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Characteristics of Nearshore Ice in Southwestern Alaska

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ABSTRACT

A description of Bering Sea nearshore ice conditions in southwestern Alaska is presented based on a compilation of fast ice edge statistics and analysis of specific ice events from satellite imagery. Landsat imagery was used at 1:500,000 scale to map Bering sea nearshore ice conditions for the period 1973-76 inclusive. Maps of fast ice edge locations were then compiled on a seasonal basis representative of 1) winter, 2) late winter - early spring, and 3) mid-to-late spring. These seasonal locations of fast ice edge were then compared to determine seasonal trends in fast ice extent. This information was combined together with bathymetric, climatological, and tidal data to produce a regional description of characteristic nearshore ice conditions along the Bering Sea coast from the Yukon River delta to Izembeck Lagoon on the Alaska Peninsula. In addition to these specific results, it was found that nearshore ice conditions vary considerably from north to south within the study area as a result of climatic trend, regional pack ice motions, tidal variations and prevailing local winds. These factors combine to produce a transition from extensive, stable fast ice in the north to fast ice which is extremely limited in extent and somewhat unstable in the south.

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 (6 feet).- Because of the low buoyancyaf'ice, most of the vertical extent of fast ice is 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 (1 foot) followed by a storm that withdraws the ice from shore, breaks most of it up into small [1 meter (3 foot)] 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 conditions are possible. In 1973, an "ice push" event occurred at Kotzebue, Alaska, where a stable sheet of moderately thick [approximately 1-meter (3 foot)] fast ice was driven as much as 15 meters (50 feet) onto the beach just south of town, carrying with it a large surplus landing barge used as a salmon cannery.[1] Kovacs and Sodhi[2] have documented a number of these events occurring in the Beaufort Sea region, as well as a related phenomenon, 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 ridges 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 (40. feet) and ridges are seldom sufficiently thick to be grounded in water deeper than 20 meters (65 feet). While a great deal of work has been done determining these limits in the Beaufort Sea,[3,4,5,6] a relatively small amount of work has-been done in the Bering.[6,7,8]

Floating fast ice is not always bounded by a zone of grounded ridges [sometimes called stamukhi).[9] Whether or not a grounded ridge zone exists, in some regions fast ice-can extend seaward UP to 100 , kilometers (60 miles) or more.[10] If the grounded ridge zone is present, it tends to protect the enclosed floating 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 seaward. The stability of attached ice is quite tenuous and it cart be easily converted into pack ice by a dynamic ice-breaking event. Often in these nearshore areas, large ridges can be found parallel to share but located in waters too deep for them to be grounded.

Figure 1 gives some idea of fast ice conditions that can be found in regions where grounded ridge zones are common. The situation depicted in figure 1 shows relatively undeformed bottom-fast ice along the beach with tidal cracks occurring near the two meter (6 foot) 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 around stronger floes. This pattern extends out to the grounded ridges. The dimensions of the floes and piles around them, as well as the distance to the grounded ridges can vary widely. For instance, the floes could be 30 or 3,000 meters (30 to 3000 yards) in diameter and the ice piles could be 1 or 10 meters (3 to 35 feet) above sea level. The distance to the grounded ridges could be from 1 to 30 kilometers (.5 to 20 miles) offshore. Because of the necessary vertical exaggeration in this figure, 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.

Seaward of 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 (4 to 8 inches) and then failed in tension, forming a new flaw lead. This narrow lead now defines the edge of fast ice. Seaward of this lead, the ice can truly be classified as pack ice.

While Bering Sea nearshore ice conditions at some locations are similar to those described by figure 1, two factors influence ice behavior in most 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 compressed against the coast, at-many locations along the Bering coast the ice is almost continually being advected from shore by winds and currents..[6,7,11,12]

Figure 2 shows an ice profile more typical of fast ice in the Bering Sea than that of figure 1. A grounded ridge is shown some distance from shore, but certainly closer than the 15-meter (50 foot) isobath. In order to be even semi-permanent, this ridge must be sufficiently groundedto withstand the bouyant forces during high tides, and must have a geometry such 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 arid-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.. As a result, 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 nat nearly-as stable as fast ice-in areas with little tidal range.

Attached ice can occasionally be found beyond the grounded ridge zone, but because of tidal variations, the flaw lead is most often found just seaward of the grounded ridges. Again, as in figure 1 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 pack ice motion has a persistent 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 influence 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 (20 feet). At other locations, conditions similar to those found in the Beaufort Sea are found, with ice ridges grounded along the 20-meter (65 foot) isobath.

PACK ICE BEHAVIOR ALONG THE WESTERN ALASKAN COAST

From the preceding discussion, it is evident that the extent and morphology of fast ice is determined in part by the behavior of the adjacent pack ice. While pack ice in the Beaufort Sea remains reasonably static during the ice season, the behavior of pack "ice in the eastern Bering Sea is quite dynamic. Various authors [11,12,13], have noted that pack ice motions in the eastern Bering Sea are generally from north to south. Stringer and Henzler[14] have measured southward pack ice motions in this region as great as 28 km (17 miles)/day. At times, northerly pack ice motions are observed as well.[7,14,15] In general, the southward pack ice velocities are significantly larger than the northward velocities. Furthermore, the southward displacements tend to be associated with winds resulting from the prevailing weather systems, while the northerly Misplacements have been associated with oceanic currents influencing ice motions at times of weak winds.[7,15]

LOCATION OF FAST ICE ALONG THE SOUTHWESTERN ALASKAN COAST

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[16] and will not be described 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. A series of three maps was compiled showing the location of the edge of fast ice for the seasons mid-winter, late winter - early spring, and mid-to-late spring during 1973, 1974, 1975, and 1976. From these data, an average ice edge for each, season was determined. In order to reveal temporal changes of location of the average ice edge, these average edges were compiled onto one map (figure 3). Obviously, any significance placed on trends apparent on this map must be tempered by consideration of the year-to-year variability exhibited by the ice edge data. At some locations, the edge of fast ice varied considerably in position during each season. Although the average edges in these locations may show a temporal trend, this obviously has only minor significance' if the variation within each season is greater than the change between seasons. In other locations, the variability of the fast ice edge within each season is small compared to the changes in the average position from season to season. In these cases, temporal trends-with year-to-year dependability are indicated.

