ICE GOUGING ON THE SUBARCTIC BERING SHELF

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ABSTRACT

Ice impacting the sea floor gouges surficial sediment of the shallow, Bering epicontinental shelf, Alaska. Two types of ice gouge have been recognized: the single gouge, a single gouge furrow, and multiple gouges or raking, a wide zone of numerous, subparallel gouge furrows. Single gouges, the most common type, are cut by single-keeled pieces of thick ice, whereas multiple gouges are formed by multikeeled, thick, pressure-ridge ice* Gouges occur in water depths of 30 m or less, but are most dense in water 10 to 20 m deep. Although some gouge incisions are as deep as 1 m, most gouges are 0.5 m or less. Ice gouges trend parallel to pack ice movement, which in turn generally moves parallel to isobaths and coastline configuration, Mean gouge trend in Norton Sound is west-east, in northeastern Bering Sea north-south.

The annual ice cover in this subarctic setting is thin (less than 2 m). Ice thick enough to gouge the substrate forms in compression and in shear zones; there moving pack ice collides with and piles up against other pack ice or stationary shorefast ice to develop numerous pressure ridges. Southward-moving pack ice in northeastern Bering Sea and westward-moving pack ice in Norton Sound converge with, and shear past, a 10-30-km wide shorefast ice zone that covers the shallow water offshore of the Yukon Delta. The intensity of ice deformation in this zone causes the highest gouge density in the study area. In contrast, northeastern Norton Sound is an area of ice divergence and only minimal ice gouging. The rest of Norton Sound and northeastern Bering Sea is either in ice-divergence areas or water depths are too great for ice to touch bottom, thus ice gouge density in these places is low. Gouging is extremely rare inshore of the shear zone, because shorefast ice is relatively static and protects inshore areas from the dynamics of the shear or compression zone and consequent ice gouging.

INTRODUCTION

Development of natural resources in northern latitudes has led to increased research on the effects of ice on shelf sediment in arctic regions such as the Beaufort Sea (Reed and Sater, 1974; Reimnitz and others, 1973; Reimnitz and others, 1977; Barnes and others, 1978). Until recently, however, research on ice gouging had not been done in subarctic regions such as the Bering Sea. A variety of gouge features are found in many areas of northeastern Bering Sea, even though ice conditions there are not as severe as in high-latitude arctic regions. Ice gouging into the sea floor is a potential hazard to future resource development and sea-floor installations such as pipelines and wellheads.

This paper discusses general ice conditions and ice movement in northeastern Bering Sea, the effect of ice as an erosional and depositional agent that influences the geomorphology and depositional history of the shallow subarctic Bering Sea shelf, and ice gouging as a potential hazard to resource development in and around Norton Basin. Terminology used is adopted from Barnes and others (1978), particularly in the use of the word “gouge” to describe the feature and the process of ice interacting with the sea floor.

Geographic Setting

The floor of northeastern Bering Sea is a broad, shallow epicontinental shelf (Figs. 1 and 2). Water depths in Chirikov Basin range from 20 m on the eastern side to 50 m in the central part. The shelf is generally flat and featureless except for a prominent series of ridges and swales that subparallel the coastline off Port Clarence. A large, elongate marine re-entrant forms Norton Sound, bounded on the north by Seward Peninsula, on the east by the Alaskan mainland, and on the south by the Yukon Delta. Except in a broad trough in the northern part of the sound, where depths are as great as 27 m, water depths in Norton Sound range from 10 to 20 m. The offshore part of the Yukon Delta is a zone of extensive shoals covering about S000 km^2 (Fig. 2)* Water depths 10 to 30 km offshore do not exceed 3 m, at which point there is a gentle break in slope and the depth increases to 10 m as far as 50 to 70 km from shore. The substrate of the Yukon prodelta, derived from the Yukon River, consists of coarse silt to very fine sand, whereas sediment in Chirikov Basin consists mostly of glacial gravel and transgressive fine sand (Nelson and Hopkins, 1972; McManus and others, 1977).

Ice Conditions and Movement

Ice overlies northern Bering Sea annually from November through June (Muench and Ahlnas, 1976; Shapiro and Burns, 1975). Depending on the severity of the winter, multiyear ice may migrate into Bering Sea from southern Chukchi Sea. Keel depth of 90% of the pack ice (any free-floating ice regardless of origin) is less than 1 m, although depths to 20 m have been reported (Arctic Research Laboratory, 1973).

Ice in open sea pans in Norton Sound is 0.7 to 1.2 m thick (Brewer, and others, 1977), but can get as thick as 2 m (Carole Pease, 1979, pers. comm.). Shorefast ice (ice anchored to the land) extends seaward to about the 10 m isobath and is best developed in the southern part of Norton Sound, around the Yukon Delta (Ralph Hunter, written comm., 1976; Dupré, 1977, Stringer and others, 1977) (Fig. 2).

Analysis of Landsat photographs (Dupré and Ray, Sec. II, this volume; Stringer and others, 1977; Muench and Ahlnas, 1976; Shapiro and Burns, 1975) has contributed to a preliminary understanding of ice dynamics in the Bering Sea. Pack ice in the northern Bering Sea originates from (1) in situ northeastern Bering Sea ice and (2) advected Chukchi Sea ice. Chukchi Sea ice can move through the Bering Strait and into the northern Bering Sea during episodes of rapid deformation and subsequent rapid southerly movement of pack ice caused by episodes of strong northerly winds (Shapiro and Burns, 1975).

Ice movement in the northeastern Bering Sea is controlled by the interplay of: (1) prevailing winter northeasterly geostrophic wind (Muench and Ahlnas, 1976), (2) erratic onshore wind (NOAA, 1974), (3) northward-flowing water current on the eastern side of the Bering Sea (Coachman and others, 1976) (Fig. 2), and (4) a counterclockwise current gyre in Norton Sound (Nelson and Creager, 1977) (Fig. 2). Late winter and early spring winds tend to push ice generally southward in northeastern Bering Sea, whereas waning late spring winds allow pack ice to be increasingly influenced by the northward-flowing water currents (Fig. 2).

In Norton Sound the dominant direction of ice movement is southwestward out of the sound. This drift creates a zone of divergence in the northeastern part of the sound and a zone of convergence in the southwestern or Yukon prodelta area of the sound (Dupré and Ray, Sec. II, this volume; Stringer and others, 1977) (Fig. 2). Periodic changes in wind and water current tend to move ice in and out of the sound, thereby making it possible for Bering Sea ice, or even advected Chukchi Sea ice, to work its way into the sound.

Zones of convergence can be zones of pressure-ridge or shear-ridge formation characterized by colliding, piling up, and deforming of the edges of fast ice and of pack ice (Reimnitz and Barnes, 1974). The best-developed pressure ridges in northeastern Bering Sea form around the Yukon Delta, where Bering Sea pack ice on the western prodelta and Norton Sound pack ice on the northern prodelta collides with the Yukon Delta fast ice (Dupré and Ray, Sec. II, this volume; Stringer and others, 1977).

