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NEARSHORE ICE CHARACTERISTICS IN THE EASTERN BERING SEA

by

William J. Stringer

Geophysical Institute
University of Alaska
Fairbanks, Alaska

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William J. Stringer
Assistant Professor
of Applied Science

Juan G. Roederer
Director
Geophysical Institute

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Geophysical Institute
Fairbanks, Alaska

ABSTRACT

A description of Bering Sea nearshore Ice conditions is presented based on compilation of fast ice edge satellite data, and observations of specific ice events and results from other studies. Landsat imagery at 1:500,000 scale was used to map Bering Sea ice conditions between 1973 and 1976 In nearshore areas. From these maps, secondary single attribute maps were compiled, giving the edge of fast ice at various epochs during these four years. Maps were then compiled on a seasonal basis representative of 1) midwinter, 2) late winter - early spring, and 3) mid-to-late spring. The seasonal average maps were then compared to determine seasonal trends in fast ice edge location.

This information was analyzed together with imagery showing specific ice events and bathymetric charts, wind data, tidal variations and observed ice trajectories. The result is a regional description of average nearshore ice conditions along the Bering Sea coast from Cape Prince of Wales to Cold Bay on the Alaskan Peninsula. Over this distance a north-south transition is found from fast ice conditions similar to those in the Beaufort and Chukchi Seas (fast ice bounded by grounded ridge systems located at 20 meters depth), to conditions generated by large tidal variations, offshore winds and highly mobile ice, with the result that fast ice is found only in highly protected, shallow waters.

1. BACKGROUND

Any discussion of oceanic ice in the nearshore area necessarily centers on "fast ice," ice fixed with respect to shore. Although fast ice is found along almost all ice-bound coasts, its characteristics vary from one location to another. This variation depends on many factors including the local bathymetry, internal stresses in the adjacent ice pack, local surface winds, tides, and currents. Usually the fast ice is composed largely of annual ice, with perhaps occasional interfused pieces of multiyear ice. In Alaskan waters, annual ice seldom grows to a thickness of more than two meters. Because of the low buoyancy of ice, most of the vertical extent of fast ice is located below sea level. Obviously then, at water depths less than two meters, the fast ice is actually bottom-fast after it grows sufficiently in thickness.

Changes in sea level, either resulting from tides or weather patterns create a "hinge" between the floating fast ice and the bottom-fast ice. The hinge usually takes the form of a crack between the two ice types. As the winter progresses and the ice grows in thickness, the active tidal crack will generally move seaward, leaving old cracks to the shoreward often bridged by blowing snow. In areas where tidal variations are low, the pattern of these tidal cracks can be fairly simple. At locations with large tidal variations, as found in the Bering Sea, there will be a tidal crack zone with the currently active tidal cracks determined largely by the instantaneous tide state as well as ice thickness.

This pattern is superimposed on the ice state created during freeze-up in the nearshore area. While it is possible for the ice to simply freeze in place, growing thicker with time, this is often not the case. In reality a wide variety of ice conditions can be found, depending on the history of ice dynamics in that particular freeze-up season. The original ice sheet, for instance, may freeze to a thickness of 30 centimeters followed by a storm that withdraws the ice from shore, breaks most of it up into small (1 meter) plates, and then drives it into shore again. The plates might then freeze together in an extensive rubble field and form the fast ice for that year.

Other initial condition? are possible. In 1973, an "ice push" event occurred at Kotzebue, Alaska, where a stable sheet of moderately thick (l-2 meter) fast ice was driven as much as 15 meters onto the beach just south of town, carrying with it a surplus landing barge used as a salmon cannery (Mr. Albert Francis, personal communication). Kovacs and Sodhi (1979) have documented a number of these events occurring in the Beaufort Sea region, as well as a related phenomena, ice piling events, where instead of an ice sheet being pushed across the beach and adjoining tundra, a large pile of broken ice is created at or near the beach.

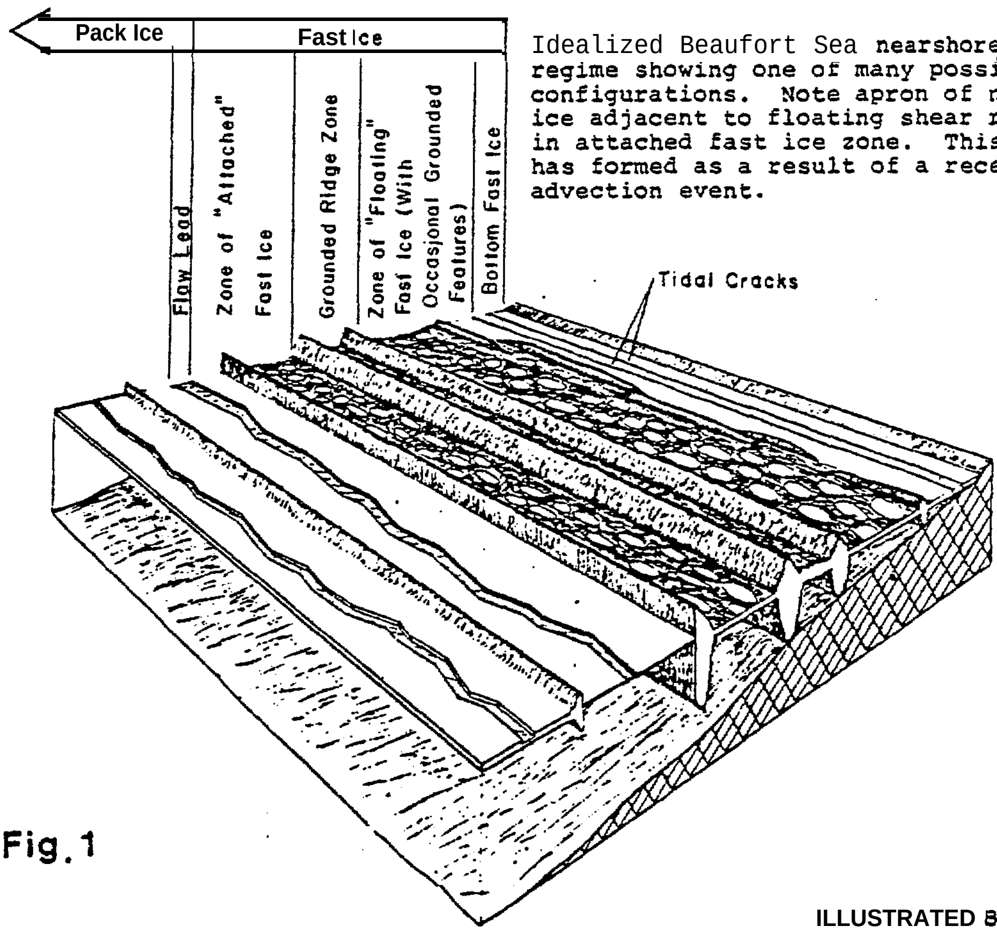
Offshore, the floating fast ice is often anchored by pressure and shear ridges with sufficient keel depth to be grounded on the ocean floor. Generally, few large grounded ridges are found in shallow water (up to 12 meters) and ridges are seldom sufficiently thick to be grounded in water deeper than 20 meters. While a great deal of work has been done determining these limits in the Beaufort Sea (Reimnitz and Barnes 1973; Kovacs and Mellor 1974; Kovacs 1976; and Stringer . 1978), a relatively small amount of work has been done in the Bering (Stringer 1978; Ray and Dupre 1980; Dupre 1980).

Floating fast ice is not always bounded by a zone of grounded ridges (sometimes called stamukhi, see Reimnitz and Barnes 1976). Whether or not a grounded ridge zone exists, fast ice can extend seaward up to 100 kilometers or more (Stringer 1974). If the grounded ridge zone is present, it tends to protect the enclosed fast ice from deformation resulting from pack ice forces, although deformations may still take place within this protected zone.

The grounded ridge (or stamukhi) zone, is an important feature because it often determines the boundary between fast ice and pack ice. The '.'flaw lead" is often found just seaward of the deepest grounded ridge. Large quantities of pack ice energy are expended in this zone that must be accounted for when modeling nearshore ice mechanics. With the increased attention given to offshore structures related to petroleum development, the grounded ridge zone has become important from the standpoint of physical hazards to man-made structures.

Beyond the grounded ridge zone, an apron of floating fast ice (Here called “attached ice in order to emphasize the absence of grounded features to the seaward) can often be found extending a distance from a few meters to many kilometers into the ocean. The stability of attached ice is quite tenuous and it can be easily converted” into pack ice by an ice-breaking event. Often in these nearshore areas, large ridges can be found parallel to shore but located in waters too deep to be grounded.

Figures 1 and 2 give some idea of the range of conditions that can be found. The situation depicted in figure 1 shows relatively undeformed bottom-fast ice along the beach with tidal cracks occurring near the two meter isobath. Offshore in water a few meters’”deep, occasional piles of pressured ice may in fact be grounded. These piles of ice often act as single point anchors and are generally created as weaker ice is pressured



Idealized Beaufort Sea nearshore ice regime showing one of many possible configurations. Note apron of new ice adjacent to floating shear ridge in attached fast ice zone. This ice has formed as a result of a recent advection event.

Fig. 1

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R.D. HENZLER

around stronger pans. This pattern extends out to the grounded ridges. The dimensions of the pans and piles around them, as well as the distance to the grounded ridges can vary widely. For instance, the pans could be 30 or 3,000 meters in diameter and the ice piles could be 1 or 10 meters above sea level. The distance to the grounded ridges could be from 1 to 30 kilometers offshore. Because of the necessary vertical exaggeration in these figures, the angle of repose of ice ridges shown appears *to* be much steeper than in reality. In addition, the thickness of unpressured ice is exaggerated in the vertical plane, giving a false impression of the geometry involved.

