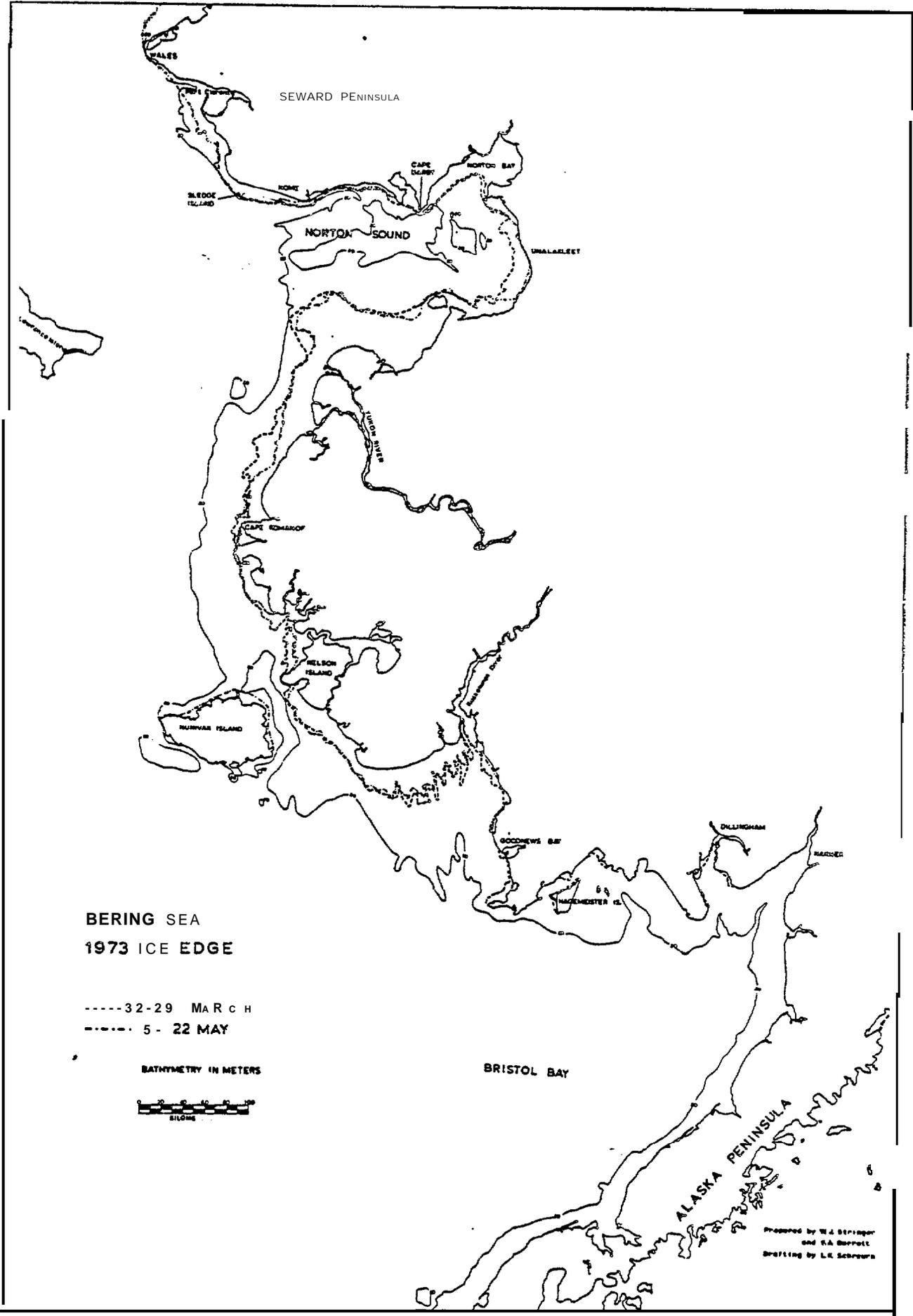
Prepared by W.J. Stringer
and S.A. Barrett
Drafting by L.K. Schreurs