Methods

Data for this study were gathered by the U.S. Geological Survey during September 1976, July 1977, and September 1978 aboard R/V SEA SOUNDER and during June and July 1978 aboard R/V KARLUK. Approximately 5,100 km of side-scan sonar trackline was obtained (Fig. 1). Normally, seismic units with energy sources of 200 kHz, 12 kHz, 7 kHz, 3.5 kHz, and 2 kHz were run simultaneously with side scan for additional bottom and subbottom information. The 6-m keel depth of the R/V SEA SOUNDER limited ship operations to water deeper than 8 m, whereas the shallow draft of the R/V KARLUK (1 m) allowed surveying in nearshore areas and in the shallow waters off the Yukon Delta. Geophysical and navigational operations are described in Thor (1978).

An EG and G side-scan sonar system*, consisting of a dual-channel graphic recorder and a towed transducer fish, was used to survey the sea floor. Side-scan sonar, an alternative method to conventional vertical echo sounding, employs a 105 kHz acoustic beam whose axis is slightly below horizontal. This acoustic beam can resolve topographic irregularities and objects on the sea

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floor with as little as 10 cm of relief. Reflected echoes are graphically recorded in a form that approaches a plan view map. Discussions on theoretical and practical aspects of side-scan operation and interpretation can be found in Belderson and others (1972) and Flemming (1976). Normally the Bide-scan was operated at 100-m sweep (the scan range on either side of the ship); although at times, the 50-m sweep was used to help resolve details of the gouging. In addition, a 200 kHz high-resolution fathometer was operated to measure the incision depth of ice gouges (Fig. 3). Vertical relief of gouges on the fathometer record or on the horizon line of monographs is generally masked by the recording of sea swell or ship's motion on the chart paper.

Gouge data were collected from the monographs by counting the number, measuring the trend, and noting the time of occurrence of all gouges seen on the records. Distortion of sea floor features on the sonograph occurs parallel to the line of travel because of the difference in ship's speed and the recorder's paper-advance speed. To obtain absolute compass trend of gouges, a distortion ellipse protractor, which corrects for the apparent angle produced by ship paper speed, was used to measure gouge angle with respect to ship's track. This information was then normalized at 10-km intervals. Normalization entailed two procedures: (1) correction of the number of observed gouges and (2) averaging of observed gouge trends. The number of observed gouges per 10-km interval was multiplied by l/sin (where angle equals the angle between ship's course and gouge trend) to correct for the fact that ship's course usually was not normal to the gouge trend. Any angle other than 90° between ship's course and gouge trend will give a false picture of gouge density (Barnes and others, 1978). Averaging observed gouge trends involved graphing the measured trends for the 10-km intervals and noting the average dominant and "subordinate trend or trends. Each average trend per 10-km interval was then plotted on the base map to define areas of similar gouge trend.

GEOMETRY AND TYPE OF ICE GOUGING

Two basic types of ice gouge have been recognized on the sea floor of northeastern Bering Sea: (1) single gouges and (2) multiple gouges or raking. A single gouge, the dominant type of ice-produced mark on the Bering Sea floor, is a groove produced by a single ice keel plowing through the surficial sediment (Figs. 3-A, 3-B, 4-A, 4-B, and 4-C) (Reimnitz and others, 1973; Reimnitz and Barnes, 1974). Single gouges are ubiquitous throughout Norton Sound; although the highest density occurs around the prodelta of the Yukon River (Fig. 5).

Single gouge widths range from 5 to 60 m; a width of 15 to 25 m is most common. Gouge patterns range from straight, through sinuous, to sharp-angled turns (Fig. 4). Incision depths of gouges, as measured on the sea-floor profile of monographs (Fig. 4-E) and on the 200 kHz fathometer record (Fig. 3-B), can be as deep as 1 m. Most gouges range in depth from 0.25 to 0.5 m or less. These figures may be conservative because of the geometric relation between the narrow width of the gouge and the spread of the acoustic cone of the fathometer transducer (Reimnitz and others, 1977). The original incision depth is impossible to determine unless the gouge is seen as the keel plows the bottom, because the gouge has subsequently been infilled.

Multiple gouges or raking (Figs. 4-F and 4-G) are produced when multi-keeled floes (such as pressure ridges) plow or rake the bottom sediment, creating numerous parallel furrows (Reimnitz and others, 1973; Reimnitz and

Barnes, 1974). Unlike single gouges, raking is not ubiquitous, but in the Yukon prodelta area the raking process is locally more prevalent than single gouging. Zones of raking are 50-100 m to several kilometers wide. The deepest incisions caused by raking observed on the records are about 1 m; but raking, like single gouges, usually produces incisions less than 0.25-0.5 m deep.

TREND AND DISTRIBUTION OF GOUGES

Analysis of the trend and distribution of gouges allows recognition of five areas of gouging with similar trends (areas I - V), and two large areas almost devoid of gouges (VI and shorefast ice zone) (Fig. 5). Absolute direction of ice movement cannot be predicted because criteria needed to make certain distinctions, such as gouge terminations, were not seen on the monographs.

In areas I and II (Fig. 5), the dominant trend of gouges is distinctly subparallel to isobaths and the coastline. There is more data scatter in areas III, IV, and V, but gouges again are generaly parallel to isobaths and the coastline. The greatest data scatter is seen in area V, but this may reflect the irregular bathymetry of ridge and swale topography off Port Clarence. Except for a couple of gouges off the northwestern end of St. Lawrence Island, area VI is devoid of ice gouges.

Density of ice gouges is as much as 25 times higher around the Yukon Delta area, where the water is 10 to 20m deep, than in other areas of northeastern Bering Sea (Table I and Fig. 5, areas I and 11). Not coincidentally, the Yukon prodelta is the largest expanse of shallow water in the study region, Here density of ice gouges can be as high as 75 gouges/km^2. Density of ice gouging is 60 times higher in water 10 to 20 m deep than in water 5 to 10 m deep or in water 20 to 39 m deep (Table II). Gouging has not been seen in water shallower than 5 m or deeper than 30 m.

Table I

Gouge Density by Area

Area	km^2	Trackline km	Total number of gouges	Average density (gouges/km^2*)
I	5,500	530	1,684	3*1B
II	8,000	1,005	5,080	5.05
III	9,500	1,100	917	0.83
IV	15,500	400	993	2.48
V	7,900	1,120	216	0.19
VI	50,400	766	4	0.03

*Assuming 1 km trackline of side-scan sonar is representative of 1 km^2.

Table 11

Gouge Density by Water Depth Interval

Depth interval(m)	km'	Trackline km	Total number of gouges	Gouges/km^2*
0-10	16,500	480	147	0.31
10-20	24,600	2100	8,593	4.09
20-30	32,700	1300	143	0.11
30-40	26,000	750	0	0
40-50	12,600	450	0	0
>50	5,400	170	0	0

*Same as Table 1.