Beyond the grounded ridges, the attached 'ice is depicted as being relatively smooth but with some hummocking. Finally a large floating ridge is encountered which, if it were located further inshore would be grounded. As depicted here, this ridge was recently the edge of fast ice with active differential motion taking place along it. However, at some point, the ice opened and moved seaward, forming a large flaw lead. This flaw lead froze to a thickness of 10 or 20 centimeters arid then failed in tension, forming a new flaw lead. This narrow lead now defined the edge of fast ice. Beyond the lead, the ice can truly be classified as pack ice.

Figure 2 shows another common nearshore ice situation. Here, a rubble pile is found on the beach with the active tidal crack located beyond its base. Just offshore, ice is piled against the beach and grounded in a few places. In some years many such ice piles are found near the beach in exposed locations (Barrow, for instance). Ice of, this type makes activities involving transportation across the fast ice particularly difficult, Beyond the grounded ice, a second tidal crack might be found, followed by floating fast ice with occasional minor ridges which may be grounded if located in relatively shallow water. Farther offshore, smooth pans separated by hummocked ice are found, Finally, near the 14-meter isobath, the grounded ridge zone is encountered. As depicted here, the pack ice in the past has been driven along the outside edge of the outermost grounded ridge, creating a shear ridge similar *to* the floating ridge in the attached ice zone of figure 1. In the present case, however, the attached ice has not recently

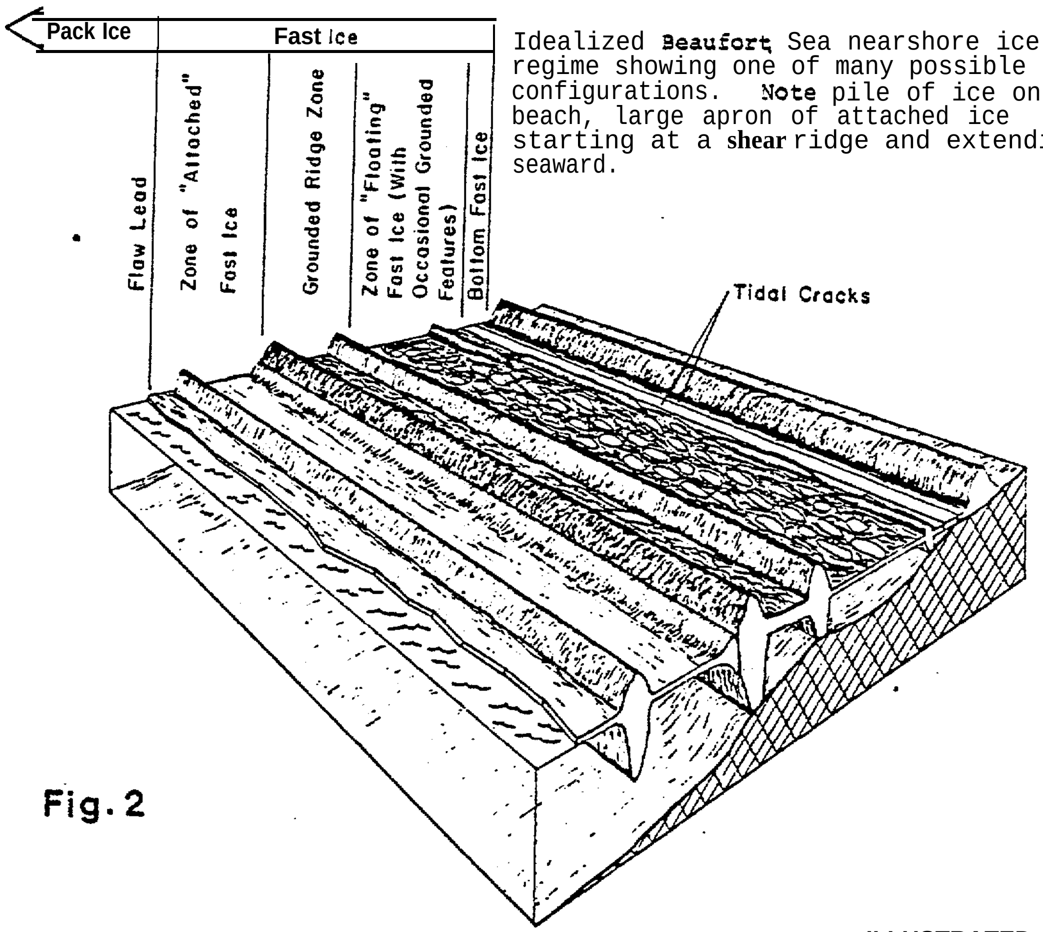

Fig. 2

Idealized Beaufort Sea nearshore ice regime showing one of many possible configurations. Note pile of ice on beach, large apron of attached ice starting at a shear ridge and extending seaward.

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withdrawn but has remained adjacent to the grounded ridges, creating a zone of thin ice. The flaw lead is found offshore from a large floating ridge *in* the attached ice.

The pack ice begins at this point and extends seaward. Again, it should be emphasized that the vertical scale creates an inaccurate impression of horizontal dimensions: The distance between the grounded ridge zone and the large offshore ridge could be on the order of ten or twenty kilometers. However, observations by Landsat (Stringer 1978) and laser profilimeter (Tucker et al. 1980) show that these large shear ridges formed by differential motions of ice sheets are found generally in the nearshore area. Hence, their frequency diminishes with increasing distance from the grounded ridge zone.

2. FACTORS DETERMINING BERING SEA NEARSHORE ICE CONDITIONS

The description of nearshore ice conditions and behavior presented up to this point is largely based on observations in the Beaufort and Chukchi Seas and applies to some areas of the Bering Sea. However, two factors influence ice behavior in some areas of the Bering Sea that are almost totally absent in the Beaufort: tides and ice advection. While the Beaufort coast experiences tides with a variation of only a few decimeters, tides at many locations on the Bering coast range over several meters. Also, while Beaufort Sea ice is almost always packed in against the coast, in many locations along the Bering coast the ice is almost continually being pushed away from shore by winds and currents (Stringer 1978; McNutt 1979; Pease 1980, Ray and Dupre 1980).

Figure 3 shows an ice profile more typical of fast ice in the Bering Sea than figures 1 and 2. A grounded ridge is shown some distance from shore, but certainly closer to shore than the 20-meter isobath. In order to be even semi-permanent, this ridge must be sufficiently grounded to withstand the bouyant forces during high tides, and have a geometry

Idealized Bering Sea nearshore ice regime showing effect of large tidal variations on fast ice. As depicted here, low tide has caused the fracturing of floating fast ice . and the breakup of attached fast ice. This effect tends to limit the extent and stability of Bering Sea fast ice.

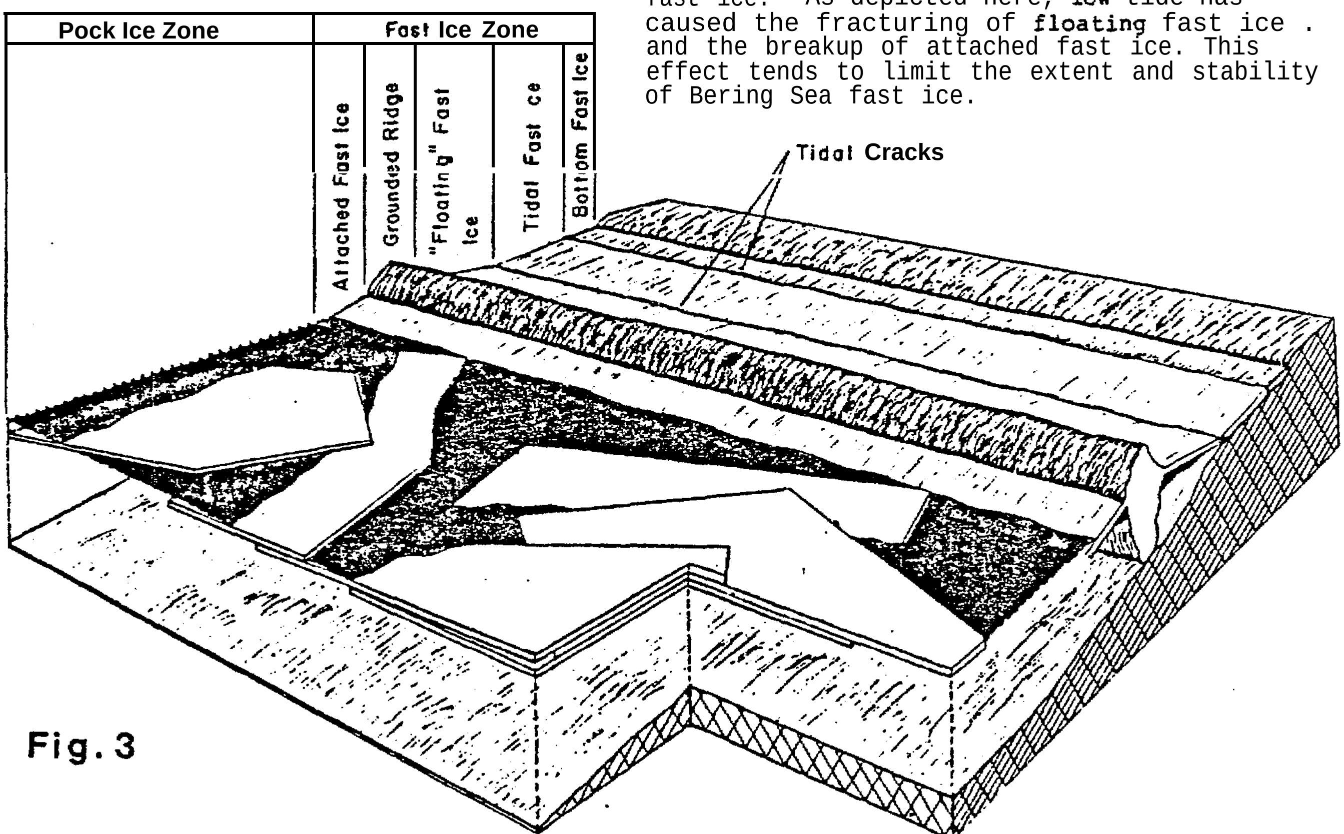


Fig. 3

ILLUSTRATED BY R. D. HENZLER

so that tidal fluctuations do not cause disintegration. Obviously, grounded ridges cannot present a continuous dam against the large forces created during tidal variations. Hence, breaks and other disruptions of these ridges are common.

