UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

THE ORIGIN, DISTRIBUTION, AND DEPOSITIONAL HISTORY OF GRAVEL DEPOSITS ON THE BEAUFORT SEA CONTINENTAL SHELF, ALASKA

by

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This report is preliminary
and has not been edited or
reviewed for conformity with
Geological Survey standards
and nomenclature

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ABSTRACT

Two distinct gravel populations are present on the Beaufort Sea continental shelf. First, a geographically arcuate deposit that is convex seaward has been designated as the Chert Facies. This deposit is restricted to landward of the 10 meter bathymetric contour and west of Heald Point. The Chert Facies, originally a fluvial gravel deposit and probably part of the basal transgressive, represents reworked Gubik Formation. The Chert Facies is derived from the Brooks Range. The second population is the Dolomite Facies. This facies is a blanket deposit covering much of the shelf and occurs in most water depths greater than 10 meters. The Dolomite Facies extends on land into the Quaternary Gubik Formation east of Prudhoe Bay and probably to Point Barrow. Rocks of the Dolomite Facies are exotic to Alaska and represent ice rafted clasts.

The distribution of the Dolomite Facies shelf gravel indicates an easterly source compatible with a proposed provenance surrounding the Amundsen Gulf of the Canadian Archipelago. Radiocarbon dates from undisturbed sediment underlying the gravel on the upper slope indicate that low Holocene sedimentation rates are the reason for gravel exposure in this region and on the outer shelf.

Considerations of sea level fluctuations, possible times available for the transportation of gravel from the proposed source area to the study area, and radiocarbon dates indicate influxes of ice rafted debris during the mid-Wisconsin transgression and probably between

15,000-10,000 years B. P. Correlation of the Gubik Formation at Heald Point with the Barrow unit of the Gubik Formation at Point Barrow on the basis of incorporated dolomite and orthoquartzite clasts is suggested.

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INTRODUCTION

The U.S. Geological Survey has been investigating shelf processes in an ice covered ocean since the summer of 1970. The study area is the Beaufort Sea.

Reconnaissance studies in 1970 and 1971 showed gravel to be a significant constituent of most of the shelf sediments. These reconnaissance studies revealed the presence of two distinct gravel facies. One facies, rich in chert and restricted to nearshore shallow depths, is termed the "Chert Facies." The second facies which is rich in dolomite and concentrated on the open shelf is termed the "Dolomite Facies." The dissimilarity between these two facies suggested that a separate investigation of the gravel deposits was warranted to compliment other sedimentological studies (Barnes and Reimnitz, 1974, Reimnitz and Barnes, 1974).

The facies above will be defined and compared, their distribution will be examined, and their origins and depositional histories will be discussed.

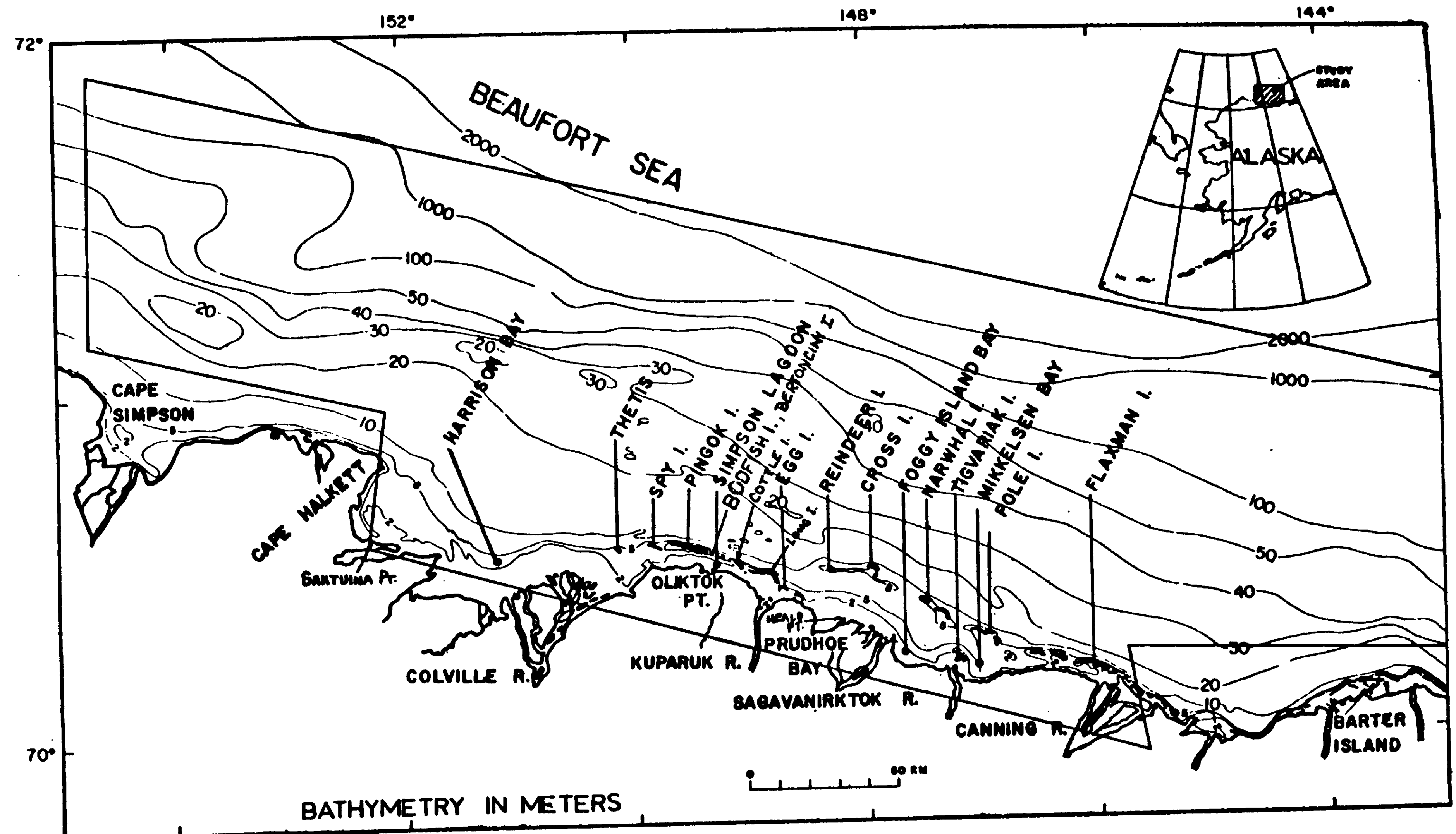

Figure 1. Study Area and Location Map.

LOCATION AND PREVIOUS STUDIES

The Beaufort Sea is that portion of the Arctic Ocean located immediately north of the Alaskan Coast, extending from Point Barrow, Alaska eastward to the Canadian Archipelago (Fig. 29). Geographical names important in this study are included in Figure 1. Three vessels were used from 1970-73 for the collection of field data including the R. V. Loon, a 40 foot vessel owned and operated by the U. S. Geological Survey; the R. V. Natchik, owned and operated by the Naval Arctic Research Laboratory at Point Barrow, Alaska; and the United States Coast Guard ice-breaker Glacier, with participating scientists from various organizations including the U. S. Geological Survey.

The general study area (Fig. 1) may be divided into two parts: one, Cape Simpson in the west to Barter Island in the east and seaward of the 20 meter contour. Within these boundaries samples were collected by investigators aboard the USCG Glacier. Two, Cape Halkett in the west to Flaxman Island in the east landward of the 20 meter contour, where sampling was conducted by investigators aboard the R. V. Loon and R. V. Natchik. Much of the coastline lies behind the shelter offered by barrier islands both west and east of Prudhoe Bay (Fig. 1).

Figure 1 also shows generalized contours which do not properly reflect the complexity of the existing bathymetry. Whereas most of the shelf is relatively flat, numerous offshore ridges exist and small scale relief directly attributable to ice gouging is evident on side scan sonar and fathometer records.

Until recently only Carsola (1954) had published work dealing with marine geology in the Beaufort Sea. Carsola noted gravel in the shelf sediment and postulated that it had been transported by ice. The earliest detailed study of the shelf gravels was made by Hanna (1954). His work dealt with an area seaward of Point Barrow. Hanna described some dredge hauls and speculated on the possibility that beach debris was frozen into shore fast ice and subsequently transported offshore after breakup. Rex (1953), having examined beach sediment at Point Barrow, noted that ..."Beaches southeast of Point Barrow contain more quartzite pebbles than those southwest of Barrow." In the eastern Beaufort Sea, Canadian investigators (Yorath and others, 1971) described a "...semi-elliptical region of sandy gravel, sand and hard pebbly lutite occurring northwest of Herschel Island. These have been tentatively interpreted as relict glacial deposits and ice-pressed tills."

Numerous sightings of large boulders in the tundra near and along the coast were reported in the early exploration literature and are summarized by Leffingwell (1919). Leffingwell named large boulder deposits at Flaxman Island the Flaxman Formation or as they are commonly termed today, the Flaxman boulders. Further discussion of the boulders, along with a listing of more recent sightings and petrographic descriptions, was published by MacCarthy (1958). He agreed with Leffingwell that these boulders were exotic to Alaska and are probably of ice-rafted origin. MacCarthy also noted that no boulders have been found above an altitude of 8 meters and suggested a minimum of 8 meters of uplift on the coastal plain since their deposition during the mid-Wisconsin transgression. It will be shown in this study that these boulders are similar in lithology to those found offshore.

Naidu and Mowatt (1974) considered the significance of the gravel fraction in shelf sediments and concluded that this material is relict rather than a contemportary deposit.

Whereas nearly all the above investigators agree that ice-rafted material exists on the Beaufort Sea shelf and that it is incorporated into the Gubik Formation, there is little agreement as to the provenance of these rocks. Leffingwell (1919) concluded that the most likely source area was the Mackenzie River valley. Mowatt and Naida (1974) feel that the northern Canadian Archipelago, specifically Ellesmere Island, is the major source area with subordinate contributions from the Coronation Gulf region at the eastern end of the Amundsen Gulf.

Unfortunately, all previous investigators confined their observations to crystalline rocks which, offshore, comprise only 10 percent of the samples. Sedimentary rocks, particularly dolomite, at times comprise up to 80 percent of these samples. This author feels the key to provenance lies with the dolomite clasts. When dolomite is considered in the search for a source area the crystalline rocks, though subordinate, become the final key to the most likely source area.

The thickness of Holocene sediment is important in describing the distribution of gravel in the study area. High-resolution seismic profiling shows anomolously thin sediment around the deltas and much of the shallow shelf region (Reimnitz and others, 1972).

Glaciation

Numerous glacial epochs have been recorded in Alaska, but all available evidence indicates that the Arctic coastal plain has not been glaciated (Hopkins, 1967). The Brooks Range and southern foothill provinces have been frequently glaciated (Coulter and others, 1965). Figure 3 shows the limits of glaciation mapped in the Brooks Range, with the arcuate distribution of glacial limits reflecting the trend of the Brooks Range.

Bathymetry

The Beaufort Sea shelf has little bathymetric relief and an average slope of two minutes of arc (.5m/km) with a high of four and one half minutes of arc (1.3m/km). The shelf width ranges from a minimum of 40 kilometers to a maximum of 76 kilometers. Whereas the slope is generally a planar feature, a trough cuts the slope above the shelf break at approximately 70 meters in the western part of the study area. In Canadian waters to the east the shelf is incised by the Mackenzie Sea Valley (Shearer, 1971). The shelf break lies at approximately 74 meters (Carsola, 1954), which is anomalous when compared to the world wide Pleistocene shelf breaks averaging 130 meters (Shepard, 1973).

Nearshore bathymetry is characterized by irregular rather than smooth contours, reflecting the action of ice as an agent in the modification of bathymetry. Diving observations, side scan sonar records,

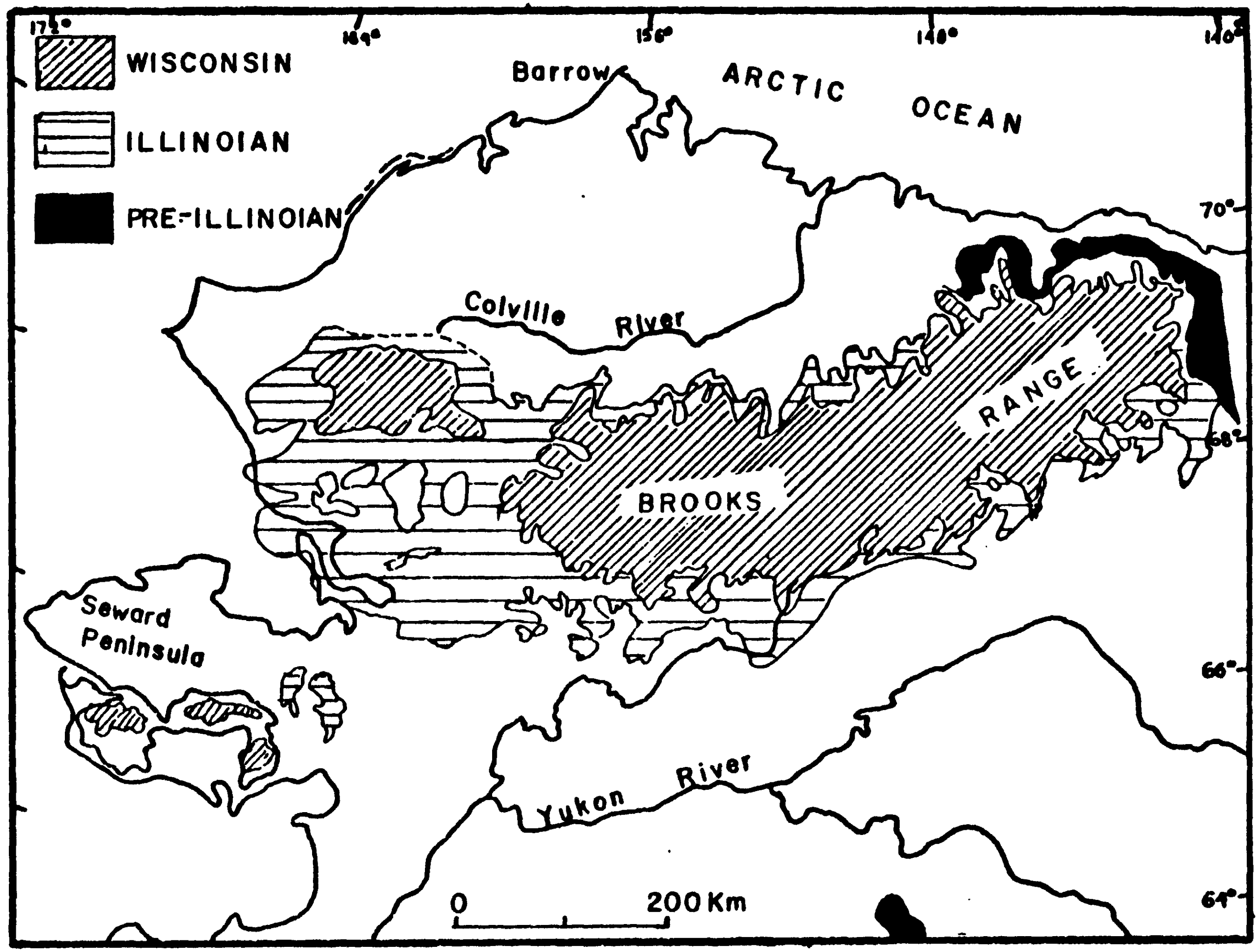

Figure 2. Extent of Quaternary Glaciations on the Alaskan Northslope (after Coulter and Others, 1968).

and fathometer records indicate that the cause of irregular bathymetry is ice gouging. Submerged ridges are prominent features northeast of Pingok Island (Fig. 1). East of Prudhoe Bay the bathymetry is dominated by the Reindeer-Cross Island ridge which extends to and probably beyond Narwhal Island (Reimnitz and others, 1972).

Methods of Study

Samples for this study have been gathered over a four year period (1970-73) using different vessels on four expeditions to the study area. Most samples collected in water depths in excess of 20 meters were collected by investigators aboard the USCGC Glacier. Samples from shallower depths were collected by investigators aboard the R. V. Loon and R. V. Natchik. Side scan sonar surveys, *in situ* diving observations and bottom photographs provided information for evaluating the validity of the gravel distribution published in this report.

Terrestrial samples were collected from all environments capable of supplying gravel to the shelf. These include the major rivers debouching in the study area (Colville, Kuparuk, Putuligayuk, Sagavanirktok, and Canning Rivers), coastal beaches, barrier islands, and the Quaternary Gubik Formation.

River and coastal bluff samples were shoveled into a large canvas bag without preference.

Nearshore samples were taken with a Van Veen bottom sampler. Samples taken during the Glacier expeditions represent both disturbed grab samples and relatively undisturbed box core samples. Box cores, approximately 10x20x30-50 cm, yield larger samples as well as well preserved sedimentary structures. Box core samples were subsequently cut and x-rayed.