GEOLOGICAL SIGNIFICANCE

Trend and Density of Gouges

The interplay of geomorphology, water depth, oceanic conditions, and location of compression or of shear zones (Fig. 2) determines the pattern of ice gouging in northern Bering Sea (Figs. 5 and 6). The orientation of ice gouges is dependent on the direction of ice drift under the influence of wind and water current. The dominant trend of ice gouges, therefore, in Norton Sound is east-west and in the Bering Sea north-south (Figs. 5 and 6).

Land promontories, such as the Yukon Delta, tend to block ice movement and to cause the formation of compression and shear zones. Formation of ice ridges around the Yukon Delta by the collision and shearing of moving pack ice with stationary shorefast ice accounts for the high density of ice gouges in areas I and II (Fig. 5). Areas within the zone of shorefast ice, such as the large area around the Yukon Delta (Fig. 5), are devoid of gouges. This is because only the edge of the shorefast ice is deformed by the pack ice, and subsequent deformation occurs continually seaward through a process of migration of the compression/shear zone through time (Dupré, 1978). Areas III and IV are characterized by low density of ice gouges (Fig. 5). Gouging in areas III and IV is the product of ridges formed in an ice-divergence zone by intercollisions of pack ice. Density of ice gouges in area V is low because this area is not in a convergence zone and at most places water depth exceeds normal ice-keel depths. Area VI does not seem to have any ice gouging because water depths (Fig. 2) exceed normal ice-keel depths (Fig- 5).

Age of Ice Gouges

Although no specific studies were made to determine the age and longevity of gouges, the gouges seem to be modern ephemeral phenomena that ‘recur annually. West of Port Clarence and in the nearshore area of Nome, ice gouges cut through ripple- and sand-wave fields that are in dynamic equilibrium with present wave or current motion (Nelson and others, 197S; Hunter and Thor, 1979) (Figs. 4-A and B). Here old gouges, highly modified by ripples or sand waves and new gouges suggests that gouges are being formed each winter.

A number of geologic processes act to rapidly destroy gouges once they have formed. Initial smoothing of ice gouges can be enhanced by: (1) the saturated, silty substrate that tends to seek a minimum relief equilibrium with sides of the gouge flowing or slumping toward the center of the gouge, and (2) the constant oscillatory pounding of wave motion on the sea floor that causes shear failure in the soft sediment (Henkel, 1970), causing rouge sides to collapse toward the center. The 'dish-shape' profiles of most gouges (Figs. 4-E and G) indicate that these are normal factors in the process of gouge destruction.

Repeated surveys of ice gouges in water less than 20 m deep in the Beaufort Sea have shown that gouges are frequently smoothed over completely in one season (Barnes and Reimnitz, 1979). In the Bering Sea, the ice-free season is 3 to 4 months longer than in the Beaufort Sea, allowing more time for considerably stronger open-water wave and current regimes of the Bering Sea to destroy gouges. In Norton Sound, storm waves and currents caused by advance and retreat of storm-surge water, in addition to normal tidal and geostrophic currents, resuspend and transport large quantities of surficial sediment (Cacchione and Drake, 1978; Nelson and Creager, 1977). Destruction of gouges is augmented by biological reworking of surficial sediment, an active process in Norton Sound (Nelson and others, in press). In summary, gouges will tend to be either eroded or buried because they are not in equilibrium with the dynamic physical processes on the sea floor. This reinforces the hypothesis that gouges in Bering Sea are present-day phenomena involving development of some new gouges each ice season.

Ice/Sediment Interaction

Ice acts as both an erosional and a depositional agent. Ice gouges, mixes, and deforms the substrate, and promotes current scour. Ice partially controls the geomorphology of the Yukon Delta (Dupré and Thompson, 1979).

Sediment mixing and deformation of the substrate are important processes in densely gouged areas such as the Yukon prodelta where pressure-ridge raking can gouge 1 m into the sediment. One event of pressure ridge raking can affect several square kilometers of sea floor.* Such an event can mix or disrupt several million cubic meters of sediment. A zone of deformed sediment in box core No. 48 (11-18 cm interval, Fig. 3-c) possibly represents an ice-gouge event.

Sharpness of gouge morphology is highly dependent on the type of substrate being gouged. The sediment of the Yukon prodelta is a moderately cohesive sandy silt that will hold a shape better than the coarser-grained sediment of central Norton Sound or offshore from Port Clarence (Clukey and others, 1978; Nelson and Hopkins, 1972; McManus and others, 1977). The gouge shown in figure 5-A and some gouges shown in figure 4 are examples of forms with sharp relief in a competent substrate. Gouges shown in figure 4-A are smoother in form because they cut into a cohesionless sand substrate in the Port Clarence area.

Prominent broad (50-150 m wide), shallow (0.6-0.8 m deep) depressions on the western Yukon prodelta are associated with areas of intense ice gouging and strong bottom currents (Larsen and others, 1979). Topographic disruption by ice gouges in these areas apparently causes flow separation in the strong

* tiea of gouging times depth of gouging. Ex. 2000 m (length of gouged zone) x 1000 m (width of gouged zone) x 0.5 m (depth of gouge) = 1,000,000 m^3.

currents, thereby initiating scour depression for extensive distances downstream. Consequently, large regions of scour may continue to expand away from intensely gouged areas (Fig. 4-H).

The extensive depositional sand shoals of the Yukon Delta front coincide with the seaward extent of shorefast ice, stamukhi (grounded pressure ridges) and zones of dense ice gouging (Figs. 2 and 6). Reimnitz and Barnes (1974) have noted this relation in the Colville Delta area of the Beaufort Sea. They postulate that pressure ridges and stamukhi act as sediment traps or dams, channelize winter currents, or bulldoze sediment to form shoals. Thus, a cycle is formed in the sense that shoal areas determine the extent of shorefast ice and the location of a shear zone and pressure ridges, which in turn cause shoals to develop. Duprè (1979) hypothesizes that the geomorphology of onshore and offshore parts of the Yukon Delta are similarly controlled by ice.

RESOURCE DEVELOPMENT: POTENTIAL HAZARDS

To summarize, gouges are ubiquitous throughout northeastern Bering Sea in water depths of 5 to 30 m. Ice-gouge density varies from rare to sparse in northeastern Bering sea and northern Norton Sound; maximum density is around the Yukon Delta (Fig. 6). Depth of ice gouges is fairly uniform throughout northeastern Bering Sea and seems to be independent of gouge density. Although maximum observed ice-gouge depth is about 1 m and maximum observed current scour about 1 m, the combination of these forces could affect the bottom to depths of several meters, thus presenting some design problems and potential hazards to installations in or on the sea floor. Pipelines and cables should be buried below the combined effective depth of ice gouging and current scour, plus a safety factor.