Inshore from the grounded ridges, floating and bottom-fast ice are found. The extent of both of these ice types depends greatly on the tide state, since the Bering coast has extensive mud flats covered by very shallow water. Several active and inactive tidal cracks can be found. Because of lateral motions caused by tidal currents and disruptions of the grounded ridges by tidal fluctuations, fast ice in the Bering Sea is not nearly as stable as fast ice in other areas with little tidal variation.

Attached ice can occasionally be found beyond the grounded ridge system, but because of tidal variations, the flaw lead is most often found just seaward of the grounded ridges. Again, as in figures 1 and 2, the necessary vertical exaggeration should be considered when viewing this schematic drawing.

Advective export of Bering Sea nearshore ice also contributes to fast ice limitation. There are many areas along the Bering coast where ice motion has a significant seaward component, and as a result, grounded ridges are seldom built in these locations. This contrasts sharply with Beaufort Sea nearshore ice where the pack ice is nearly always present along the fast ice boundary and is often driven along the fast ice with a shoreward component of force, thus creating the well known shear ridges often found in that area.

These two distinguishing influences, tidal fluctuations and ice advection, occur with varying degrees of impact along the Bering coast. At some locations both factors combine to severely limit the edge of fast ice to isobaths even less than 6 meters. At other locations, conditions similar to those found in the Beaufort Sea are found, with ice ridges grounded along the 20-meter isobath.

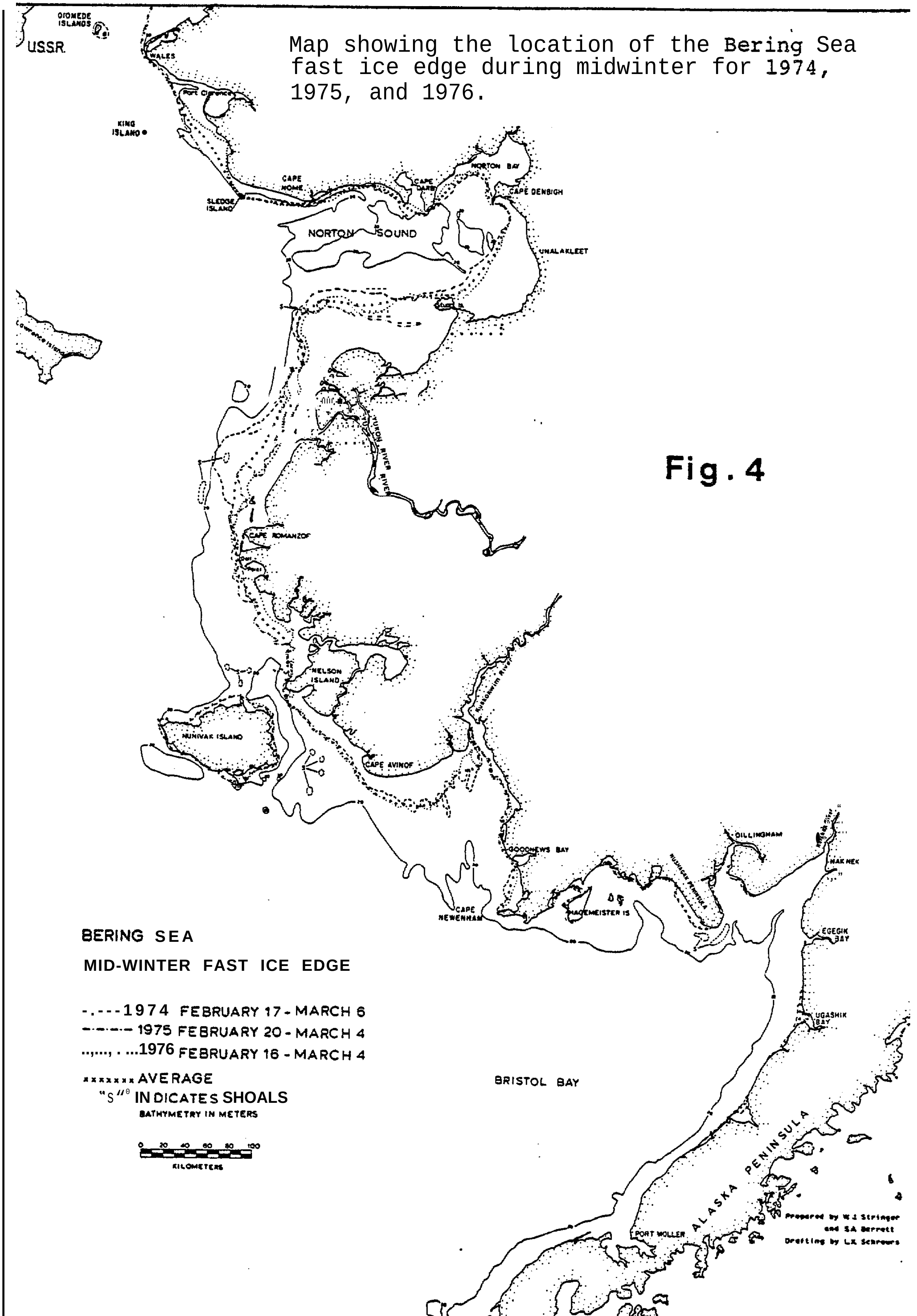
3. THE LOCATION OF BERING SEA FAST ICE

In order to identify ice characteristics on a site-specific basis, maps of nearshore ice conditions were prepared from Landsat imagery at 1:500,000 scale showing the location of fast ice, pack ice, leads, ridges, hummock fields , and other identifiable features as well as shoreline and bathymetry. The techniques involved in preparation of these maps have been described elsewhere (Stringer 1979) and will not be elaborated here.

The individual maps of Landsat scenes, each covering an area of approximately 160 km x 160 km (100 x 100 nautical miles) were reduced to 1:1,000,000 scale and combined to produce composite single attribute maps of the Bering Sea nearshore area at specific instances. The most important sea ice characteristic for determining nearshore ice conditions was found to be the edge of fast ice. By dividing the ice season into three periods, a series of three maps was compiled showing the location of the edge of fast ice at specific instances over several years.

Figures 4,5, and 6 show fast ice edges monitored during the periods of mid-winter, late winter - early spring, and mid-to-late spring between 1973 and 1976. Shown along with these ice edges is the average ice edge. in order to reveal temporal changes of location of the average ice edge, these average edges were compiled onto one map (Fig. 7). Obviously, any significance placed *on* trends apparent *on* this map must be tempered by consideration of the variability exhibited by the ice edge data. At some locations, the edge of fast ice varies considerably in position during each period. Although the average edges in these locations show a temporal trend, it has only minor significance. In other locations, the variability of the fast ice edge for each period is small compared to the changes in the average position from period to period. Strong temporal trends with year-to-year dependability are indicated,

Finally, figure 8 was prepared showing the regional nearshore ice characteristics of the Bering Sea. This map was prepared on the basis of the considerations just described and by analysis of Landsat images for ice features such as ridges, hummock fields, etc., and smaller scale



Map showing the location of the Bering Sea fast ice edge during midwinter for 1974, 1975, and 1976.

Fig. 4

Map showing the location of Bering Sea fast ice edge during late winter-early spring for 1973 and 1974.