All materials were eventually returned to the laboratory where the gravels were separated from the finer fraction, washed, and sieved at even phi intervals. Both fine and coarse fractions were weighed to obtain the weight percents of gravel.

The gravel fractions from all samples were laid out on a laboratory table and examined with a hand lens. From this examination sub-samples of all lithologies present were selected for thin-sectioning and petrographic analysis. After the petrographic analysis was completed, the remaining clasts were identified with a hand lens and the lithologic percentages computed. The -3ϕ to -4ϕ fraction is the most common size class in all environments sampled. Thus, the lithologic percentages of this class are used exclusively to facilitate the comparison of all gravel samples. Comparison of the lithology of this size class with that of other size classes in a sample indicates the -3ϕ to -4ϕ lithology is representative of the entire sample.

The roundness of dolomite clasts from the central and outer shelf was estimated using the Krumbein Visual Roundness Scale (Krumbein, 1941).

GENERAL GEOLOGIC SETTING

The northslope of Alaska may be divided into three physiographic provinces (Fig. 3). These provinces include the Brooks Range Province, the Arctic foothills province, and the Arctic coastal plain (O'Sullivan, 1960).

Brooks Range Province

This province represents an extension of the Canadian Rockies. Mountain peaks over 9000 feet occur in the northeastern Brooks Range. The average height of the range diminishes from 5000-6000 feet in the east to 3000-4000 feet in the west. The Range is composed of tightly folded and thrust faulted sedimentary to weakly metamorphosed sedimentary rocks, whose structure strikes generally east-west. The northern half of the range is composed mainly of Devonian and Mississippian rocks with Mississippian carbonates most extensively represented by the Lisburne Limestone. Mafic igneous and granitic rocks with ages of 160 $\pm$ 5 million years (Late Jurassic) and 431 $\pm$ 13 million years (Late Ordovician or earliest Silurian) respectively, are also present in the range. This province has been subjected to considerable thrust faulting and folding that occurred during the Late Devonian, and Cretaceous to early Tertiary times (Tailleur and Brosge, 1969). The northern boundary of this province is almost coincident with the change in outcrop from Paleozoic to Mesozoic rocks.

Arctic Foothills Province

This province is bounded on the south by the Brooks Range and on the north by the Arctic coastal plain. The southern part of this province is characterized by ridges and isolated hills. Topographic highs are underlain by resistant sandstone, limestone, chert, and conglomerate, whereas the valleys are underlain by shale. Shale of Triassic, Jurassic, and early Cretaceous age is the dominant rock type.

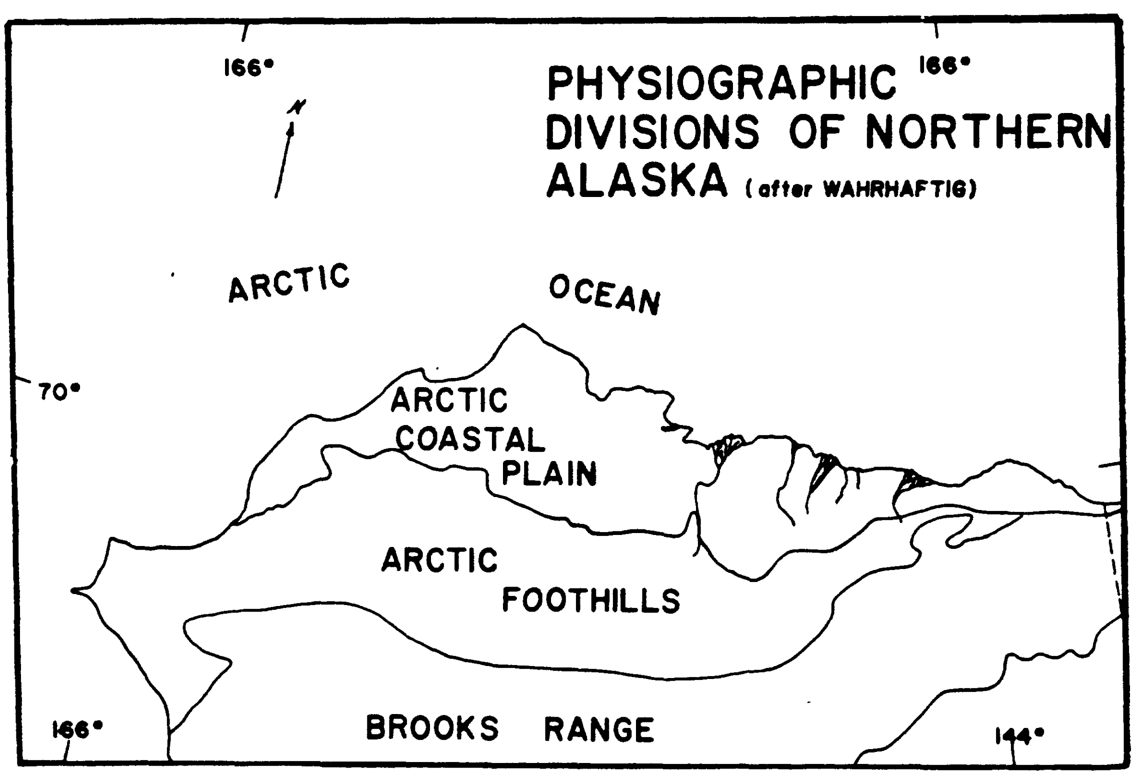

Figure 3. Physiographic Provinces of Northern Alaska (after Wahrhaftig, 1965).

The northern part of this province consists of plateau-like upland flats underlain by Lower and Upper Cretaceous strata deformed into east-west trending folds the amplitude of which decreases northward.

Arctic Coastal Plain

This province represents a typical tundra environment with numerous lakes, immature drainage patterns, and an almost total lack of significant relief. Located in the continuous permafrost zone, the coastal plain is marked by a polygonal ground pattern created by frost-wedging (Fig. 12). The coastal plain is mantled by Quaternary sediment and underlain by Tertiary shales and conglomerates east of the Colville River.

Stratigraphy of the Gubik Formation

The Quaternary Gubik Formation is the only formation exposed in the study area. The Gubik Formation is dominantly marine, but includes fluvial, lacustrine, and eolian deposits. This formation represents a shallow nearshore shelf environment where frequent shifting of the strandline occurred (Black, 1964).

Boulders and cobbles within the Gubik Formation occur from Point Barrow (Lewellen, personal communication) to at least Heald Point. In many of these places the boulders protrude through the surface of the tundra (MacCarthy, 1958). These boulders are lithologically similar to the Flaxman Boulders (Leffingwell, 1919) and have been designated as part of the Flaxman Formation by MacCarthy (1958).

The Gubik Formation has been divided into three main lithologic members described below.

<u>Skull Cliff member</u> - This unit is the oldest in the Gubik Formation. The Skull Cliff member commonly consists of poorly sorted, clay to cobble-size sediment. The sediment is often sticky or greasy and the color ranges from blue-black to dark gray. This member is mostly marine and was deposited unconformably on Cretaceous rocks west of the Colville River. The observed maximum thickness is 6.1 meters. This member is poorly exposed.

<u>Meade River member</u> - The Meade River member is the middle unit of the Gubik Formation consisting of clean, light-colored, well-sorted quartz sand. The member is mostly marine, but locally lacustrine and eolian sediment dominates. The Meade River member is generally unconformable on the Skull Cliff member, but it is locally unconformable on Cretaceous bedrock and conglomeratic at the base. The unit is especially loess-like in the southern and southeastern parts of the coastal plain. The maximum thickness approaches 51 meters.

<u>Barrow member</u> - The Barrow unit is generally the youngest of the three members but in part it is contemporaneous with the Meade River unit. The Barrow unit consists of poorly-sorted to well-sorted clay, silt, sand and gravel. This unit is generally marine at the base, but lacustrine and fluvial deposits characterize the uppermost part. Locally ice constitutes more than half the volume and organic matter is abundant in the upper part. The Barrow unit rarely rests unconformably on Cretaceous rocks, but usually interfingers with the Meade River unit.

The Barrow unit is less than 10 meters thick.

REPRESENTATIVE LITHOLOGIES OF THE STUDY AREA

A distinct difference occurs in the lithologic nature of the beach, barrier island, and shelf gravels west and east of Prudhoe Bay (Fig. 4). West of the bay and in water shallower than 10 meters the gravel is dark in color and composed of varicolored chert and sandstone with subordinate amounts of coarsely crystalline quartz. All of this material has been well rounded. East of Prudhoe Bay, at all depths, and west of the bay beyond the 10 meter contour, the gravel is light in color and except for those on the barrier islands quite angular in comparison to the chert gravels. The largest clasts in the light gravel are considerably larger than their chert gravel counterparts.

Lithologic assemblages encountered will be discussed as two distinct facies which are lithologically almost mutually exclusive. They are the dolomite and the chert facies. Dolomite facies rocks sampled on the shelf are also incorporated into the Gubik Formation, but they were not necessarily deposited synchronously. The boundary between the two facies may be seen in Figure 5. The chert facies appears as an arcuate form, whereas the dolomite facies is a widespread blanket deposit.

Gravel from both facies has been grouped into six lithologic classes: chert, dolomite, clastics, limestone, metamorphic, and igneous. A general description of each class follows.

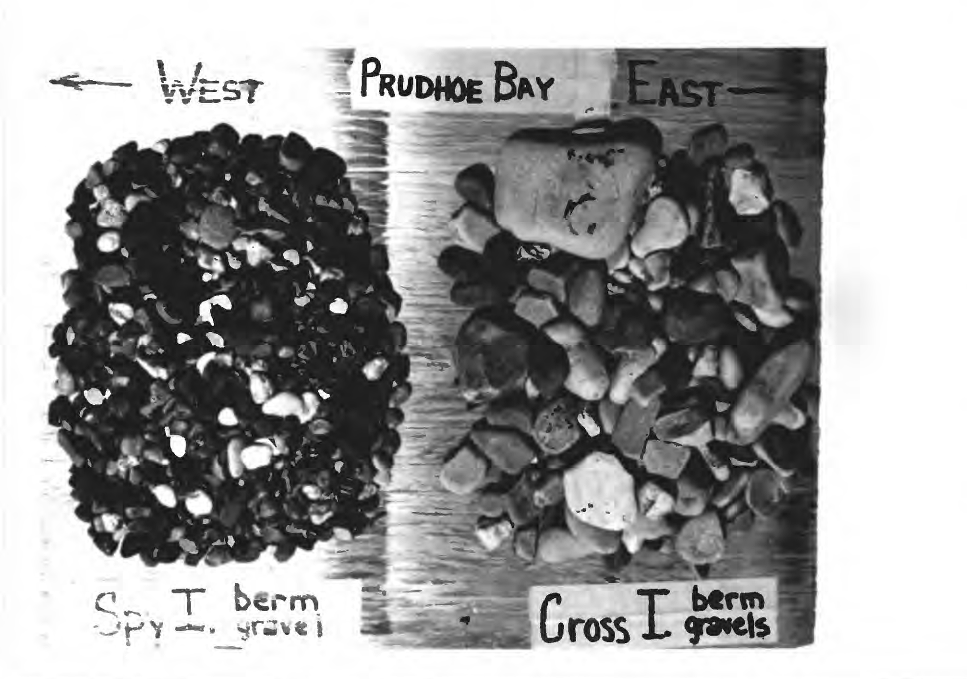

Figure 4. Chert Facies and Dolomite Facies Gravel.

Chert

The chert class includes green, brown, gray, and black chert as well as some white chert with light-brown banding. All chert except the white variety is common in samples of the chert facies and rare in the dolomite facies. Often much of the chert borders on microcrystalline quartz.

Dolomite

Dolomite clasts are green, gray, or buff and very finely crystalline to microcrystalline. Some specimens are stromatolitic. Thin sections of the dolomite show that detrital quartz, feldspar, and some heavy minerals are often present, such that at times the specimens may be more accurately termed sandy dolomites. Surficial modification includes ferrimanganic coatings (usually restricted to central and outer shelf samples), perhaps indicating long residence on the sea floor, and striae, snub scars, and faceting which suggest a glacial origin.

Clastics

This group includes a wide range of rock types. Chert facies clastics are typically a salt and pepper sandstone composed of colored chert, quartz and cemented with silica or more rarely calcite. Often these sandstones are conglomeratic with quartz and chert pebbles up to 1 cm. Other clastics included in the chert facies are siltstones, shales and rare coal. Dolomite facies clastics are dominantly orthoquartzites. The orthoquartzites border on metamorphic quartzites. Subordinate amounts of greywacke and shale are also present.

Limestone

The limestone clasts are generally well-weathered and gray to white. Little limestone material is found in the marine study area.

Metamorphic Rocks

Slate, phyllite, and quartzite are included in this classification. Chert facies samples contain rounded quartz pebbles, probably representing vein material, and for convenience have been included in this class. Petrographic analysis has shown that a small percentage

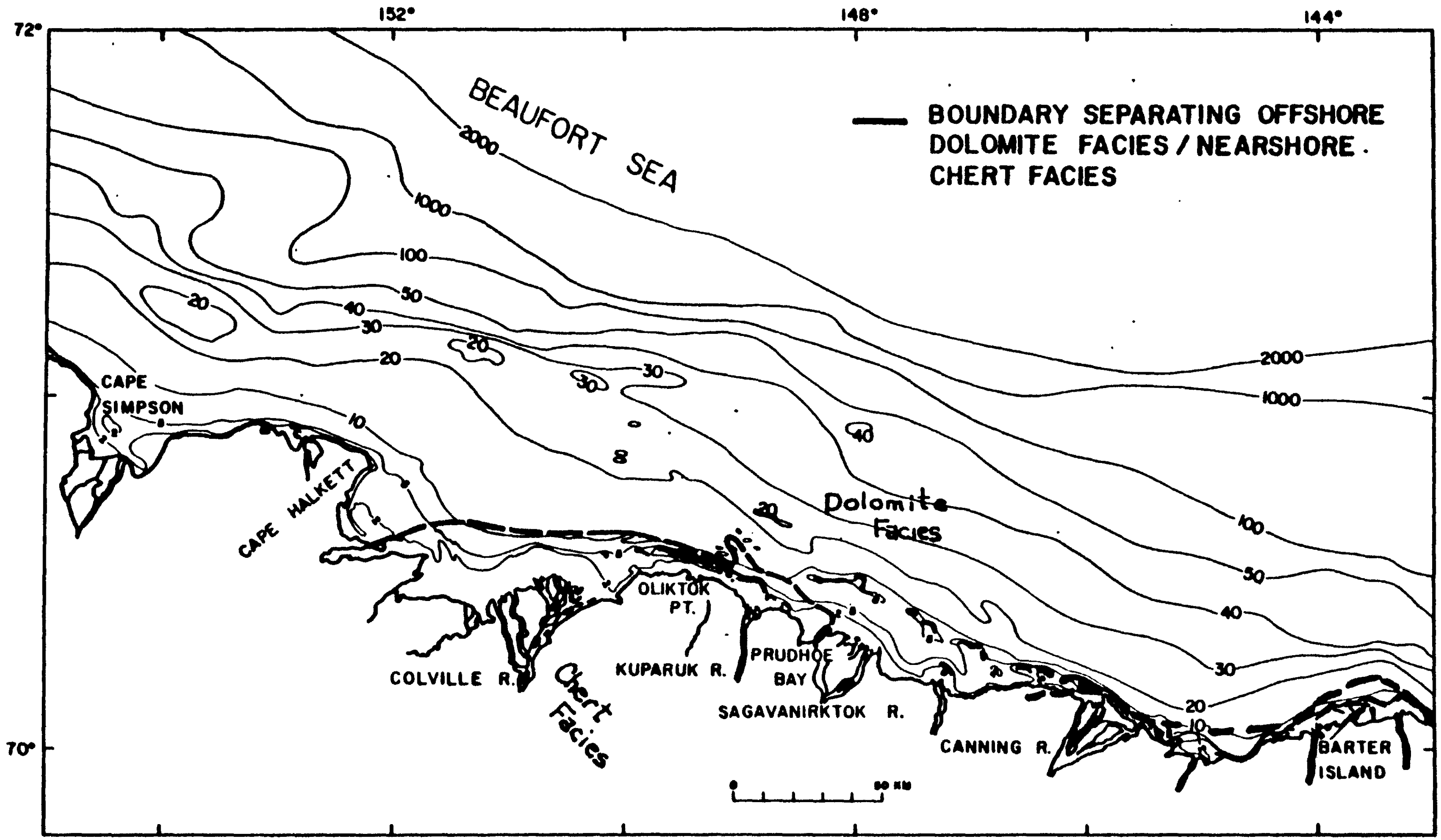

Figure 5. Boundary Separating the Chert and Dolomite Facies.

of the rocks identified as quartzites are metamorphic in origin and the majority are sedimentary quartzites. As it was not possible to thin-section all specimens, 10 percent of all rocks identified as quartzites are considered metamorphic and the remainder are considered orthoquartzites. Also included in this class are two specimens of augite-hornblende amphibolite taken from the beach on the east side of Prudhoe Bay. Gneissic rocks should also be included with other metamorphic rocks, but because of their similarity and occurrence with granites and other igneous rocks they are included in the igneous classification.