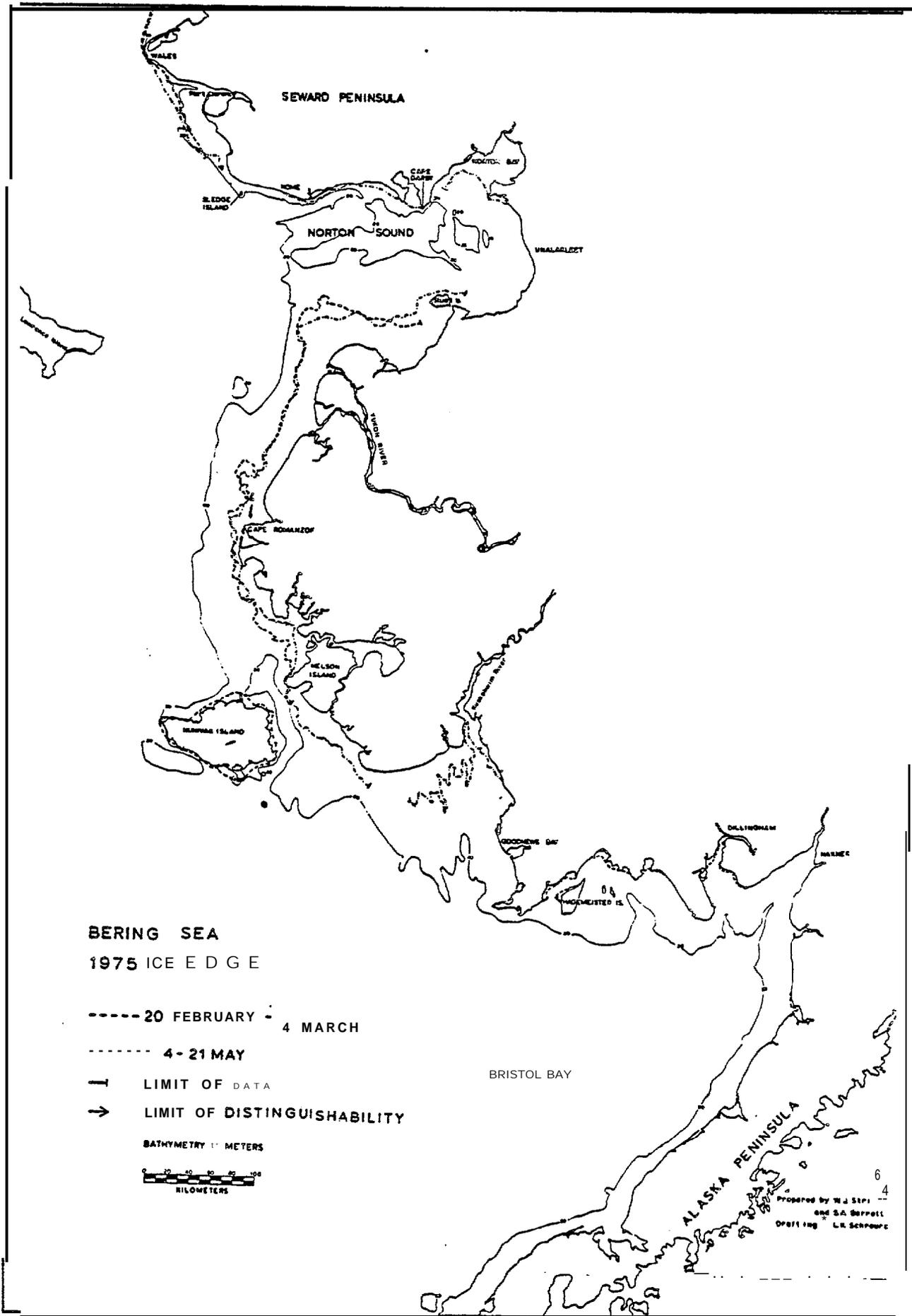
CHUKCHI SEA
SEA ICE MORPHOLOGY
LATE SPRING

- Average Edge of Contiguous Ice
- ▨ Severe Ridging
- ▧ Moderate Ridging



Prepared by W.J. Stringer
and S.A. Barrett
Drafting by L.K. Schreurs





**BERING SEA
1975 ICE EDGE**

----- 20 FEBRUARY - 4 MARCH

..... 4 - 21 MAY

— LIMIT OF DATA

→ LIMIT OF DISTINGUISHABILITY

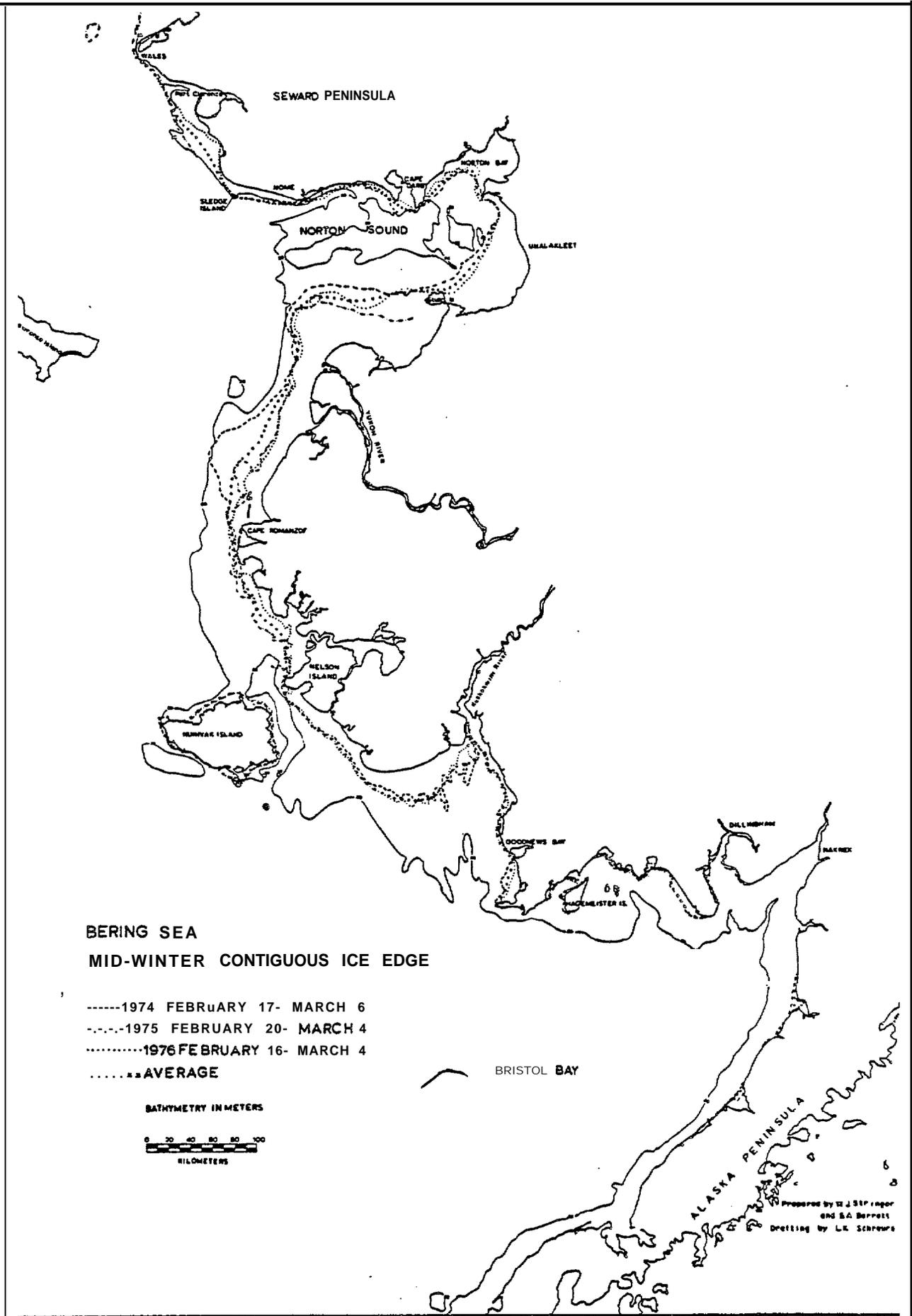
BATHYMETRY 1' METERS



BRISTOL BAY

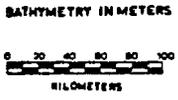
ALASKA PENINSULA

Prepared by W.J. Stepi
and S.A. Barnett
Drafting L.R. Schreier

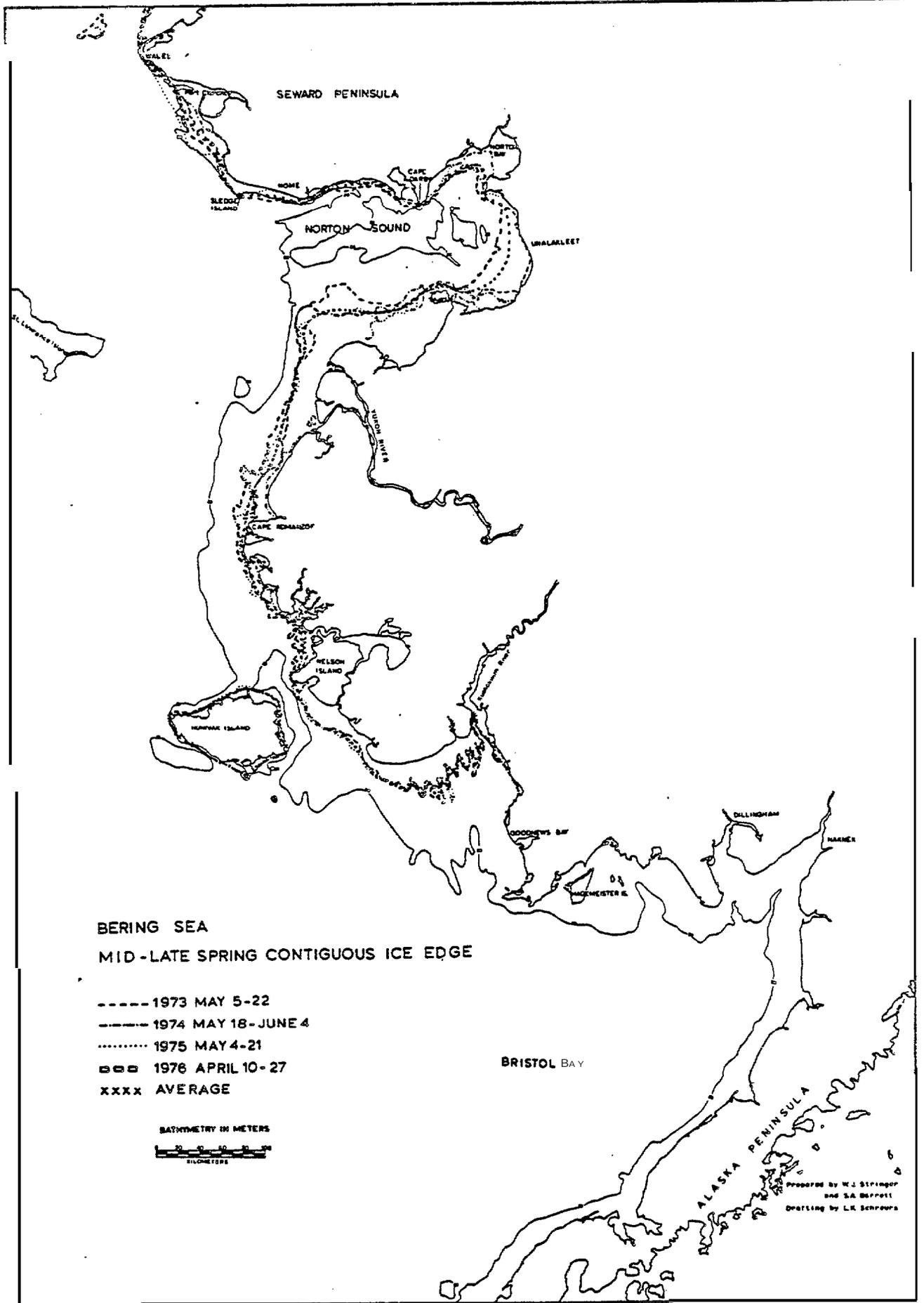


**BERING SEA
MID-WINTER CONTIGUOUS ICE EDGE**

- 1974 FEBRUARY 17- MARCH 6
- - - - -1975 FEBRUARY 20- MARCH 4
-1976 FEBRUARY 16- MARCH 4
-AVERAGE



Prepared by W.J. Sizer
and S.A. Bennett
Drafting by L.K. Schreurs



SEWARD PENINSULA

NORTON SOUND

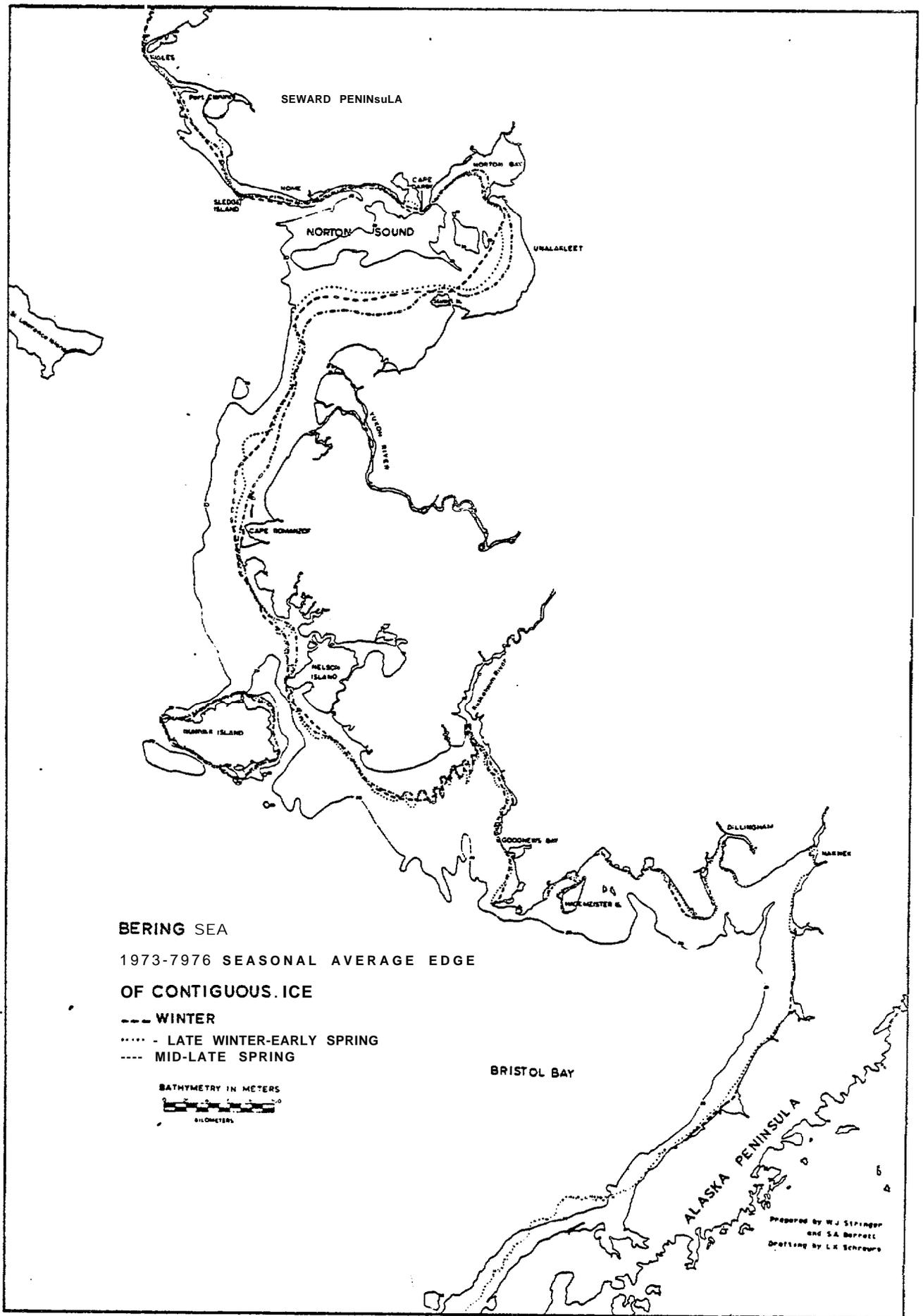
BERING SEA

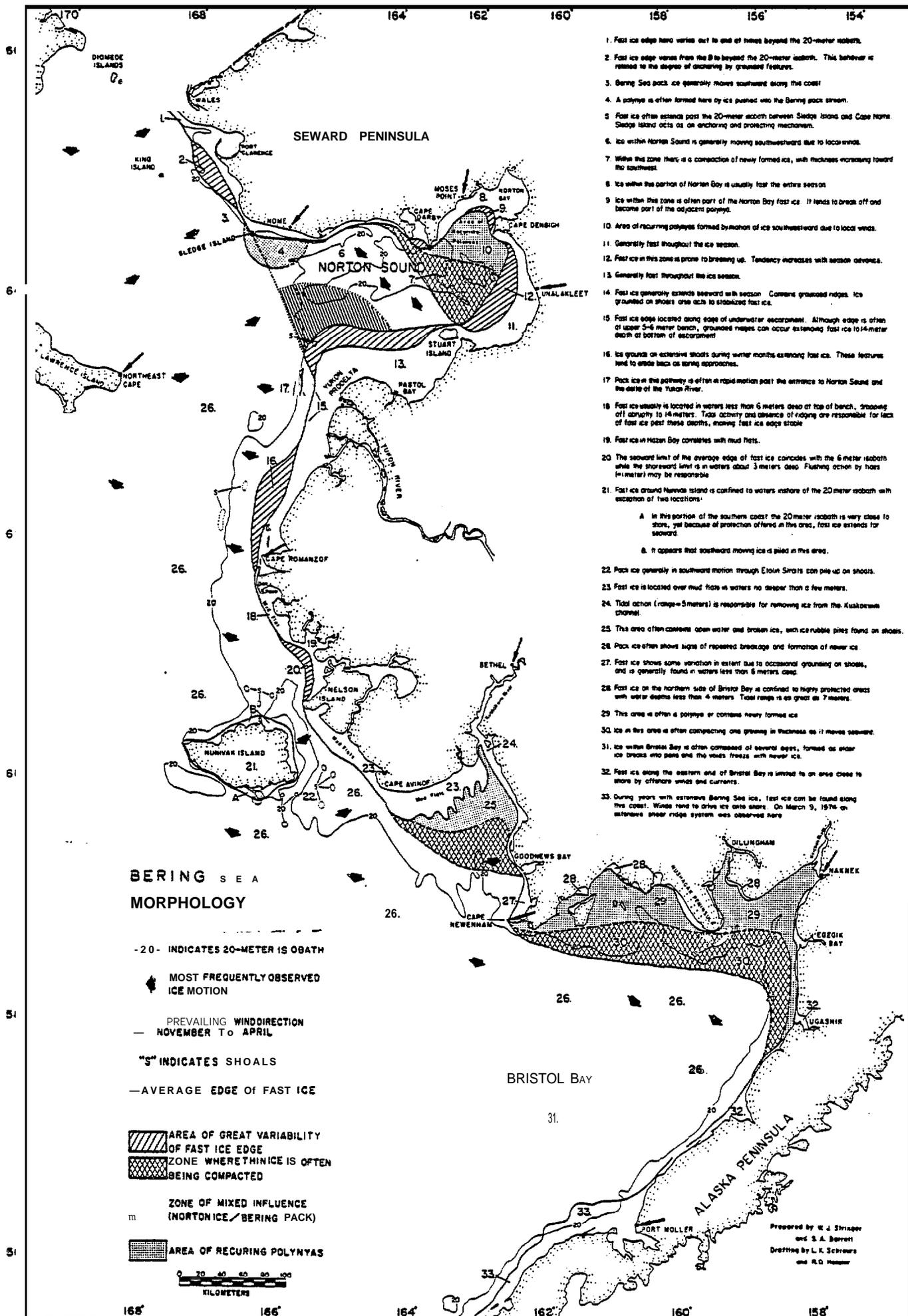