Special studies of nearshore areas off Nome and Port Clarence were conducted because both are potential centers for commercial development and activity. Nome, already a well established small city, is the focal point for barge traffic in the northern Bering Sea. Port Clarence, the only natural harbor in the northern Bering Sea has high potential for development as a site for future shipping activity.

Offshore Nome, being an area of ice divergence, is not heavily gouged. Although several gouges were found offshore, none were in water shallower than e m. Several of these gouges are probably not related to ice. They are very narrow (less than 1 m) compared to typical ice gouges (more than 5 m wide) and are possibly produced by anchor, anchor chain, or cable drag from the tugs and barges that frequent the port of Nome.

Several gouges were found near Port Clarence at the northern end of the Port Clarence spit and on the northern side of Port Clarence inside the tidal inlet. But, none occurred in water less than 8 m deep.

ACKNOWLEDGMENTS

We thank William Dupré, University of Houston, for data concerning pack ice movement and shorefast ice limits; Ralph Hunter, U. S. Geological Survey, for data on shorefast ice limits: and David Drake U. S. Geological Survey, for data on ice thickness. Jim Evans and Ron Williams compiled data on gouges from monographs. Valuable discussions on ice processes and interpretation of monographs were held with Peter Barnes, Erk Reimnitz, and Larry Toimil, U.S. Geological Survey. Marybeth Gerin helped with figure layout and drafting. Erk Reimnitz and Harry Cook, U.S. Geologcial Survey, made helpful comments on the manuscript. The officers, crew, and technical staff of the R/V SEA SOUNDER made data collection a successful and enjoyable endeavor.

The cruises were supported jointly by the U.S. Geological Survey and by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration, under which a multi-year program responding to the needs of petroleum development of the Alaska continental shelf is managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) Office.

REFERENCES CITED

Arctic Ressearch Laboratory

1973 Ice Character in Bering and Chukchi Seas

Naval Oceanic Systems Center, Dept. of Navy, San Diego, CA.

Barnes, P.W., David McDowell, and Erk Reimnitz

1978 Ice gouging characteristics: Their changing patterns from 1975-1977, Beaufort Sea, Alaska: U. S. Geological Survey Open File Report 78-730, 42 pp.

Barnes, P.W., and Erk Reimnitz

1979 Ice gouge obliteration and sediment redistribution event; 1977-1978, Beaufort Sea, Alaska, U.S. Geological Survey Open File Report 79-848, 22 pp.

Belderson, R.H., N.H. Kenyon, A.H. Stride, and A.R. Stubbs

1972 Monographs of the sea floor: Elsevier Pub. Co., New York, 185 pp.

Brewer, W.A., and others

1977 Climatic atlas of the outer continental shelf waters - coastal region of Alaska: v. 2 - Bering Sea, Arctic Environmental Information and Data Center, Anchorage, Alaska.

Cacchione, D.A., and Drake, D.E.

1978 Sediment transport in Norton Sound, Northern Bering Sea, in Environmental Assessment of the Alaskan Continental Shelf, Annual Report of Principal Investigators for the year ending March 1978, Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, 12: 308-450.

Clukey, E.C., Hans Nelson, and J.E. Newby,

1978 Geotechnical properties of northern Bering Sea sediment: U.S. Geological Survey Open File Report 78-408, 48 pp.

Coachman, L.K., K. Aagaard, and R.B. Tripp

1976 Bering Strait: The regional physical oceanography: Washington University Press, Seattle, 186 pp.

Dupré, W.R.

1977 Yukon Delta coastal processes study: Environmental Assessment of the Alaskan Continental Shelf, Annual Report of Principal Investigators for the year ending March 1977, Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of commerce, 14: 508-553.

Dupré, W.R.

1978 Yukon Delta coastal processes study: Environmental Assessment of the Alaskan Continental Shelf, Annual Report of Principal investigators for the year ending March 1978, Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, 11: 384-446.

Dupré, W.R., and R. Thompson

1979 The Yukon Delta: A model for deltaic sedimentation in an ice dominated environment: Proceedings Offshore Technology Conference, v. 1, paper no. 3434: 657-664.

FATHAUER, T.F.

1975 The great Bering Sea storms of 9-19 November, 1974: Weatherwise Magazine, American Meteorological Society, 28: 76-83.

Flemming, B.W.

1976 Side-scan sonar: A practical guide, in Side Scan Sonar, A comprehensive presentation: E.G. and G. environmental Equipment Division, Waltham, MA, A-1 - A-45.

Fleming, R.H., and Heggarty, D.,

1966 Oceanography of the southeastern Chukchi Sea, in: Willimovsky M.H., and J.M. Wolfe, eds., Environment of Cape Thompson region Alaska: Washington, D.C., U.S. Atomic Energy Commission 697-754.

Goodman, J.R., Lincoln, J.H., Thompson, T.G., and Zeusler, F.A.

1941 Physical and chemical investigations: Bering Sea, Bering Strait, Chukchi Sea during the summers of 1937 and 1938: Washington University publications in Oceanography, v. 3, no. 4 105-169 and appendix 1-117.

HENKEL, D.J.,

1970 The role of waves in causing submarine landslides: Geotechnique, v. 10, 75-80.

Hunter, R. E., and Thor, D.R.

1979 Depositional and erosional features of the northeastern Bering Sea inner shelf (abs.): Amsterdam, International Association of Sedimentologists, Program and Abstracts, Eleventh International Congress in Sedimentology, (in press).

Husby, D.M.

1969 Report of oceanographic cruise U.S.C.G.C. NORTHWIND, northern Bering Sea-Bering Strait-Chukchi Sea, July 1969: U.S. Coast Guard Oceanographic Report, no. 24, 75 pp.

Husby, D.M.

1971 Oceanographic investigations in the northern Bering Sea and Bering Strait, June-July 1969: U.S. Coast Guard Oceanographic Report **no.** 49, 50 pp.

LARSEN, M.C., HANS *NELSON,* and **D.R.** THOR

1979 Geologic Implications and potential hazards of scour depressions **on** Bering shelf, Alaska: Environmental Geology, v. 3, 39-47.

McManus, D.A., V. **Kolla, D.M.** Hopkins, and **C.H.** Nelson,

1977 Distribution of **bottom** sediments on the continental shelf, northern Bering Sea: U.S. Geological Survey Professional Paper 759-C, **C1-C31.**

McMANUS, D.A., and C.S., **SMYTH**

1970 Turbid bottom water on the continental shelf of northern Bering Sea: Journal of Sedimentary Petrology, v. 40, 869-877.