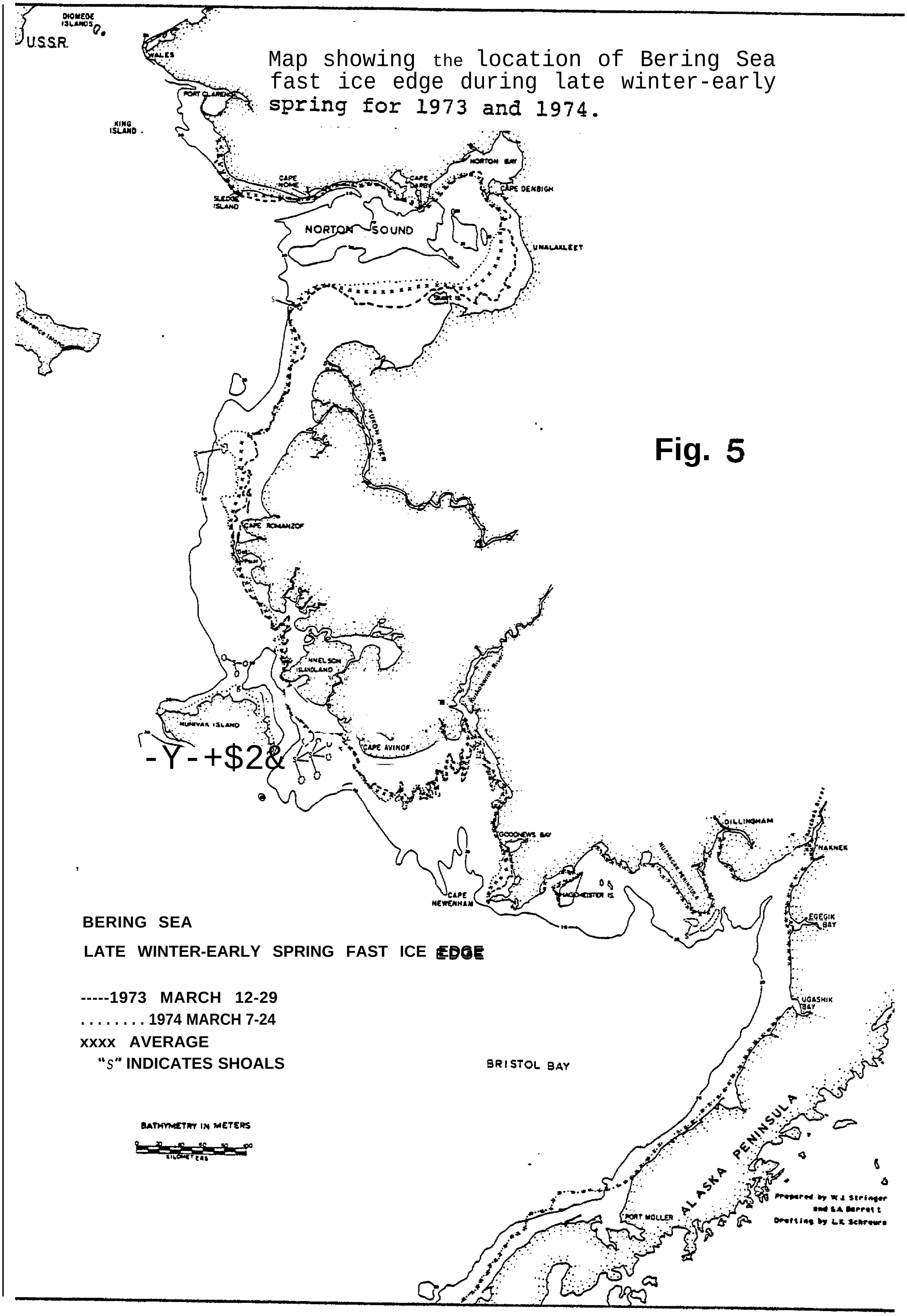


Fig. 5

Map showing the location of Bering Sea fast ice edge during mid-to-late spring for 1973, 1974, 1975, and 1976.

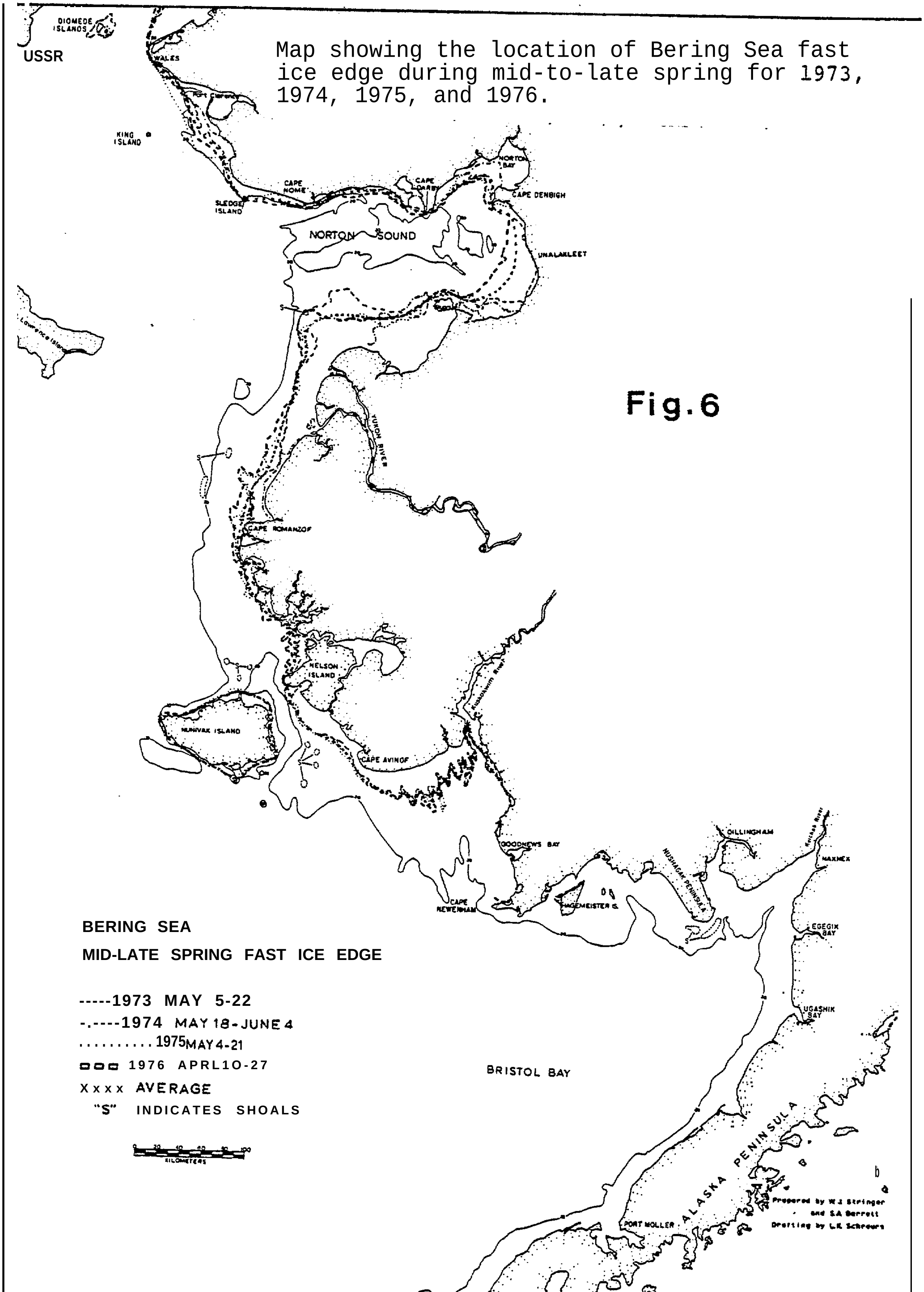
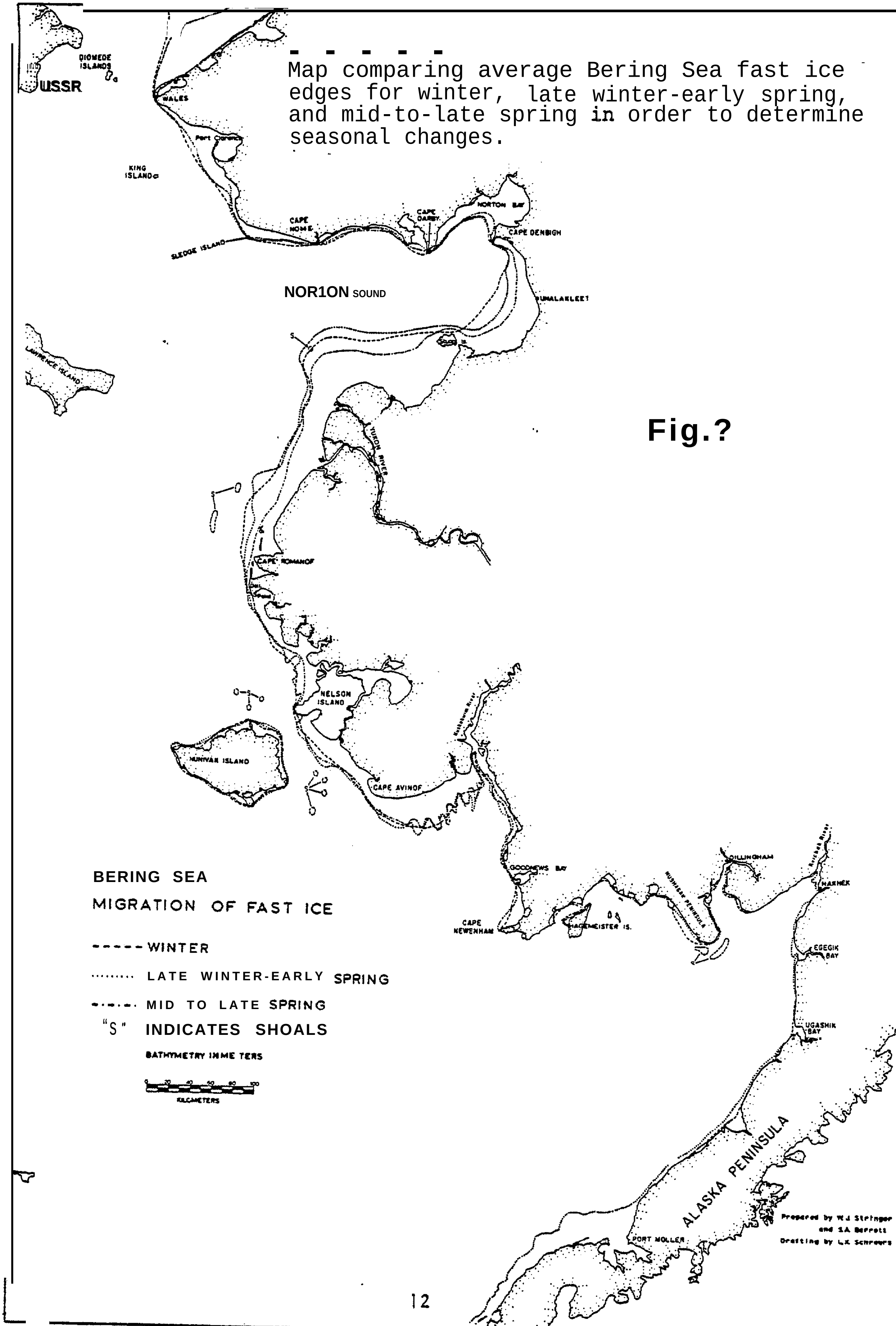


Fig.6

Map comparing average Bering Sea fast ice edges for winter, late winter-early spring, and mid-to-late spring in order to determine seasonal changes.

Fig.?



Map summarizing Bering Sea regional nearshore ice characteristics.

