HEAVY-MINERAL TRENDS IN THE BEAUFORT SEA

By

Gretchen Luepke

Open-file report
1975

HEAVY-MINERAL TRENDS IN THE BEAUFORT SEA

Gretchen Luepke

Abstract

Sediments of the Beaufort Sea, off the North Slope of Alaska contain a great variety of heavy minerals. These include garnet, chrome spinel, augite, pigeonite, diopside, hornblende, enstatite, hypersthene, epidote, clinozoisite, zoisite, apatite, tourmaline, chloritoid, sphene, zircon, and opaque minerals. Much rarer constituents are glaucophane, lamprobolite, rutile, kyanite, staurolite, and riebeckite.

The heavy-mineral fractions that were not treated with hydrochloric acid contain "iron-stained aggregates", grains of unidentifiable material encrusted with limonite. Samples containing relatively high percentages of iron-stained aggregates and altered opaque minerals occur in depths less than 10 m and within 16 km from shore.

Garnet increases in abundance from east to west, which corresponds to a similar increase in garnet abundance in coastal outcrops of the Gubik Formation sands. Only garnet and iron-stained aggregates appear to have source-related distribution patterns. The other heavy minerals lack distinct distributive provinces, reflecting an environment dominated by intense mixing by ice-gouging and bioturbation and a homogenous source area. Waves and currents are not strong enough to sort sediments at depths greater than 10 m except during summer storms.

The source of the Beaufort Sea heavy minerals is dominated by contributions from the Alaskan North Slope deposits of Tertiary and younger age. The Colville River, largest in the region, is probably the most influential in transporting sediments, but because of wave and current-mixing of sediments on the shelf, exact contributions from each river drainage cannot be ascertained. Coastal erosion of the Gubik Formation is probably at least as important as the Colville River in supplying heavy minerals to the Beaufort Sea.

HEAVY-MINERAL TRENDS IN THE BEAUFORT SEA

Introduction

Purpose. As part of the environmental-baseline studies of the offshore North Slope of Alaska, a study was made of the heavy minerals in the Beaufort Sea to ascertain the source areas and transport routes of sediments on the continental shelf.

Setting. The Beaufort Sea lies north of Alaska from Point Barrow eastward to the islands of the Canadian Arctic Archipelago (fig. 1). The present study area extends from Point Barrow to Barter Island, off the Alaska coast.

Two geomorphic provinces dominate the North Slope of Alaska. The arctic coastal plain is a gently-sloping surface of low relief extending from the coast to the arctic foothills. The Gubik Formation, a dominantly marine unit of Pleistocene age, blankets the entire coastal area immediately adjacent to the Beaufort Sea (Payne and others, 1951). Thickness averages about 20 metres. The Gubik unconformably overlies the Sagavanirktok Formation (Early Tertiary) and the formations of the Colville and Nanushuk groups (Cretaceous) (see fig. 2).

Pack ice covers the shelf for nine months of the year, eliminating waves and mitigating the effects of wind-driven currents and storm tides. During the open-water period, the most common waves observed have periods of 2 to 3 seconds and heights of 20-30 cm. Surface currents nearshore are wind-driven. Meteorological tides are of larger amplitude than astronomical tides in the arctic coastal zone (Wiseman, Suhayda and Hsu, 1974, p. 51-59).

Eighty percent of the North Slope (see fig. 1) drains into the Beaufort Sea (Walker, 1974, p. 517). The 600-km Colville River and its massive tributary system drain seventy-eight percent. Rivers such as the Kuparuk and Sagavanirktok are comparatively short and empty into lagoons bounded by offshore bars and barrier islands (Walker, 1974, p. 537).

Barnes and Reimnitz (1974, p. 444) measured currents below the ice cover that show an overall westward movement of near-bottom water on the inner shelf at 2 cm/sec parallel to the coastline. Mountain (1974, p. 27) notes an eastward flow of surface water on the outer shelf. Hufford (1974, p. 569) states that subsurface currents appear to behave independently and often opposite of surface currents; 1971 and 1972 measurements showed bottom currents flowing eastward at speeds less than 15 cm/sec.

Subsurface currents may change directions from season to season. But long-range sediment transport along the coast appears to be westerly. Documentation of this westerly transport is multifaceted: Barrier islands migrate westward (Wiseman and others, 1973, p. 161; Reed and Sater, 1974, p. 563); sediment plumes from rivers, seen on ERTS-1 imagery, veer westward (Barnes and Reimnitz, 1974, p. 444); ice moves dominantly westward under the influence of the Pacific Gyre off northern Alaska (Reimnitz and Barnes 1974, p. 301).

Previous studies show that weight percentages of heavy minerals in different size fractions in the Beaufort Sea are unrelated to grain size. Table 1 lists the specific areas studied and the size-fractions in which weight-percentages of heavy minerals were determined.

TABLE 1. Studies of heavy-mineral weight-percentages in the Beaufort Sea.