MUENCH, R.D., and **K. AHLNAS**

1976 Ice movement and distribution in the Bering **Sea** from March to June 1974: Journal of Geophysical Research, v. 81, no. 24, 4467-4476,

National Oceanic and Atmospheric Administration

1974 Local **climatological** data - annual summary with comparative data for **Nome, Unalakeet, Shismaref** and Wales, **Alaska.**

NELSON, **HANS,** and J. **CREAGER**

1977 Displacement **of** Yukon-derived sediment from Bering Sea to **Chukchi** Sea during Holocene time: **Geology, v. 5,141-146.**

Nelson, Hans, M E. Field, D.A. Cacchione, and D.E. Drake

1978 Areas of active large-scale sand wave and ripple fields with scour potential on the Norton Basin sea floor, in: Environmental Assessment of the Alaskan Continental Shelf, Annual Report of Principal Investigators for the year ending March 1978, Environmental Research Laboratory, Boulder, Colorado. NOAA, U.S. Department of Commerce, v. 12, 291-307.

Nelson, Hans, and D.M. Hopkins

1972 Sedimentary processes and distribution of particulate gold in the northern Bering Sea: U.S. Geological Survey Professional Paper 689, 27 pp.

Nelson, Hans, R.W Rowland, Sam Stoker. and B.R. Larsen

1980 Interplay of physical and biological sedimentary structures of the Bering Sea epicontinental shelf, in Hood, D. (cd.), Bering Sea Shelf: Oceanography and Resources: NOAA, (in press).

Pratt, R., and F. Walton,

1974 Bathymetric map of the Bering shelf: Boulder, Colorado, Geological Society of America, scale 1:1,440,000.

Reed, J.C., and J.E. Sater, (eds.)

1974 The coast and shelf of the Beaufort Sea: Arlington, Virginia Arctic Institute of North America, 750 pp.

Reimnitz, Erk, and P.W. Barnes

1974 Sea ice as a geologic agent on the Beaufort Sea shelf of Alaska in Reed, J.C., and J.E. Sater (eds.), The coast and shelf of the Beaufort Sea: Arlington, Virginia, Arctic Institute of North America, 301-351.

Reimnitz, Erk, P.W. Barnes, and T.R. Alpha

1973 Bottom features and processes related to drifting ice: U.S. Geological Survey Miscellaneous Field Studies Map MF-532.

REIMNITZ, ERK, P.W. BARNES, L.J. TOIMIL, and JOHN MELCHIOR

1977 Ice gouge recurrence and rates of sediment reworking, Beaufort Sea, Alaska: Geology, v. 5, 405-408.

Sackinger, W.M., and J.C. Rogers

1974 Dynamics of break-up in shorefast ice in Reed, J.C., and J.E. Sater (eds.), The coast and shelf of the Beaufort Sea: Arlington Virginia, Arctic Institute North America, 367-376.

Shapiro, L.H., and J.J. Burns

1975 Satellite observations of sea ice movement in the Bering Strait region: Climate of the Arctic, Report, University of Alaska, Fairbanks, 379-386.

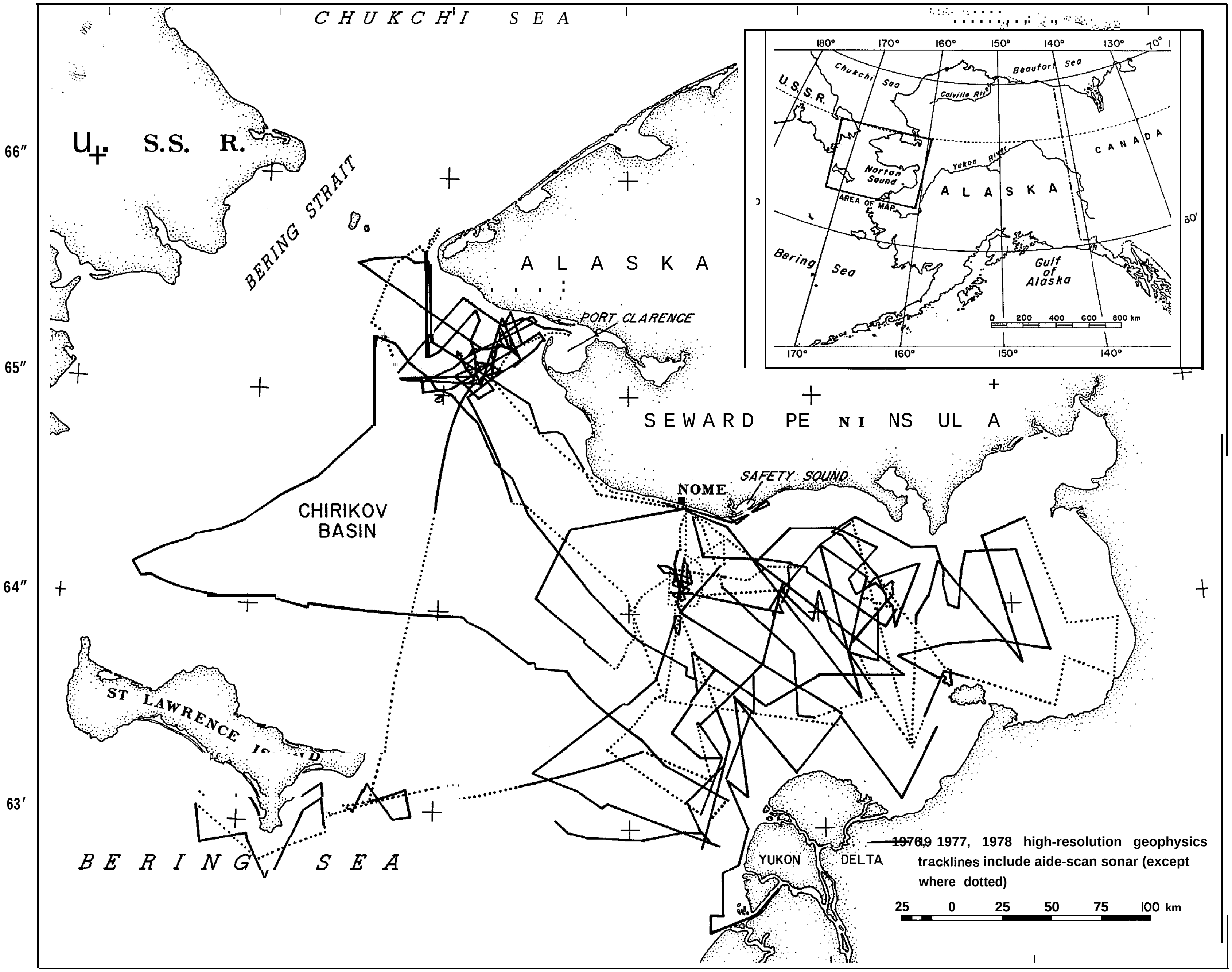
Stringer, W.J., S.A. Barrett, Nita Blavin, and Diane Thomson

1977 Morphology of Beaufort, Chukchi, and Bering Seas nearshore ice conditions by means of satellite and aerial remote sensing: Environmental Assessment of the Alaskan Continental Shelf, Annual Report of Principal Investigators for the year ending March 1977, Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 15,' 42-150.

