DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

HIGHLIGHTS FROM RECENT BEAUFORT SEA SEDIMENTOLOGIC INVESTIGATIONS

by

Erk Reimnitz[1], P.W. Barnes[1]. S.C. Wolf[1],
S.M. Graves[1], E.W. Kempema[1], and D.M. Rearic[1]

Open-File Report 85-502

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards (and stratigraphic nonclature).

[1]USGS, Menlo Park, California

Figure 1. Map of the study area, roughly defining the shelf break between the 60 and 200 m isobaths and the farthest seaward points along our 10 survey tracks to which ice gouges can be traced with different survey tools. The locations for bottom photographs and a current meter mooring are shown.

Figure 2. Simpson Lagoon paleoshorelines (after Naidu et al, 1984) and our interpretation of lagoon profile evolution along shaded N-S line. Depths to massive fluvial gravel generalized from soil borings.

Figure 3. The yearly variation in the average disruption width per kilometer observed in each of the corridors.

Figure 4. Trajectories of bottom and surface current drifters from their August 1983 drop points to their late 1983 and summer 1984 recovery points. In contrast to the westward trajectories from previous studies in the western Beaufort Sea, nearly all drifters released near the border traveled eastward.

Figures 5A and 5B. Isopach maps of Holocene marine sediment accumulations in the western part of the study area with available borehole locations. Arrows mark the locations of cut-and-fill channels, and adjacent numbers give depth of channel fill in meters.

HIGHLIGHTS FROM RECENT BEAUFORT SEA SEDIMENTOLOGIC INVESTIGATIONS

by

Erk Reimnitz, P.W. Barnes, S.C. Wolf, S.M. Graves, E.W. Kempema, and D.M. Rearic

The Deepwater Limit of Ice Gouging on the Beaufort Sea Shelf

Ice gouge patterns on the Alaskan Beaufort Sea shelf extend from the coast seaward to water depths of at least 64 m (Figure 1). The maximum measured draft of sea ice in the Arctic Ocean, however, is only 47 m (Lyon, 1967). Thus the numerous gouges seaward of the 47 m isobath might be relict, cut during times of lower sealevel many thousand years ago (Lewis, et al., 1982). Furthermore, sedimentation rates along the shelf break are very low, and a rain of particles settling vertically in a quiet environment on these bedforms would not likely obliterate them soon.

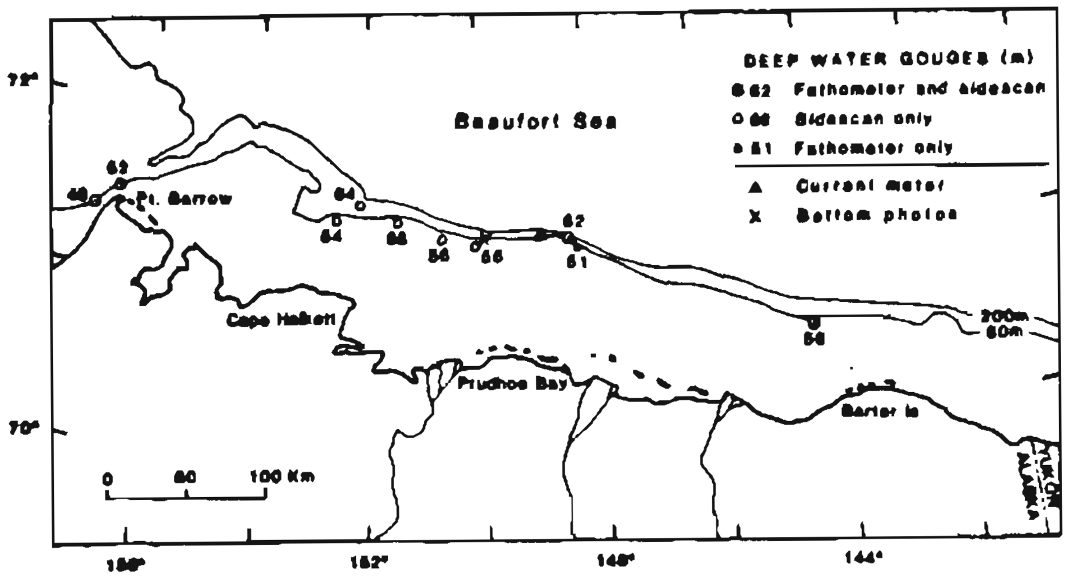


Figure 1. Map of the study area, roughly defining the shelf break between the 60 and 200 m isobaths and the farthest seaward points along our 10 survey tracks to which ice gouges can be traced with different survey tools. The locations for bottom photographs and a current meter mooring are shown.

Several lines of evidence suggest, however, that these deep-water gouges are modern features (Reimnitz, et al., 1984). Continuous, 380-day current records at 60 m depth near the shelf edge show that the environment is dynamic, with long-period current pulses up to 70 cm/sec capable of transporting medium to coarse sand as bedload and fine sand in intermittent suspension. A rich benthic fauna also reworks the upper 20 cm of sediment and provides sedimentary particles for current transport. One would expect that the water depth along the seaward limit of the ice gouged shelf surface, if of relict origin, should shoal eastward in the region where isostatic rebound after deglaciation has occurred. The depth limit of gouging instead varies irregularly between 49 and 64 m water depth along the shelf edge, as one would expect from an interaction of sporadic ice reworking to 64 m depth during the last 200 years and continuous reworking by currents and organisms. For offshore petroleum development, this interpretation is important in that bottom-founded structures at >47 m water depth may not be safe from ice impact.