Igneous Rocks

Igneous rocks are almost restricted to the offshore samples and the Gubik Formation east of Prudhoe Bay. West of Prudhoe Bay the Gubik Formation contains isolated igneous boulders (MacCarthy, 1958). Granitic rocks, gneissic granite, diorite, andesite, basalt, and gabbro are present. The largest are granitic rocks, but the most abundant are mafic. It was often difficult to determine whether rocks should be classified as granitic gneisses or gneissic granites. Therefore, gneissic rocks have been included within the igneous classification.

Figure 6 shows two distinct gravel populations are present in the area indicating that at least two entirely different provenances are necessary to explain the composition of the two facies. Figure 6B shows that samples from the chert facies are primarily chert and clastic rocks with little dolomite. Similarly, few dolomite facies samples have chert as more than a minor constituent. Figure 6A shows the dearth of limestone in the dolomite facies, whereas limestone is fairly well represented in samples from the rivers in the chert facies. This reflects the contribution from the Brooks Range, perhaps the Lisburne Limestone of Mississippian age, which crops out across the breadth of northern Alaska. Figure 6C shows that the dolomite facies samples contain more igneous rocks than the chert facies. Those igneous rocks associated with the chert facies are usually granitic rocks, whereas those associated with the dolomite facies include types ranging from acidic to basic igneous rocks.

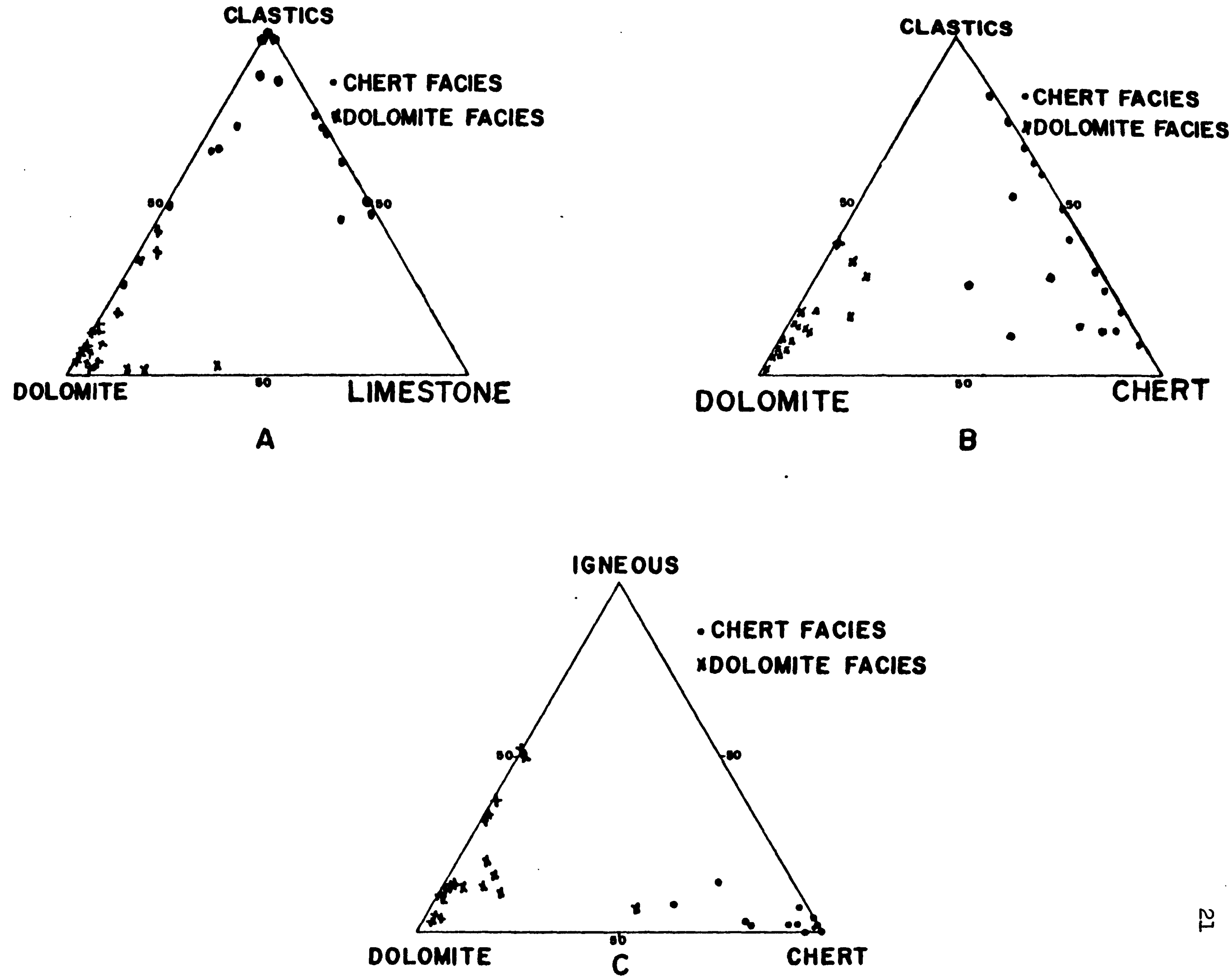

Figure 6. Comparison of the Common Lithologic Constituents of the Chert Facies and Dolomite Facies.

CHERT FACIES

Onshore Occurrences

During the Summer of 1972 the major rivers in the study area were sampled (Fig. 7). The composition of the samples is given in Table 1.

Table 1

WEIGHT PERCENT COMPOSITION OF MAJOR RIVER GRAVELS.

Sample	Dol.	Ign.	Clastics	Ls.	Chert	Met.
Colville A.	0	1	60	0	30	9
Colville B.	0	1	58	0	32	9
Kuparuk R.	0	2	49	1	35	13
Putuligayuk	0	0	51	21	18	10
Sagavanirktok	6	4	29	29	21	11
Sagavanirktok 73	1	0	34	37	23	5
Canning R.	37	38	6	1	0	18

Colville A and B were collected by investigators on reconnaissance flights from USCGC Glacier approximately 111 kilometers from the coast near Umiat. Kuparuk River samples were collected from gravel bars marking the floodstage level and at the normal summer river level. Putuligayuk River samples were collected from a mid-channel bar and

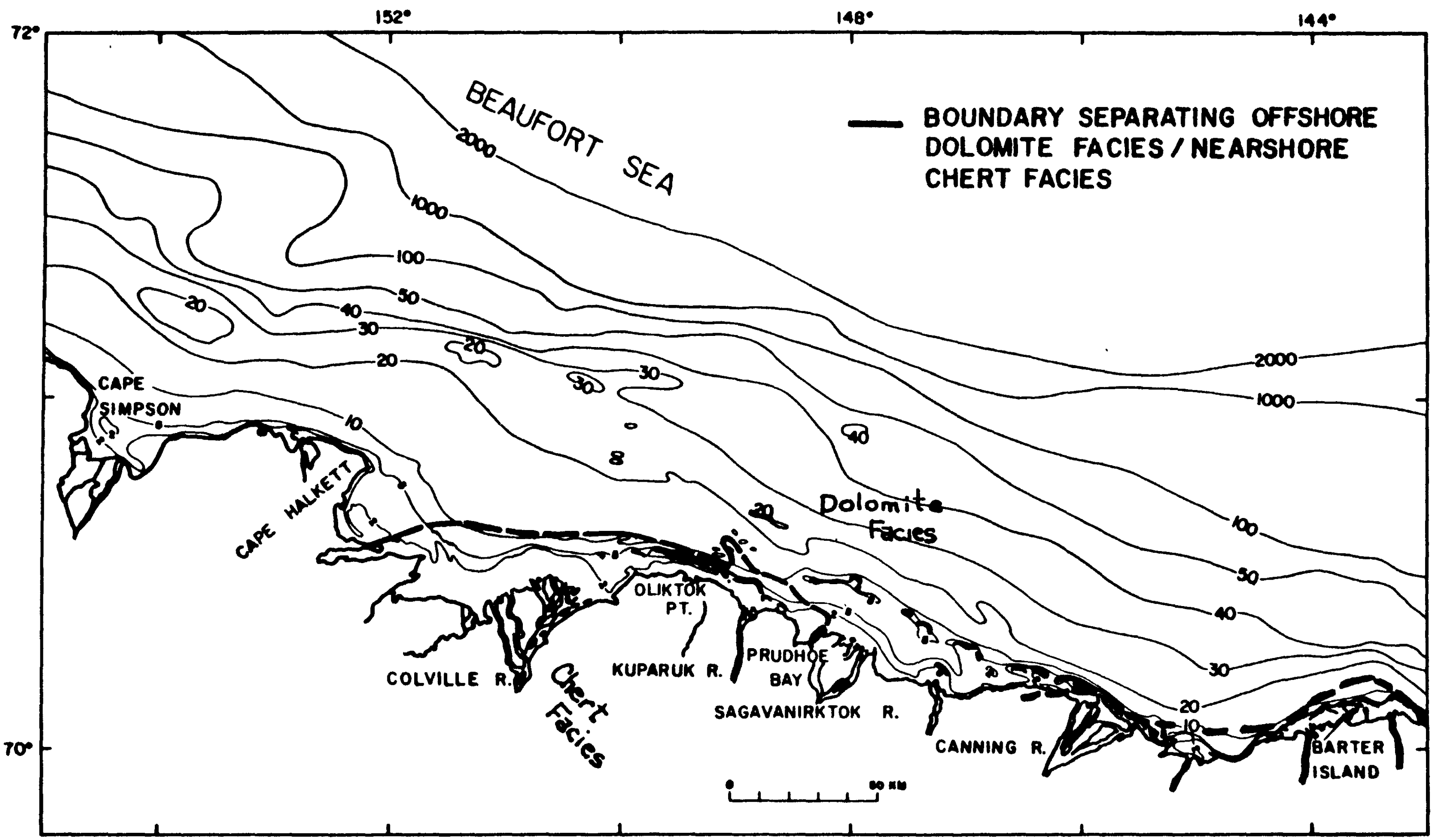

Figure 5. Boundary Separating the Chert and Dolomite Facies.

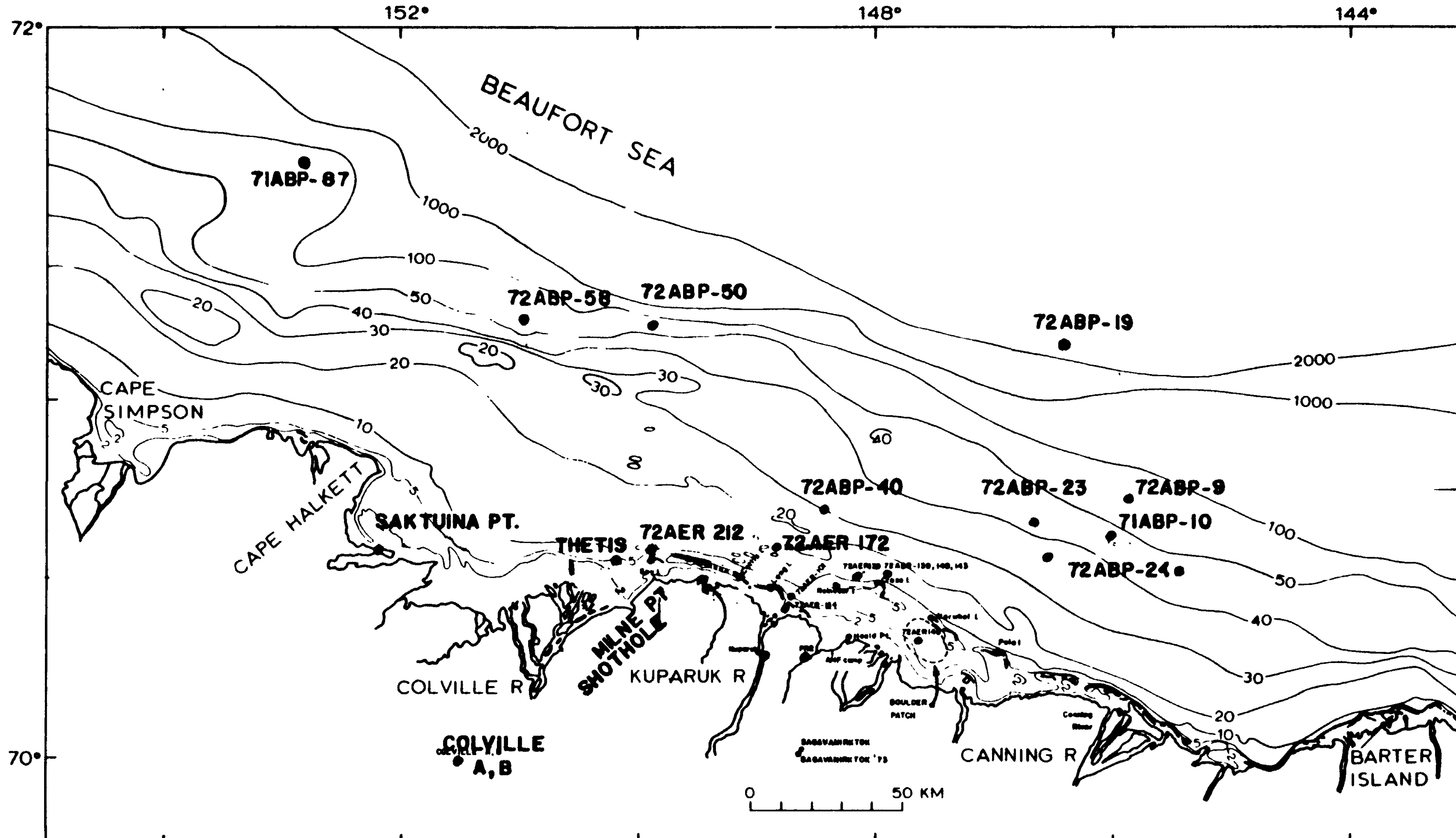

Figure 7. Samples Examined in Detail for Lithology, and Roundness.

construction gravel pits farther downstream. Sagavanirktok River samples were obtained from the present stream bed and also from the Gubik Formation exposed along the river (Sagavanirktok 73).

The major constituent of all river gravels sampled, except for the Canning River, is clastic rock fragments followed by chert. Significant amounts of limestone are present only in the Putuligayuk and Sagavanirktok Rivers.

In the summer of 1973 a section of river bank along the Sagavanirktok River was examined. Whereas the 1972 sample (Sagavanirktok - Table 1) was taken from a gravel bar, the 1973 sample (Sagavanirktok 73 Table 1) was taken from an outcrop of the Gubik Formation just above river level. The composition of these samples as shown in Table 1 is very similar. Field observations along the Putuligayuk River (a local river originating within the Gubik Formation) and Kuparuk River indicate the stream gravels are also similar to gravel in the Gubik Formation. The majority of clastic rocks in Table 1 are salt and pepper sandstone characteristic of the chert facies.

Presently, no material larger than coarse sand is being transported by the major rivers to the marine deltaic or contiguous shallow marine shelf. Samples taken seaward of the 1.5 meter contour off the Colville, Kuparuk, Putuligayuk, and Sagavanirktok Rivers yield only sand and finer sediment.

Barrier Island Occurrences

The barrier islands in the study area show the most obvious distinction between the two gravel facies (Fig. 4). The major constituents of both facies are compared for samples from the chert facies barrier islands in Table 2.

Table 2

MAJOR CONSTITUENTS OF CHERT FACIES ISLANDS (PERCENT)

Sample	Chert	Dolomite
Thetis I.	75	0
Spy I.	76	4
Cottle I.	53	1
Long I.	55	4

Islands composed of chert facies rocks contain particles smaller than -4ϕ in diameter with subordinate amounts of material between -4ϕ to -5ϕ and virtually no material larger than -5ϕ except for few very large exotic boulders (Fig. 8).

Chert facies island gravel consists of chert with subordinate amounts of metamorphic and clastic rocks. The ratio of clastic rocks/chert decreases in the nearshore samples and on the barrier islands because of the more rapid breakdown of the less competent sandstone fraction. All rocks are generally well rounded. Metamorphic rock fragments are generally represented by well rounded quartz pebbles which probably represent vein material. Barrier islands and rivers show a decrease in chert clasts eastward across the study area. No samples were taken from the Niakuk Islands northwest of Heald Point, but field examination showed them to be composed primarily of chert.

Offshore Occurrences

While conducting sampling operations on the nearshore shelf, it was observed that often when a grab sample containing chert pebbles was brought aboard it contained a highly consolidated, dark gray, clayey silt (Reimnitz and others, 1974). The silt is compacted and contains little water. Numerous samples, not considered as representative, were collected from the flukes of the anchor which showed this coexistence; the gravel is always found overlying consolidated silt. This relationship may also be seen in the stratigraphic log of a hole drilled on

Figure 8. Dolomite Facies Boulder From Bodfish Island.