NEARSHORE ICE CHARACTERISTICS OF SOUTHWESTERN ALASKA"

Figure 4 was prepared showing the regional nearshore ice characteristics of the Bering Sea. This map was prepared on the basis of the fast ice edge considerations described in the previous section and by analysis of Landsat images for ice features such as ridges, hummock fields, etc., and smaller scale satellite imagery for dynamic ice motions and other nearshore characterstics. The following sections describe zones delineated in figure 4. Figure 5 is a NOAA satellite image of the entire Bering coast showing many of the conditions to be described. This image was obtained on March 19, 1975 and is in many respects representative of the average ice conditions to be found in the region.

The Yukon delta to Cape Avinof

Zone 1 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 (6 to 40 feet). 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 driven into this region, the edge of fast ice has not been observed to build out to the 20-meter (65 foot) isobath as it does in the Beaufort Sea under somewhat similar conditions.

In zone 2, which lies between the Yukon delta and 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 (35 miles) offshore at depths of 8 and 10 meters (25 and 35 feet) 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. This process appears to occur irregularly, resulting in a highly variable fast ice edge location during the first two seasonal periods. However, the shoreward trend by the third seasonal period appears to be statistically significant.

Between Cape Romanzof and Hazen Bay (zone 3), the seasonal average fast ice edges are again highly coincident (see figure 3). Then, approaching Nelson Island, across Hazen Bay (zone 4), a significant variability is found. The reason for the change in fast ice edge behavior here appears to be related to tidal currents: A rather abrupt bathymetric transition from 6 to 16 meters (20 to 50 feet) crosses both zones. In zone 3 the average ice edges "agree well with this break, while in zone 4 the ice edges oscillate across the break. The coincident portion (zone 3) lies along the edge of mud flats marking the prodelta of a former mouth of the Yukon River, while the oscillating portion (zone 4) lies across the mouth of Hazen Bay. It appears that 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 (13 and 16 feet) and the tidal range, which is as great as 3.5 meters (12 feet) diurnally at Cape Romanzof, should result in high velocity tidal currents.

From Nelson Island, southward to Cape Avinof (zone 5), the seasonal edges of fast ice are again coincident.. These boundaries agree with the 8-meter (25 foot) isobath. Offshore from here, as far south as the southern side of Nunivak Island, there are severa? shoals at 4 to 6 meters (13 to 20 feet) depth located as far as 30 kilometers (18 miles) 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..

Nunivak Island

Despite the large flux of ice down the Bering coast and the existence of several relatively shallow shoals [6 meters (20 feet)] just north of the island, Nunivak Island does not seem to retain an extensive expanse of fast ice. On the north side, facing the southward flow of ice 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 (zone 6), fast ice reaches its 'greatest extent from shore and is found at its greatest depth in the vicinity of the island: 20 meters. However, the seasonal average edges of fast ice on the east side of the island (zone 7) are coincident and located well inshore from the 10-meter (35 foot) isobath and quite close to shore.

At Cape Corwin, the southeastern prominence of the island, the edge of fast ice becomes tangent to the curve of land farming the cape. From there, the fast ice extends across a wide bay to Cape Mendenhall, where it is again tangent to the coast (zone 8).

From Cape Mendenhall to the southwestern edge of the island, the 20-meter (65 foot) isobath is quite close, if nat 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.

Cape Avinof to the Alaskan Peninsula"

From Cape Avinof to the mouth of the Kuskokwim River (zone 9), the edge of fast ice is located along the edge of extensive mud flats on the north side of Kuskokwim Bay. Although some variation cart be seen, for the most part, the fast ice edge is consistently located from year to year and season to season on the finger-like projections of these mud flats. (See figure 3) 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, several shoals frequently are marked by accumulations of fast ice.

The mouth of the Kuskokwim River contains an embayment of the fast ice edge which reaches quite far upriver and is constant in location from season to season. The Kuskokwim is navigable by ocean-going ships far past this point and has a reasonably deep channel. The tidal range here is up to 5 meters (15 feet), and 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 (zone 10), the edge of fast ice is located on shoals 5 to 10 kilometers (3 to 6 miles) offshore. Here the edge of fast ice moves closer to shore with advancing season, indicating a thermodynamic retreat of floating fast ice.

From JackSmith Bay to Goodnews Bay (zone 11), 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 (6 to 15 feet). The diurnal tidal variation here is approximately 3 meters (10 feet) and is probably sufficient to remove any ice that might be temporarily grounded on these shoals. Winds in this vicinity are characteristically out of the northeastern quadrant and tend to remove ice from this coast rather than result in ridge-building events.

From Goodnews Bay to Cape Newenham (zone 12), 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 (25 feet). There is one shoal at a depth of just over 2 meters (6 feet) 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 (zones 13) at water depths generally less than 4 meters (15 feet). This is largely due to the combined effect of extreme tidal range meters (23 feet) average diurnal range at Naknek] and strong offshore winds-, compounded by the fact that the Bering Sea is only partially bounded by the Alaskan

Peninsula and Aleutian Islands to the leeward. These factors combine in the following ways: 1) sea level variations and resulting currents break up and raft away ice not firmly anchored. 2) fast ice becomes unattached and moves towards the southwest; 3) the prevailing winds are toward the southwest.