Reference	Area/Sediment type	Size-fractions compared
Naidu & Sharma 1972, p. 7-8	Point Barrow to Barter Is. Offshore sediments	0.75-0.25 mm 0.25-0.125 mm 0.125-0.062 mm
Dygas, Tucker & Burrell 1972, p. 112	Colville River sands; coastal & barrier-beach sands	0.25-0.125 mm 0.125-0.062 mm 0.062-0.038 mm
Burrell, Dygas & Tucker 1974, p. 125-126	Simpson Lagoon, btw. Oliktok & Beechey points offshore sediments	0.500-0.250 mm 0.250-0125 mm 0.125-0.062 mm
This report	Point Barrow to Barter Is. Offshore Sediments	2.00-0.062 mm

The percent of heavy minerals in the areas studied by the above authors averages about 5%; only rarely do fractions contain percentages of heavy minerals greater than 10%. The beach and river sands contain higher overall percentages of heavy minerals than do the offshore sands.

Naidu and Mowatt (1974) discuss relative heavy-mineral weight-percents in deltaic and shallow-water Beaufort Sea sediments, noting a more normal grain-size relationship (i.e., higher heavy-mineral percents with decreasing grain-size) in the deltaic sediments.

Studies of heavy-mineral distribution patterns have been made in other shelf seas bordering the Arctic Ocean. Holmes (1967) did not find enough significant differences in heavy-mineral assemblages of the Laptev Sea (fig. 1) to attempt any interpretation. General uniformity of mineral composition in the East Siberian Sea was also noted by Naugler (1967). However, he found garnet decreases uniformly toward the center of the study area from the west, and orthopyroxene dominates the eastern regions. Silverberg (1972) studied heavy-mineral distributions in both the Laptev and East Siberian seas and identified three heavy-mineral provinces: clinopyroxene-garnet (west); amphibole-clinopyroxene-epidote central; and clinopyroxene-epidote-amphibole-opaque minerals (east).

Carsola (1954, p. 1570) examined Beaufort Sea sediment with a binocular microscope and noted that heavy minerals appeared to constitute a varied assemblage. The present study, the first to study in detail heavy-mineral species in Beaufort Sea sediment, confirms this impression.

Methods. Heavy-minerals were separated in tetrabromoethane (S.G. = 2.96), from microsplits of the sand-size fractions (2.0-0.062 mm) of 153 samples (Table 2). Three surface samples were taken at the mouth of the Colville and Sagavanirkto, rivers and 20 km upstream in the Kuparuk River; all other samples were taken in offshore areas (fig. 1). The weight of the splits ranged from 3.5 to 28.0 grams (average ≈ 14 g).

TABLE 2. Weight-percentages of heavy minerals in the sand-size fraction (2.0-0.062 mm). For sample locations refer to Figure 1. Percentages marked with asterisk (*) are an average of two.

SAMPLE	% HEAVY-MINERALS	SAMPLE	% HEAVY-MINERALS	SAMPLE	% HEAVY-MINERALS	SAMPLE	% HEAVY-MINERALS
1.	0.79	38.	1.7	76.	1.9	113.	0.57
2.	2.0	39.	2.8	77.	4.6	114.	0.62
3.	0.84	40.	0.40	78.	1.8	115.	0.93
4.	1.7	41.	0.15	79.	2.1	116.	0.97
5.	1.3	42.	1.5	80.	2.3	117.	1.3
6.	1.6	43.	2.9	81.	2.4	118.	0.59
7.	1.5	44.	1.5	82.	2.6	119.	0.60
8.	2.0	45.	2.8	83.	0.92	120.	1.0
9.	0.10	46.	2.1	84.	0.96	121.	0.35
10.	2.5	47.	0.14	85.	2.7	122.	0.15
11.	4.7	48.	0.38	86.	1.2	123.	0.77
12.	1.1	49.	1.5	87.	1.8	124.	1.3
13.	1.2	50.	1.9	88.	3.8	125.	1.3
14.	1.2	51.	1.2	89.	0.77	126.	1.4
15.	2.4	52.	0.77*	90.	0.17	127.	0.47
16.	3.4	53.	1.4	91.	1.5	128.	1.4
17.	1.8	54.	0.76	92.	0.22	129.	1.0
18.	1.3	55.	0.48	93.	0.49	130.	1.1
19.	1.7	56.	0.59	94.	0.86	131.	0.64
20.	2.8	57.	0.76	95.	3.6	132.	0.79
21.	2.4	58.	1.2	96.	2.0	133.	1.6
22.	1.3	59.	0.79	97.	0.93	134.	0.41
23.	0.50	60.	0.78	98.	0.90	135.	0.77
24.	0.54	61.	0.65	99.	1.2	136.	0.81
25.	1.0	62.	0.27	100.	0.56	137.	0.44
26.	1.1	63.	0.25	101.	0.90	138.	0.70
27.	4.3	64.	0.30*	102.	1.1	139.	0.70
28.	2.1	65.	0.45	103.	1.2	140.	0.69
29.	1.3	66.	0.29	104.	0.41	141.	0.91
30.	1.8	67.	0.30	105.	0.43*	142.	0.79
31.	1.0*	68.	0.69	106.	0.42	143.	0.40
32.	2.0	69.	0.56	107.	0.60	144.	1.2
33.	2.1	70.	0.79	108.	0.69*	145.	1.05
34.	1.9	71.	0.52	109.	0.94	146.	0.66
35.	1.8	72.	0.38	110.	0.33	147.	1.1
36.	1.4	73.	0.93	111.	0.11	148.	1.9
37.	2.2	74.	1.9	112.	0.93	149.	1.9
		75.	1.8			150.	1.3
						151.	1.4
						152.	0.80
						153.	0.75

The heavy-mineral concentrates were sieved and grains were mounted in Lakeside 70 (n - 1.56). Some of the concentrates prepared early in the study were not microsplit. Comparisons of slides prepared with and without splitting revealed no major differences in mineral frequencies. Point-counts were made of 42 selected samples (see Table 3; fig. 1 for locations) in the 0.25 - 0.062 mm size range; for seven of these samples the 0.25 - 0.125 mm size range; for seven of these samples the 0.25 - 0.125 mm size range was also point-counted, to determine if size-related differences in mineralogy occurred. No significant differences were detected.