Reindeer Island. One open shelf sample which had shells associated with the gravel was dated by radiocarbon methods at 4800bp (72AER-122, depth= 9.0cm, 70 33.72'Nx149 27.2'W). Thus, the underlying silt is older than this and probably represents a pre-Holocene deposit.

Seismic profiling studies combined with bottom sampling invariably shows that chert facies gravel occurs in areas with little (less than 5 meters) or no Holocene sediment cover.

A scuba diving program was included during the 1972 field season. These dives, designed to supplement geophysical and bottom sampling data with *in situ* observations, were performed in many areas shown in seismic profiles as having little or no Holocene sediment. In most dives the bottom was seen to be mantled by an unconsolidated semi-liquid silt seldom more than 10 cm thick. In some areas this layer is probably the only material resuspended by bottom currents or storm surges. In areas with thin Holocene sediment this transient layer is underlain by gravel, consolidated silt or both. Normally, the gravel layer is less than 15 cm thick so the consolidated silt surface below is easily detected by divers if present. There were some instances where divers were unable to penetrate to the silt. In some places no gravel was detected, but the silt surface was. The consolidated silt is recognized by its resistance to excavation and its slippery hard surface. Using this criterion, long distances could be traversed and the presence of gravel and silt confirmed by grabbing hand holds for extra propulsion along the bottom. Where more than a thin veneer of gravel was detected, the divers usually stopped to force a hand downward until the silt horizon

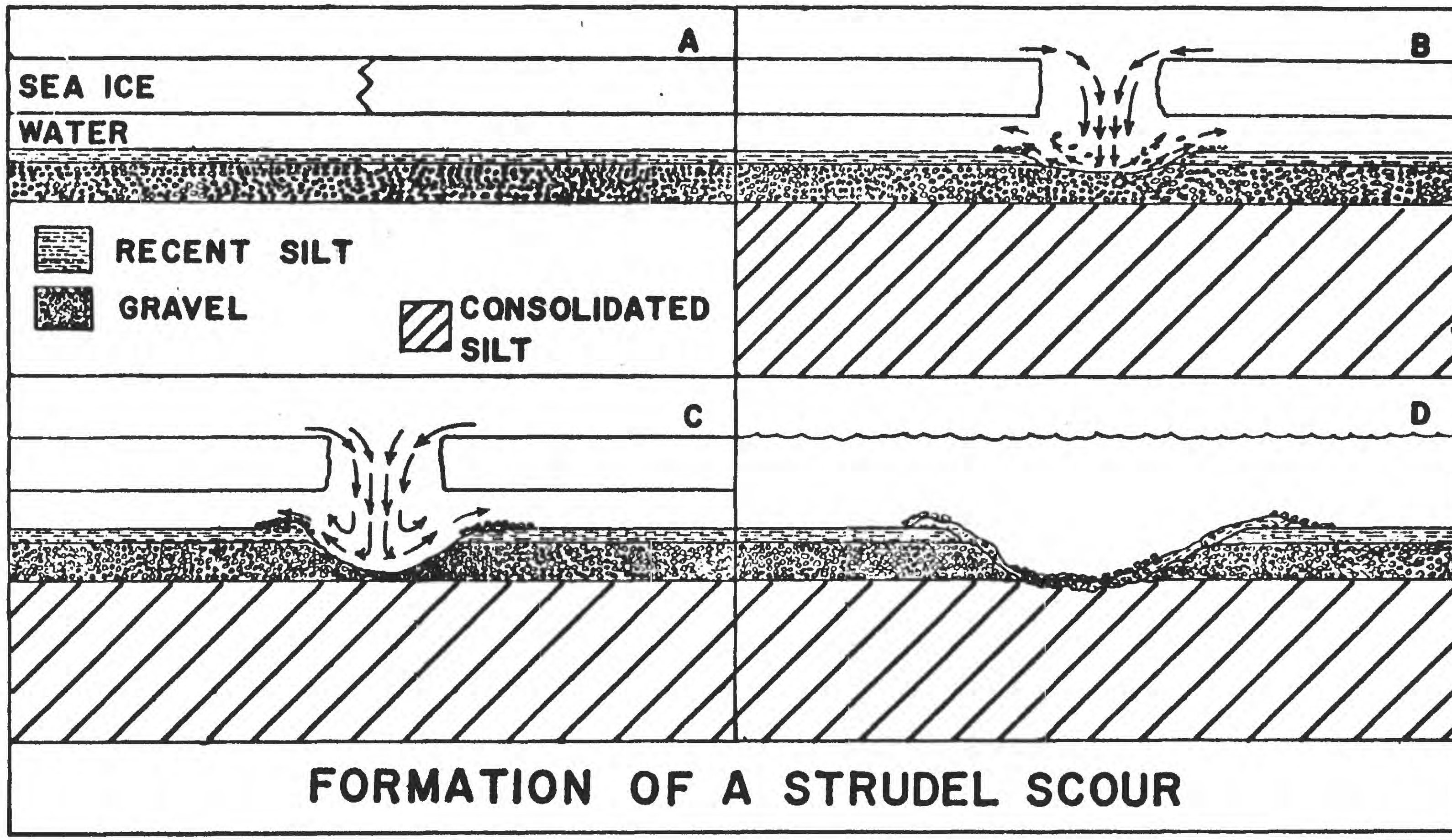

Figure 9. Strudel Scour Examined *in situ* Using SCUBA.

was reached.

The gravel-silt contact discussed above was also observed in areas of strudel scours (Reimnitz and others, 1974) which are depressions formed in the very shallow marine deltaic environment during spring breakup. During the spring breakup of rivers frozen over the preceeding winter, river overflow water sinks below the sea ice through holes and cracks in the ice. The water rushes through the orifice and where the water below the ice is sufficiently shallow forms a scour depression. Normally the depth of the depression is limited by gravel or consolidated silt, but some scour depressions, observed within the seismic section, penetrate this boundary.

One strudel investigated was roughly crescent-shaped with a maximum depth of 1 meter below the sea floor and walls sloping at approximately 35 . A ridge surrounding the depression stood 30-40 cm above the surrounding sea floor. Gravel was strewn about, but was restricted to within 2 meters of the rim except in adjacent areas where ice had recently gouged the bottom. Gravel was encountered in walls of the excavation below the surface of thin recent sediment and the floor of the strudel was composed of residual gravels underlain by highly consolidated silt. The gravel, composed primarily of angular to rounded chert, resembled that on the inshore barrier islands. Figure 9 shows the stratigraphic sequence encountered in this strudel scour and its method of formation.

A second scour located inside Simpson Lagoon was also examined. This strudel, although exhibiting a different stratigraphic sequence, is floored by gravel of the same composition as the other scour depression (Reimnitz and others, 1974). These dives support the seismic interpretation of thin Holocene sediment nearshore and the superposition of gravel above the consolidated silt.

DOLOMITE FACIES

Most dolomite facies samples were collected by investigators aboard the USCGC Glacier during the 1971-73 seasons. Grab and box core samples were used for the determination of lithology and gravel percentages.

Dolomite facies samples are dominated by green, gray, and buff, very-fine to microcrystalline dolomite. Many specimens have glacial striae (Figs. 8, 10). All samples included in the dolomite facies contain at least 50 percent dolomite. Few limestone clasts contribute to the total carbonate content. With the exception of dolomite, pink, red, gray, and buff colored orthoquartzite is the most common sedimentary rock.

Offshore samples average 10 percent igneous rocks, whereas the onshore dolomite facies samples contain more, both in average size and percent of the total sample. The amount of igneous rock ranges from 3 percent to a high of 48 percent. Generally, samples with small amounts of igneous rocks have correspondingly greater amounts of dolomite. Mafic suites dominate this assemblage, including andesites, diabases, basalt, diorites and gabbros, in that order. Granitic rocks ranging from weathered granite to granitic gneisses are probably the most conspicuous rocks in this class. They are generally pink. Investigators familiar with Brooks Range geology are convinced no such bedrock exists in Alaskan territory (Reiser, Detterman, Brosge, personal communication). Detterman, however, reports seeing pink granite pebbles in the beach wash near the International boundary.

Onshore Occurrences

Since 1970, the author has noticed numerous boulders within the study area. These boulders, usually orthoquartzites, pink granites, and mafic igneous rocks are exposed in slump materials in the coastal bluffs or protruding through the tundra surface (Figs. 7, 12).

One such granitic boulder (140x70x55 cm) was excavated south of the Arctic Marine Freighters (AMF) basecamp (Figs. 7, 13). This boulder may be considered one of the Flaxman Boulders (Leffingwell, 1919). In Figure 13, the cobbles displayed with the boulder were extracted during the excavation. These cobbles are about 5-8 centimeters in diameter with the largest being 10 centimeters. They were distributed throughout the excavation. Thirty-five rocks were counted and the lithologies are shown in Table 3.

Table 3

COBBLES ASSOCIATED WITH THE EXCAVATED GRANITE BOULDER

Samples Counted	Lithology	Shape
32	Dolomite	very angular
1	Andesite	well rounded
1	Siltstone	angular
1	Ortho-quartzite	angular

Most dolomites within the study area are angular to subrounded, except on the barrier islands where they are well-rounded. The very angular appearance of the dolomites in Figure 13 may be due to fracturing by freeze and thaw. This was extremely common among dolomites along the beach at Heald Point (Fig. 14). The angularity may also be due to a lack of reworking of the gravel.

Figure 10. Striated Dolomite Cobble From Heald Point.

The soil underlying the boulder was slightly silty, medium grained sand which is mineralogically mature containing only well-rounded quartz and chert grains. A sample of this sand was examined for microfossils, but yielded only one poorly preserved ostracod valve.

Figure 11. Boulder Exposed in Slump Material, Heald Point.

The mineralogical maturity and rounded sand grains suggest deposition on a shallow shelf, subsequent uplift and dissolution of any calcareous microfissils.

A trench approximately two meters in length was dug leading away from the previous circular excavation. The purpose of the trench was to ascertain whether the cobbles in Figure 13 are common throughout

Figure 12. Granite Boulder Exposed on the Tundra and Common Arctic Polygonal Ground Pattern.

the section or concentrated around the boulders. Another 30 specimens were recovered (Table 4). Numerous small pebbles were encountered at the beginning of the excavation and discarded until the prevalence of these rock fragments was realized. Thus, only the most obvious hand specimens were counted.

North of the excavation site, along the east coast of Prudhoe Bay, boulders are scattered along the beach and in the water. Many of these boulders are exposed only during extremely low water levels associated with easterly winds. These boulders and their associated gravel concentrations form a linear deposit along the coastline and extending approximately 200 meters from shore. Beyond this limit

Table 4

COMPOSITION OF ROCK SPECIMENS FROM THE TRENCH

Samples Counted	Lithology
19	Dolomite
4	Orthoquartzite
4	Chert
2	Granite
1	Shale

coarse debris is probably covered by recent silt. Figure 15 shows a view southwest from Heald Point into Prudhoe Bay.

Prompted by Leffingwell (1919), who states ..."at Heald Point Flaxman till underlies about 12 feet of silt. The exposure showed only 2 or 3 feet of blue clay containing boulders," an investigation of this site was undertaken. The coastal bluffs decrease in height toward the point. A 1 meter tundra cap was underlain by 2 meters of clayey silt dominated by ground ice, below which the exposure was undercut and obscured by slump deposits. Two dolomite cobbles were found frozen into the section (Fig. 16) at a depth of 3.0 meters below the tundra surface.

Of the largest rocks, commonly with 1 meter dimensions, granites, granitic gneisses, and mafic rocks are the most abundant with lesser amounts of dolomite and orthoquartzite present. Glacial striae along with faceting and snub scars, indicating a glacial origin are common

Figure 13. Granite Boulder Excavation and Cobbles From the Section. Located South of the AMF Basecamp.

on all rock types. Heald Point was the only location where slate was a relatively common rock type.

Other fairly distinctive rocks at Heald Point, although not particularly abundant, are stromatolitic dolomite, augite-hornblende amphibolite, and a very distinctive extremely coarse-grained, red conglomerate with red chert and white quartz pebbles up to 5 cm long.

It seems reasonable considering the presence of cobbles in the section with the same lithologies as those found on the beach and the conformity of the boulder distribution with the shoreline to assume that these rocks represent material concentrated by the winnowing of finer sediment from the east bank of Prudhoe Bay. This deposit contin-

Figure 14. Frost Fractured Dolomite From Heald Point.

ues around Heald Point and along the western edge of the Sagavanirktok delta.

Boulders of the same lithologies as those found at Heald Point (orthoquartzite and mafic rocks) are found on the coast slightly east of Milne Point and on the west and north shores of Bodfish Island, both of which lie within the chert facies boundary.

Other evidence for some overlap of the two facies was observed on the Niakuk Islands located 1 mile northwest of Heald Point. The gravel of these islands appears similar to the chert facies barrier islands, but boulders of the dolomite facies sit atop these small islands. The water surrounding these islands is shallow and a skiff

Figure 15. Boulders Exposed Along the Eastern Shore of Prudhoe Bay.

can be walked ashore. During one of these walks numerous large boulders were encountered below the waterline. Unfortunately no sample was taken from these islands. Leffingwell (1919) observed these islands and states "...a small sand island about a mile northwest of Heald Point contains a block of tundra which is about 40 yards in diameter and from 4 to 5 feet high. There are numerous large boulders upon the tundra, upon the beach, and in the water." From this description the author concludes there are probably dolomite pebbles mixed with the chert gravel on the Niakuk Islands. Presently, no such tundra cap exists on the islands. The only remnants of the dolomite facies are the boulders resting on the island surface.

Figure 16. Dolomite Cobble From the Section, Heald Point.

The Niakuk Islands occurrence of dolomite indicates that deposition of the chert facies gravel occurred prior to the deposition of the dolomite facies. Subsequent uplift, growth of a tundra surface followed by the destruction of that surface along with the dolomite bearing Gubik Formation immediately below has led to the present dolomite/chert mixture on these islands. Foundation drilling studies show a gravel-rich layer a few meters below the tundra surface in much of the Prudhoe Bay area. This gravel is rich in chert. It is apparently this gravel layer that is exposed on the Niakuk Islands and perhaps on the islands west of Prudhoe Bay.

Barrier Island Occurrences

The barrier islands north and east of Prudhoe Bay are predominantly composed of dolomite gravel (Table 5). Orthoquartzite and igneous rocks are the most common subordinate rock types on the barrier islands except on Pole Island. Pole Island and Saktuina Point, exhibit transitional characteristics between the dolomite facies and chert facies similar to the Niakuk Islands.

Table 5

LITHOLOGIC COMPOSITION OF DOLOMITE FACIES ISLANDS (PERCENT)

Island	Dol.	Ign.	Clastics	Ls.	Chert	Met.
Reindeer	54	9	28	0	7	2
Cross	64	10	15	0	4	7
Narwhal	65	18	10	0	6	1
Pole	31	5	23	1	36	3

Clast size between the dolomite and chert facies islands differs considerably. Although Figure 4 shows the dolomite facies gravel as being much larger than chert facies gravel, the method of sampling makes the mean gravel size similar. This sampling method yields the values in Table 6 for the mean particle size (Mz) (Folk and Ward, 1957). Apparently this clast size represents the equilibrium gravel size affected by normal beach face processes exclusive of storm conditions.

Table 6

MEAN DIAMETER OF BEACH GRAVEL
OF ALL BARRIER ISLANDS SAMPLED

Island	Mz(ø)*	Island	Mz(ø)
Thetis I.	-2.0	Reindeer I.	-2.5
Spy I.	-2.2	Cross I.	-1.9
Cottle I.	-2.3	Narwhal I.	-2.3
Long I.	-2.3	Pole I.	-2.6

* Mz(ø) = Mean Particle Size

Larger average sized gravel clasts are found on the highest berms and represent storm deposits. The largest cobble seen on the dolomite facies islands, exclusive of the Flaxman Boulders, was 25 cm.

Relative to the chert facies islands the dolomite facies islands are modified to a greater extent by sea ice. Figure 17 shows a gravel surface at Narwhal Island created by sea ice impinging on the seaward face of the island. Figure 18 shows the catastrophic modification of sediment on the beach face at Cross Island. At times the ice transgresses the beach face as far inland as the center of the island (50-100 meters) as shown by preserved ice gouges.