The Eroding Coast of the Alaskan Beaufort Sea, its Sediment Supply and Sinks

Using two 1:50,000-scale NOS charts, from surveys spaced 30 years apart, this study delineates patterns in coastline changes and sediment yields from erosion for 344 kms of Alaska's Beaufort Sea coast. Excluding the large Colville Delta, which advances at an average rate of 0.4 m/yr, the overall coastline is eroding at a rate of 2.5 m/yr. In places the local long-term erosion rates are as high as 18 m/yr, while accretion rates near the active mouths of the Colville River are as high as 20 m/yr. The coastal plain deposits in the western third of the study area are fine-grained mud; here average erosion rates are highest (5.4 m/yr). The rest of the study area is composed of sandy to gravelly deposits, which erode at a rate of 1.4 m/yr. This difference suggests that the grain size of bluff material exerts the dominant control on coastal retreat rates. Other important factors include bluff height, ice content and thaw settling, bluff orientation, and degree of exposure to the marine environment. Vertical crustal motion has not played an important role during Holocene time, as evidenced by the constant elevation of 120,000 yr old shoreline deposits traceable for 200 km from Barrow to the Colville River (Hopkins and Carter, 1980), and by 30 yr observations on tidal benchmarks along the Beaufort Sea coast.

In calculating sediment yield we consider not only the materials in coastal bluffs above sea level, but the submerged profile to 2m depths. Assuming this profile to be in dynamic equilibrium, we account for material eroded to a depth of 2m below msl as the profile migrates landward. The upper part of this roughly 5 m thick eroded section contains up to 75% ice, and the sediment yield is reduced accordingly in our calculations. The annual yield from coastal retreat thus calculated is $2.5 \times 10^6 m^3$, with the offshore contribution slightly higher than the onshore contribution. Based on our evaluation of sparse data on sediment carried by Arctic streams, we estimate the annual sediment yield from the adjacent drainage areas is $2 \times 10^6 m^3$, a rate that is slightly less than that from coastal erosion.

Knowledge of recent patterns in coastal retreat, coupled with knowledge of factors controlling this retreat, allows us to estimate the configuration and location of past and future coastlines (Figure 1). We find no support for the theory of Wiseman, et al. (1973), that the evolution of coastal embayments and lagoons begins with the breaching and coalescing of large lakes, followed by thaw settlement. Rather, the existence of older, coarse-grained, and erosion-resistant barrier-island and beach deposits excerts a strong influence on the locus and shape of some of the newly forming embayments. Others, however, remain unexplained.

If the present coastal-retreat rates have been sustained since sea level approached its present position about 5,000 yr BP, then the corresponding ancient shoreline (at 5,000 yr BP) could have ranged from 7 to 27 km seaward of the present one, in accordance mainly with grain-size variations in coastal bluffs. Furthermore, if erosion occurred only to 2-m water depths, as assumed in our sediment yield calculations, 10-20 km wide and 2m deep platforms should be widespread around the Arctic Ocean. Since such wide platforms do not exist, and since we can show that thaw settling contributes much less to the shape of the marine profile in the Arctic than previously proposed (Klyuyev, 1965; Tomirdiaro, 1975) coastal retreat must be associated with erosion reaching to depths much greater than 2 m. The sediment yield therefore could be many times larger than we calculated. A growing body of evidence from interpretations of boreholes, seismic reflection data, Foraminifera, and soil engineering properties of surficial sediments shows that the seafloor of the inner shelf seaward to at least 20-m depth is indeed an erosional surface truncating older strata. Considering the rapid, and deep-reaching erosion, shallow bays, lagoons, and barrier islands do not provide adequate long-term sediment sinks accommodating materials introduced at the present high rates. Modern deposits found in some of these features may be held there for some time, but are soon re-introduced to the sea as the shelf profile moves through the locality (Figure 2). We therefore conclude that the sediment yield from coastal retreat and rivers largely