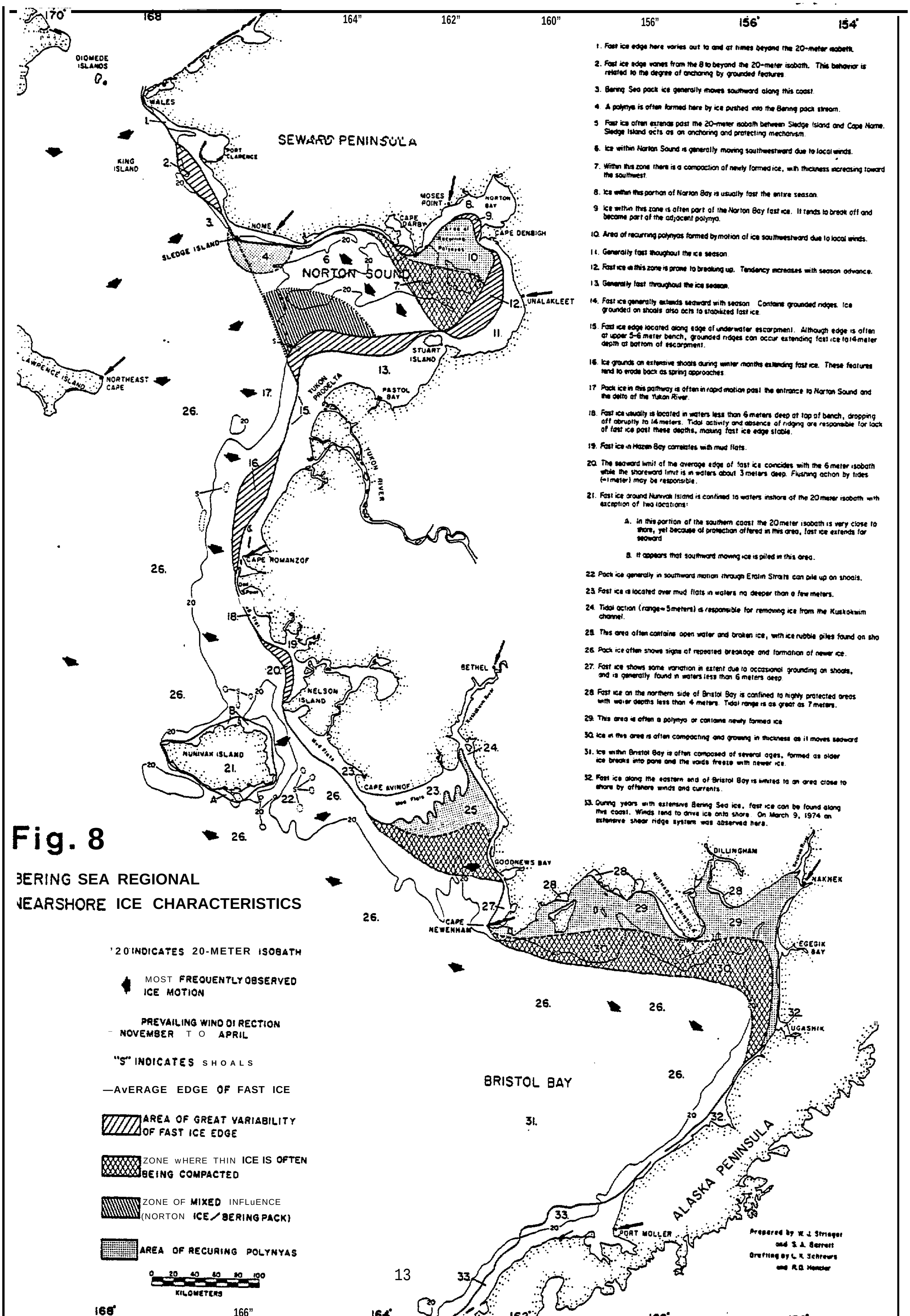


Fig. 8

BERING SEA REGIONAL NEARSHORE ICE CHARACTERISTICS satellite imagery for dynamic ice motions and other nearshore characterstics. The following section describes in more detail the nearshore ice descriptions of figure 8 (items 1-33).

4. CHARACTERISTICS OF BERING SEA NEARSHORE ICE

In the following sections the material presented in figure 8 is explained and expanded. In order to describe ice conditions along a segment of the coast, it is necessary to first describe the pack ice conditions just offshore. Thus, the-order of presentation here is a description of offshore ice behavior followed by a description of the adjacent coastal ice conditions.

Ice Motion Through Bering Strait

The Bering Strait, with the Diomede Islands in its center, represents a highly restricted ice passage between the Chukchi and Bering Seas. For some time, popular belief held that ice motion through the strait was generally from south to north in response to oceanic currents. This was supported by many ship-based springtime observations of broken pack ice passing northbound through the strait, often at speeds of several knots due to late season lows to the south causing southerly winds (Pease 1980). Shapiro and Burns (1975) and Ahlnas and Wendler (1979) have shown that occasional "breakout" events occur to the south when Chukchi Sea pack ice is extruded through the strait at fairly high velocities. These events have been examined in more detail by Pritchard et al (1979) and found *to* occur only during somewhat rare (two to three times annually) meteorological conditions which result in northerly winds across the ice in the strait, combined with a reversal of the usual south-to-north currents. During these events fairly large quantities of ice can pass through the strait, resulting in extensive grounded ice ridge systems on Prince of Wales Shoal just to the north of the Alaskan side of the strait (Stringer, 1978)". It would seem reasonable that during this process, relatively deep-draft first year ice features would be created and transported into the Bering Sea and perhaps into western Norton Sound, but not eastern Norton Sound (Ahlnas and Wendler 1979).

Nearshore Ice Conditions - Bering Strait to Yukon Delta

At Wales, the edge of fast ice closely follows the coast. This is largely due to the combined effect of deep waters (> 20 meters) adjacent to the coast and ice motions through Bering Strait. From Wales to the Port Clarence entrance, the edge of fast ice is generally inshore from the 20-meter isobath in all periods.

At the entrance to Port Clarence, the edge of fast ice usually bridges the narrow embayment of the 20-meter isobath into the port. However, a tongue of open water occasionally follows this indentation. Just south of the Port Clarence entrance lies a group of shoals as shallow as 4 meters. These often appear to be anchoring the fast ice, sometimes creating a seaward bulge extending as far as the 20-meter isobath. South from the Port Clarence shoals, the period edges of fast ice draw together and approach the 20-meter isobath from the coastal side.

At Sledge Island the 20-meter isobath makes an abrupt 80° turn to the east, entering Norton Sound. The period average edges of fast ice follow this isobath past Nome and on to Cape Nome. in this region the edge of fast ice exhibits considerable variability during at least two periods. Hence, the indication that the period averages agree should *not* mislead the reader to the conclusion that the edge of fast ice here is stable. In fact, it can occasionally be found well toward shore or beyond the 20-meter isobath. Extensive grounded ice piles were observed off Nome during the spring of 1973. These piles were located well inshore of the 20-meter isobath. At that time, attached fast ice extended considerably farther offshore to approximately the 20-meter isobath. Although ice is generally moving away from this coast, the presence of these ice piles is evidence that at times the ice can be driven against this shore.

Inside Norton Sound there is no correlation between the edge of fast ice and the 20-meter isobath. From Cape Nome to Cape Darby, the edge of fast ice follows the coast rather closely in waters around 16 meters deep. At Golovin Bay, just west of Cape Darby, the edge of fast ice shows considerable variability as it bridges the mouth of the bay.

At Cape Darby, the edge of fast ice follows the headland closely, making a 90° turn from a NW-SE trend to a NE-SW trend. The bathymetric configuration here is quite steep and the possibility of grounded features anchoring the ice decreases quite rapidly with distance from shore. From Cape Darby, the edge of fast ice is indented at the mouth of Norton Bay, nearly touching the headland at Cape Denbigh. This edge of fast ice follows more or less the 12-meter isobath, but as the mid-winter ice edge map (figure 4) shows, the edge of fast ice can exhibit some variability across Norton Bay.

From Cape Denbigh to Stuart Island the edge of fast ice characteristically bridges the southeastern end of Norton Sound, located as far as 50 kilometers from shore in waters very close to 20 meters deep. However, the bottom of Norton Sound is relatively flat and it is unlikely that depth is a controlling factor in fast ice edge location here. Figure 7 indicates a systematic trend of average ice edge location toward shore with time in this portion of Norton Sound. Analysis of the locational distribution in each period shows that this trend is reasonably valid. Furthermore, the variation of ice edge location from period to period for each year also shows this effect. However, the variation of the ice edge within each period is such that only the mid-winter average location of the fast ice edge can be relied upon with any confidence. The late spring ice edge, for instance, can vary from near the shore to nearly 30 kilometers seaward.

From Stuart Island, the fast ice edge follows a westerly course to a point south of Cape Nome, yet 50 to 60 kilometers offshore from the mouth of the Yukon River. At that point, it makes a broad turn to follow the coast to the south. The seaward extent of fast ice here appears to be determined 'largely by the location of the Yukon prodelta. The fast ice edges are all located in the vicinity of an underwater slope between two relatively flat plains at depths of 6 and 12 meters. Figure 7 shows that the average fast ice edge location here builds seaward from the mid-winter period to the late winter - early spring period, then erodes back even further than mid-winter during the mid-to-late spring period. This appears to be the result of ice piling on the prodelta slope. Although many major ridges can be seen on Landsat imagery of the Beaufort

Sea, only a few can be seen on Bering Sea images. This portion of the prodelta region is one of the locations where such major ridges have been observed. Furthermore, Thor arid Nelson (1980) report a high density of ice scour features in this area as a result of ridge keel motions.

A shoal is located at the very northwestern tip of the prodelta at a reported depth of 7 meters. Shertler (1978) has reported floebergs imaged on side-looking airborne radar and aerial photography. Examination of the data presented suggest that these are grounded rubble piles located on this shoal. Landsat imagery of this area from 1973 to the present indicates that it is likely that ice grounded on this shoal has acted to anchor fast ice in the prodelta region.