Heavy minerals were identified and counted following a line in the grain mount where the cross-hairs touched a grain. To help insure a random count, half the total number of grains were counted in east-west sweeps, the other half in north-south sweeps. Care was taken that the two areas did not overlap.

This method actually gives only number frequency, which gives a sample bias, in that a larger grain is more likely to be encountered during the analysis than a smaller one. The discrepancy is minimized by counting a limited size range (Galehouse, 1969, p. 814). Grains were identified as to mineralogic species when possible. The opaque minerals and aggregates were separated into iron-stained and unstained groups (see Table 3).

To insure the preservation of apatite, no samples were initially treated with HCl. Later, microsplits of five selected heavy-mineral concentrates were heated in concentrated Hcl over low heat for 30-45 min. The results were compared with the respective nontreated microsplits.

Micas and carbonate grains were noted in most samples, particularly those taken close to shore. Because of their wide specific-gravity range (2.7 - 3.1 for the micas, 2.7-2.9 for calcite and dolomite; from Allman and Lawrence, 1972, p. 181, Table 28), they are not considered true "heavy minerals" and are therefore omitted from the point-counting.

Description of Heavy Minerals

A great variety of heavy minerals were identified: opaque minerals, garnet, chrome spinel, augite, diopside, pigeonite, hornblende, enstatite, hypersthene, epidote, clinozoisite, zoisite, apatite, tourmaline, chloritoid, sphene, and zircon. Extremely rare, but positively identified, were glaucophane, lamprobolite, rutile, kyanite, staurolite, and riebeckite. One grain of lawsonite was seen in the acid-treated microsplit of the Kuparuk River heavy-mineral concentrate.

Opaque minerals. Opaque minerals compose an average of 17% of the heavy minerals counted, with extremes at 6% and 35%. Magnetite is present (detected with a horseshoe magnet) in virtually all samples. Where magnetite was not detected, the percent of heavy minerals was consistently less than 1%, and the weight of the heavy-mineral fraction less than 0.1 g. The lack of magnetite in these samples is probably a function of either the small heavy-mineral fraction or of sorting. Ilmenite is probably also present, although opaque grains with a whitish (leucoxene?) alteration were rare. Pyrite (authigenic) was seen in the 0.25 - 0.125 mm fraction of sample 70ABP-1.

The forms of the opaque grains ranges from crystalline to well-rounded. Some grains were surficially altered to iron-oxide. This will be discussed later.

Treatment in hydrochloric acid did not systematically change the percents of opaque minerals. Usually the counts remained within ± 5%, but in one sample the percentage decreased 24%.

Chrome spinel. Chrome spinel composes between 1 and 8 percent of the heavy minerals in all samples. This mineral is usually partially translucent and isotropic. The grains show very high relief and forms varying from crystalline to well-rounded. Concoidal fractures may be present. Translucent beer-bottle-brown-colored grains are probably picotite (Morris, 1952). Similar translucent to nearly opaque grains are blood-red, an anomalous color for picotite.

Garnet. Percentages of garnet ranged from 1 to 11%. Samples containing greater than 5% garnet all lay west of Cape Halkett (fig. 3). East of Cape Halkett the distribution is uniformly low. Colorless and pink garnet occurs in all samples. The colorless variety generally is more numerous and more etched than the pink variety. In samples taken west of Cape Halkett, garnets with yellowish hues were seen; this was the rarest variety noted. All garnets were rounded to some degree and many contained inclusions. No systematic attempt was made to identify these inclusions, although in one sample they were clearly rutile.

Clinopyroxene. As a group, clinopyroxenes constitute a range of 11 to 26% of all samples, with a maximum of 35%. HCl-treatment, while not necessarily rendering species more identifiable, invariably increased the percentage of identifiable clinopyroxene grains by at least 7% and as much as 18%. The sample from the Colville River contained 34% clinopyroxene after acid treatment, compared to 16% before treatment.

These differences did not alter the overall distribution of clinopyroxenes. The percentages of this group ranged from 1 to 16% within 18 km of the coast and from 13 to 35% beyond 18 km.

Augite, diopside, and pigeonite were identified, but it was frequently impossible to identify a clinopyroxene as to species, even where the sample was acid-treated. Because of this difficulty, the clinopyroxene were grouped together for correlation purposes.

Augite, the most abundant clinopyroxene, had many colors: green, brown, colorless, occasionally purplish. Form ranged from prismatic to well-rounded. Saw-toothed etching of grains was occasionally noted.

Diopside, the most difficult clinopyroxene to positively identify, had a very high birefringence and a characteristic extinction angle (about 39°). Where identified, diopside and pigeonite occurred in roughly equal amounts, always less than 5% of the heavy mineral fraction.