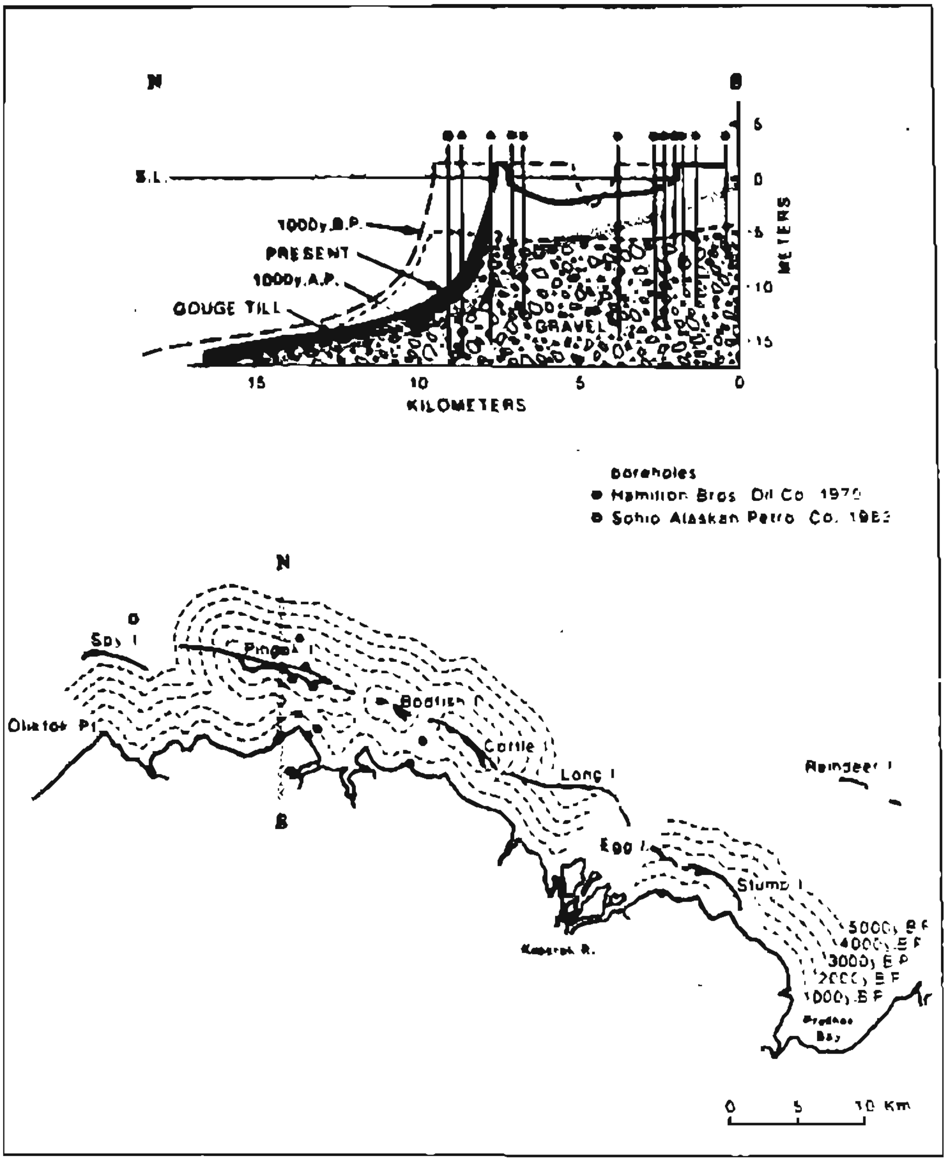


Figure 2. Simpson Lagoon paleoshorelines (after Naidu et al, 1984) and our interpretation of lagoon profile evolution along shaded N-S line. Depths to massive fluvial gravel generalised from soil borings.

by-passes the shelf. Part of this sediment flux is seen in form of a 2-3 m thick, transient "roto-till" layer draped over large regions of the open shelf, a result of ice-keels plowing up underlying strata and mixing these sediments with modern materials and fauna.

Within the conterminous United States, the Gulf of Mexico coast has the highest erosion rates. The Texas coast, fringed by a low coastal plain of unconsolidated sediments, marked by vertical crustal stability, and therefore in some respects similar to that of the Beaufort Sea, retreats about 1.2 m/yr (May, et al, 1983), or about half the Beaufort Sea average. Since coastal erosion in Arctic regions is restricted to three summer months when waves and coastal currents are active, erosion rates there must be multiplied by a factor of four for a meaningful comparison with the rates of ice-free low-latitude coasts, which experience waves and currents year round.

Accordingly, Arctic erosion rates are 8 times higher than Texas rates, when compared on a year round basis. Additionally, Arctic fetches are severely restricted during the navigation season by the ever present polar pack, unlike the long and constant Texas fetch which allows for generation of larger and more pervasive waves. Lastly, most of the damage to low latitude coastlines is done by winter storms, when the Arctic coastline is well protected by ice. Classic wave theory therefore can not account for the sediment dynamics of the Arctic coastal zone.

Considering the rapid shoreline development by petroleum industry, our poor understanding of Arctic coastal processes begs for accelerated research in this unique setting.

Rates of Sediment Reworking by Sea Ice in the Beaufort Sea

Repetitive sidescan sonar and precision bathymetric surveys made between 1975 and 1980 were used to assess seafloor changes due to ice gouging along 8 shore-perpendicular corridors, and to gain insight into the question of when, where, and how gouges are produced on the inner shelf of the Beaufort Sea. We find that the percentage of seafloor area impacted annually by ice keels increases from the coast seaward to at least the 25m isobath, the offshore limit of repeated surveys. Up to 7.4% of the total seabed area scanned along the roughly 15 km-long corridors may be disrupted in a single year (Figure 3). Total seafloor disruption in single km-long segments ranges as high as 60 %. The maximum new gouge incision depth measured is 1.4 m. High gouge densities are associated with wide, shallow "multiplet" gouging events (Barnes, et al, 1984), where long sections of pressure-ridge keels raked the bottom. Small annual variations in the amount and intensity of new gouges indicate rather consistent reworking of the inner shelf by this process. Where shoals occur within survey corridors our seafloor monitoring has documented the predicted sheltering of seafloor areas on the landward side.