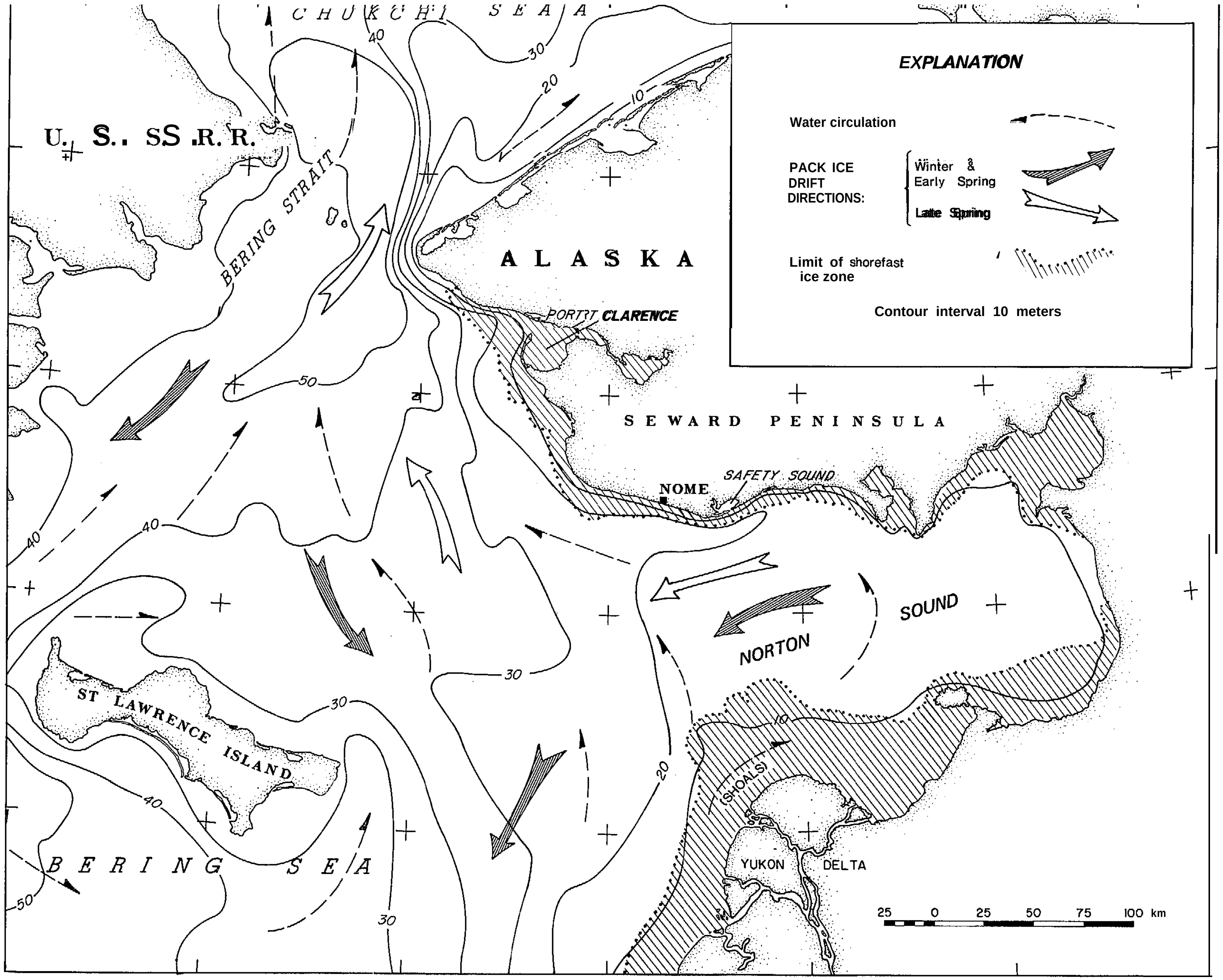
Thor, D.R., and Hans Nelson

1978 Continuous seismic reflection profile records, SEA 5-77-BS Cruise northern Bering Sea: U.S. Geological Survey Open File Report 78-608, 8 pp., 2 pls.

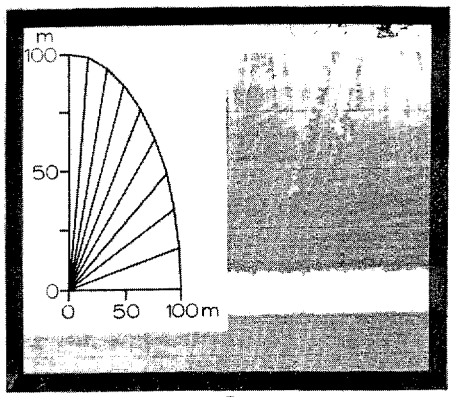
List of Figures



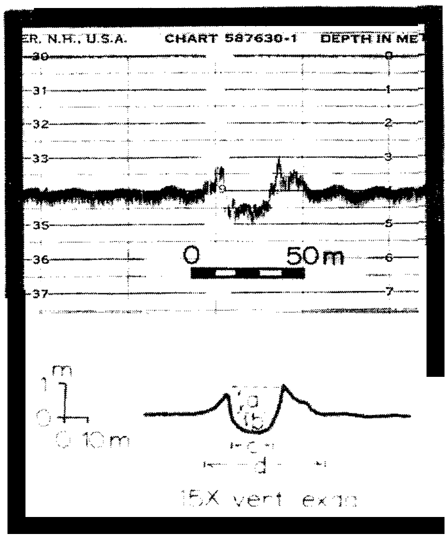
CHUKCHI SEA
U.S.S.R.
66°
65°
64°
63°
BERING STRAIT
ALASKA
PORT CLARENCE
SEWARD PENINSULA
NOME
SAFETY SOUND
CHIRIKOV BASIN
ST LAWRENCE ISLAND
BERING SEA
YUKON DELTA
1976, 1977, 1978 high-resolution geophysics tracklines include side-scan sonar (except where dotted)
25 0 25 50 75 100 km
180° 170° 160° 150° 140° 130° 70°
Chukchi Sea
Beaufort Sea
U.S.S.R.
Colville River
CANADA
Yukon River
Norton Sound
AREA OF MAP
ALASKA
Bering Sea
Gulf of Alaska
0 200 400 600 800 km
170° 160° 150° 140°