Hornblende. Hornblende, with its characteristic extinction angle ($12 - 30^{\circ}$) and pleochroism, constitutes 1 to 18% of all samples, usually less than 11%. HCl-treatment did not systematically alter the percentages of hornblende identified. However, lamprobolite grains

were more likely to be found in acid-treated samples, possibly because they were masked by limonitic alteration in untreated samples. Overall hornblende percentages tend to increase with distance from shore.

The blue-green and green varieties of hornblende occur in about equal proportions. The brown varieties, if present, are less abundant than either green or blue-green varieties. Lamprobolite (basaltic hornblende) was seen in 14 samples but it is extremely rare, always composing less than 1% of the heavy-mineral fraction. It is distinguished from ordinary brown hornblende by its much smaller extinction angle ($0-12^{\circ}$) and red-brown color.

Orthopyroxene. Enstatite and hypersthene rarely exceed 4% of the heavy-mineral fraction. Enstatite occurs slightly more frequently than hypersthene. Enstatite may occur as prismatic or rounded grains; hypersthene more commonly is prismatic.

The pleochroism of the hypersthene is in general extremely faint, indicating that the variety may be ferrohypersthene (Naugler, 1967, p. 42). True hypersthene, with its intense pleochroism, is not as common as ferrohypersthene in these sediments. In some cases hypersthene could only be distinguished from enstatite is by its optic sign.

Epidote group. In the Beaufort Sea sediments, the epidote groups constitutes an average of 6% of the heavy-mineral fraction, with extremes at 2% and 9%. Acid-treatment slightly increased the number of identifiable epidote grains.

Epidote (pistacite) is the most common mineral of this group. It is optically negative and characteristically yellow-green but occasionally colorless. Epidote aggregates (yellow-green grains which do not go extinct) are common, sometimes exceeding the number of single-crystal grains.

Clinozoisite and zoisite are generally less common than epidote; together they may equal the amount of epidote. Zoisite appears to be the more common of the two, though these minerals may be hard to distinguish. Both ferrian (normal interference colors) and non-ferrian (anomalous deep-blue interference colors) varieties of zoisite are present.

Apatite. Apatite constitutes about 1% of the heavy-mineral fraction of all samples mostly in small, equidimensional to elongate, rounded grains. The mineral occasionally occurs in prismatic grains. Apatite was not seen in acid-treated samples.

Apatite is a uniaxial mineral, but sometimes grains may show a pseudo-biaxial figure (Milner, 1940, p. 243). In the Beaufort Sea sediments, pseudo-biaxial figures were seen most commonly in thick grains (birefringence in first-order yellow). Such grains can be confused with zoisite, although this mineral is optically positive in contrast to apatite.

Tourmaline. Tourmaline is ubiquitous but generally composes less than 1% of the heavy-mineral fraction. Although an acid-treated microsplit from the Kuparuk River contains 3%, acid-treatment did not in general increase the amount of identifiable tourmaline.

Both brown and blue-gray varieties of tourmaline are present, although the brown variety is by far more common. Grain-form ranges from prismatic to well-rounded. Overgrowths are rare.

Chloritoid. Chloritoid usually constitutes less than 1% of the heavy-mineral fraction. The largest amount (3%) of chloritoid was seen in the acid-treated sample from the Kuparuk River. It occurs as small, platy grains.

Sphene. Except for one sample containing 2% sphene, this mineral invariably makes up less than 1% of the heavy-mineral fraction. The grains are colorless to yellow-brown and rounded.

Zircon. Zircon, though rare, is present in nearly all samples. Several varieties were seen: euhedral, colorless, unzoned crystals; colorless to slightly yellow, rounded, ovoid grains; pinkish, zoned crystals.

Some grains identified as zircon showed very small extinction angles. The interference figures of such grains appeared to be uniaxial positive but could also have been biaxial positive with a low 2V. It is therefore possible that such grains are monazite, a mineral difficult to distinguish from zircon.

Other minerals. Glaucophane, kyanite, staurolite, riebeckite, and lawsonite occurred too sporadically to be significant. Glaucophane, however, was identified consistently in samples from the Colville River and its delta. Rutile, though extremely rare, was identified in samples near the mouths of the Sagavanirktok and Kuparuk rivers and in many samples west of the Sagavanirktok.

Aggregates. The term "aggregate" refers here to a grain containing one or more minerals identifiable in varied degrees. Two categories of aggregates were point-counted.

The first group, called here "unstained aggregates", is made up of grains consisting of two or more minerals (for example, an opaque mineral and a clinopyroxene), or an unidentifiable grain which did not go extinct.

The second category consists of "iron-stained aggregates". Such grains are not mineralogically identifiable but are encrusted with a yellow-orange iron-oxide material, probably limonite. Treatment with HCl does not render these grains identifiable, but does destroy the limonite, leaving the grains white.

Both categories of aggregates combined generally compose 20 to 50% but could, in a few samples, constitute as much as 71% of the heavy-mineral fraction. Samples containing more than 60% aggregates occur invariably within 16 Km of the coast. Of the five acid-treated samples, the percentages of aggregates remained about the same in two and decreased in the others.