Chert facies islands and Reindeer Island are fringed with a gravel apron which usually disappears at a depth of 2 meters; however, Cross Island and Narwhal Island are surrounded by vast gravel concentrations. *In situ* diving observations off the northwest coast of Cross

Island revealed ice gouges with a depth of nearly 2 meters incised into sandy gravel bottom sediments (Fig. 19). This gravel occurs down to a depth of 4.5 meters at this site. Grab samples in nearby areas show that much gravel lies near the seafloor, below a thin transient clayey silt layer, even at a depth of 14 meters. This gravel is stratified into coarse sand and gravel layers. These deposits are apparently reworked by storm surges. A similar distribution occurs to the north, and west of Cross Island and probably off the other dolomite facies islands to the east. Little evidence to support this eastern distribution exists due to the inaccessibility of the area. Ice usually grounds along the Reindeer-Cross Island ridge here, making small boat

Figure 17. Gravel Pushed Onshore by Sea Ice, Narwhal Island. Arrow Indicates Direction of Ice Push.

Figure 18. Ice Push Modification of Beach Sediment, Cross Island.

operations impossible.

Offshore Occurrences

Most offshore samples (deeper than 20 meters) were collected by investigators aboard the USCGC Glacier. One striking feature of the pebbles in these samples is their angularity (Fig. 20). Roundness studies of selected samples using 50 dolomite pebbles per sample were performed using the Krumbein visual roundness scale (Krumbein, 1947). The -3ϕ to -4ϕ fraction was used for the determinations. The Krumbein method was chosen instead of the more commonly used Cailleux reference arc method (1945) for expedience. vanAndel and others (1954) reviewed both methods and found they yielded comparable results. The greatest advantage of the Cailleux method is the larger volume of literature available for the comparison of the results obtained.

If the dolomite facies rocks represent fluvial or glaciofluvial deposits, roundness calculations should reveal the effects of differential abrasion during transport. If these rocks represent ice-rafted debris there should be little evidence of differential abrasion. Table 7 shows the results of the examination.

Table 7

ROUNDNESS DATA -50 PEBBLES/STATION (SCALE = .1-.9)

Sample	Roundness	Mean	Deviation
71ABP-10	.439	.418	.028
72ABP-19	.345	.418	.073
72ABP-23	.390	.418	.028
72ABP-24	.408	.418	.010
72ABP-27	.427	.418	.009
72ABP-40	.394	.418	.024
72ABP-50	.506	.418	.088
72ABP-58	.432	.418	.014

Mean = .418 Standard Deviation = .044

Figure 19. Ice-gouged Sediment North of Cross Island.
Depth: 6 meters.

The roundness values in Table 7 are similar, and hypothesis testing at the 95% confidence level indicates no significant difference between samples. Thus, the gravel was probably not deposited by streams. This leaves ice as the most likely agent of deposition, a conclusion reached by other investigators (Leffingwell, 1919; MacCarthy, 1958; Naidu and Mowatt, 1973; Mowatt and Naidu, 1974).

Dolomite facies samples collected from the central and outer shelf show glacial striae on many of the clasts; however, here striae are almost restricted to dolomite clasts, whereas onshore rocks of all lithologies exhibit striae. Possibly the size and lithology of the materials observed is the cause of the restriction of striae to dolomite clasts. Striae on mafic rocks are wider, shallower, and more difficult to create than those on the dolomite clasts. The only mafic rocks on which striae were seen were the boulders. As offshore clasts are smaller than the onshore boulders these striae may have been missed.

Ferrimanganic coatings and limonite staining of many clasts, particularly larger cobbles, are often restricted to one surface, clearly revealing the position in which they rested on the sea floor. The large cobbles are usually oriented with their maximum cross-sectional area in contact with the bottom. Informal laboratory tests on small clasts in a large diameter settling tube show non-equant

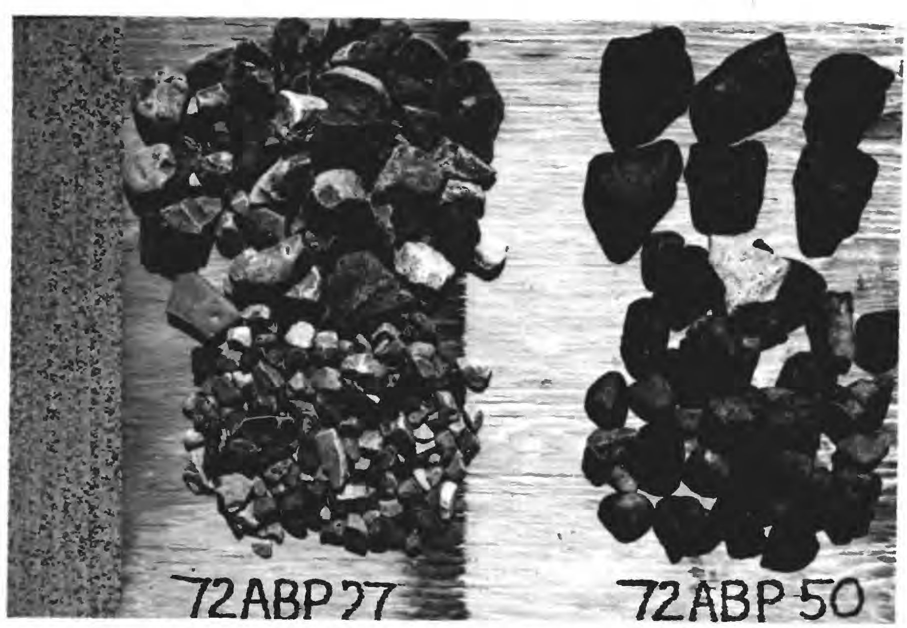

Figure 20. Angular Offshore Dolomite Facies Gravel.

clasts assume an orientation with their maximum cross-sectional area normal to the direction of travel shortly after being released, regardless of the orientation upon release.

A particularly interesting shallow water deposit is located in Foggy Island Bay, immediately south of Narwhal Island. This deposit called the "boulder patch" is shown in Figure 7. Rock types included in the deposit are orthoquartzite boulders as large as 2 meters in diameter, granitic boulders, and smaller dolomite clasts. The boulder patch is, in appearance and lithology, a submerged analog of that deposit surrounding Heald Point. The boulder patch is also the only part of the study area where a sufficient substrate is present for the development of an extensive algal community. Here the author encountered a predominantly lamanaroid flora accompanied by a rich benthic fauna of pelecypods and gastropods.

On the basis of sedimentary structures exhibited on x-ray radiographs (Figs. 21, 22, 23) Barnes and Reimnitz (1974) divide the open Beaufort Sea shelf into three zones. Zone 1 (Barnes and Reimnitz, 1974, Figure 6) is characterized by well sorted and layered sandy sediments developed under the influence of the open season waves and currents. This zone occurs between the 10 and 20 meter contours. Zone 2 (Fig 21) occurs at all shelf depths but is especially well developed on the mid-shelf. This zone consists of unstructured gravelly muds and is characteristic of those areas of sea bottom intensely affected by ice gouging. Finally, Zone 3 is best developed on the outer shelf and upper slope and consists of a relatively thin gravel

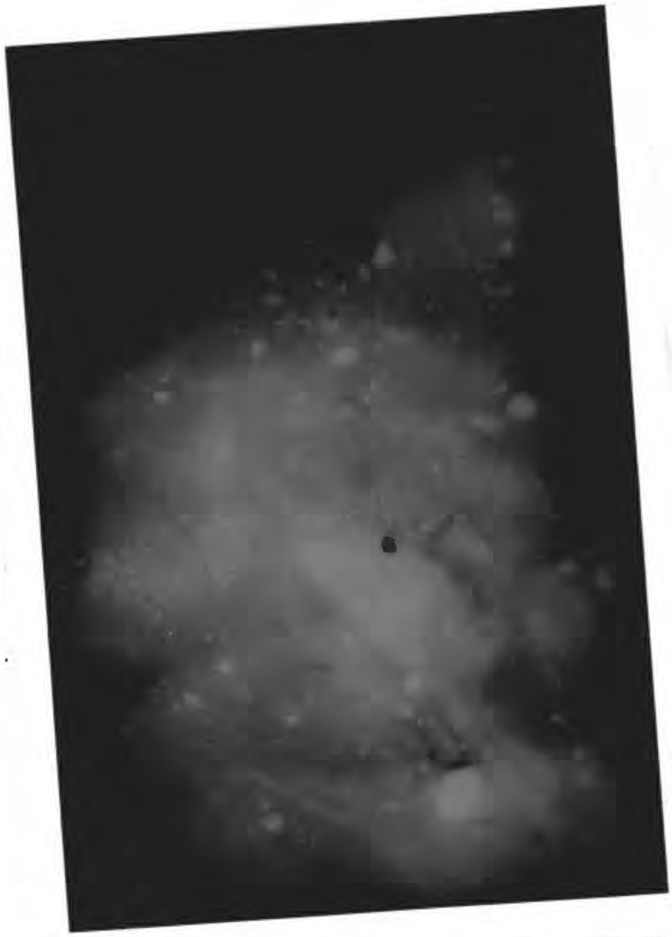

Figure 21. X-ray Radiograph of the Central Shelf Facies of Barnes and Reimnitz (1974).

veneer overlying massive or laminated marine muds (Fig. 22). Radiocarbon dating of the laminated marine sediment 9 cm below the gravel surface in Figure 22 indicates an age of 14,980 ± 200 B. P. Thus, the gravel on the shelf edge and upper slope must have been deposited during the Holocene transgression. Figure 23 shows an extremely coarse surficial gravel deposit from the outer shelf.

Figure 22. X-ray Radiograph of the Shelf Edge and Upper Slope Facies of Barnes and Reimnitz (1974).

Naidu and Mowatt (1973) ascribe a relict nature to dolomite facies gravel based on the apparent insignificance of contemporary ice-rafting on the Beaufort shelf, no coarse to fine gradation from the coast to outer shelf, and the fact that shelf gravels appear to be in disequilibrium with present hydrodynamic conditions. Barnes and Reimnitz (1974) question the arguments presented to support these -

observations, but generally agree with their conclusion. Crude calculations by Barnes and Reimnitz based on: 1) the number of gravel occurrences observed; 2) estimates of the average amount of gravel in each occurrence; 3) the area observed; 4) the rate of pack movement; and 5) the ice cover over the shelf, yields an estimated accumulation rate of $5 mg/cm^2/10^3 yr$. Considering a 5-10 m section of Holocene shelf sediment this would amount to 85 mg of gravel per cm^2 on the shelf: approximately 2 orders of magnitude lower than required for observed concentrations. Thus, they conclude ice-rafting is insignificant at the present time. Four years of observations by the author also supports this conclusion.

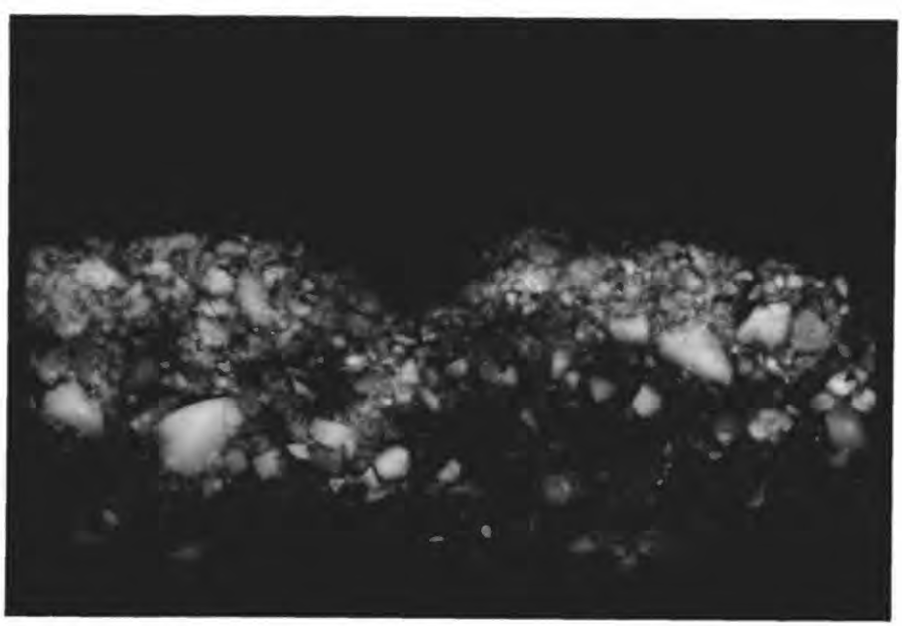

Figure 23. X-ray Radiograph of the Outer Shelf Surficial Gravel.

Lewellen (personal communication) reports numerous sightings of gravel on ice off Point Barrow and he has obtained some samples from one floe. These samples have been inspected by the author and except for some coarse-grained mafic rocks (coarser than most of the shelf samples) are not similar to dolomite facies rocks.

It appears that some of the offshore dolomite facies rocks were deposited during the Holocene transgression and are now relict deposits. Nearshore dolomites, shoreward of the 16 meter contour (including the boulder patch and those onland) present another problem. They were either deposited during the Holocene transgression or represent reworked Gubik Formation, essentially in place, with the finer fraction winnowed out. These possibilities will be considered in the discussion below.

DISTRIBUTION OF GRAVEL IN THE STUDY AREA

Figure 24 is a map of the percent by weight distribution of material coarser than -1ø and represents a compilation of sample data from 1970-73. A comparison of the gravel distribution with the boundary between facies (Fig. 5), shows the map is essentially a distribution map of the dolomite facies.

Chert facies gravel which is abundant over much of the inner shelf cannot be contoured at this scale. The extreme variability of sediment types over short lateral distances, especially in areas of strudel scour (Reimnitz and others, 1974), make contouring impossible. Chert facies gravel is only exposed where recent sediment is lacking. The chert-dolomite facies boundary indicates the chert facies is an arcuate deposit reasonably conformable with the coast. Other information, particularly the occurrence of dolomite facies boulders on the chert facies Niakuk Islands, suggests the relationship is more like that shown in Figure 25. This figure shows that a preexisting chert facies deposit underlies the exposed Gubik Formation (including rocks from the dolomite facies), which was subsequently eroded causing the mixture or superposition of dolomite and chert facies rocks.

The dolomite facies distribution is divided into an eastern and western concentration. The concentrations are separated by a broad band of sediment 20-50 km wide, containing little gravel and extending across the shelf and slope north of the Colville River. This band also extends west-northwestward from the Colville to the inner limits of the

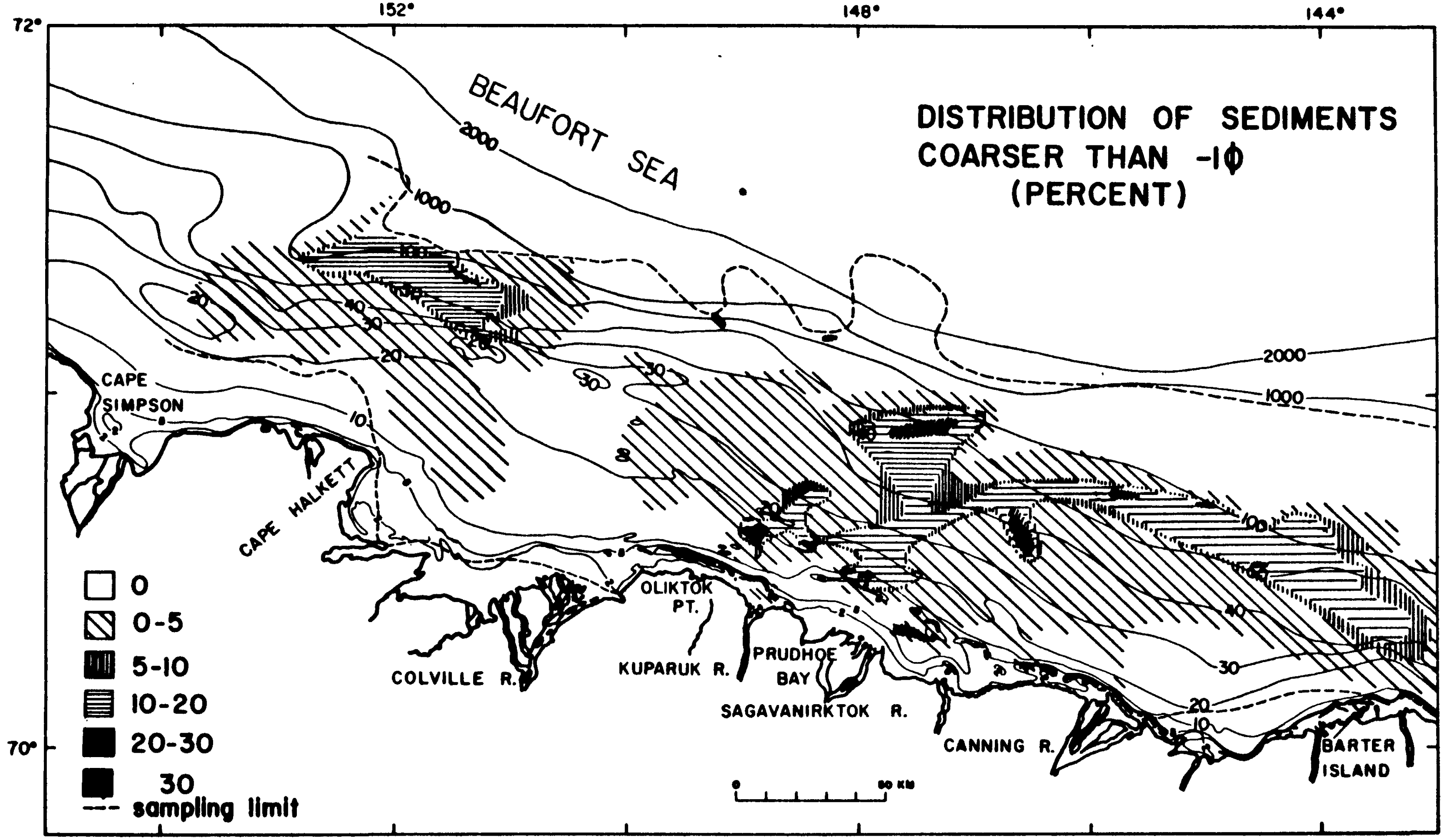

Figure 24. Distribution of Surficial Sediment Coarser Than -1ϕ.

study area.