These same conditions generally prevail from Naknek to Port Moller (zone 14). From Port Moller southwestward to Izembeck Lagoon (zone 15), 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 drive ice across Bristol Bay and onto this coast. During 1 March 1974, a heavy ice year,[17] 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, which were of sufficient size to be seen on Landsat imagery, were located some distance inshore of the 20-meter (65 foot) isobath, however, and were probably formed from relatively thin tee.

Bristol Bay Pack Ice

Pack ice in Bristol Bay appears to be greatly influenced by the absence of a physical barrier far 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 southwest-ward motion of ice out of Bristol Bay. This motion is so 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 on the north and east sides of the Bay 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 see southwestward 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 floes with dimensions on the order of 10 to 20 kilometers (6 to 12 miles). The voids between these floes then freeze. This new sheet may then break up, followed by the freezing of the new leads and voids. Evidence fur several cycles of this activity can often be seen.

Figure 6 is Landsat scene 1594-21160 obtained on 9 March 1974. This scene shows typical ice conditions along the northern side of Bristol Ray. Open water can be seen on the lee side of the land and islands. Farther offshore, a stepwise gradation to thicker, older ice types can be seen, suggesting that the ice moves in accordance to a series of discrete ice-moving events. This scene illustrates why build-up 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 previously in the discussion of fast ice behavior along the Alaska Peninsula.

CONCLUSIONS

The specific characteristics of nearshore ice along the southwestern Bering Sea coast of Alaska have been summarized in figure 4 and discussed in the previous sections of this article. Taken together; these specific conclusions show that nearshore ice conditions in this region exhibit a wide range of conditions between the Yukon River delta at the northwestern extreme of the study area and the Alaska Peninsula at the study area's southeastern limit. 'In-the-vicinity of the Yukon River delta, fast ice conditions tend to be similar to the Beaufort Sea morphology with extensive fast ice held in place by grounded ice features. As one travels along the coast from the Yukon delta toward the Alaska Peninsula, fast ice becomes less extensive and tends to he located in more isolated and sheltered locations. Finally, along the Alaska Peninsula, fast ice occurrence becomes even more rare., However, south of Izembeck Lagoon again a condition reminiscent of Beaufort coast fast ice can occasionally be found. The reasons for these changing fast ice morphologies appear to be linked to the following factors:

a) There is a general moderation in climate from north to south in the study area due to the pronounced maritime influence of the north Pacific Ocean. As a result, ice growth rates and cumulative ice thickness decrease from north to south. This, in turn, results in weaker ice which is mare easily broken loose and made subject to advection processes,

b) The tidal range varies from .5to 6 meters (1.5 to 20 feet) from north to south across the study area. Tidal variations tend to cause fractures between bottom-fast ice and floating fast ice as well as provide flotation for grounded ice. Furthermore, tidal currents are a source of stress on the ice tending to break it in tension and advect it seaward. These tidal effects can be particularity pronounced in shallow areas such as those found in some portions of this study area.

c) There is a prevailing pack ice motion toward the south in this region. As a result, along west facing coasts some shear ridging is possible, causing well anchored fast ice, particularly in the area of the Yukon River delta and the Alaska Peninsula. However, over much of the study area, this pack ice motion is divergent from the coast, resulting in the creation of either a wide flaw lead or polynya adjacent to the-fast ice. As a result, ice broken free or rafted away from the fast ice is not held in place to be refrozen to the fast ice as it would be in places where pack ice is held tightly against shore.

d) In figure 4 the vector azimuth of prevailing winds between November and April is shown at the locations of reporting meteorological stations in this region.[18] It can be seen that throughout the study. area, the prevailing winds are directly offshore from all west and south facing coasts. As a result, ice broken free from the fast ice tends to be advected seaward into the adjacent flaw lead or polynya..

On the basis of this work, it has been possible to perform an assessment of ice-related physical hazards and pollution transport mechanisms associated with offshore petroleum development in this region.[19] This assessment was performed in conjunction with the Outer Continental Shelf Environmental Assessment Program prior to leasing by the government of tracts for petroleum recovery.

REFERENCES

1. A. Francis, personal communication. Kotzebue, Alaska.

2. A. Kovacs and D.S. Sodhi, "Ice Pileup and Ride-up on Arctic Beaches," Proceedings of the 5th International Conference on Port and Ocean Engineering under Arctic Conditions, August 13-?8, 1979, Trondheim, Norway, Volume I, pp. 127-146 (1979].

3. E. Reimnitz 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-T 32240 (1973);

4. A. Kovacs and M. Mellor, "Sea Ice Morphology and Ice as a Geologic Agent in the Southern Beaufort Sea," The Coast and Shelf of the Beaufort Sea, Proceedings ofa Symposium on Beaufort Sea Coast and Shelf Research, January 7-9, San Francisco, California, pp. 113-161 (1974).

5. A. Kovacs, 'Grounded Ice in the Fast Ice Zone Along the Beaufort Sea Coast of Alaska," Cold Regions Research and Engineering Laboratory Report No. 76-32 (1976).

6. W.J. Stringer, "Morphology of Beaufort, Chukchi, and Bering Seas Nearshore Ice Conditions by Means of Satellite and Aerial Remote Sensing," Final Report to NOAA Arctic Project Office, University of Alaska, Fairbanks, Alaska, Contract No. 03-022-55, Task no. 8 (1978).

7. V.M. Ray and W.R. Dupre, "The Ice Dominated Regimen of the Norton Sound Region of Alaska," The Eastern Bering Sea, its Oceanography and Resources, Eds. D.W. Hood and J.A. Calder, NOAA, Library of Congress No. 81-600035, pp. 263-278 (1980).

8. W.R. Dupré, "Yukon Delta Coastal Processes Study," Final Report to NOAA Arctic Project Office, University of Alaska, Fairbanks, Alaska, Research Unit 208, (1980).