Discussion

Distribution. The heavy minerals never composed more than 5% the sand-size fraction (see Table 2). No significant relationship was apparent between percent of heavy minerals and either mean grain-size or depth of sample. The patterns of concentration were quite random, though percentages greater than 1% seemed to lie in a belt beyond the barried islands and generally shoreward of the shelf break. Percentages are comparable to those obtained by other workers (Burrell, Dygas and Tucker, 1974; Dygas, Tucker and Burrell, 1972; Naidu and Mowatt, 1974; Naidu and Sharma, 1972). Of all the heavy-mineral species, only garnet and iron-stained aggregates show any definite distribution patterns in the Beaufort Sea. Both of these patterns may well be source-dependent.

Six samples of the Gubik Formation taken near Point Barrow contain an average of 8.5% garnet, a maximum of 15%. On the other hand, samples of the Gubik taken at six different localities east of the Colville River, between Simpson Lagoon and Prudhoe Bay, contain less than 1% garnet.

The higher percentages of garnet in marine sediments west of Cape Halkett (fig. 3) would seem to suggest either a westward direction for sediment transport or little transport from the source rocks. Currents effectively keep the garnet supplied from the Gubik Formation moving westward.

In samples containing high percentages of iron-stained aggregates, the opaque minerals present commonly show iron-oxide alteration. For both groups the staining ratio, the ratio of the frequency of iron-stained to unstained grains, was calculated.

As seen in Figure 4b the staining ratio for opaque minerals is generally less than 1.0. Only close to the mouths of the major rivers does the ratio exceed 2.0. The staining ratios for aggregates (fig. 4a) follow a similar pattern. Only one sample at the mouth of the Sagavanirtok contains relatively few iron-stained aggregates. This same sample also contains few iron-stained opaques (see also Table 3).

The percentage of iron-stained grains (opaque minerals + aggregates) diminishes rapidly with increasing depth to about 20 m, beyond which the percentage remains on the order of 19.5%, never exceeding 27% (fig. 5).

The prevalence of iron-stained aggregates at lesser depths close to shore probably results from proximity to source. These aggregates occur in the Pleistocene Gubik Formation, which forms seacliffs bordering the coastline. The widespread Cretaceous formations of the region are commonly oxidized at the surface (David M. Hopkins, oral commun., 1975). The low clinopyroxene percentages within 18 km of the coast are probably an artifact resulting from extensive iron-staining of grains in samples from this area.

Table 4. Minerals of the Beaufort Sea grouped as to average specific gravity.

Avg. S.G. = 3.0 - 3.49	Apatite
	Augite
	Clinozoisite
	Diopside
	Enstatite
	Epidote
	Glaucophane
	Hypersthene
	Lamprobolite
	Lawsonite
	Pigeonite
	Riebeckite
	Tourmaline
	Zoisite
Avg. S.G. = 3.5 - 4.49	Chloritoid
	Chrome spinel
	Garnet
	Hornblende
	Kyanite
	Limonite
	Rutile
	Sphene
	Staurolite
Avg. S.G. = 4.5 - 5.5	Opaque minerals
	Zircon

Data from Allman and Lawrence 1972, Table 28, p. 181, supplemented where necessary with data from Milner, 1940.

Closely associated samples, particularly in shallow water, tend to show distinctive differences in mineralogy; percentages of opaque minerals, for example, may differ by 10-15%. To examine possible reasons for these differences, all identified minerals were divided into three specific-gravity groups (Table 4). The percent of minerals in the "low" specific-gravity range (3.0-3.49) is dominated by the amount of pyroxene; the "medium" range (3.5-4.5) by iron-stained aggregates (limonite S.G. = 3.6-4.0); and the "high" range (greater than 4.5) by opaque minerals. Because the distribution of iron-stained aggregates appears to be controlled by proximity to the shoreline, the ratio of minerals in the high range to that of the low range was used. This quantity is defined as the density ratio.

$$\text{Density Ratio (D.R.)} = \frac{\text{\% minerals of S.G.} > 4.5}{\text{\% minerals of S.G.} = 3.0\text{-}3.49}$$

Density ratios for 32 samples were plotted against depth (fig. 6). In depths greater than 20 m, D.R. never exceeds 1.1. In water shallower than 20 m, several samples have D.R. greater than 1.1, and two near the mouth of the Sagavanirktok exceed 1.8. Although some samples from water depths less than 20 m have low density ratios, the highest values occur only in shallow water.

Although the number of samples from this study with very high density ratios is too small to be statistically significant, it is interesting to speculate on the origin of the apparent decrease in density-ratio range with depth where source is not a factor. A wide range of density ratios in closely-spaced samples suggests hydraulic sorting. A narrow range of density ratios would suggest mixing.

Hydraulic sorting. Waves in the Beaufort Sea normally range from 2 to 3-second periods and 20 to 30 cm height. A storm of Pingok Island (see fig. 1) in 1972 produced swells of 9 to 10-second periods and 1.5 to 2.5 m height. The storm lasted several days and produced longshore currents with velocities as much as 50 cm/sec. (Wiseman, Syhayda and Hsu, 1974, p. 51).

Threshold orbital velocities (u_m) which would act to sort sediments may be calculated for the typical and extreme wave regimes noted above from the equations of Komar and Miller (1974).

Table 5 shows u_m as calculated for waves of given period (T) height (H), and water depth (h).

TABLE 5. Representative threshold orbital velocities for specific waves.