From the descriptions given above, it should not be assumed that fast ice around the perimeter is flat and featureless, We have already described an ice piling event observed off Nome in 1973. Echert (private communicate on, 1979) describes three rubble piles within the Norton Sound fast ice zone:

1. Approximately 2 miles east of Point Dexter, Norton Bay.
   Size: 100 x 33 x 8 meters   Water depth: 5 meters
2. Approximately 2 miles west of Stuart Island.
   Size: 150 x 67 x 8 meters   Water depth: 5 meters
3* Approximately 8 miles north of the Apoon (north-flowing) mouth of the Yukon River.
   Size: 230 x 100 x 5 meters   Water depth: est. 3 meters

These rubble piles were well within the fast ice zone and were probably formed during the initial freeze-up process.

Ice Behavior Within Norton Sound

Having described the location of the fast ice edge around Norton Sound, we can now discuss the behavior of ice within the sound. The central part of the Norton Sound basin is relatively flat, varying from 18 *to* 30 meters in depth. Nelson (1980) reports observing apparent ice keel gouges at water depths up to 22 meters. Hence, at least occasionally, deep-draft ice features may be found within this basin. However, there is also evidence that a significant part of Norton Sound is covered by relatively thin ice not likely to pile sufficiently to cause such great keel depths: a virtually constant feature of Norton Sound is a large polynya located in the northeastern sector. New ice is usually being formed here and transported westward by winds (see wind direction arrows on Fig. 8) toward the entrance to the sound. Long before it arrives there, considerable thickening takes place through compaction and normal thermal accretion. The polynya is created by almost constant north-northeasterly winds across the northern shore of eastern Norton Sound and nearly constant easterly winds across the western end of the sound (Brewer et al. 1977) as shown by the wind direction arrows on figure 8.

Figures 9 and 10 are Landsat images showing portions of Norton Sound, illustrating the range of ice conditions described above.

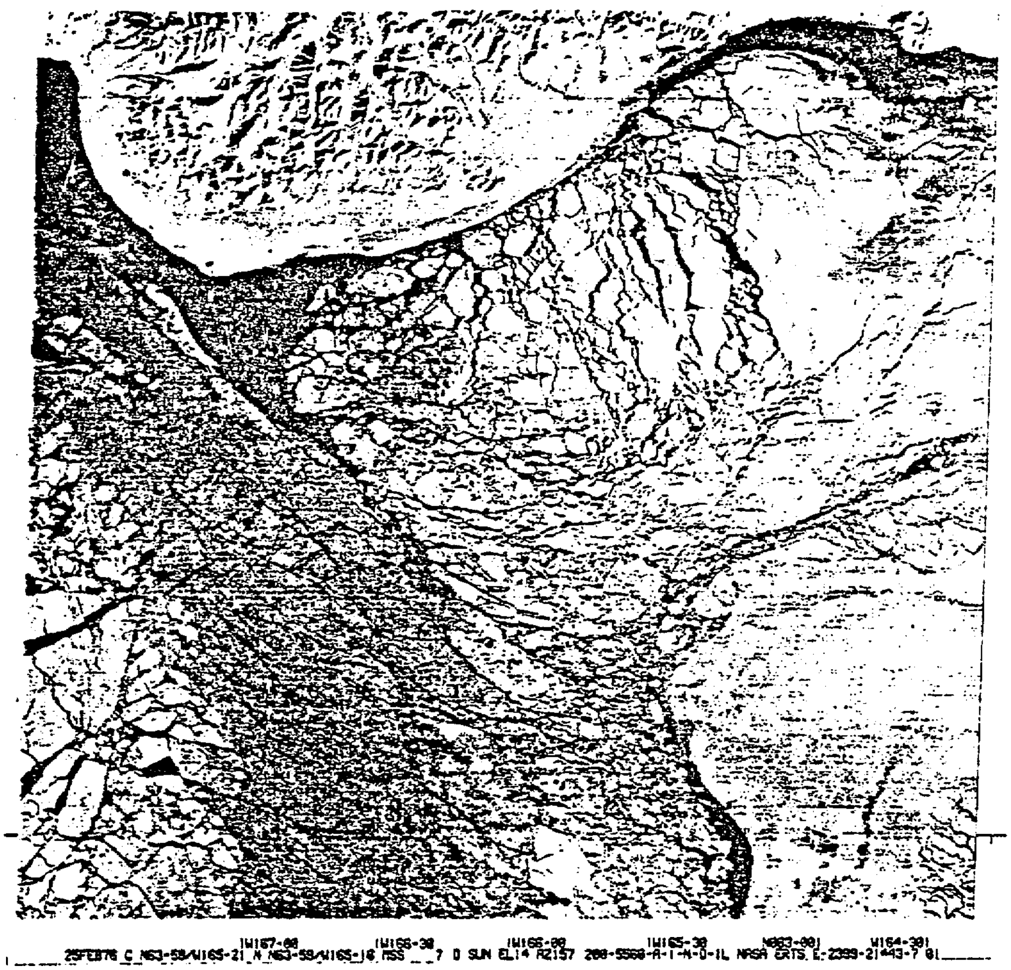


Fig.9

LANDSAT image obtained February 25, 1976 showing the entrance to Norton Sound.

Figure 9, scene number 2399-21443 obtained on 25 February 1976, shows the entrance to Norton Sound. The Sledge Island polynya can be seen left of center. The Yukon Delta can be seen in the lower right hand corner with extensive fast ice on the Yukon prodelta. Several different ages of ice are apparent on the image. The ice within the entrance to Norton Sound and far outside the entrance are both older than the band of younger ice extending down the Bering coast past the entrance to the sound. In the few days preceding this image, the Bering Sea pack moved offshore approximately 20 kilometers, allowing the band of newer ice to form. At the same time, older ice moved out of Norton Sound past the mouth of the Yukon and to the south. Hence, a band of large pans can be seen spilling out of Norton Sound to the south.

Figure 10, scene number 2397-21330, was obtained two days prior to the scene just described. This scene shows inner Norton Sound with

Fig.10

LAMSAT image obtained 'February 23, 1976 showing central portion and eastern end of Norton Sound. Note large polynya at eastern end of sound.

approximately 30% overlap with the area of the previous scene. Of interest here is the Norton Sound polynya which opened up during the recent ice-moving event and has since frozen over with new ice. Farther toward the entrance to the sound, young ice cat-i be seen which was moved out of the polynya area during the event. This ice was probably new ice at that time. This image illustrates the cyclic nature of the Norton Sound polynya. Also indicated on this image is the variability of the fast ice on the eastern side of the sound: a large chunk of attached fast ice has recently been detached and has subsequently been broken into pans. The voids between the pans then froze. A very recent ice-breaking event resulted in a series of fractures running through this region on a SW-NE trend.

Pack Ice Behavior Along the Western Alaskan Coast: Bering Strait to the Yukon Delta

Various authors (McNutt 1980, Nelsen et al 1980, and Pease 1980) have noted that Bering Sea pack ice is generally moving from north to south past the west coast of Alaska. Although the winds at Nome have a significantly easterly component, ice from the north of St. Lawrence island has been observed to pass around the eastern side of the island and proceed along the western edge of the Yukon prodelta. Two distinct regimes of ice motion are often observed in this vicintiy. Cox (private communication) has prepared maps based on satellite imagery showing the Bering Sea pack ice motion southward past the end of Norton Sound, and the motion of ice outbound from Norton Sound blending along a line of shear at the entrance to Norton Sound. A distinct line of demarcation can often be found running from north to south, dividing these two ice regimes. Ray and Dupre (1980) have also analyzed ice motions in this vicinity in detail and has concluded, "In general, the seasonal pack ice in Norton Sound is largely derived in situ, and tends to flow to the west and southwest in response to the prevailing winds or to flow sluggishly (eastward) in response to relatively weak oceanic currents during periods of relatively weak winds."

Along the western side of the Yukon prodelta is a region where the seasonal average ice edges are nearly coincident. Their location agrees well with the edge of the prodelta where water depths change abruptly from two to twelve meters. Occasionally grounded shear ridges have been observed along this zone, but their presence has not significantly increased the extent of fast ice. Although Bering Sea pack ice is often being driven into this region, the edge of fast ice has not been observed to build out to the 20-meter isobath as it does in the Beaufort Sea under somewhat similar conditions.

South of the Yukon delta to Cape Romanzof, the edge of fast ice exhibits a great deal of variability. This is due at least in part to two shoals 60 kilometers offshore at depths of 8 and 10 meters and other shoals at intermediate distances. During the winter months, ice appears to be prone to piling on the outer shoals, forming anchors for extending the fast ice.

Just south of Cape Romanzof, the average fast ice edges are again highly coincident. Then, approaching Nelson Island, a significant temporal variability is shown. It is difficult to ascribe any particular cause to this behavior. A rather abrupt bathymetric transition from 6 to 16 meters crosses this zone. The more closely coincident portion of the average ice edges agrees well with this break, while farther south the ice edges oscillate across the break. The coincident portion lies along the edge of mud flats marking the prodelta of a former mouth of the Yukon River, while the oscillating portion lies across the mouth of Hazen Bay. Possibly the edge of fast ice to the north is determined by ice bottom-fast to the mud flats, while to the south the edge of fast ice is irregular due to tidal currents into and from Hazen Bay. The depth of the bay is between 4 and 5 meters and the tidal range, which is as great as 3.5 meters diurnally at Cape Romanzof, is sufficient to cause high velocity tides into and out of the bay.

South of Nelson Island, around to Cape Avinof, the seasonal edges of fast ice are again coincident. These boundaries appear to coincide with the 8-meter isobath. Offshore from here, as far south as the southern side of Nunivak Island, there are several shoals 4 to 6 meters deep located as far as 30 kilometers from the coast. Ice passing from north to south through Etolin Strait between the mainland and Nunivak Island often piles on these shoals creating relatively large (several kilometers) islands of grounded ice.