9. E. Reimnitz and P.W. Barnes, "Marine Environmental Problems in the Ice-covered Beaufort Sea Shelf and Coastal Regions," Annual report to NOAA Arctic Project Office, University of Alaska, Fairbanks, Alaska, Contract RK6-6074, Research Unit 205 (1976).

10. W.J. Stringer, "Shore-fast Ice in Vicinity of Harrison Bay, Northern Engineer, Volume 5, No. 4, pp. 36-39 (1974).

11. S.L. McNutt, "Remote Sensing Analysis of Ice Growth and Distribution in the Eastern Bering Sea," The Eastern Bering Sea, its Oceanography and Resources, Eds. D.W. Hood and J.A. Calder, NOAA, Library of Congress No. 81-600035, pp. 141-165 (1980).

12. C.H. Pease, "Eastern Bering Sea Ice Dynamics and Thermodynamics," The Eastern Bering Sea, its Oceanography and Resources, Eds. D.W. Hood . and J.A. Calder, NOAA, Library of Congress No. 81-600035, pp. 213-222, (1980).

13. R.D. Muench and K. Ahlnas, "Ice Movement and Distribution in the Bering Sea" from March to June 1974," Journal of Geophysical Research, Volume 81, No. 24, pp. 4467-4476 (1976).

14. W.J. Stringer and R.D. Henzler, "Ice Displacement Vectors Measured in Norton Sound and the Adjacent Bering Sea," prepared for NOAA Arctic Project Office, University of Alaska, Fairbanks, Alaska, Contract No. 03-5-022-55, Task .'IO, Research Unit 267 (1981).

15. C.H. Pease and S.A. Sale, "Drift Characteristics of Northeastern Bering Sea Ice During 1980," NOAA Technical Memorandum ERL PMEL-32, July 1981.

16. W.J. Stringer, "Morphology and Hazards Related to Nearshore Ice in Coastal Areas," Coastal Engineering, -V~lume 5, pp. 229-245 (1981). . .

17. H.J. Niebauer, "Recent Fluctuations in Sea Ice Distribution in the Eastern Bering Sea," The Eastern Bering Sea, its Oceanography and Resources, Eds. D.W. Hood and J.A. Calder, NOAA, Library of Congress No. 81-600035, pp.133-140 (1980).

18. W.A. Brewer, Jr., H.W. Searby, and J.L. Wise, "Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska," Library of Congress No. 77-620020, Arctic Environmental Information and Data Center Publication B-77, (1977).

19. W.J. Stringer, "The Role of Sea Ice as a Physical Hazard and a Pollutant Transport Mechanism in the Bering Sea," prepared for - NOAA Arctic Project Office, University of Alaska, Fairbanks, Alaska, Contract No. 03-5-022-55, Research Unit 267 (1980).

Glossary

ANNUAL ICE:
Ice which has formed since the last summer.

ATTACHED ICE:
Floating fast ice extending seaward beyond firmly grounded features of the fast ice.

FAST ICE:
Sea ice that forms and remains. attached to shore.

FIRST-YEAR:
Sea ice not more than one winter's growth but greater than 30 cm (1 foot) thick.

FLAW LEAD:
A separation between pack ice and fast ice that is navigable by surface vessels.

FLOE:
Any relatively flat piece of sea ice 20 meters (65 feet) or more across..

HUMMOCK :
A hillock of broken ice which has been forced upwards by pressure.

MULTI-YEAR ICE:
Sea ice that has survived at least two summers melt.

NEW ICE:
Recently formed ice up to 10 cm (4 inches) thick.

OPEN WATER:
A large area of freely navigable water in which sea ice is present in concentrations less than 1/10.

PACK ICE:
Any area of sea ice other than fast ice.

PILING:
The process of ice forming ridges, hummock fields, or rubble fields.

POLYNYA:
Any non-linear opening enclosed in ice.

PRESSURED ICE:
Ice which has been deformed into ridges or other features as a result of compressive forces.

RAFTING:
Pressure processes whereby one piece of ice overrides another.

RUBBLE FIELD:
An extensive area of piled and hummocked ice.

RIDGE:
A line or wall of broken ice forced up by pressure.

SHEARING:
When ice velocity varies significantly in the direction normal to its motion. This results in rotational forces.

TIDAL CRACKS:
Crack at the line of junction between an immovable ice foot or ice wall and fast ice, the latter subject to rise and fall -of the tide.

YOUNG ICE:
Ice in transition between new stage and first-year ice [10-30 cm (4-12 inches)].