The lack of gravel around the Colville River delta and other major rivers probably represents the influx of fluvial sediment not including gravel which results in the dilution, followed by the masking of pre-existing gravel. Gravel does exist beneath the sedimentary veneer on the Colville River delta and contiguous shallow marine shelf. as shown by drilling logs compiled from the drilling of seismic shot-holes (Hamilton Bros. Oil Co.).

The northwestward-trending band of surficial sediment containing no gravel fits a pattern of westward longshore transport by nearshore westerly currents documented by Short (1973). The sediment band extending across the shelf and upper slope may represent a situation similar to the transport of Mackenzie River sediment. Satellite photos show this sediment is initially transported westward and then turns abruptly north in the vicinity of Herschel Island.

The greatest concentrations of gravel usually occur on the shelf edge and upper slope. However, in the eastern accumulation these high values extend sporadically across the entire shelf. Sediment containing more than 30 percent gravel was encountered in the above areas seaward of the 10 meter contour. Two notable exceptions are the "boulder patch" and areas of strudel scour.

The large inner shelf accumulations form a lineation superimposed upon the trend of the Reindeer-Cross Island Ridge. Clasts from these concentrations consist of well to very well rounded pebbles with one cobble measuring 10 cm. Diving observations on the southeastern

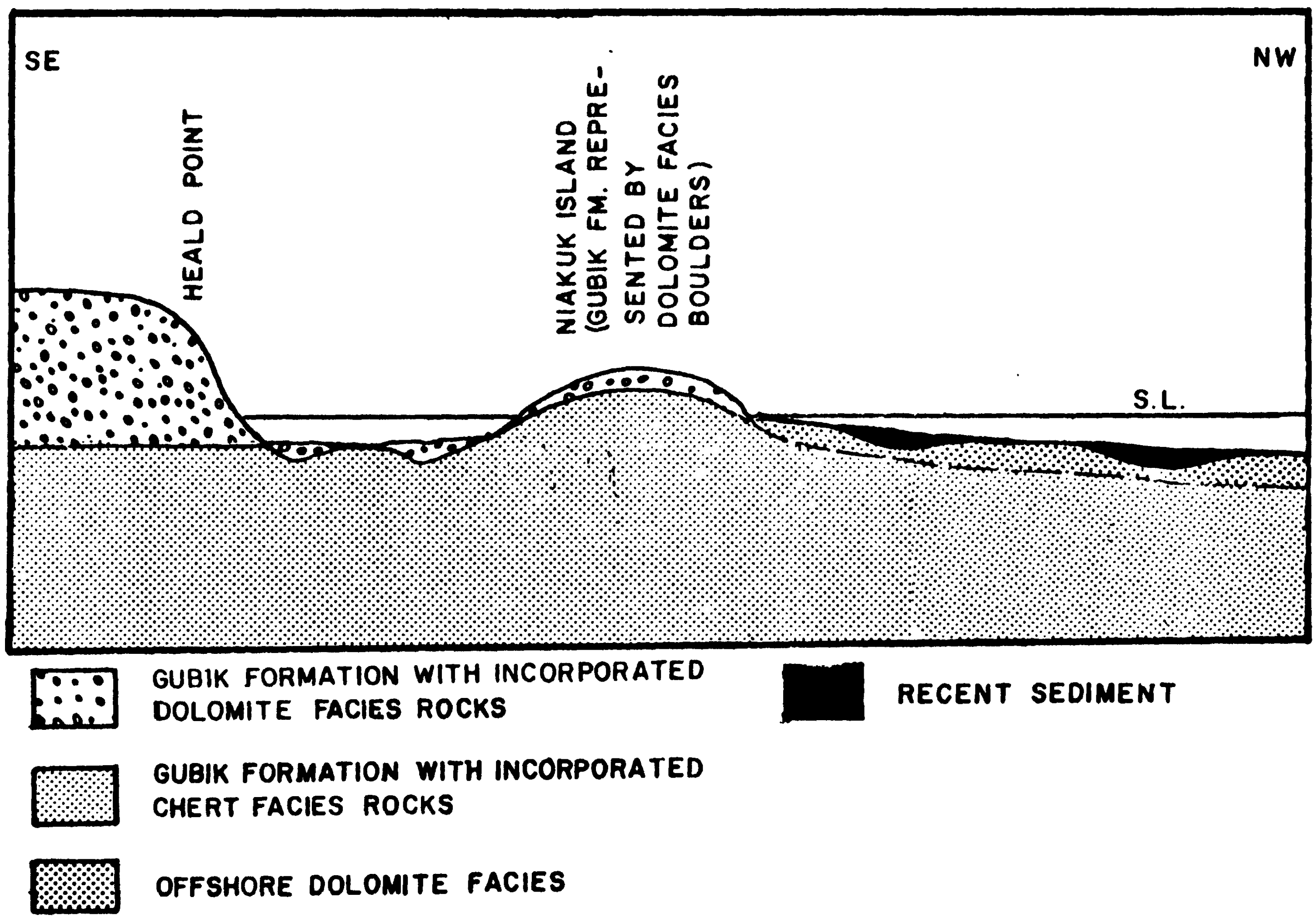

Figure 25. Relationship Between the Dolomite and Chert Facies at Heald Point.

most ridge north of Bodfish Island (Reimnitz and others, 1972), at a depth of 15.5 meters, show the trough south of the ridge is floored by mud. The mud grades into sand and gravel as one proceeds to the ridge crest which is capped by sand. Clast size ranges from pea size lower on the ridge to pebbles up to 3 cm higher on the ridge flank. Seismic profiling records show the ridges are probably Holocene constructional features rather than structural highs. The shape of the pebbles and their distribution on the ridge flank suggest that these features may represent barrier islands constructed at a stillstand during the Holocene transgression and subsequently inundated.

Large concentrations of gravel extend across the shelf northeast of Prudhoe Bay. On the central shelf ice scours the seafloor as shown on side scan sonar records (Reimnitz and Barnes, 1974) and Holocene sediments are very thin as defined by seismic profiling surveys. On some parts of the central shelf gravel immediately underlies recent silts. North of Reindeer Island at a depth of 27 meters, a grounded iceberg had pushed up a large gravel ridge and exposed gravel below recent sediment (Forgatsch, personal communication). Thus, some of the high gravel concentrations result from the mixing of older gravel into more recent sediment.

The western accumulation shows high concentrations of gravel in an area of low ice scour intensity (Reimnitz and Barnes, 1974). These concentrations must be due to very low rates of sedimentation. Box cores show cobbles on the surface in this area. If this material is no longer being ice-rafted and ice gouging is relatively unimportant in the western concentration, low sedimentation rates may be assumed to be the cause for exposed gravel.

Gravel concentrations along the shelf edge are also due to low sedimentation rates. The radiocarbon date obtained for the upper slope on box core 71ABP-18 shows less than .5 meters of sediment has accumulated in the past 15,000 years.

DISCUSSION OF RESULTS

The two facies discussed have very different origins and depositional histories. The areal distribution of the chert facies indicates that it forms an arcuate deposit derived from the rivers of northern Alaska. Shallow marine and barrier island samples within the chert facies area exhibit the same rock types as the major rivers with an increase of more competent constituents. The gravel exposed in the river beds of the Sagavanirktok, Putuligayuk and Kuparuk Rivers has the same composition as the Gubik Formation through which they flow. It has already been established that little, if any, material coarser than sand is presently transported by the major rivers to the marine deltaic or contiguous shallow marine environment. The similarity of chert facies gravel to the river gravel, which in turn is similar to the Gubik Formation gravel, indicates the chert facies represents fluvial deposits eroded from the Gubik Formation and deposited offshore in the past, or the Gubik Formation was reworked during the Holocene transgression. The Gubik Formation probably underlies part of the shelf in the study area as it does in the Point Barrow area (Lewellen, 1973).

The origin of the dolomite facies is more obscure than that of the chert facies. The dolomite facies is not as restricted as the chert facies (Fig. 5). The greatest accumulations of dolomite facies gravel occur in the eastern part of the study area (Fig. 24). This data is compatible with Barnes and Reimnitz (1974) who show that the mean size of sediment finer than -1ϕ decreases to the west indicating

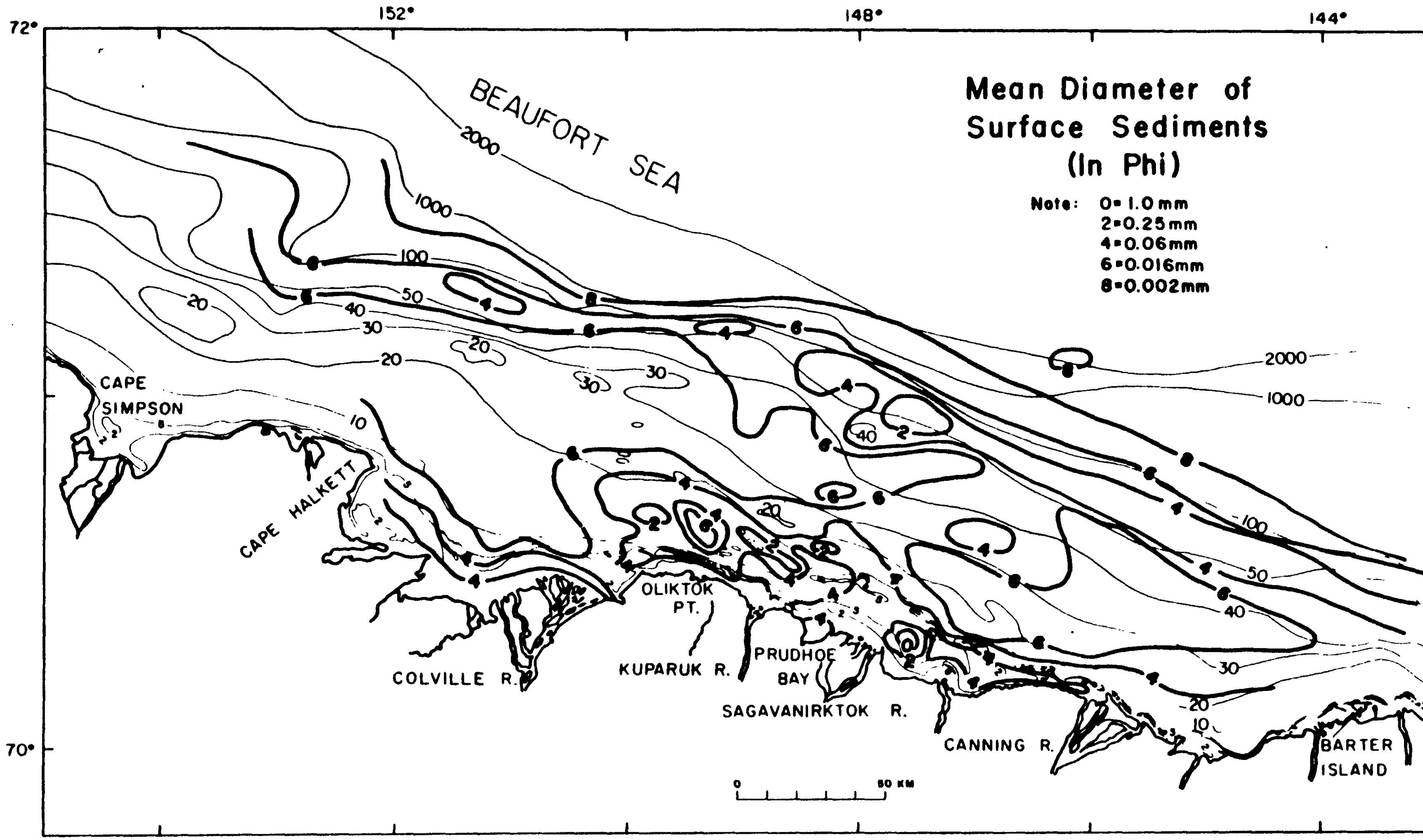

Figure 26. Mean Size Distribution of Sediment (After Barnes and Reimnitz, 1974).

an eastward source (Fig. 26). This conclusion has also been reached by Leffingwell (1919), MacCarthy (1958), Naidu and Mowatt (1973), and Mowatt and Naidu (1974).

Dolomite facies gravel represents ice-rafted material exotic to Alaskan terrain. Therefore, an alternate source must be found. Leffingwell (1919) was one of the first to consider a distant source for large boulders along the Alaskan coast, particularly at Flaxman Island. Primarily because of granitic material along the Alaskan coast, and the presence of this material in Mackenzie Valley moraines, Leffingwell (1919) suggested that boulders from the Flaxman Formation originated from the Mackenzie River drainage. Naidu and Mowatt (1973) state that "... most probably these gravels were deposited by icebergs similar to the present-day ice islands that have originated from ice shelves of Ellesmere Island in Canada," but do not indicate whether or not they think Ellesmere Island is the source. Mowatt and Naidu (1974) feel that ..."the Ellesmere Island area seems to represent the most favorable situation, in terms of lithologies and terrains, in conjunction with the present current patterns in the Arctic Basin. The only other general region which seems to have the requisite bedrock geology at present is the south shore of Coronation Gulf, but there are problems in demonstrating the feasibility of gravel transport from this area to the Beaufort Sea shelf of northern Alaska."

These investigators have concentrated on the crystalline rocks within the dolomite facies as have other investigators looking for the source of Arctic Basin gravel (Schwarzacher and Hunkins, 1961), and the origin of ice island T-3 (Stoiber and others, 1956). This author feels the answer lies in finding the source of the dolomite, the dominant lithologic constituent and not an extremely common sedimentary rock in the Arctic.

Stoiber and others (1956) studied rocks from T-3 and their paper includes a good summary of the rocks bordering the Arctic Ocean. Gravel on ice island T-3 apparently originated from the Ellesmere Island ice shelf but contains virtually no sedimentary rocks save one greywacke pebble. Schwarzacher and Hunkins (1961), dredging from drift station Alpha, obtained dolomite pebbles from the Canadian Basin and suggested that their source might be Axel Heiberg or Ellesmere Island, or the north coast of Greenland. The dolomite pebbles are white or light brown, invariably recrystallized into dolomitic marble, with crystal sizes of 0.01 mm to 0.50 mm. These may be contrasted to Beaufort shelf dolomites which are buff, gray, or green, very-finely crystalline to microcrystalline, unmetamorphosed rocks. The information provided by the above investigators rules out the northern Canadian Archipelago as the source for dolomite-rich gravel.

A survey of the geology of northern and northwestern Canada (Douglas, 1970) shows that the most probable source area is that surrounding the Amundsen Gulf. This area was recognized in 1947 by Washburn to be a possible source for the Flaxman boulders. In a footnote Washburn states "...rocks closely similar to all Flaxman stones described by Leffingwell are known to occur <u>in situ</u> on the mainland coast between Darnley Bay and Queen Maud Gulf and, excepting the granites, also on Victoria Island."

The Canadian physiographic provinces surrounding the Amundsen Gulf, within easy reach of the Arctic Ocean (Fig. 27) include the Anderson Plain, Horton Plain, Victoria and Banks Islands (Douglas, 1970). Victoria Island is dominated by Ordovician-Silurian dolomite, especially in the south-facing Amundsen Gulf. Minor amounts of sandstone and shale of Cambrian age and gabbro and basalt of Proterozoic age are also exposed.

Anderson Plain is composed of Middle and Upper Devonian dolomite with subordinate limestone and shale. Ordovician-Silurian dolomite crop out on Cape Perry, whereas Cape Bathurst is composed primarily of Cretaceous shale and white sandstone.

The Horton Plain contains abundant Ordovician-Silurian dolomite strata with subordinate amounts of Cambrian green shale and sandstone and Proterozoic basalt, stromatolitic dolomite, and sandstone. Farther from the coast large amounts of orthoquartzite are present.