T, sec.	H, cm	h, m	u_m, cm/sec	sed.grain-size moved
3	30	4	9.8	0.085 mm
10	250	10	107	11.93 mm
10	250	15	80	6.05 mm
10	250	20	63	3.47 mm
10	250	30	43	1.42 mm
10	250	50	20	0.22 mm

Table 6. Non-opaque minerals and formations of Alaska North Slope where identified (Brosge, Whittington and Morris, 1966; Keller, Morris and DeHerman, 1961; Morris, 1952; Patton and Tailleur, 1964, Payne and others, 1951; and this paper)

FORMATION / MINERAL	Beaufort Sea Sediments	Gubik/Meade Unit	Sagavanirktok	Prince Creek/ Tuluvak Tongue	Schrader Bluff	Seabee	Chandler	Ninuluk	Grandstand	Topagoruk	Tuktu	Fortress Mt.	Torok	Okpikruak	Tiglukpuk	Kingak	Shublik
Garnet	x	x	x	x	x	x	x	x	x				x		x	x	
Chrome spinel	x	x		x	x	x	x	x	x		x						
Augite	x	x										x	x	x	x	x	
Hornblende	x	x		x	x	2	x	1	1			x	x	x	x[1]		
Epidote	x	x										x		x	x		
Zoisite	x	x												x			
Clinozoisite	x	x															
Tourmaline	x	x	x	x	x	x	x	x	x		x	x	x			x	x
Apatite	x	x		x	x	x	x	x					x				
Glaucophane	x	x		x	x	x		x	x			x					
Hypersthene	x	x															
Chloritoid	x	x		x	x	x	x	x	x								
Zircon	x	x	x	x	x		3	4	3	3	3	3	3		3	x	5
Rutile	x				6												
Sphene	x	x												x			
Kyanite	x		x														
Staurolite	x												x				

1) blue-green
2) green
3) zoned
4) clear prisms
5) ovoid
6) seen only in Sentinel Hill Member

A certain threshold orbital velocity is required to initiate transport of a given sediment-grain-size. Thus a wave of T-10 sec and u_{max} = 20 cm/sec will move 0.20 mm (medium-grained) sand at depths of 50 m. But a wave of T=3 sec and u_{max} = 9.8 cm/sec will not move 0.125 mm (fine-grained) sand at a depth of 4 m (Komar and Miller, 1974, p. 772, fig. 7).

Therefore, during the three-month summer period of normal waves in the Beaufort Sea, sands are influenced by waves only in the shallowest depths, probably less than 5 m, and wave-generated currents are not likely to be significant for sorting. Waves from storm such as that observed in 1972 would be strong enough to sort sediments over most of the shelf. In winter, waves are unimportant, due to ice-cover.

At shallow depths off river mouths, the bottom is dotted with strudel scours (Reimnitz, Rodeick and Wolf, 1974, p. 418, fig. 11), depressions caused by water pouring through drain holes in the ice cover during the spring ice-breakup (Reimnitz and Bruder, 1972, p. 162). These depressions could serve as concentrating areas for heavy minerals. The scouring process itself is potentially a sorting mechanism. For grains of a given size, the minerals with higher specific gravities are more likely to resist further transport once deposited, especially in a depression (Brady and Jobson, 1973, p. 26).

In depths greater than 15 m, ice-gouging of the seafloor is most pronounced in winter (Barnes and Reimnitz, 1974, p. 464, fig. 19) in winter. Sediments within areas of strong ice-gouging are probably deeply disturbed. Thicknesses of Recent sediments are 5 m or less, well within the range of the deepest modern gouges (Reimnitz and Barnes, 1974, p. 302). In heavily-gouged areas, older material may be mixed in with surface sediments (Reimnitz and Barnes, 1974, p. 346).

Both bioturbation and ice-gouging are undoubtedly at work in waters deeper than 15 m. During summer, the potential for ice-gouging is present in shallow water but decreases with increasing depth because of fewer ice keels with drafts sufficient to reach the bottom (Barnes and Reimnitz, 1974, p. 463). Seasonal effects of bioturbation are unknown at present. The random pattern of mineral distribution reflects this mixing process.

Source area. A series of six samples from the Meade Unit of the Gubik Formation were collected from the 2.5 m interval of an ice cellar at 9 m depth, at the Naval Arctic Research Laboratory near Point Barrow. Most of the minerals identified in the Beaufort sediments, including iron-stained aggregates, are represented in the Meade Unit samples. The Gubik Formation characteristically contains rounded grains (Morris, 1952). The Meade Unit however, also contains many prismatic grains; hypersthene is almost exlucsively prismatic. Beaufort Sea sediments contain both rounded and prismatic grains.

Kyanite has been identified in the Sagavanirktok Formation (Payne and others, 1951). Sphene is present in trace amounts in the Okpikruak Formation (Keller, Morris and Detterman, 1961), as well as the Gubik Formation Meade Unit (this paper). Staurolite was tentatively identified by Keller in the Killik-Itillik region (Tailleur, oral commun., 1975). The mineral identified in earlier works by Morris as andalusite was found to be apatite (Patton and Tailleur 1964, p. 72). The present study confirms this identification.

A summary table (Table 6) lists non-opaque minerals identified in the Beaufort Sea and the formation onshore in which they have been found. Minerals not previously identified in either the Beaufort Sea sediments on the Alaska North Slope are diopside, pigeonite, enstatite, lamprobolite, riebeckite, and lawsonite. These minerals are, however, sufficiently uncommon that they were probably not encountered at the time.