Ice Around Nunivak Island

Despite the large flux of ice down the Bering coast and the existence of several relatively shallow shoals (6 meters) just north of the island, Nunivak Island does not seem to retain an extensive expanse of fast ice. On the north side, facing the flow of ice southward along the Bering coast, fast ice bridges the embayments between Cape Etolin, the peninsula at the northern tip of the island, and Cape Mohican at the western end, passing quite close to each headland and right along the bluff at Cape Mohican. To the east of Cape Etolin, fast ice reaches its greatest extent from shore and is found at its greatest depth in the vicinity of the island. Just to the east of Cape Etolin, the edge of fast ice for all periods comes close to the 20-meter isobath. It is likely that ice passing through Etolin Strait is driven into this area forming extensive expanses of fast ice. However, the period average edges of fast ice on the east side of the island are all located together well inshore from the 10-meter isobath and quite close to shore. Tidal flushing through Etolin Strait is the probable cause for this behavioral characteristic.

At Cape Corwin, the southeastern prominence of the island, the edge of fast ice becomes tangent to the curve of land forming the cape. From there, the fast ice extends across a wide bay to Cape Mendenhall, where it is again tangent to the coast.

From Cape Mendenhall to the southwestern edge of the island, the 20-meter isobath is quite close to the island, if not coincident with the edge of the island. It is quite unlikely that any fast ice is grounded here. The edge of fast ice is quite close to shore except for an area where it bridges a wide bay just to the west of Cape Mendenhall. This ice is not likely to be grounded but remains fast because it is protected from the general north-to-south ice motion past the island.

From Cape Avinof to the mouth of the Kuskokwim River, the edge of fast ice is located along the edge of extensive mud flats on the north of Kuskokwim Bay. Although some variation can be seen, for the most part, the fast ice edge is consistently located from year to year and period to period season on the finger-like projections of these mud flats. Individual Landsat images often show evidence of tidal flushing here. Large blocks of ice are broken loose and transported further offshore or set adrift. Further into the bay, there are several uncharted shoals which frequently have fast ice located on them.

Figure 11 shows Landsat scene 1220-21440, obtained on 28 February 1973. This scene illustrates the Etolin Strait region, with Nunivak Island on the left and the mountainous Nelson Island left of top center. The scene clearly shows the motion of ice along and away from the coast in this area. There is open water along most of the coast and on the south side of Nunivak Island. Fast ice can be seen on the shoals within

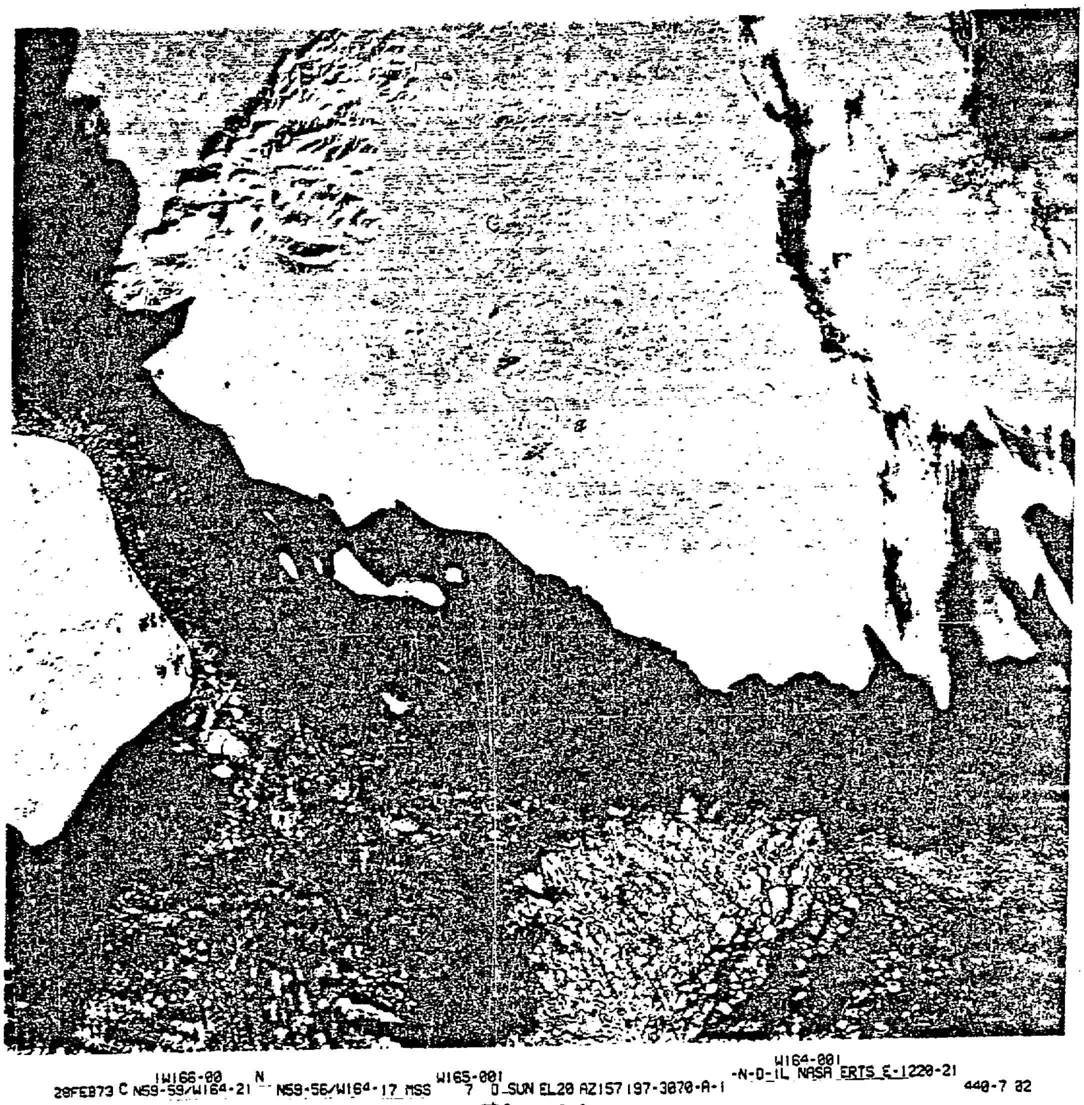


Fig.11

LANDSAT image obtained February 28, 1973 showing Nunivak Island, Etolin Strait and the area of extensive mud flats west of the mouth of the Kuskokwim River. Note ice stranded on shoals in lower Etolin Strait.

Etolin Strait. The southward motion of ice through the strait is illustrated by the polynyas on the south side of these shoals. Farther offshore, older thicker pack ice can be seen embedded in a matrix of newer ice, illustrating the continuous break-up of pack ice and formation of new ice in this region.

In the mouth of the Kuskokwim River is an embayment of the fast ice edge which reaches quite far upriver and is consistent in location from period to period. The Kuskokwim is navigable by ocean-going ships far past this point and has a reasonably deep channel. The tidal range here is 5 meters with the diurnal range around 4 meters. There is little doubt that the large tidal fluctuations are responsible for keeping this area free from fast ice.

Around the east side of Kuskokwim Bay to Jacksmith Bay, the edge of fast ice is located on shoals 5 to 10 kilometers offshore. Here the edge of fast ice moves more or less closer to shore with advancing season. From Jacksmith Bay to Goodnews Bay, the edge of fast ice follows the coast very closely despite the presence of extensive shoals further offshore at depths of two to four meters. The diurnal tidal variation here is approximately 3 meters. This variation is probably sufficient to remove any ice that might be temporarily grounded on these shoals. Winds in this vicinity are characteristically out of the north-eastern quadrant and tend to remove ice from this coast rather than result in ridge-building events.

From Goodnews Bay to Cape Newenham, the edge of fast ice during winter and early spring, (later there is none) bridges a wide embayment with depths on the order of 8 meters. There is one shoal at a depth of just over 2 meters north of Cape Newenham. However, the ice does not appear to be anchored at that location.

From Cape Newenham to Naknek along the northern side of Bristol Bay, fast ice is only found in well protected embayments at water depths generally less than 4 meters. This is largely due to the combined effect of extreme tidal variations (7 meters average diurnal range at Naknek) and strong offshore winds, compounded by the fact that the Bering Sea is only parially bounded by the Alaskan Peninsula and Aleutian Islands to the leeward. These factors combine in the following ways: 1) tidal variations break up and raft away ice not firmly anchored in place; 2) the pack ice is free to move towards the southwest; 3) the prevailing winds are toward the southwest. These same conditions generally prevail from Naknek to Egegik Bay. Starting at about Egegik Bay and going southwestward there is a general tendency for a greater extent of fast ice. However, the presence of ice here is dependent in part on the severity of the ice year and in part on the occurrence of meteorological events required to place ice here. During 1 March 1974, a heavy ice year (Niebauer 1980), winds drove the Bristol Bay pack ice onto the shore of the Alaska Peninsula, creating an extensive area of fast ice, including massive ridges. These ridges were located some distance inshore of the 20-meter isobath, however, and were probably formed from relatively thin ice.

Bristol Bay Ice Conditions

Pack ice in Bristol Bay appears to be greatly influenced by the absence of a southwest barrier for ice motion to the southwest. This circumstance, combined with the presence of strong offshore prevailing winds around the perimeter of the bay, results in a general southwestward motion of ice out of Bristol Bay. Normally, this motion is so sufficiently persistent that Landsat and lower resolution satellite imagery nearly always show open water along the northern side of the bay. As described in detail previously, fast ice is not extensive and is generally found only in highly protected locations.

Due to the nearly constant motion of ice away from the coast and the resulting open water, there is often new ice forming along a broad band running east to west all across the northern side of the bay. It is often possible to clearly see the transition from open water to new ice, young ice and first year pack ice on a single Landsat image. Superimposed on this behavioral pattern is a second characteristic: as the ice moves out of Bristol Bay into a less confined area, it breaks up into large pans with dimensions on the order of 10 to 20 kilometers. The voids between these pans then freeze. This new sheet may then break up, followed by the freezing of the new leads and voids. Evidence for several cycles of this activity can often be seen.