MID-LATE SPRING CONTIGUOUS ICE EDGE

- 1973 MAY 5-22
- - - - - 1974 MAY 18-JUNE 4
- 1975 MAY 4-21
- 1976 APRIL 10-27
- XXXX AVERAGE



Prepared by W.J. Stringer
and S.A. Bennett
Drafting by L.K. Schreurs





1. Fast ice edge here varies out to end of lines beyond the 20-meter isobath.
2. Fast ice edge varies from the 8 to beyond the 20-meter isobath. This behavior is related to the degree of anchoring by grounded features.
3. Bering Sea pack ice generally moves southwest along the coast.
4. A polynya is often formed here by ice pushed into the Bering pack stream.
5. Fast ice often extends past the 20-meter isobath between Sledge Island and Cape Nome. Sledge Island acts as an anchoring and protecting mechanism.
6. Ice within Norton Sound is generally moving southwestward due to local winds.
7. Within this zone there is a connection of newly formed ice, with thickness increasing toward the southwest.
8. Ice within this portion of Norton Bay is usually fast for the entire season.
9. Ice within this zone is often part of the Norton Bay fast ice. It tends to break off and become part of the adjacent polynya.
10. Area of recurring polynyas formed by motion of ice southwestward due to local winds.
11. Generally fast throughout the ice season.
12. Fast ice in this zone is prone to breaking up. Tendency increases with season advances.
13. Generally fast throughout the ice season.
14. Fast ice generally extends seaward with season. Common grounded ridges. Ice grounded on shoals one acts to stabilize fast ice.
15. Fast ice edge located along edge of underwater escarpment. Although edge is often of lower 3-6 meter bench, grounded ridges can occur extending fast ice to 14-meter depth of bottom of escarpment.
16. Ice grounds on extensive shoals during warmer months extending fast ice. These features tend to erode back as spring approaches.