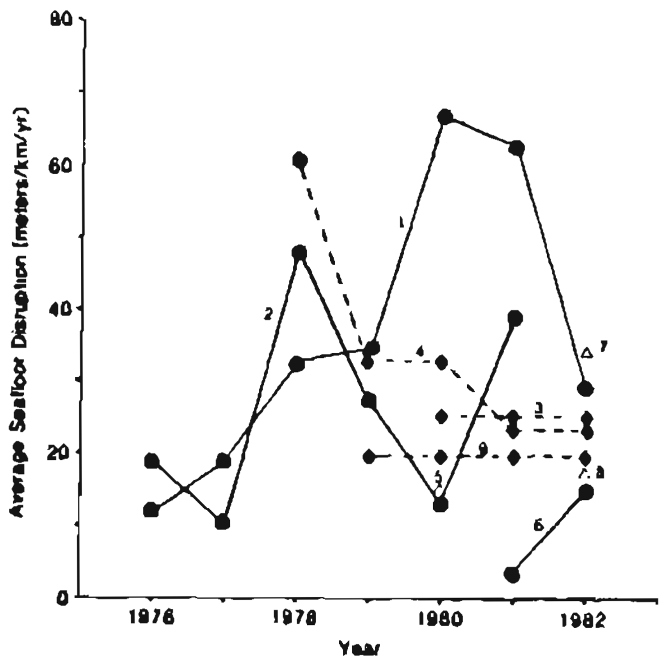


Figure 3. The yearly variation in the average disruption width per kilometer observed in each of the corridors.

Flow Divergence near U.S./Canada Boundary confirmed from Recent Drifter Releases

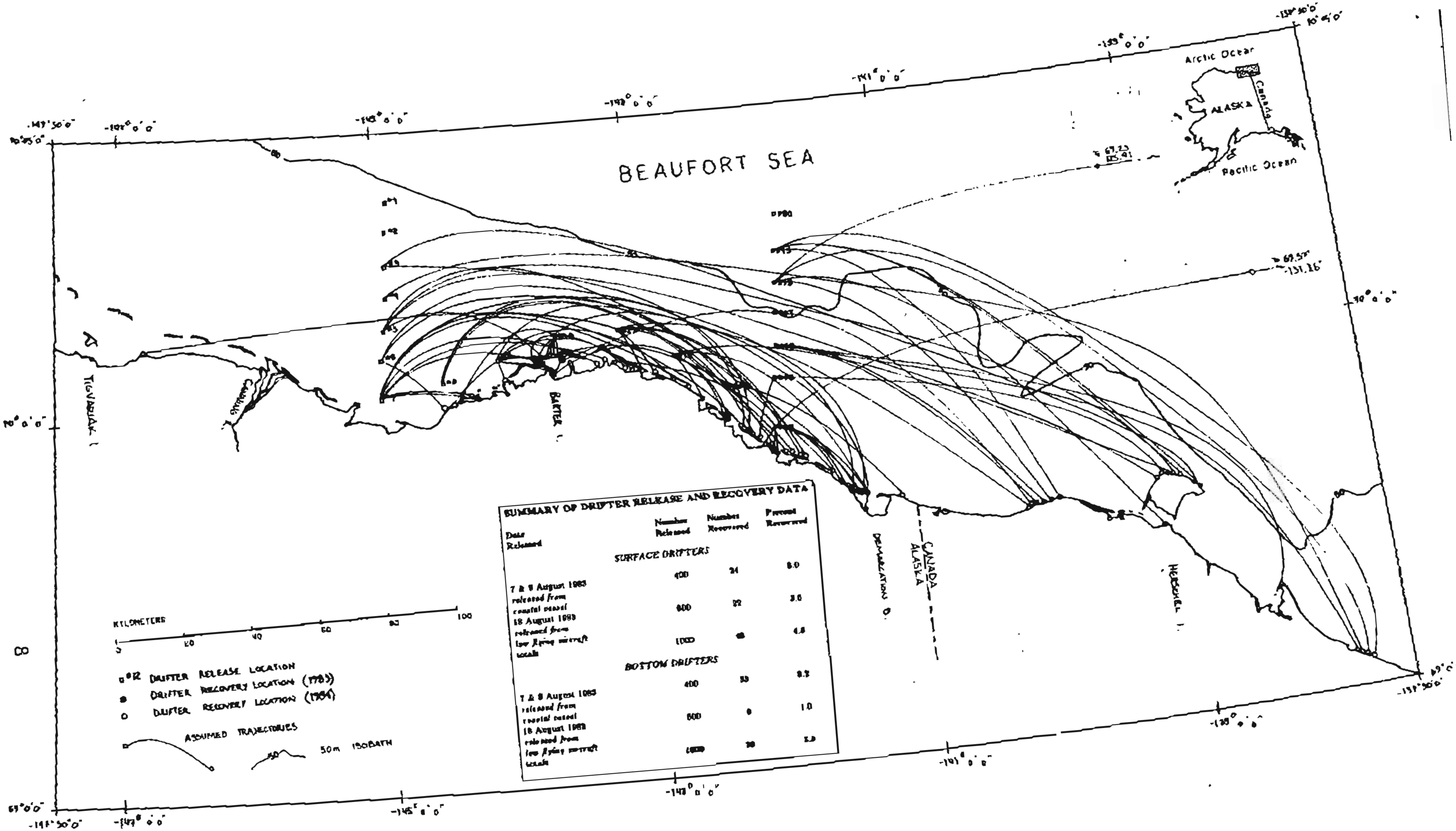
Ice gouges on the Alaskan Beaufort shelf are produced by keels plowing from northeast to southwest, semi-parallel to the coastline (Barnes et al, 1984). In contrast, gouges on the Canadian Beaufort shelf are produced by ice plowing from northwest to southeast (Lewis, 1977). The divergence indicated by changing ice gouge patterns across the international border suggests a divergence in the water circulation on the continental shelf. On the Alaskan shelf, currents are wind-driven and predominantly westerly (Matthews, 1981), while off the Mackenzie River, easterly currents predominate (Harper, in press). Again, a divergence is indicated. In 1972 surface drifters were released on the Alaskan shelf from about Barter Island to the west. Most of the drifters traveled westward, as would be expected. However, several drifters originating from the easternmost drop points moved eastward into Canada, also suggesting a divergence (Barnes and Toimil, 1979).