Figure 12 shows Landsat scene 1594-21160 obtained on 9 March 1974. This scene shows ice conditions along the northern side of Bristol Bay. Open water can be seen on the lee side of the land and adjacent islands. Farther offshore, a stepwise gradation to thicker, older ice types can be seen, illustrating that the ice moves in accordance to a series of discrete ice-moving events. This scene illustrates why buildup of extensive fast ice in this region is a rare event, requiring unusual circumstances. Although the characteristic motion is out of Bristol Bay, at least “occasionally a storm can drive ice onto the coast. One such event was described in terms of fast ice behavior along the Alaska Peninsula.

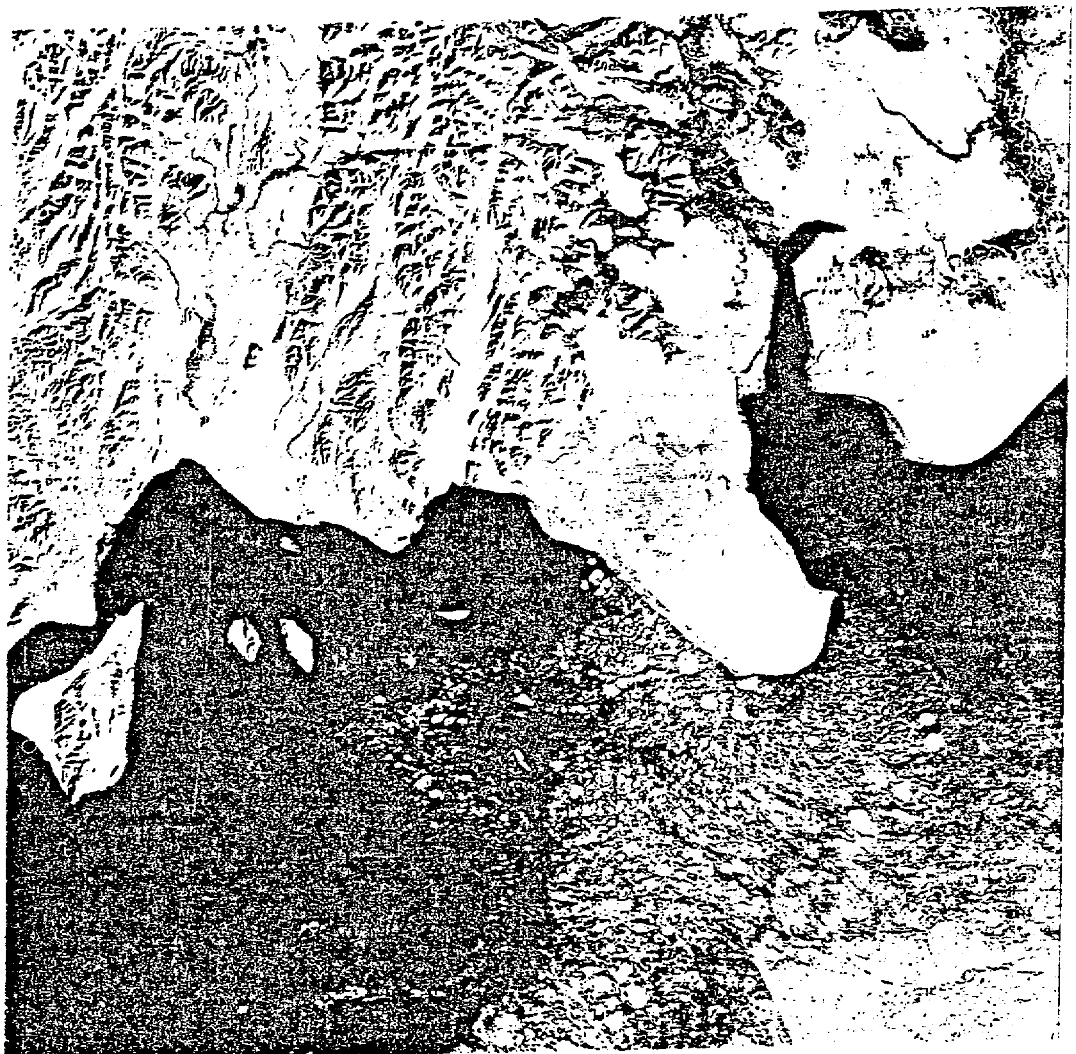


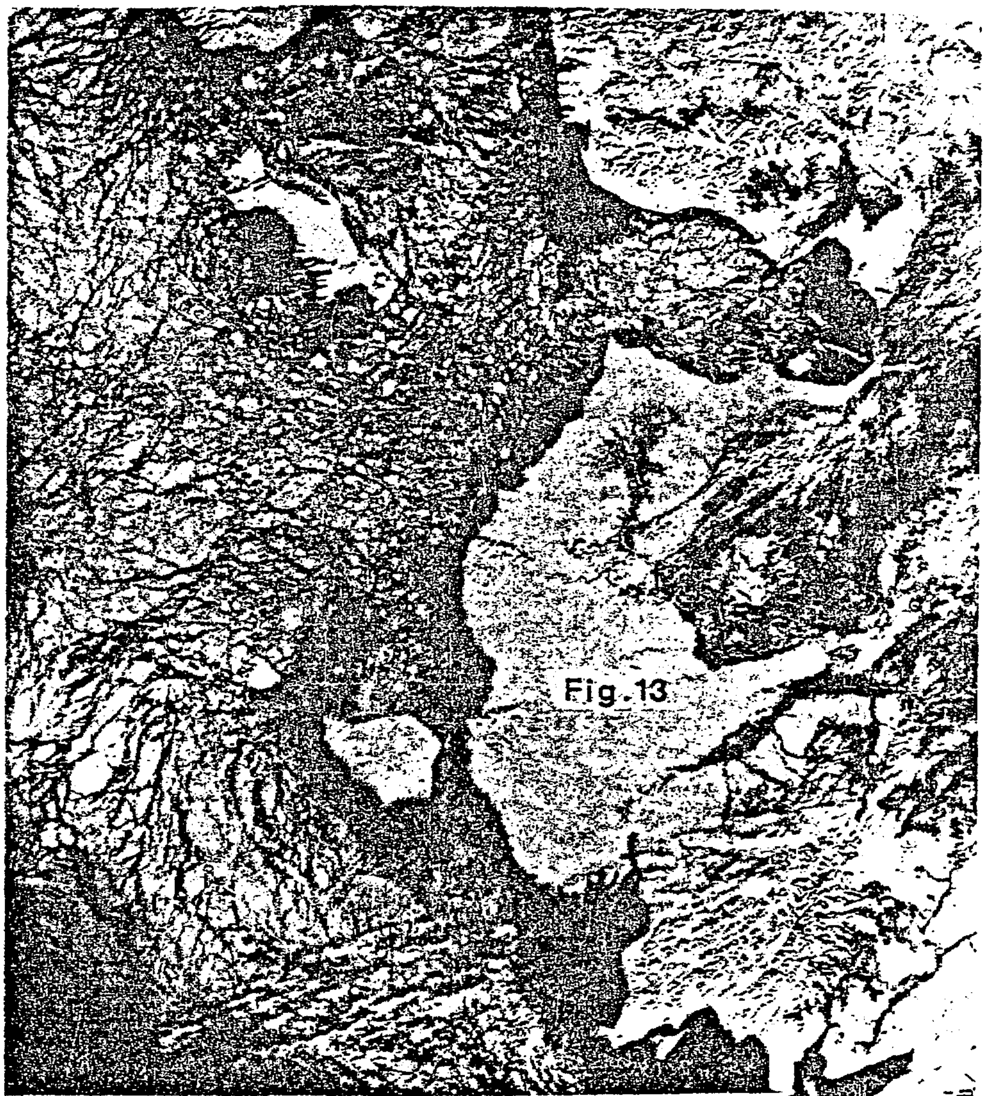
Fig.12

LANDSAT image obtained March 9, 1964 showing the central portion of the north side of Bristol Bay.

5. CONCLUSIONS

Nearshore ice conditions along the Alaskan Bering coast exhibit a wide range of characteristics from Cape Prince of Wales to the Alaska Peninsula. From Wales to Sledge Island, conditions are largely the same as found along the northern Chukchi coast, while off Nome, fast ice conditions are often similar to Beaufort fast ice. However, as one travels southward along the coast, fast ice is found only in shallower and more shielded locations. Finally, along the perimeter of Bristol Bay, fast ice is located only on mud flats and the upper reaches of estuaries.

Figure 13 is a NOAA satellite image of the entire Bering coast



NOAA satellite image obtained March 19, 1975 showing entire Alaskan Bering Sea coast under study. The conditions seen here are typical and tend to support the description of Bering nearshore ice characteristics generated by this study.

obtained on 19 March 1975. This image illustrates the relationship between pack ice and fast ice conditions described previously.

Figure 8 was compiled to present in one figure the general characteristics of Bering Sea nearshore ice. Although there is considerable agreement between the satellite image in figure 13 and figure 8, it should be borne in mind that figure 13 is a selected, instantaneous satellite image and that the characteristics of figure 8 are based on an average of ice statistics. While the schematic diagram presented in figure 8 is generally correct, it should be stressed that specific conditions will produce variations from the average.

Beyond figure 8, it is concluded that there are four factors responsible for Bering Sea ice behavioral characteristics:

1. There is a general moderation of climate as one moves southward, resulting in conditions limiting the growth of ice.

2* There is a prevailing motion of pack ice toward the ice front in the southern Bering Sea. As a result, coastal pack ice motions are either directly away from the coast or along the coast. This motion causes large polynyas to open up in many areas.

3. The prevailing winds are directly offshore from all south and west facing coasts. As a result, newly formed ice in the polynyas is transported away from shore.

4. From Nome to King Salmon, the diurnal tidal range increases from 1/2 to 6 meters, These tidal variations tend to lift ice away from the sea bottom so that it may be transported by currents and winds. One source of strong seaward currents is the large tidal variation. These currents can be particularly strong in areas of mud flats with large expanses of shallow water.

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