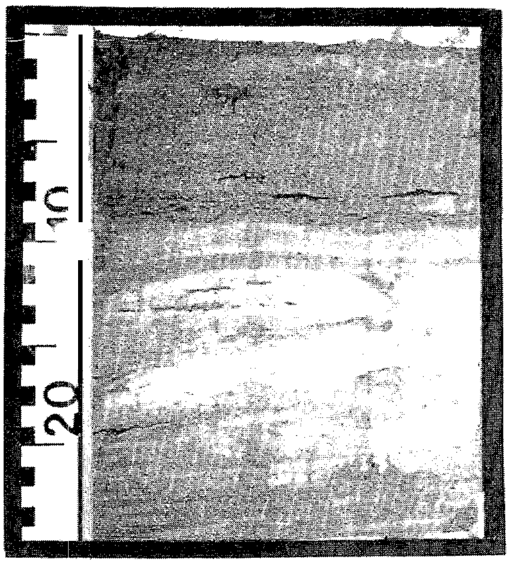
CHUKCHI SEA
U.S.S.R.
BERING STRAIT
ALASKA
PORT CLARENCE
SEWARD PENINSULA
NOME
SAFETY SOUND
NORTON SOUND
ST LAWRENCE ISLAND
(SHOALS)
YUKON DELTA
BERING SEA
66°
65°
64°
63°
10
20
30
40
50
EXPLANATION
Water circulation
PACK ICE DRIFT DIRECTIONS:
Winter & Early Spring
Late Spring
Limit of shorefast ice zone
Contour interval 10 meters
25 0 25 50 75 100 km