In 1983 both surface- and bottom-drifters were released in the vicinity of Barter Island to better define the suggested divergence. Virtually all of the recovered drifters had traveled east (Figure 4), apparently largely in response to predominant westerly winds which followed the August release. A few of the drifters traveled several hundred km to recovery sites east of the Mackenzie River.

An examination of several years of Landsat imagery of the eastern Alaskan Beaufort Sea shows numerous sediment plumes deflected eastward from their points of origin, indicating easterly surface drift. This agrees with Barter Island wind records, which show that summer winds from the west are much more common here than at Prudhoe Bay. Based only on late 1983 drifter recoveries, the minimum velocities for surface and near-bottom waters are between 0.3 to 18.2 km/day. Thus, suspended matter and any future pollutants entrained in inner shelf waters can be expected to travel eastward at similar or faster speeds. The study confirms our theory that coastal currents off eastern Alaska have a strong eastward component, with a divergence in the area between 141 and 143°W.

Anchor Ice and Sediment Dynamics

Much indirect evidence for the formation of anchor ice and related processes incorporating sediment into the ice canopy has been seen by OCSEAP investigators and others in the Beaufort Sea (i.e. Barnes, et al., 1982; Osterkamp and Gosink, 1982). Anchor ice is well known from high latitude streams and lakes, largely because it affects water flow characteristics and the operation of hydro-electric plants (Wigle, 1970; Arden and Wigle, 1972). Engineers concerned with such operations have observed the capability of anchor ice to raise large amounts of sediment, including 30 kg boulders, off the bottom. But no concerted effort has ever been made to relate anchor ice to sediment dynamics. Very little is known about anchor ice in the ocean, except for its effect on a benthic community in the Antarctic (Dayton, et al., 1969). We noted signs for frozen bottom at several sites and in different fall storms in the Beaufort Sea. Diving observations during 1982 fall storms finally documented the formation of anchor ice and of ice -bonded surface sediments in the Beaufort Sea. These findings indicate what possibly is the most important sediment transport process for polar seas is unknown to marine geologists. We speculate that anchor ice affects sediment dynamics in two important ways. The first effect is passive: anchor ice forms a protective cover for the sea floor, particularly in the surf zone, and probably largely arrests previously moving bedforms. The second effect is active: underwater ice during its formation reportedly is sticky, adhering to any particles within the water column and on the bottom (Martin, 1981). Where the substrate is fine grained, sediment particles are too light to overcome the buoyance of ice crystals in turbulent flow, and therefore are carried away (Martin, 1981). River studies of the phenomenon indicate that during the sticky stage, flocs and masses of ice with entrained sediment