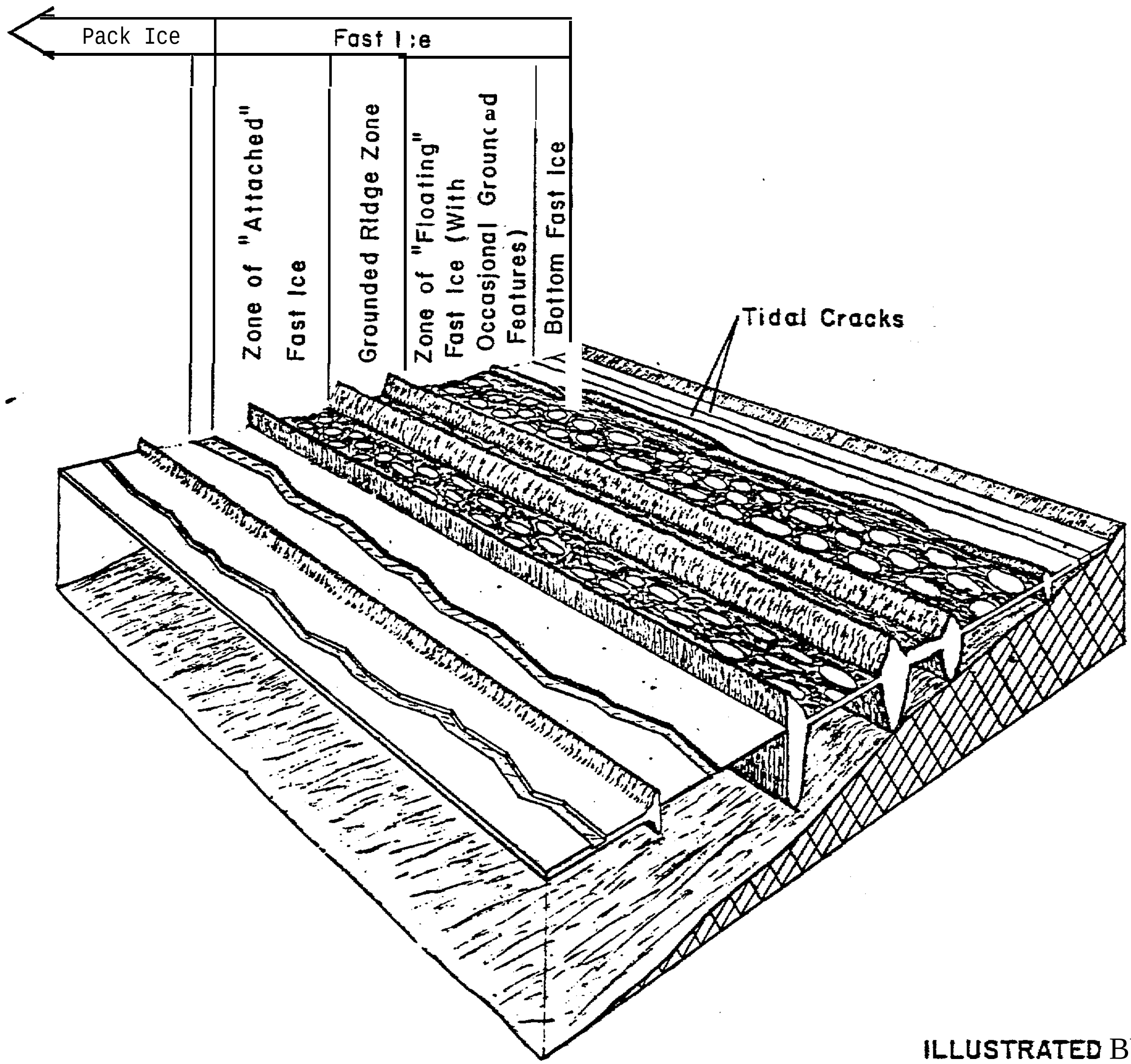

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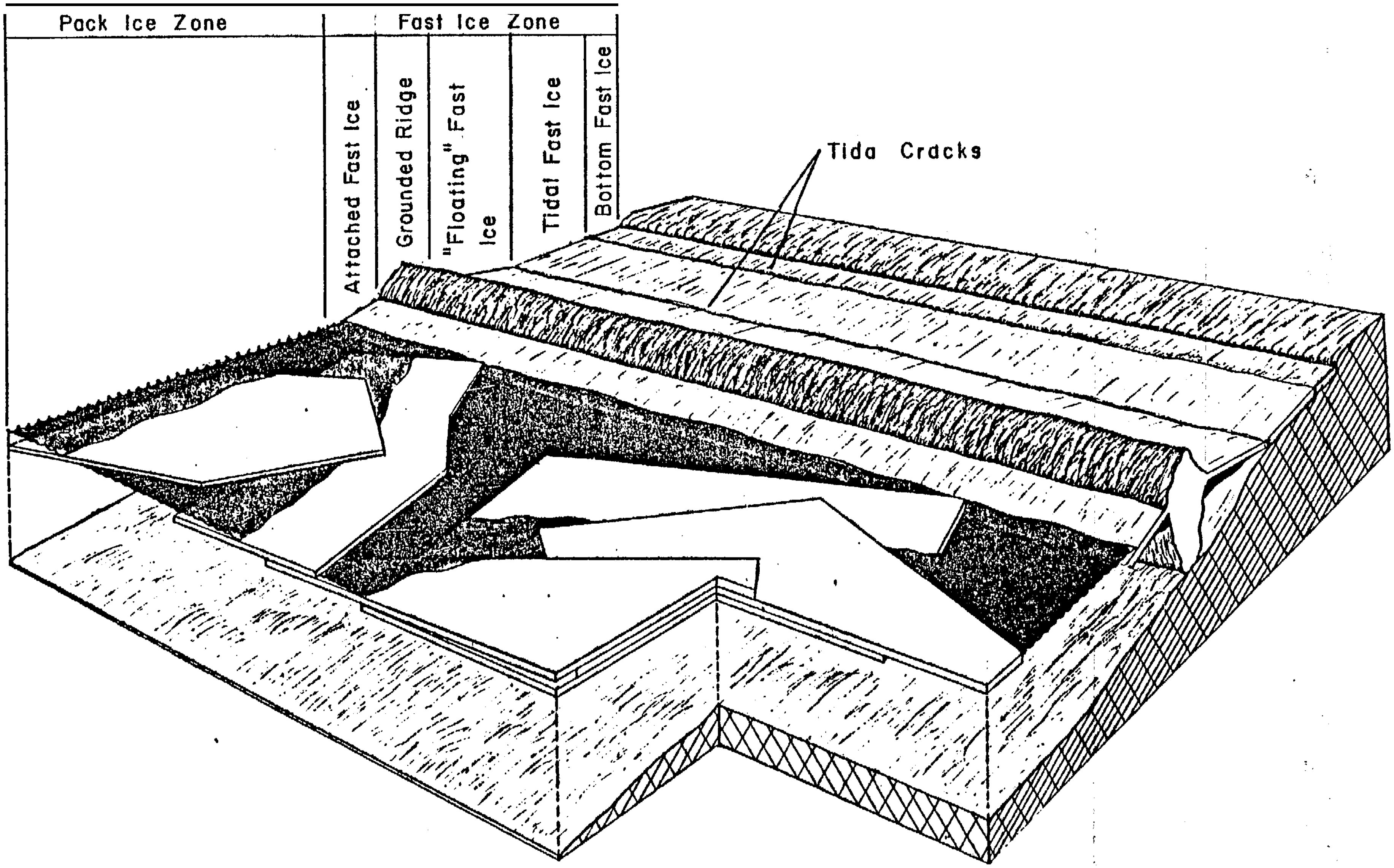
Figure 1