Because there are no distinctive exotic heavy minerals described in the Beaufort Sea sediments, ice-rafting does not appear to be significant.

Sediment is probably shed directly from the coastal cliffs as well as transported as bed-load by major rivers and small, local streams. Also, much of the sediment may be relict.

It seems reasonable to say that the source of the Beaufort Sea sediments is the Alaskan North Slope and dominantly the Gubik Formation. Because of the extensive mixing of the sediment and lack of distinctive mineral assemblages, the contribution of each major drainage to the Beaufort Sea is masked.

Conclusions

In sediments of the Beaufort Sea, heavy minerals never composed over 5% of the sand-size fraction. Twenty-four heavy-mineral species have been identified. This great variety attests to the mineralogic immaturity of the sediments and to the heterogeneity of the source area.

Except for garnet and iron-stained aggregates, the heavy minerals lack distinct distribution provinces. The iron-stained aggregates occur in highest percentages in samples within 16 km of shore. They are probably derived from the sea cliffs bordering the Beaufort. The garnet occurs in greatest amounts west of Cape Halkett, reflecting a higher percent of garnet in the Gubik formation west of the Colville River compared to east of the river. Higher percentages of garnet may also be a reflection of the dominant westward transport of sediments in the area.

Waves and currents in the Beaufort Sea are not strong enough to sort sands at depths greater than 5 m except during summer storms. Therefore, the overall uniformity of heavy-mineral distribution suggests an environment dominated by mixing processes. Bioturbation and ice-gouging are believed to be the most significant. Sorting processes seem to occur only in depths of 1-15 m. Strudel scours may serve as concentration areas for heavy minerals.

ACKNOWLEDGMENTS

Peter W. Barnes and H. Edward Clifton reviewed the manuscript and offered many helpful discussions and encouragement throughout this project. Gloria Harris made a number of heavy-mineral grain-mounts. C. W. Gustafson collected the samples from the Meade Unit of the Gubik Formation, and L. David Carter provided Gubik Formation samples from localities between Simpson Lagoon and Prudhoe Bay. Norma Jeanne Jackson drafted the illustrations used in this report.

Robert H. Morris, U.S. Geological Survey, Denver, clarified questions concerning the identification of the mineral picotite. Irwin Tailleur provided helpful discussions about the onshore geology of Alaska's North Slope.

REFERENCES CITED

Allman, Michael and Lawrence, D. F., 1972, Geological Laboratory techniques: Arco Publ. Co., Inc., New York, 335 p.

Arnborg, Lennart, Walker, H. J., and Peippo, Johan, 1967, Suspended load in the Colville River, Alaska, 1962: Geografiska Annaler, v. 49, series A., p. 131-144.

Barnes, P. W., 1974, Preliminary results of marine geologic studies off the northern coast of Alaska; p. 184-227, In: An ecological survey of the Beaufort Sea, U.S. Coast Guard Oceano. Rept. CG 373-64.

Barnes, P. W., and Reimnitz, Erk, 1974, Sedimentary processes on Arctic shelves off the northern coast of Alaska, p. 439-476 (with discussion), In: The coast and shelf of the Beaufort Sea, J. C. Reed and J. E. Sater, eds., Arctic Inst. North America.

Barnes, P. W., Reimnitz, Erk, Gustafson, C. W., and Larsen, B. R., 1973, U.S.G.S. marine geologic studies in the Beaufort Sea off northern Alaska, 1970-1972, location and type of data: U.S.G.S. Open file rept. 561, 11 p.

Brady, L. L. and Jobson, H. E., 1973, An experimental study of heavy-mineral segregations under alluvial-flow conditions: U.S. Geol. Survey 562-K. 38 p.

Brosge, W. P., Whittington, C. L. and Morris, R. H., 1966, Geology of the Umiat-Maybe Creek region, Alaska: U.S. Geological Survey Prof. Paper 303-H, p. 501-638.

Burrell, D. C., Dygas, J. A., and Tucker, R. W., 1974, Beach morphology and sedimentology of Simpson Lagoon, p. 45-143, In: Environmental studies of an arctic estuarine system-final report, V. Alexander and others, Univ. of Alaska Institute Marine Sci. Report 74-1 (Sea Grant Rept. 73-16).

Carsola, A. J., 1954, Recent marine sediments from Alaska and Northwest Canadian Arctic: Amer. Assoc. Petroleum Geologists Bull., v. 38, n. 7, p. 1552-1586.

Chapman, R. M., and Sable, E. G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geol. Survey Prof. Paper 303-C, p. 47-167.

Collins, F. R. and Bergquist, H. R., 1958a, Test wells, Topagoruk area, Alaska: U.S. Geol. Survey Prof. Paper 305-D, p. 265-316.

Collins, F. R., and Bergquist, H. R., 1958b, Test wells, Meade and Kaolak areas, Alaska: U.S. Geol. Survey Prof. Paper 305-F, p. 341-376.

Collins, F. R., and Bergquist, H. R., 1959, Test wells, Square Lake and Wolf Creek areas, Alaska: U.S. Geol. Survey Prof. Paper 305-H, p. 423-484.