Banks Island is composed of Cretaceous shale and sandstone, Upper Devonian sandstone and shale and Tertiary-Quaternary glacial deposits. The Tertiary Beaufort Formation contains fluvial sand, gravel minor silt, and peat. The gravel is thick to thin bedded and consists of well rounded pebbles of chert, quartzite, granite, diabase, dolomite and sandstone from older rocks exposed on the island. Chert and quartzite pebbles dominate in the western and northern parts of the island. These resistant pebbles are less abundant constituents of the Beaufort Gravel in the southern part of the island. Throughout Banks

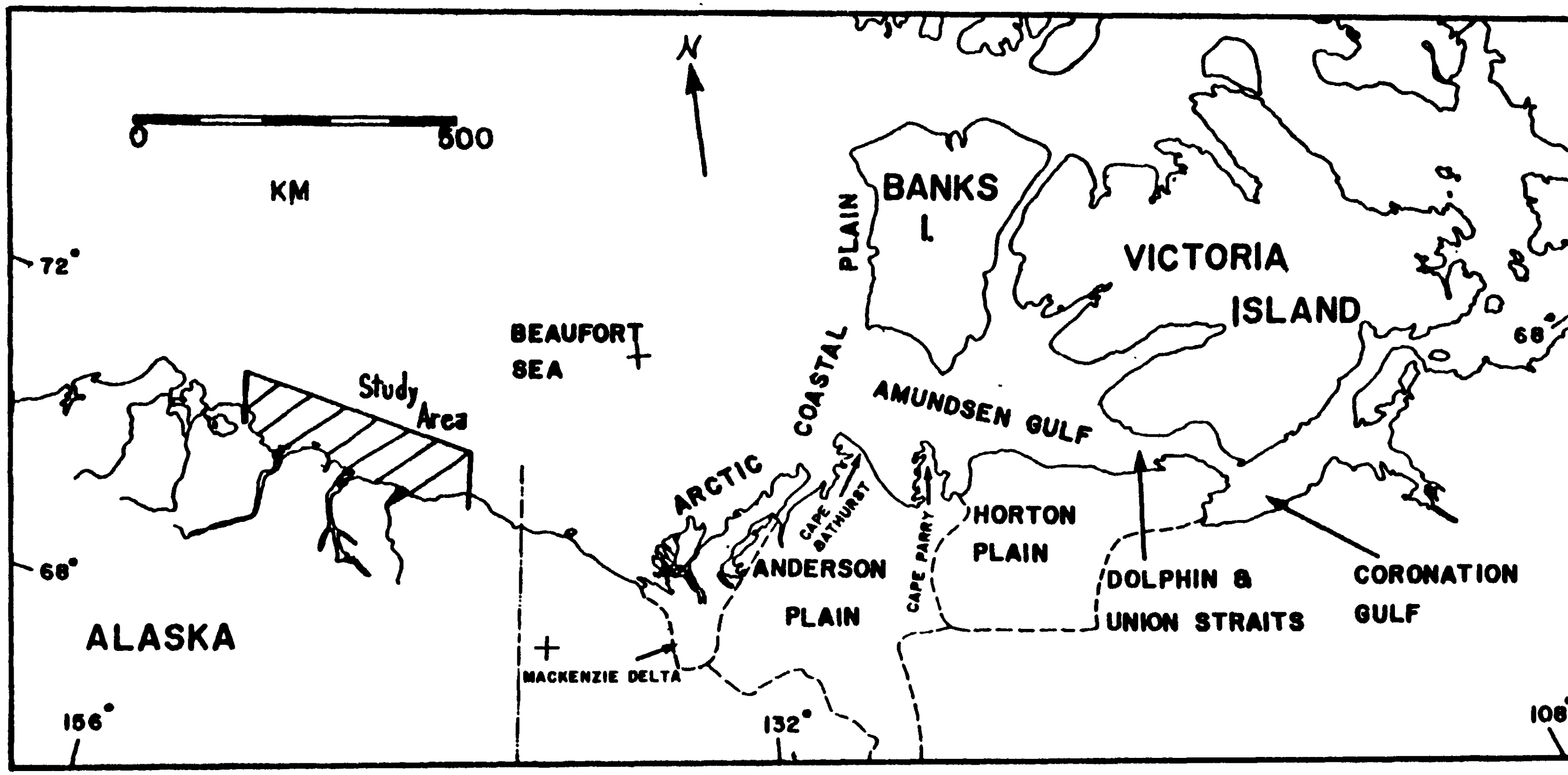

Figure 27. CANADIAN PHYSIOGRAPHIC PROVINCES (after Douglas, 1970)

Island these resistant pebbles are more abundant in the Beaufort than in younger Pleistocene deposits (Thorsteinsson and Tozer, 1962).

Because the Beaufort shelf gravel in the area of study ranges from 46-89 percent dolomite the source areas reviewed above represent favorable areas from which to derive this gravel. Many of the required mafic rocks are represented by dikes and sills, and the granitic rocks by large Canadian shield erratics. Orthoquartzites of many colors are also found within these areas.

Dolomite samples obtained from the Horton Plain area (68 23'N; 120 46'W) are similar in hand specimen as well as thin-section to those from the dolomite facies. The results of a trace element analysis of three dolomite samples from the outer Beaufort Sea shelf (72ABP-23), Cross Island, and the Horton River Plain (MQ21-14-43) are shown in Table 8 and Figure 28. Reasonably close correlation may be seen between all samples, but samples 72ABP-23 and MQ-21-14-43 are especially close. All values for these two stations are similar except for Pb and Sn. These two anomalies may be explained by the method of preparation of the samples. 72ABP-23 represents an outer shelf clast whose surface had a ferrimanganic coating. Pb and Sn anomalies probably stem from their incorporation within this coating. Thus, Figure 28 shows one sample from the Horton Plain in Canada and one from the dolomite facies on the outer shelf in the Beaufort Sea have very similar elemental distributions.

It is unlikely that the Mackenzie River drainage provided much material to the shelf gravel because ice from the Wisconsin Mackenzie

Table 8

RESULTS OF SEMI-QUANTITATIVE SPECTROGRAPHIC ANALYSIS
Fe, Mg, Ca, and Ti REPORTED IN PERCENT, ALL
OTHER ELEMENTS REPORTED IN PPM

Element*	Cross Island Conc.	72ABP-23 Conc.	MQ21-14-43 Conc.
Fe	1	1.5	1
Mg	7	7	10
Ca	7	10	7
Ti	.02	.07	.05
Mn	.03	.01	.015
B	5	15	10
Ba	30	20	20
Cr	5	5	5
Cu	2.5	7	5
Ni	2.5	5	5
Pb	15	30	10
Sn	-	30	-
V	5	15	15
Y	5	5	5
Zr	5	10	10

*Detection limits for Fe and Ca = .05%, Mg = .02, Ti = .002%, Mn, B, Cr, Pb, Sn, V, Y, Zr = 10 ppm, Ba = 20 ppm, Cu, Ni = 5 ppm.

lobe traversed Middle Devonian shale and limestone, Upper Devonian shale and sandstone and Lower Cretaceous shale and sandstone (Hughes, personal communication). Thus, except for the shield erratics, few of the dolomite facies rock types are represented in any abundance in the part of the Mackenzie River drainage in question. Small samples of morainal pebbles which may relate to the Wisconsin limit of the Laurentide ice sheet contain no dolomite. They are predominantly chert and quartz. The chert is black and dark green. Chert is a minor constituent of the

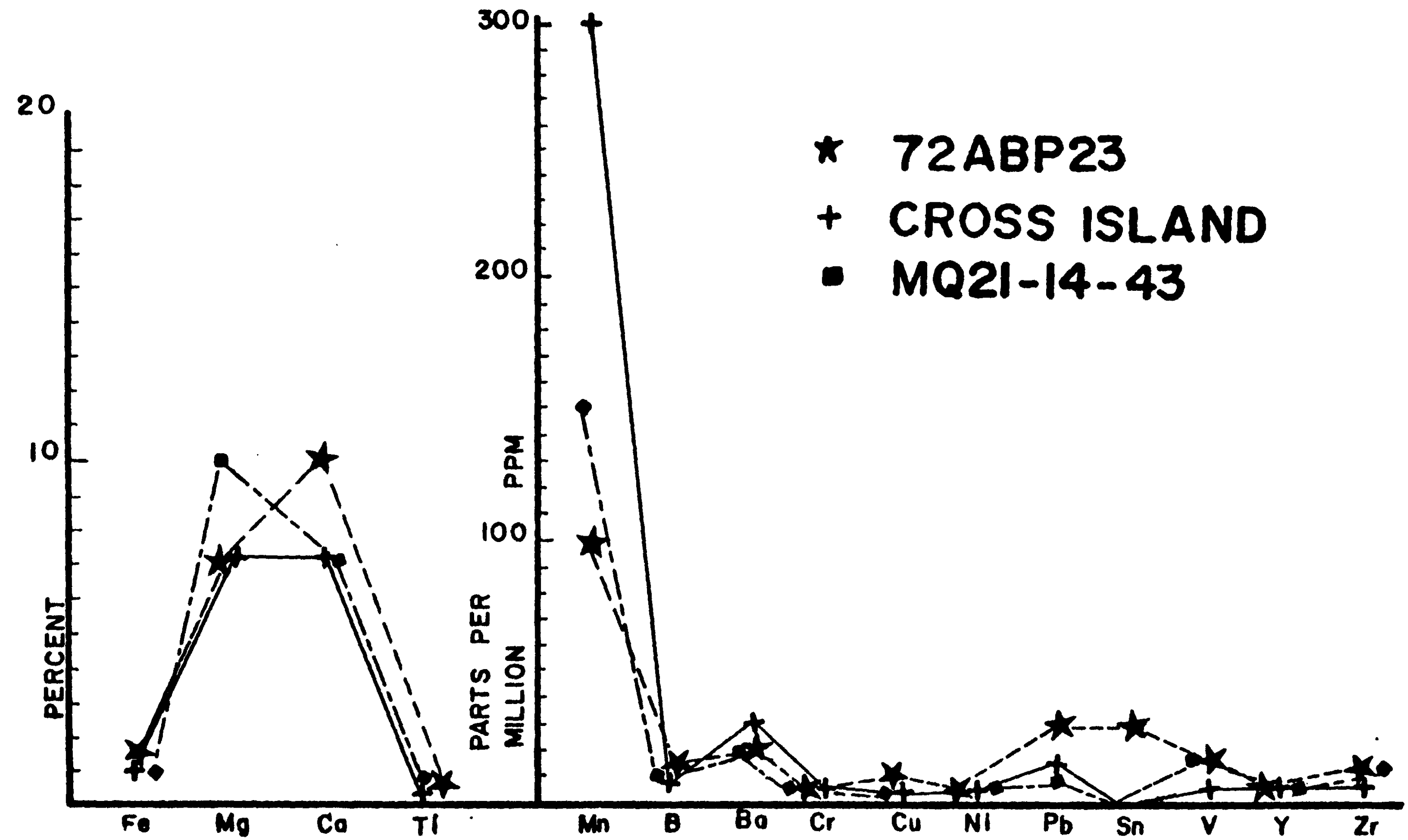

Figure 28. Trace element analysis of Three Dolomite Clast From the Horton River Plain, Canada, Cross Island, and the Outer Continental Shelf.

shelf gravel and seldom is it a dark colored chert. When chert is present it is usually white to mottled white with gray banding or white with brown banding. This distinctive chert is intimately associated with the Horton Plain dolomites (MacQueen, personal communication).

Mechanism of Transport

As the most probable source for gravel in the dolomite facies surrounds Amundsen Gulf in northwestern Canada a mechanism must be sought that will 1) transport boulders up to 1500 kilometers from the source, and 2) distribute them over the entire continental shelf and do so without showing the effect of differential abrasion on the dominant rock type. The mechanism is ice rafting and is shown in Figure 29.

Glaciation in northwestern Canada is thought to have been accompanied by a glacial tongue extending into the Amundsen Gulf and out onto the adjacent continental shelf (Prest, 1969; Bryson and others, 1968). The lobe probably existed during the early Wisconsin as well as the late Wisconsin. The retreat of the late Wisconsin ice lobe is shown in Figure 30.

Glacial ice may incorporate morainal material within or on the body of the ice. Figure 29A shows the calving of ice from the glacial tongue, much the same as reported from modern ice shelves. When sea level (dark line Fig. 29A) was below the shelf break deposition occurred on the slope. The resident pack ice would have incorporated this calved material or have restricted its movement to the area between the pack and the shore. A short summer open season is assumed

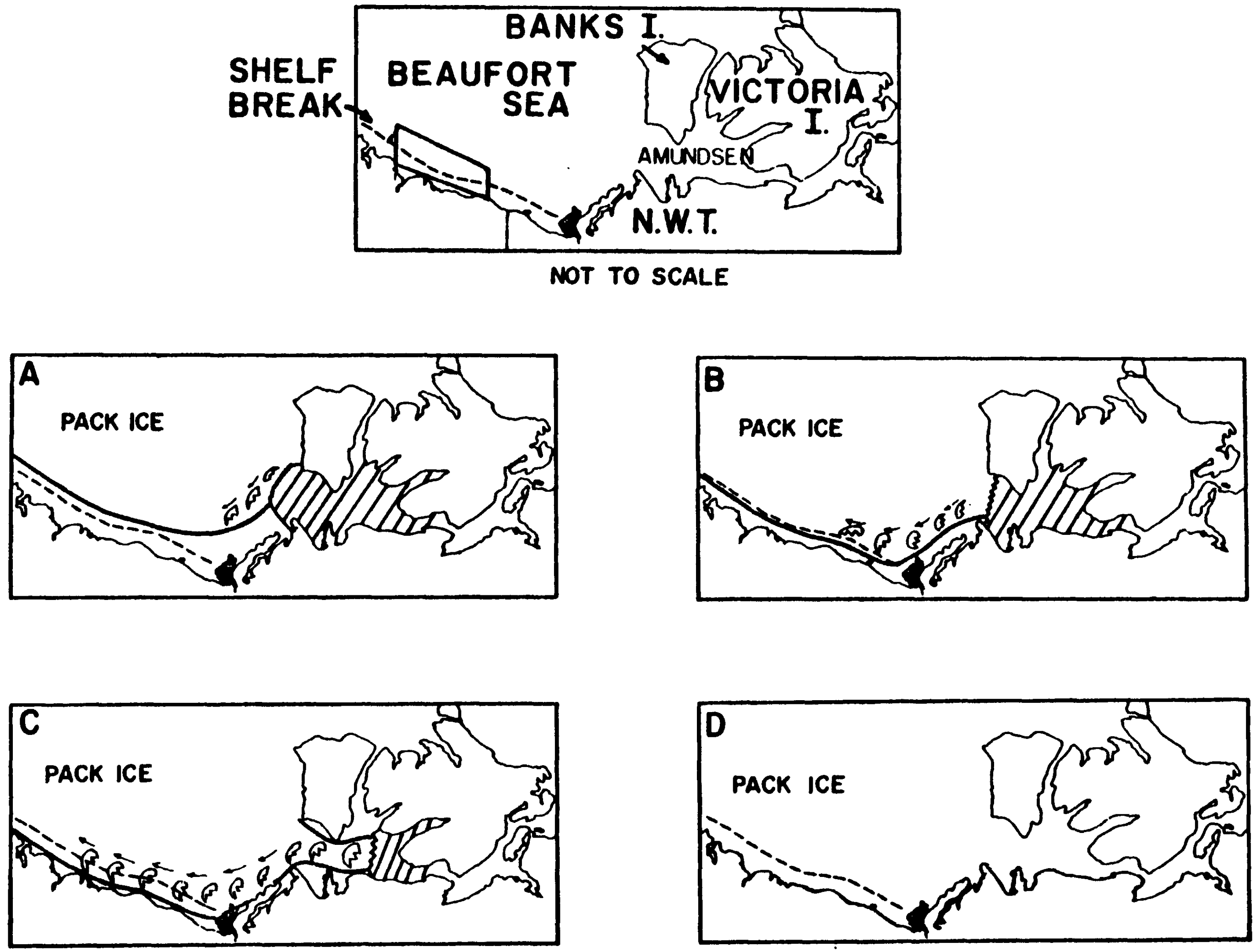

Figure 29. **TRANSPORT MECHANISM FOR ICE RAFTED DEPOSITS ON THE BEAUFORT SEA CONTINENTAL SHELF**

including river breakup and nearshore open water similar to the present situation. At the onset of deglaciation with a rapidly ameliorating climate at lower latitudes a eustatic rise in sea level would affect the Arctic while maintaining maximum glacial conditions for a short period of time. Figures B and C show a rapid increase in calving as more of the ice tongue floats as sea level rises. Finally, total deglaciation occurs and the present land and water configuration appears (Fig. 29D).

The above mechanism could account for all dolomite facies gravel within the study area but the time of deposition presents a problem. Those dolomite facies rocks incorporated in the Gubik Formation clearly cannot have been deposited during the last marine transgression. Therefore, two periods of ice-rafting seem to be required.