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R. D. HENZLER

F gure 2

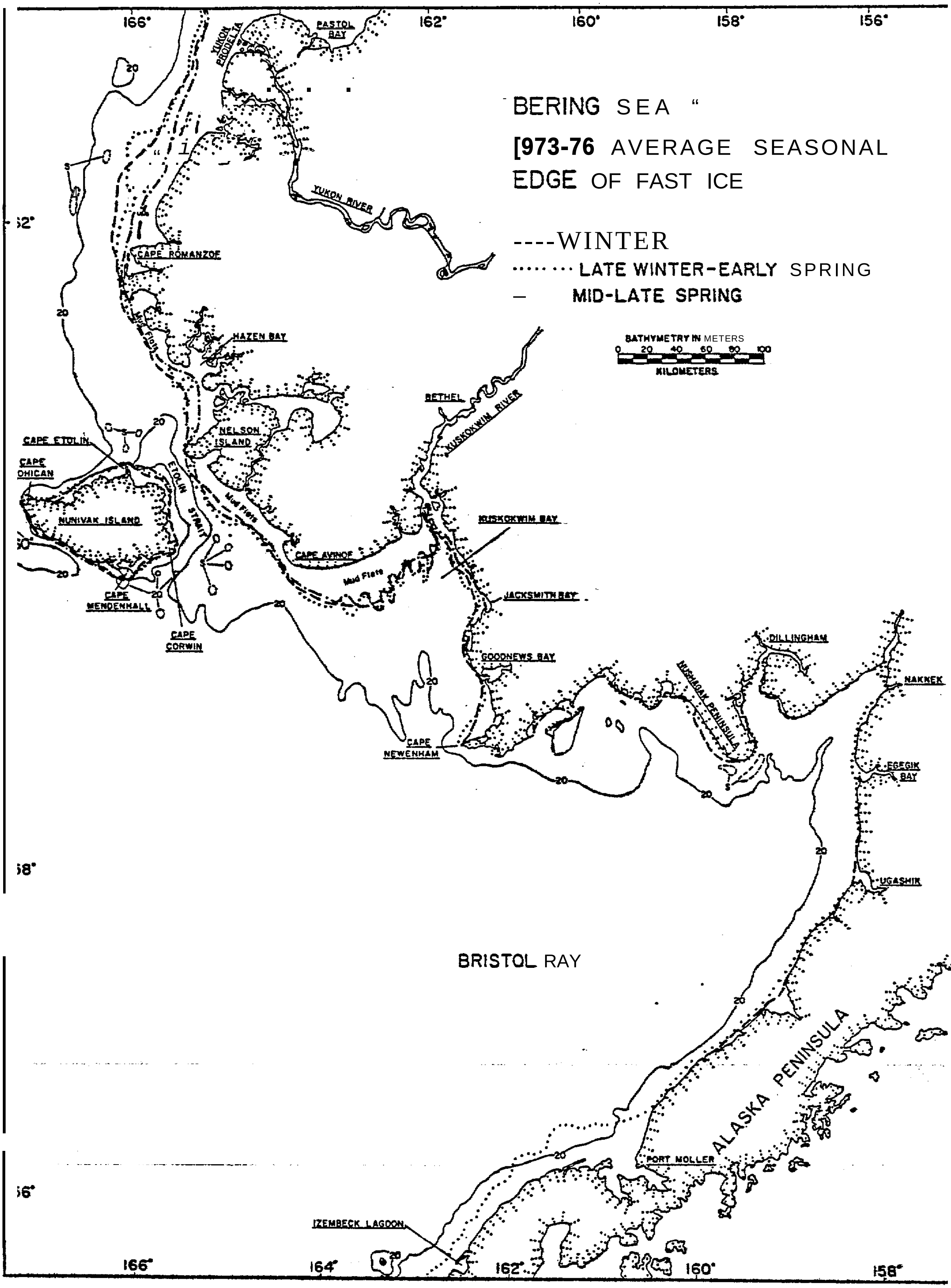
BERING SEA "
[973-76 AVERAGE SEASONAL
EDGE OF FAST ICE
----WINTER
········LATE WINTER-EARLY SPRING
— MID-LATE SPRING
BATHYMETRY IN METERS
0 20 40 60 80 100
KILOMETERS
166°
162°
160°
158°
156°
164°
YUKON PRODELTA
PASTOL BAY
YUKON RIVER
CAPE ROMANZOF
HAZEN BAY
BETHEL
KUSKOKWIM RIVER
NELSON ISLAND
CAPE ETOLIN
CAPE CHICAN
NUNIVAK ISLAND
ETOLIN STRAIT
Mud Flats
CAPE AVINOF
KUSKOKWIM BAY
JACKSMITH BAY
CAPE MENDENHALL
CAPE CORWIN
GOODNEWS BAY
CAPE NEWENHAM
DILLINGHAM
NUSHAGAK PENINSULA
NAKNEK
EGEGIK BAY
UGASHIK
BRISTOL RAY
ALASKA PENINSULA
PORT MOLLER
IZEMBECK LAGOON
20