SUMMARY OF DRIFTER RELEASE AND RECOVERY DATA

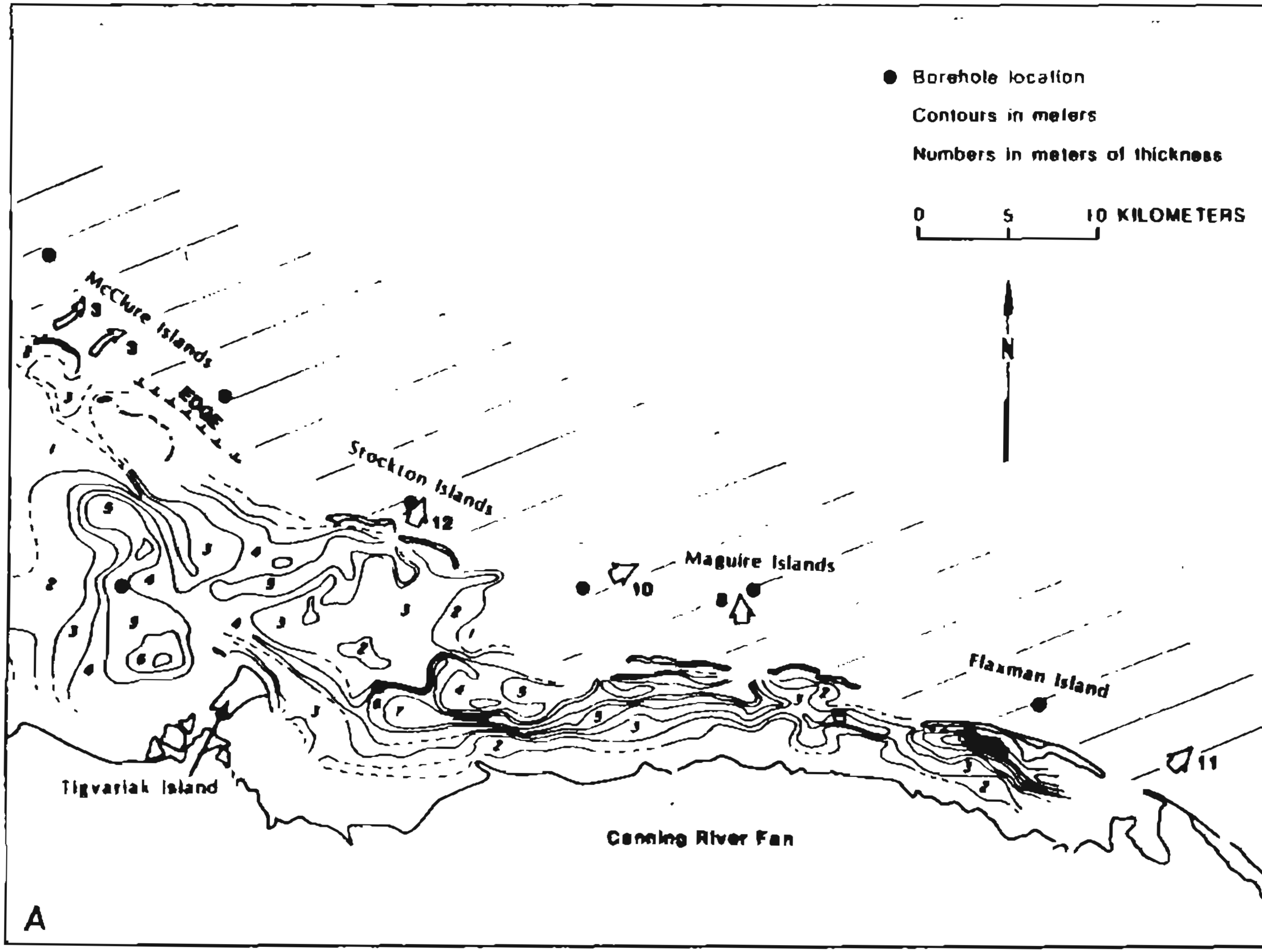
Date Released	Number Released	Number Recovered	Percent Recovered
SURFACE DRIFTERS			
7 & 8 August 1983 released from coastal vessel	400	24	6.0
	800	22	[illegible]
18 August 1983 released from low flying aircraft	1000	48	4.8
BOTTOM DRIFTERS			
7 & 8 August 1983 released from coastal vessel	400	33	8.3
	800	8	1.0
18 August 1983 released from low flying aircraft	1000	30	3.0

Figure 4. Trajectories of bottom and surface current drifters from their August 1983 drop points to their late 1983 and summer 1984 recovery points. In contrast to the westward trajectories from previous studies in the western Beaufort Sea, nearly all drifters released near the border traveled eastward.

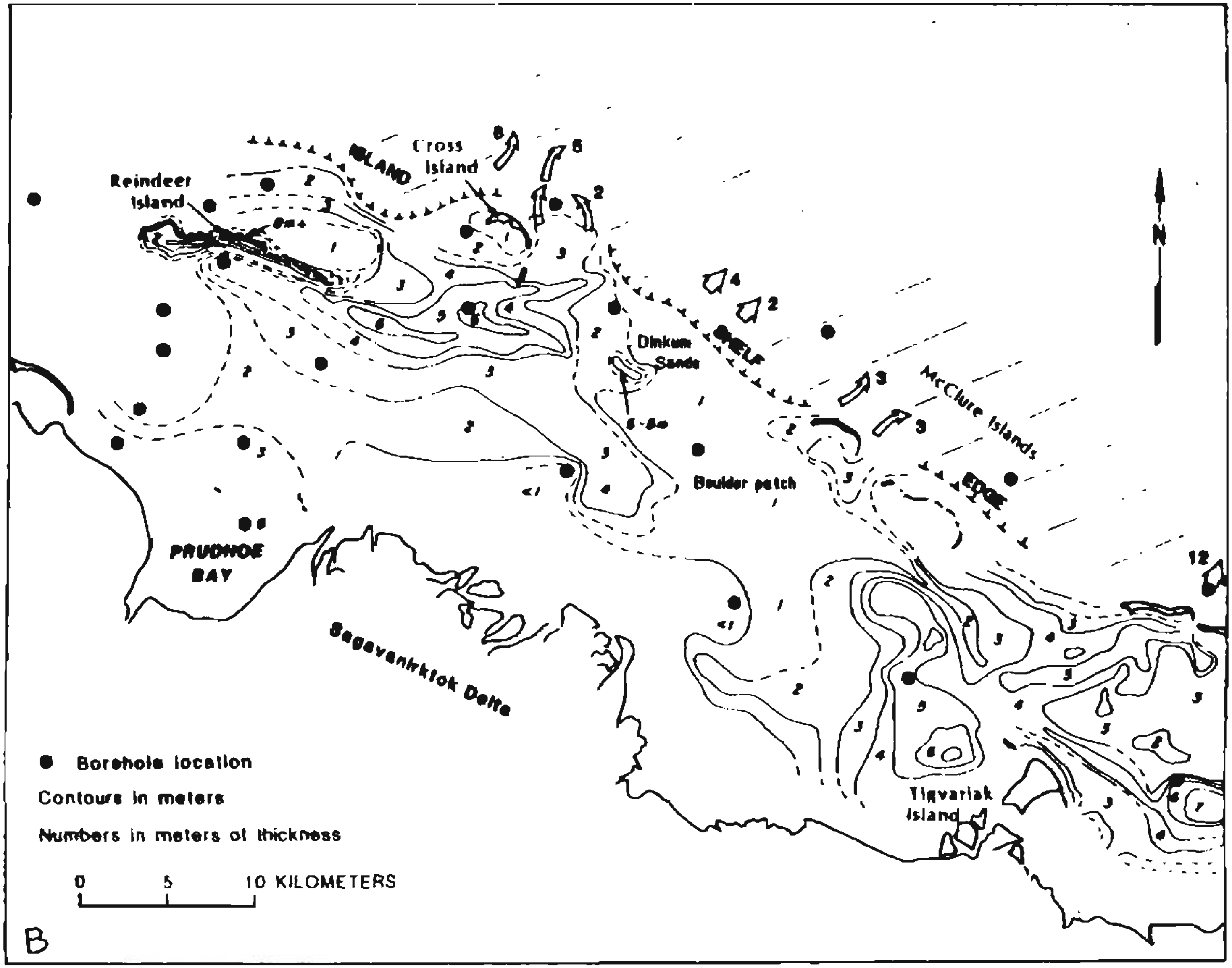
move along the bed. This suggests that the large volumes of sediment included by the seasonal ice in some winters represents only a small fraction of the sediment volumes actually moved during the fall storms. An understanding of the phenomenon will also be important for understanding the dispersal of pollutants.