m
100
50
0
0
50
100m

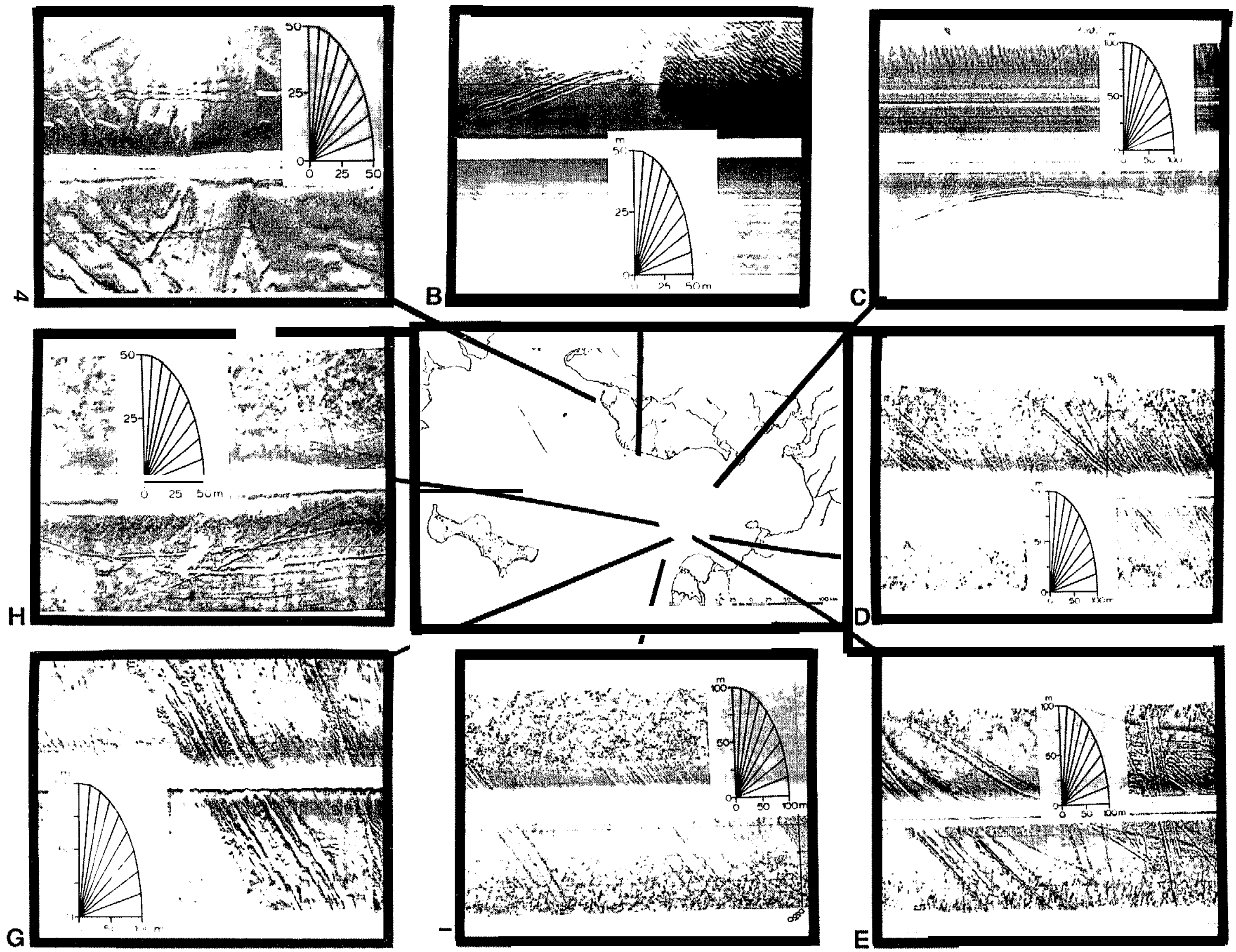
A

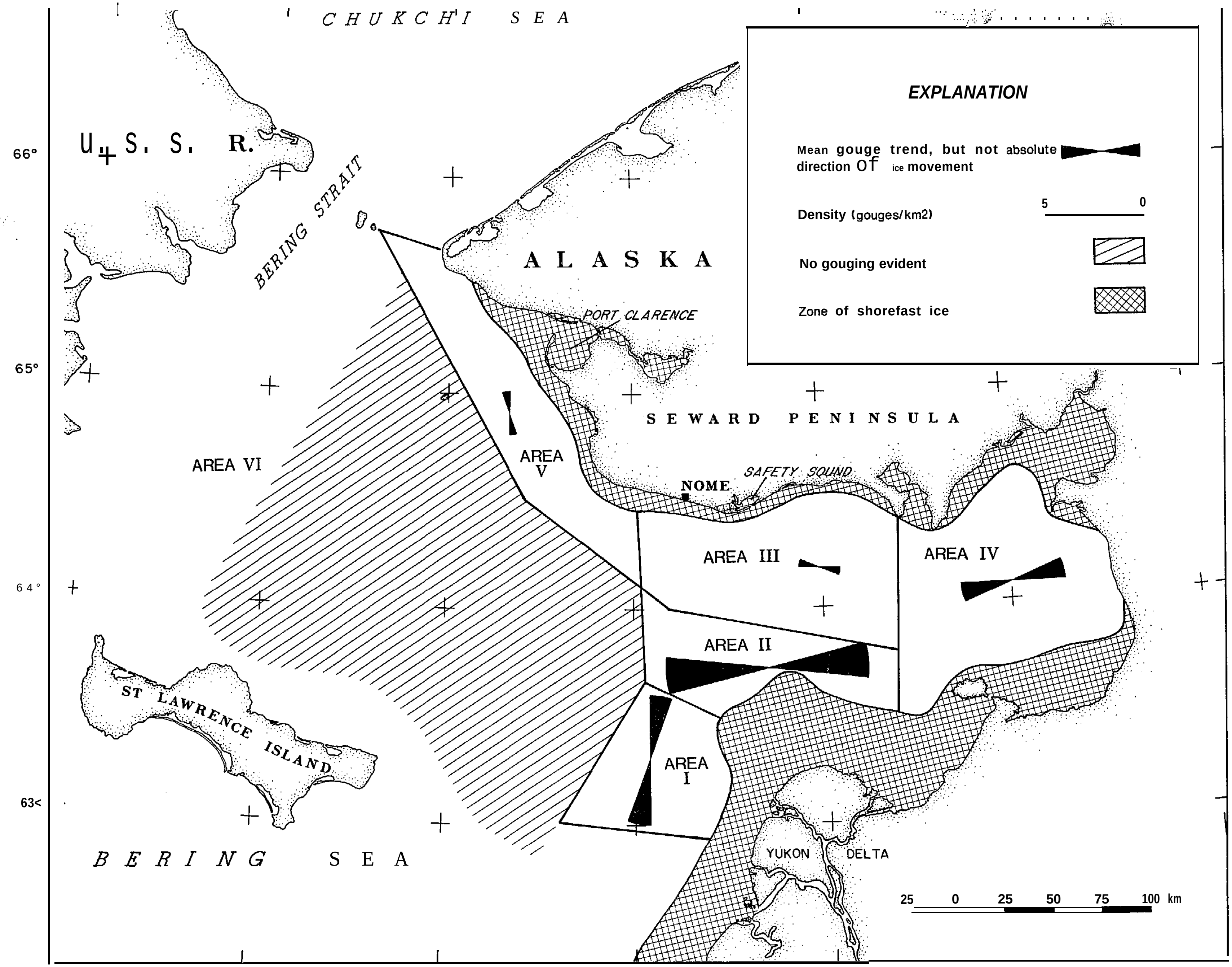

ER. N.H., U.S.A.
CHART 587630-1
DEPTH IN ME
30
31
32
33
35
36
37
0
1
2
3
5
6
7
0
50m
1 m
0
0 10m
d
15X vert. exag.

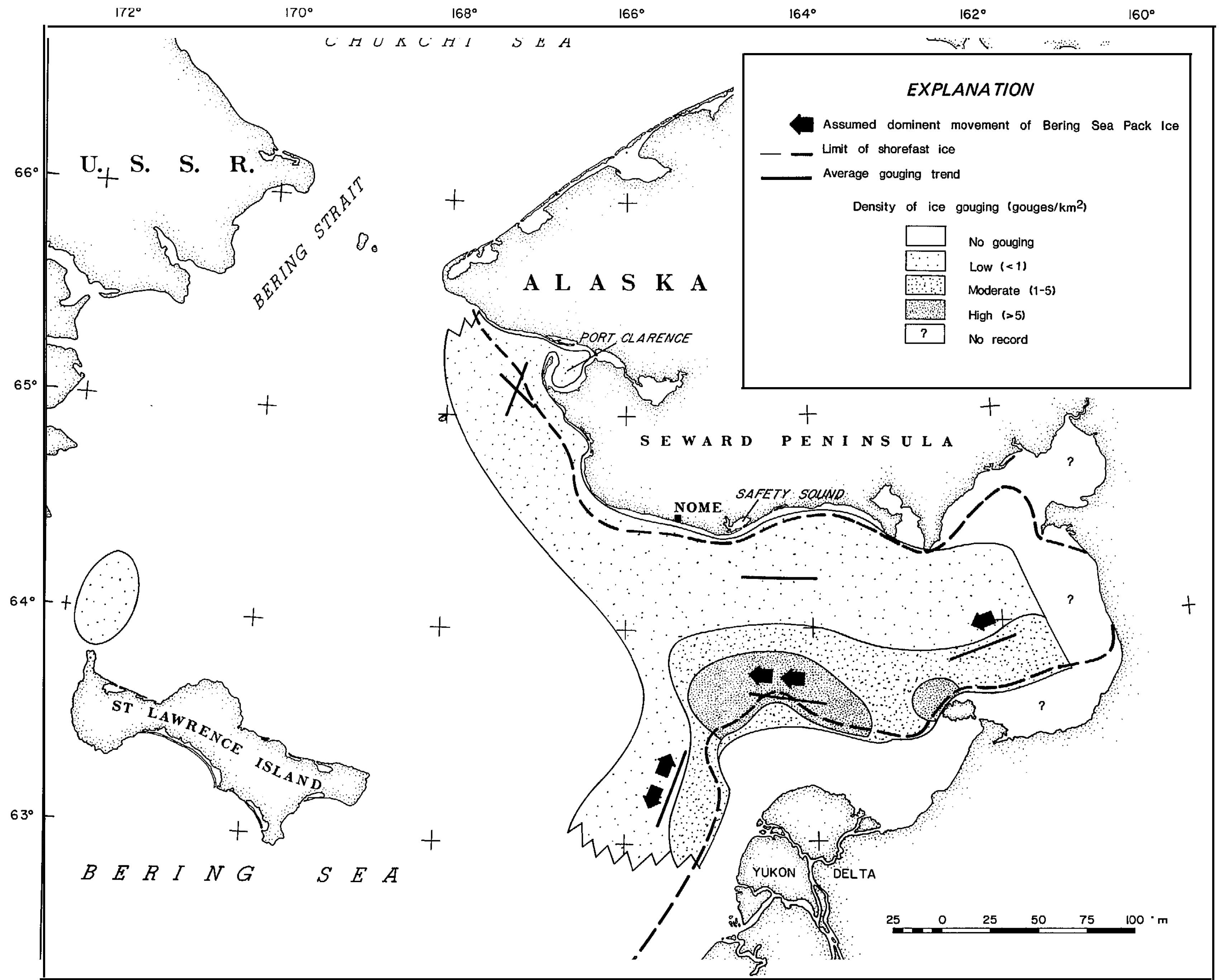
B


10
20

C


4
B
C
H
D
G
I
E
50
25
0
0 25 50
25 50m
50
100
100m


CHUKCHI SEA
U. S. S. R.
BERING STRAIT
ALASKA
EXPLANATION
Mean gouge trend, but not absolute direction of ice movement
Density (gouges/km2)
5
0
No gouging evident
Zone of shorefast ice
PORT CLARENCE
SEWARD PENINSULA
AREA V
AREA VI
NOME
SAFETY SOUND
AREA III
AREA IV
AREA II
AREA I
ST LAWRENCE ISLAND
BERING SEA
YUKON DELTA
66°
65°
64°
63°
25
0
25
50
75
100 km


EXPLANATION
Assumed dominent movement of Bering Sea Pack Ice
Limit of shorefast ice
Average gouging trend
Density of ice gouging (gouges/km2)
No gouging
Low (<1)
Moderate (1-5)
High (>5)
No record
CHUKCHI SEA
BERING STRAIT
U. S. S. R.
ALASKA
PORT CLARENCE
SEWARD PENINSULA
NOME
SAFETY SOUND
ST LAWRENCE ISLAND
BERING SEA
YUKON DELTA
172°
170°
168°
166°
164°
162°
160°
66°
65°
64°
63°
25 0 25 50 75 100 km