Figure 3

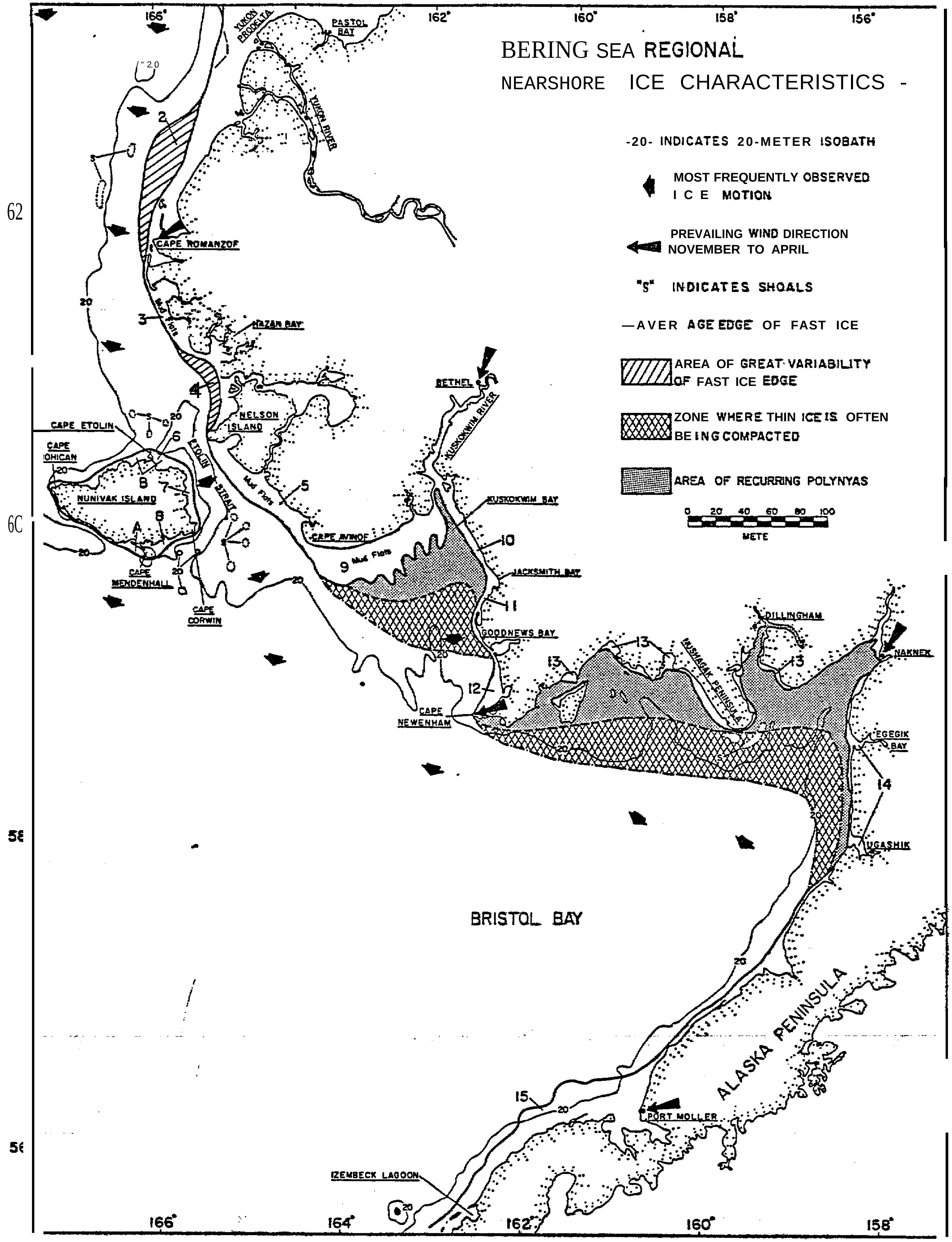
BERING SEA REGIONAL
NEARSHORE ICE CHARACTERISTICS -
-20- INDICATES 20-METER ISOBATH
MOST FREQUENTLY OBSERVED ICE MOTION
PREVAILING WIND DIRECTION NOVEMBER TO APRIL
"S" INDICATES SHOALS
—AVERAGE EDGE OF FAST ICE
AREA OF GREAT VARIABILITY OF FAST ICE EDGE
ZONE WHERE THIN ICE IS OFTEN BEING COMPACTED
AREA OF RECURRING POLYNYAS
YUKON PRODELTA
PASTOL BAY
YUKON RIVER
CAPE ROMANZOF
HAZEN BAY
NELSON ISLAND
CAPE ETOLIN
NUNIVAK ISLAND
ETOLIN STRAIT
CAPE MENDENHALL
CAPE CORWIN
CAPE AVINOF
BETHEL
KUSKOKWIM RIVER
KUSKOKWIM BAY
JACKSMITH BAY
GOODNEWS BAY
CAPE NEWENHAM
DILLINGHAM
NUSHAGAK PENINSULA
NAKNEK
EGEGIK BAY
UGASHIK
BRISTOL BAY
ALASKA PENINSULA
PORT MOLLER
IZEMBECK LAGOON
Mud Flats