Seismic Stratigraphy of Late Quaternary Inner Shelf Sediment from Prudhoe Bay to Demarcation Point

High resolution seismic reflection records collected during fourteen field seasons over the inner shelf between Prudhoe Bay and the U.S./Canada border at Demarcation Point have been interpreted. West of mid-Camden Bay seismic horizons correlate well with stratigraphic interpretations of over 20 offshore boreholes. From mid-Camden Bay to about 20 km east of Barter Island, tectonism has deformed the section, trackline coverage is sparse, and continuity, therefore, is lost. But from there eastward to the U.S/Canada border, the seismic stratigraphy appears so similar to that of the western region that correlations can be drawn with considerable certainty. Two of the major seismic horizons are unconformities marked by a number of cut-and-fill channels up to 10-m deep. These two horizons dip gently northward, and are interpreted to be the result of erosion during the last two major glaciations and lowered sea levels. These episodes were followed by deposition of at least 10 to 20 m of shallow-water marine sediments on the inner to mid-shelf, grading to deltaic and fluvial outwash deposits near the coast. The two seismic units are thought to correlate with the Sangamonian and Pelukian interglacial transgressions (Smith, 1985). Except for the tectonically deformed section near Barter Island, the lobate configuration of the two units agrees well with the locations of the present major North Slope drainage systems and sediment sources. Evidence for major offshore paleo valleys previously thought to exist was not seen in the geophysical data. The glaciomarine Flaxman unit laid down during a short Wisconsinan transgression about 70,000 to 80,000 year BP (Carter, 1983), has been eroded away in the offshore, as evidenced by only a thin lag deposit of Flaxman lithologies mantling the inner shelf surface. The modern shelf surface is also eroding into underlying, offshore dipping pre-Flaxman units. From Prudhoe Bay eastward to the U.S./Canada border at Demarcation Point the entire inner shelf is an erosional surface devoid of Holocene sediment accumulations. Erosion here is clearly facilitated by ice keels digging into the sea floor, continually excavating successively older underlying materials and mixing these with that supplied by coastal erosion and upland sources. The "Roto-tilled" unit thus produced is transient and is not accreting, but instead maintains a thickness corresponding to the maximum ice-gouge incision depth, as the level of the shelf surface is being lowered by erosion. Sediment supply to any particular area is balanced by removal through normal marine and ice-related processes. Areas where Holocene sediments are found and possibly continue to accrete are entirely restricted to bays, lagoons, barrier islands and beaches, and to offshore shoals, as shown for the western half of the study area in figures 5A and 5B.



Figures 5A and 5B. Isopach maps of Holocene marine sediment accumulations in the western part of the study area with available borehole locations. Arrows mark the locations of cut-and-fill channels, and adjacent numbers give depth of channel fill in meters.



Figures 5A and 5B. Isopach maps of Holocene marine sediment accumulations in the western part of the study area with available borehole locations. Arrows mark the locations of cut-and-fill channels, and adjacent numbers give depth of channel fill in meters.

REFERENCES

Arden, R.S. and Wigle, T.S., 1972, Dynamics of ice formation in the upper Niagra River, in International Symposium on the Role of Snow and Ice in Hydrology, Banff, Alberta, v. 2, UNESCO-WMO-IHAS, p. 1296-1313.

Barnes, Peter W., Reimnitz, Erk, and Fox, Dennis, 1982, Ice rafting of fine-grained sediment, a sorting and transport mechanism, Beaufort Sea, Alaska, Journal of Sedimentary Petrology, v. 52, p. 493-502.

Barnes, P.W., Rearic, Douglas M., and Reimnitz, Erk, 1984, Ice gouging characteristics and processes, in The Alaskan Beaufort Sea: ecosystems and environments Peter W. Barnes, Donald M. Schell, Erk Reimnitz (eds.), Academic Press Inc., Orlando,Florida, p. 185-212.