McCulloch (1967) suggests that the ice-rafted boulders protruding through the tundra (MacCarthy, 1958; Leffingwell, 1919) were deposited during the mid-Wisconsin transgression. Rocks similar to those exposed at Heald Point are incorporated into the Barrow unit of the Gubik Formation near Point Barrow (Lewellen, personal communication). The Barrow unit represents much if not all of the Wisconsin glacial epoch. Thus, deposition during the mid-Wisconsin transgression is probably correct. There is also little evidence for large scale tectonic activity since the end of the Wisconsin glacial epoch to account for the boulders above sea level.

On the basis of radiocarbon dates, the gravel on the central and outer shelf can be shown to have been deposited during the Holocene transgression. Rocks found incorporated into the Gubik Formation

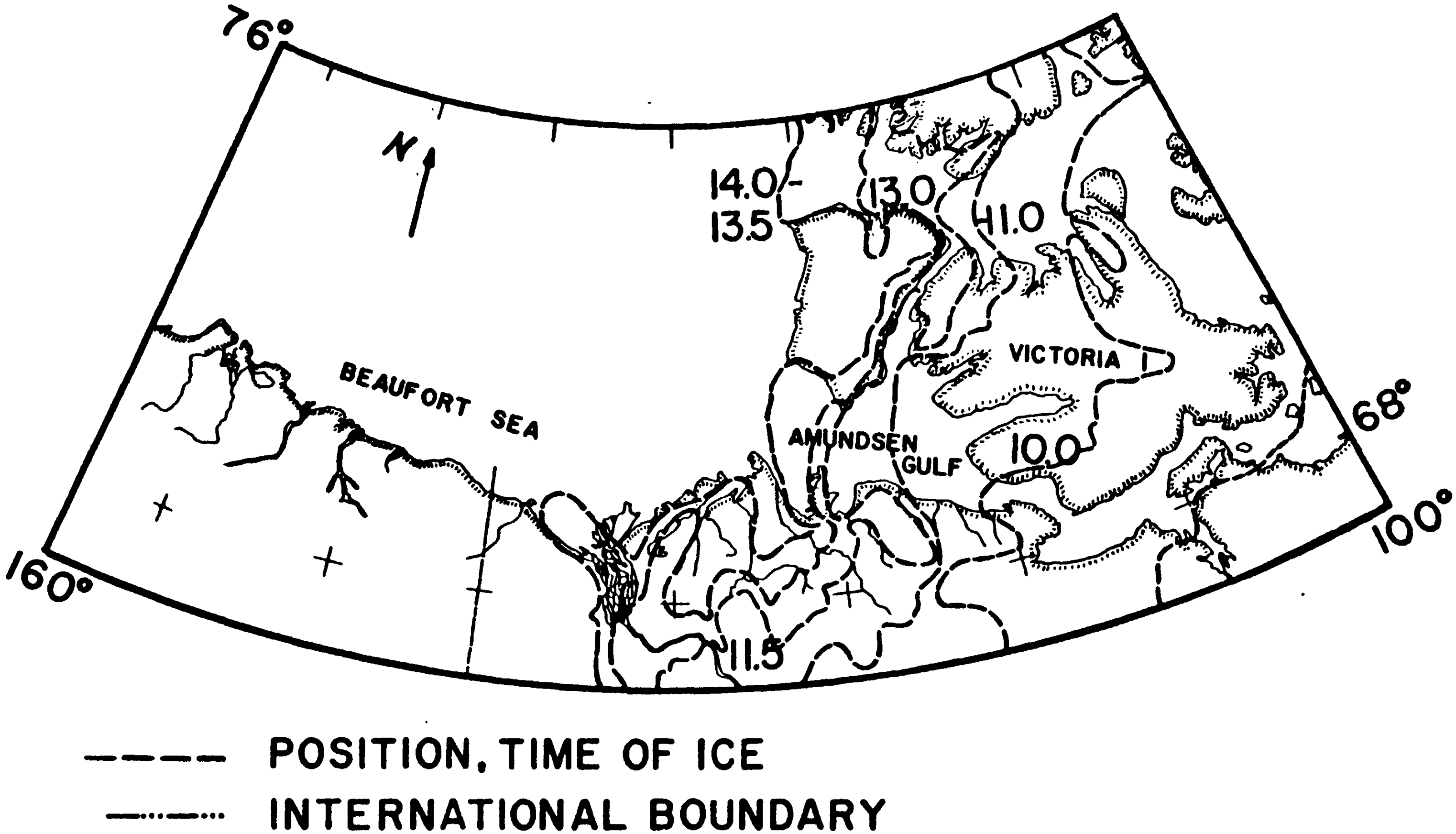

Figure 30. RETREAT OF WISCONSIN ICE (after Prest, 1969)

discussed above were probably deposited during the mid-Wisconsin transgression. Deposits in the boulder patch in Foggy Island Bay were deposited during one of these periods, but the question is which one? If they were deposited during the last transgression they are primary ice-rafted deposits. If they were originally deposited during the mid-Wisconsin, they are now lag deposits from the transgressive erosion of the Gubik Formation similar to the deposit surrounding Heald Point.

On the basis of lithology the boulders around Prudhoe Bay and Heald Point are included with other Flaxman boulders. Extremely large boulders are confined to those areas south of the dolomite facies barrier islands or landward of the Reindeer-Cross Island ridge. The boulder patch in Foggy Island Bay and on land deposits at Heald Point, Milne Point, and Bodfish Island contain boulders with dimensions of up to 2 meters.

The resulting observations from 40 scuba diving traverses in the study area and the examination of many bottom photographs from the central and outer shelf indicate few large boulders are found seaward of the Reindeer-Cross Island ridge.

The boulder patch and onshore dolomite facies deposits contain more granitic and orthoquartzitic material than those deposits on the open shelf. The Table in Appendix A shows higher relative percentages of clastic rocks (orthoquartzite) at Reindeer, Cross and Pole Islands, the Canning River delta, and 72AER-172. 72AER-172 was taken from a depth of 16.5 meters. Qualitatively, more clastic rocks are also found in the boulder patch and onshore at Heald Point. The disparity of the proportions of clastic rocks between the offshore dolomite facies and the nearshore plus onshore dolomite facies can be understood by considering sea level history in the area.

Although sea level curves cannot be strictly applied from one area to another because of possible dissimilarity of tectonic events, the sea level curve of Hopkins (1973) compares favorably with some C^{14} dates recently obtained (Barnes and Reimnitz, unpublished data). Therefore, the Bering Sea sea level curve will be used as an aid in interpreting the possible time of deposition of the inner shelf dolomite gravel.

If one considers the provenance suggested as reasonable for the source of dolomite facies gravel then it can be assumed that material may be transported whenever a glacial tongue is present in Amundsen Gulf. Figure 30 shows the retreat of the Amundsen Gulf lobe during the late Wisconsin deglaciation. Glacial calving probably occurred until approximately 10,000 B.P. By this time the ice lobe had retreated to the constriction in Amundsen Gulf south of Victoria Island (Dolphin and Union Straits) causing cessation or a greatly reduced rate of ice calving. Sea level history (Hopkins, 1973) shows that 14,000 B.P. (the oldest date in Figure 30) sea level stood approximately at the -38 meter contour (Figure 31). As the modern shelf break averages 70 meters deposition probably occurred on and seaward of the present mid-shelf region at that time. By the time retreat of the Amundsen Gulf lobe resulted in the cessation of calving bergs (approx. 10,000 B.P.) sea level stood at approximately the -20 meter contour. If these depths

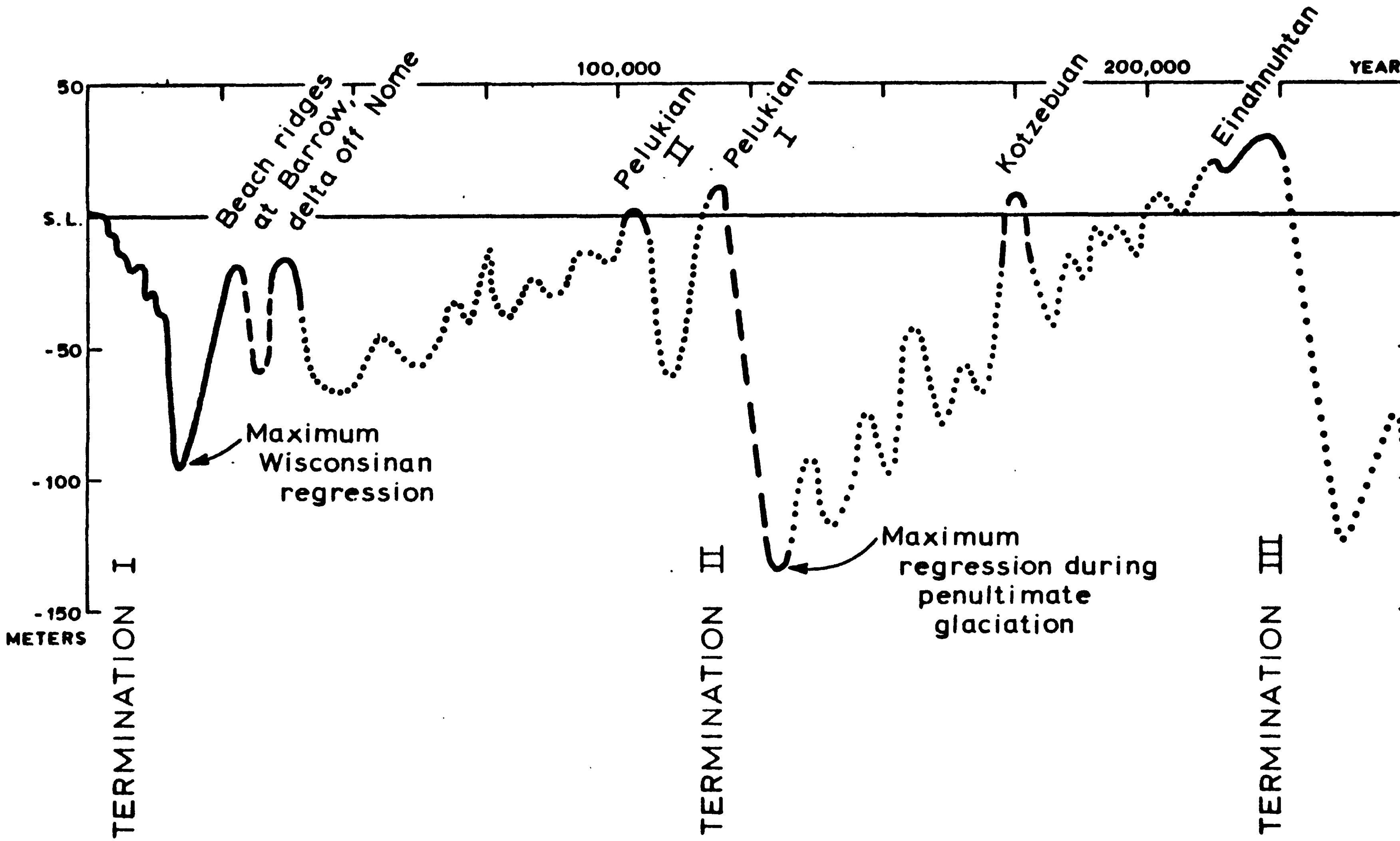

Figure 31. Sea Level History of the Bering Sea (After Hopkins, 1973).

are correct, all surficial material seaward of the -20 meter contour was deposited between the onset of the late Wisconsin glaciation and 10,000 B.P. All dolomite facies rocks landward of the -20 meter contour were concentrated from the reworking of the Gubik Formation. Therefore, all clasts coarser than sand included in the dolomite facies may be considered relict with no need to invoke modern ice-rafting as an important geologic agent in the Beaufort Sea.

Although there are indications that some ice-rafting occurs now, field observations indicate ice-rafting is insignificant on the Beaufort shelf at the present time.

CONCLUSIONS

The shallow continental shelf of the Beaufort Sea is mantled by two distinct gravel populations. A nearshore chert facies, restricted in areal distribution and originally deposited as fluvial gravel, represents part of a transgressive sequence and is composed of reworked Gubik Formation gravel. The source of the chert facies is the Alaskan Brooks Range. The offshore dolomite facies is an ice-rafted deposit with its provenance in the region surrounding the Amundsen Gulf in the Canadian Archipelago.

Apparently two periods of dolomite facies deposition have taken place. One period occurred during the mid-Wisconsin transgression. Boulders and cobbles were deposited in areas now as much as 8 meters above sea level. This period is characterized by a greater abundance of granitic rocks and orthoquartzites perhaps reflecting a source further inland from the shore of Amundsen Gulf. A second period during the early part of the Holocene transgression is indicated by surficial central and outer shelf gravel overlying marine sediment dated at 15,000 B.P. Considerations of possible sea level history of the Beaufort Sea shelf suggest some of the inner shelf dolomite facies gravel was deposited during the mid-Wisconsin high sea level stand incorporated into the Quaternary Gubik Formation, and subsequently eroded to form a lag deposit. Gravel distribution on the shelf is influenced primarily by the modification of the seafloor by ice and low rates of sedimentation. The conclusions indicate most of the shelf gravel is relict and ice-rafting is relatively unimportant as a sedimentary mechanism in the present Beaufort Sea arctic geologic environment.

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APPENDIX A

DOLOMITE FACIES SAMPLES (%)

STATION/LITHOLOGY	DOLOMITE	IGNEOUS ROCKS	CLASTIC ROCKS	LIMESTONE	CHERT	METAMORPHIC ROCKS	SAMPLE WT.
72ABP-9	80.03	10.91	4.07	.15	2.30	2.53	1302 g
72AB -19	88.96	3.09	5.25	0	1.78	.93	1069 g
72ABP-23	81.95	10.41	5.64	.12	.78	1.10	4254 g
72ABP-24	56.46	34.08	7.39	0	.64	1.43	4387 g
72ABP-40	75.72	8.71	7.11	3.36	1.16	3.92	861 g
72ABP-50	76.34	12.02	6.23	2.01	1.76	1.63	1589 g
72ABP-58	59.28	28.51	8.66	.45	.90	2.20	442 g
71ABP-87	81.89	3.15	3.15	3.94	4.33	3.54	252 g
72AER-136	59.55	8.74	13.36	1.94	12.62	3.80	309 g
72AER-139	68.48	15.22	4.72	0	10.33	1.26	184 g
72AER-140	63.00	31.41	.72	3.07	1.08	.72	554 g
72AER-143	46.31	47.95	4.10	0	1.64	0	853 g
72AER-148	80.33	12.30	3.69	1.64	2.05	0	244 g
72AER-172	75.20	4.29	12.20	1.51	1.74	5.06	863 g

DOLOMITE FACIES SAMPLES (%)

STATION/LITHOLOGY	DOLOMITE	IGNEOUS ROCKS	CLASTIC ROCKS	LIMESTONE	CHERT	METAMORPHIC ROCKS	SAMPLE WT.
Cross I.	63.83	10.01	14.54	.33	4.47	6.82	2687 g
Reindeer I.	54.47	9.31	27.82	0	6.58	1.84	806 g
Canning R.	36.59	37.88	21.27	1.10	0	3.16	1547 g
Narwhal I.	64.71	17.65	10.29	0	5.88	1.47	
Pole I.	31.38	5.13	23.12	.59	36.36	3.42	682 g

CHERT FACIES SAMPLES (%)

STATION/LITHOLOGY	DOLOMITE	IGNEOUS ROCKS	CLASTIC ROCKS	LIMESTONE	CHERT	METAMORPHIC ROCKS	SAMPLE WT.
72AER-101	1.04	0	20.88	1.95	65.11	9.60	771 g
72AER-164	10.65	1.67	23.38	1.67	49.48	13.15	479 g
72AER-212	11.54	1.79	10.00	0	60.26	16.41	390 g
Gubik Stop 1	.38	0	46.70	28.53	9.89	14.50	2103 g
PR-2	0	.27	51.20	20.56	18.12	9.85	2549 g
Gubik-Milne Pt.	0	1.23	15.10	6.01	66.72	10.94	649 g
Milne Pt. Shothole	0	0	41.49	0	43.88	14.63	670 g
Saktuina Island	23.64	6.18	8.36	0	44.00	17.82	275 g
Colville A	0	.69	59.80	0	30.09	9.42	1306 g
Colville B	0	1.13	57.97	0	32.41	8.54	3456 g
Thetis I.	0	1.23	6.52	2.09	75.15	15.01	813 g
Cottle I.	1.08	4.00	22.46	2.62	53.08	16.77	650 g
Kuparuk R.	0	1.64	49.01	.88	34.64	13.84	1712 g
Sagavanirktok R.	5.65	4.42	28.82	29.47	20.93	10.72	1381 g
Spy Island	4.24	1.54	11.32	.13	75.95	6.82	777 g
Long Island	4.29	1.52	8.84	.42	55.47	29.46	1188 g
Sagavanirktok R. 73	1.00	0	34.04	38.52	22.69	4.22	