Figure 4

Figure 5

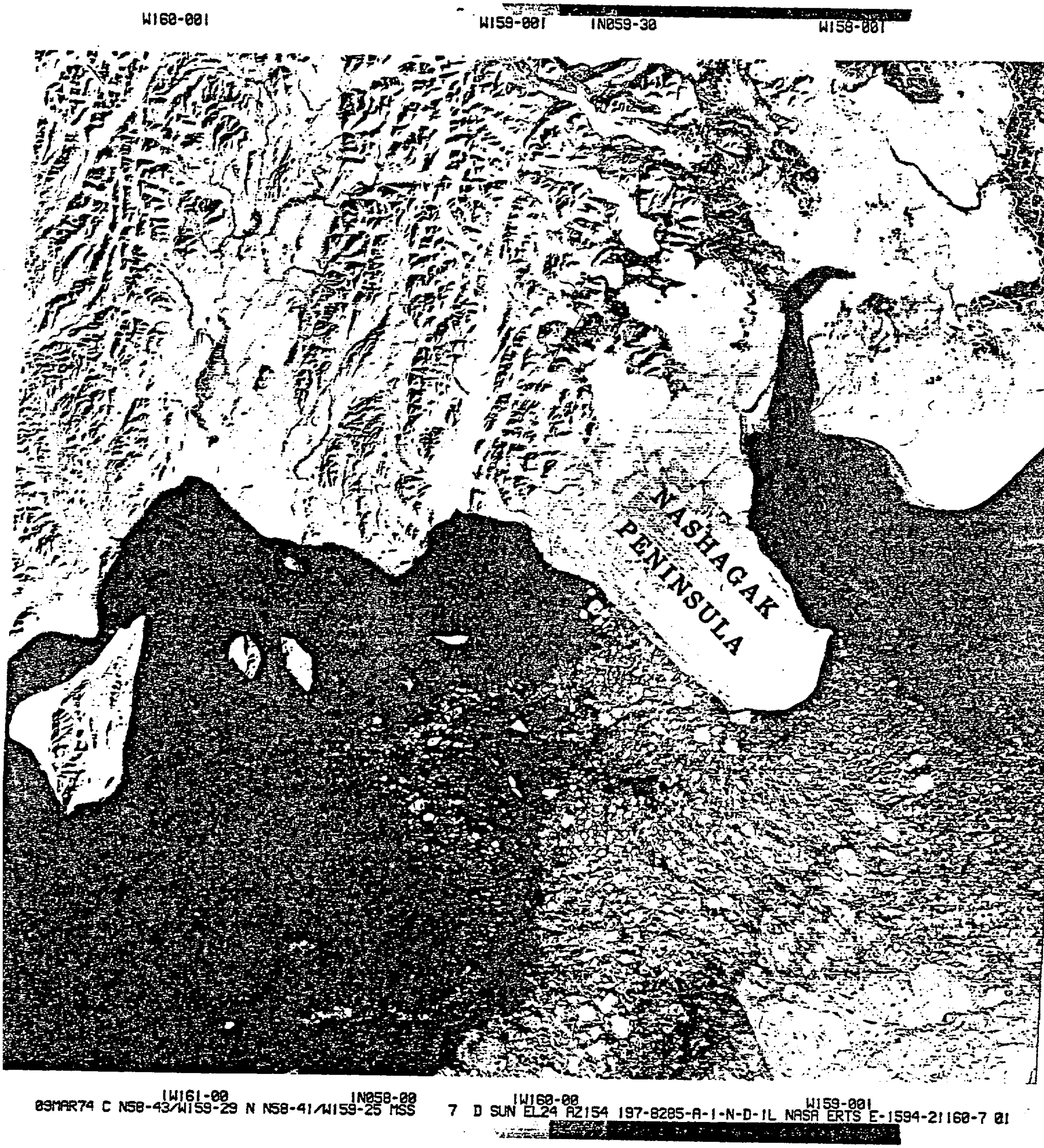
W160-001
W159-001
IN059-30
W158-001
NASHAGAK
PENINSULA
IW161-00
IN058-00
IW160-00
W159-001
09MAR74 C N58-43/W159-29 N N58-41/W159-25 MSS 7 D SUN EL24 AZ154 197-8285-A-1-N-D-1L NASA ERTS E-1594-21160-7 01

Figure 6

FIGURE CAPTIONS

Figure 1

Idealized nearshore ice configuration in a region of low tidal range and massive offshore shear ridge construction. This drawing shows an apron of bottom-fast ice bounded-on the seaward side by a series of tidal cracks. Extending seaward out to the grounded ridge zone is an extensive area of floating fast ice. The grounded ridge zone generally consists of a family of massive shear ridges grounded in waters up to 20 meters (60 feet) in depth. Beyond this is attached fast ice which can, as is shown in this example, contain floating shear ridges.'

Figure 2.

Idealized nearshore ice configuration in a region where large tidal variations result in significant limitation of the extent of fast ice. The configuration depicted here shows the usual apron of bottom fast ice (here extended farther because of the instantaneous low tide state). Because of the great tidal range, tidal cracks can be found over a broad range of distances from shore. In this case, the most shoreward stable grounded ridge is found in waters more shallow than 20 meters (60 feet), and in the example shown here, low tide has resulted in the fracturing of the floating fast ice and the breakup of the attached fast ice.

Figure 3

Map presenting seasonal average Bering Sea fast ice edges for (1) winter, (2) late winter-early spring, and (3) mid-to-late spring. Comparison of these average fast ice edges can show extension with advancing season, retreat with advancing season, or seasonal stability. This in turn, gives hints concerning processes which may be taking place: seasonal advance, for instance, can result from continuous accumulation of grounded ridges in an area where pack ice motions are favorable to creation of such accumulations.

Figure 4

Map summarizing Bering Sea regional nearshore ice characteristics.

Figure 5

NOAA satellite image obtained March ?9, 1975 showing entire Alaskan Bering Sea coast under study.. The conditions seen here are typical and support the average description of Bering Sea nearshore ice characteristics developed in this paper.

Figure 6

Landsat image obtained March 9, 1974 showing the central portion of the north side of Bristol Bay (see figures 3 and 4 for location). The analysis reported in this paper was performed on these images at 1:500,000 scale. At that scale the area shown here is 18x18 inches.