Barnes, P.W., Toimil, L.J., 1979 , Innershelf circulation patterns, Beaufort Sea, Alaska, U.S. Geological Survey, Map MF 1125.

Carter, David L., 1983, Cenozoic glacial and glaciomarine deposits of the central north slope, Alaska, in Glaciation in Alaska: extended abstracts from a workshop Robert M. Thorson, Thomas D. Hamilton (eds.), Alaskan Quaternary Center, University of Alaska Museum, Fairbanks, Alaska, p. 17-21.

Dayton, P.K., Robilliard, G.A., and DeVries, A.L., 1969, Anchor ice formation in McMurdo Sound, Antarctica, and its biological effects, Science, v. 163, p. 273-274.

Harper, J.R. and Penland, S., in press, Beaufort Sea Sediment Dynamics, Geological Survey of Canada Open-file Report.

Hopkins, D.M. and Carter, L.D., 1980, Discrepancy in correlation of transgressive marine deposits of Alaska and the eastern arctic, in Proceedings of the 9th Annual Arctic Workshop, INSTAAR, University of Colorado, Boulder, Colorado, p. 12-13.

Klyuyev, Ye. V., 1965, The role of permafrost factors in the dynamics of bottom topography in polar seas: Oceanology of the Academy of Sciences of the U.S.S.R., v. 5, no. 1, p. 78-83.

Lewis, C.F.M., 1977, The frequency and magnitude of drift ice groundings from ice-scour tracks in the Canadian Beaufort sea, in Proceedings, Fourth International Conference on Port and Ocean Engineering under Arctic Conditions, 1977 D.B. Muggeridge (ed.), Memorial University, St. Johns Newfoundland, p. 568-576.

Lewis, C.F.M., Blasco, S.M., Pelletier, B.R., and Sparkes, R., 1982, Drift ice scouring on the Canadian Beaufort Shelf, Eleventh International Congress on Sedimentology, McMaster University, Hamilton, Ontario, Canada, p. 92.

Lyon, Waldo, 1967, Under surface profiles of sea ice observed by submarine: Physics of Snow and Ice, International Conference of Low Temperature Science, Supparo, Japan, Hokkaido University, v. 1, p. 707-711.

Martin, Seelye, 1981, Frazil ice in rivers and oceans, in Ann. Rev. Fluid Mech.: v. 13, Annual Reviews Inc., p. 379-397.

Matthews, J.B., 1981, Circulation in the Sale 71 area: Beaufort Sea Sale 71 Synthesis Report D.W. Norton, W.M. Sackinger (eds.), National Oceanic & Atmospheric Administration, Boulder, CO., p. 71-178.

May, S. Kimball, Dolan, Robert, and Hayden, Bruce P., 1983, Erosion of U.S. shorelines, EOS, Transactions, American Geophysical Union, p. 521-522.

Naidu, A. S., Mowatt, T. C., Rawlinson, Stuart E., and Weiss, Herbert V., 1984, Sediment characteristics of the lagoons of the Alaskan Beaufort Sea coast and evolution of Simpson Lagoon, in The Alaskan Beaufort Sea: Ecosystems and Environments, Peter W. Barnes, Donald M. Schell, Erk Reimnitz (eds.), Academic Press Inc., Orlando, Florida, p. 275.

Osterkamp, T.E. and Gosink, Joan P., 1984, Observations and analyses of sediment laden sea ice, in The Alaskan Beaufort Sea: Ecosystems and Environments, Peter W. Barnes, Donald M. Schell, Erk Reimnitz (eds.), Acadaemic Press Inc., Orlando, Florida, p. 73-94.

Reimnitz, Erk, Barnes, P.W., and Phillips, P.L., 1984, Geologic evidence for 60 m deep pressure-ridge keels in the Arctic Ocean, Ice Symposium, August 27-31, 1984, Hamburg, Germany, v. II, p. 189-206.

Reimnitz, Erk, Graves, Scot M., and Barnes, Peter W., 1985, Beaufort sea coastal erosion, shoreline evolution, and sediment flux, U.S. Geological Survey Open-file Report 85-380, p. 18.

Sellmann, P. V., Brown, J., Lewellen, R., McKim, H., and Merry, C., 1975, The classification and geomorphic implications of thaw lakes on the arctic coastal plain, Alaska, CRREL Research Report 34421, U.S. Army Corp of Engineers, Hanover, New Hampshire, p. 21.

Smith, Peggy, 1985, Late Quaternary geology of the Beaufort Sea inner shelf near Prudhou Bay: U.S. Geological Survey Circular 945, Accomplishments During 1983 S. Bartch-Winkler, K.M. Reed (eds.), p. 100-103.

Tomirdiaro, S.V., 1975, Thermoabrasion-induced shelf formation in the eastern arctic seas of the USSR during the Holocene: DOKLADY, Earth Science Sections, v. 219, no. 1-6, p. 23-26.

Wigle, T.E., 1970, Investigations into frazil, bottom and surface ice formation in the Niagara River: International Association of Hydraulic Research Paper 2.8, p. 15.

Wiseman, W.J., Coleman, J.M., Gregory, A., Hsu, S.A., Short, A.D., Suhayda, J.N., Walters, C.D., and Wright, L.D., 1973, Alaskan arctic coastal processes and morphology, Tech. Rept. 149, Louisiana State University, Baton Rouge, LA, p. 171.