17. Pack ice in the gateway is often in rapid motion past the entrance to Norton Sound and the delta of the Tuzon River.
18. Fast ice usually is located in waters less than 6 meters deep of top of bench, breaking off abruptly to 14 meters. Tidal current and absence of ridging are responsible for lack of fast ice past these depths, moving fast ice edge stable.
19. Fast ice in Hazan Bay commences with mud flats.
20. The seaward limit of the average edge of fast ice coincides with the 6 meter isobath while the shoreward limit is in waters about 3 meters deep. Flushing action by tides (1-meter) may be responsible.
21. Fast ice around Nunivak Island is confined to waters inshore of the 20 meter isobath with exception of two locations:
 - A. In this portion of the southern coast the 20 meter isobath is very close to shore, yet because of protection offered in this area, fast ice extends far seaward.
 - B. It appears that southwest moving ice is piled in this area.
22. Pack ice generally in southward motion through Elnor Straits can pile up on shoals.
23. Fast ice is located over mud flats in waters no deeper than a few meters.
24. Tidal action (range=5 meters) is responsible for removing ice from the Kuskoowak channel.
25. This area often contains open water and broken ice, with ice rubble piles found on shoals.
26. Pack ice often shows signs of repeated breakage and formation of newer ice.
27. Fast ice shows some variation in extent due to occasional grounding on shoals, and is generally found in waters less than 6 meters deep.
28. Fast ice on the northern side of Bristol Bay is confined to highly protected areas with water depths less than 4 meters. Total range is as great as 7 meters.
29. This area is often a polynya or contains newly formed ice.
30. Ice in this area is often compacting and growing in thickness as it moves seaward.
31. Ice within Bristol Bay is often composed of several ages, formed as older ice breaks into pans and the waters freeze with newer ice.
32. Fast ice along the eastern end of Bristol Bay is limited to an area close to shore by offshore winds and currents.
33. During years with extensive Bering Sea ice, fast ice can be found along the coast. Winds tend to drive ice onto shore. On March 9, 1974 an extensive shear ridge system was observed here.

**BERING SEA
MORPHOLOGY**

-20- INDICATES 20-METER ISOBATH

▲ MOST FREQUENTLY OBSERVED ICE MOTION

— PREVAILING WIND DIRECTION NOVEMBER TO APRIL

"S" INDICATES SHOALS

— AVERAGE EDGE OF FAST ICE

▨ AREA OF GREAT VARIABILITY OF FAST ICE EDGE

▩ ZONE WHERE THIN ICE IS OFTEN BEING COMPACTED

m ZONE OF MIXED INFLUENCE (NORTON ICE / BERING PACK)

▧ AREA OF RECURRING POLYNYAS



Prepared by W. J. Straper and S. A. Barrett
Drafting by L. K. Schroeder and R. D. Hester