Collins, F. R., and Brewer, M. C., 1961, Core tests and test wells, Barrow area, Alaska: U.S. Geol. Survey Prof. Paper 305-K, p. 569-644.

Collins, F. R., and Brewer, M. C., 1964, Core tests, Simpson area, Alaska: U.S. Geol. Survey Prof. Paper 305-L, p. 645-730.

Collins, F. R., and others, 1958, Tests wells, Umiat area, Alaska: U.S. Geol. Survey Prof. Paper 305-B, p. 71-206.

Dygas, J. A., Tucker, Robert, and Burrell, D. C., 1972, Geologic report of the heavy minerals, sediment transport and shoreline changes of the barrier islands and coast between Oliktok Point and Beechey Point, p. 61-121: In: Kinney, P. J. and others, Baseline data study of the Alaskan Arctic acquatic environment, Univ. Alaska Inst. Marine Sci. Rept. R72-3.

Galehouse, J. S., 1969, Counting grain mounts - number percentage vs. number frequency: Jour. Sed. Petrology, v. 39, n. 2, p. 812-815.

Gryc, George and others, 1956, Mesozoic sequence in Colville River region, northern Alaska: Amer. Assoc. Petroleum Geologists Bull., v. 40, no. 2, p. 209-254.

Holmes, M. L., 1967, Late Pleistocene and Holocene history of the Laptev Sea: Unpubl. M. S. thesis, Univ. of Washington, 99 p.

Hufford, G. L., 1974, Dissolved oxygen and nutrients along the North Alaskan shelf, pp. 567-588 (with discussion), In: The coast and shelf of the Beaufort Sea, J. C. Reed, and J. E. Sater, eds., Arctic Institute of North America.

Keller, A. S., Morris, R. H., and Detterman, R. L., 1961, Geology of the Shaviovik and Sagavanirktok Rivers region, Alaska: U.S. Geol. Survey Prof. Paper 303-D, p. 169-222.

Komar, P. D., and Miller, M. C., 1974, Sediment threshold under oscillatory waves: 14th Conf. Coastal Enginnering Proc., Amer. Soc. Civil Engineers, p. 756-775.

Milner, H. B., 1940, Sedimentary petrography, 3rd ed.: Thomas Murby and Co., London, 666 p.

Mountain, D. G., 1974, Preliminary analysis of Beaufort Sea shelf circulation in summer, p. 27-42, In: The coast and shelf of the Beaufort Sea, J. C. Reef, and J. E. Sater, eds., Arctic Inst. North America.

Morris, R. H., 1952, Heavy mineral analysis of sedimentary rocks of northern Alaska: U.S. Geol. Survey Open-File Rept. 68 p.

Naidu, A. S., and Mowatt, T. C., 1974, Aspects of size distribution, mineralogy and geochemistry of deltaic and ancient shallow marine sediments, North Arctic Alaska: Univ. Alaska Inst. Marine Science Rept. 74-1, p. 145-207. (also p. 238-268, In: An ecological survey of the Beaufort Sea, U.S. Coast Guard Oceano. Rept. CG 373-64.

Naidu, A. S., and Sharma, G. D., 1972, Texture, mineralogy, and chemistry of Arctic Ocean sediments: Inst. Marine Science, Univ. of Alaska, Rept. R72-12, 31 p.

Naugler, F. P., 1967, Recent sediments of the East Siberian Sea: Unpubl. M.S. thesis, Univ. of Washington, 71 p.

Patton, W. W., Jr., and Tailleur, I. L., 1964, Geology of the Killik-Itkillik region, Alaska: U.S. Geol. Survey Prof. Paper 303-G, p. 409-500.

Payne, T. G., and others, 1952, Geology of the Arctic slope of Alaska: U.S. Geol. Survey Oil and Gas Invest. Map OM-126, 3 sheets.

Reed, J. C., and Sater, J. E., eds., 1974, The coast and shelf of the Beaufort Sea: Arctic Institute of North America, Arlington, Virginia, 750 p.

Reimnitz, Erk and Barnes, P. W., 1974, Sea ice as a geologic agent on the Beaufort Sea shelf of Alaska, p. 301-353 (with discussion), In: The coast and shelf of the Beaufort Sea, J. C. Reed and J. E. Sater eds., Arctic Inst. North America.

Reimnitz, Erk and Bruder, K. F., 1972, River discharge into an ice-covered ocean and related sediment dispersal, Beaufort Sea, coast of Alaska: Geol. Soc. America Bull., v. 83, no. 3, p. 861-866.

Reimnitz, Erk, Rodeick, C. A., and Wolf, S. C., 1974, Strudel scour - a unique Arctic marine geologic phenomenon: Jour. Sed. Petrology, v. 44, no. 2, p. 409-420.

Robinson, F. M., 1956, Core tests and test wells, Oumalik area, Alaska: U.S. Geol. Survey Prof. Paper 305-A, p. 1-70.

Robinson, F. M., 1958a, Test wells, Gubik area, Alaska: U.S. Geol. Survey Prof. Paper 305-C, p. 207-264.

Robinson, F. M., 1958b, Test wells, Grandstand area, Alaska: U.S. Geol. Survey Prof. Paper 305-E, p. 317-339.

Robinson, F. M., and Bergquist, H. R., 1959, Test wells, Titaluk and Knifeblade areas, Alaska: U.S. Geol. Survey Prof. Paper 305-G, p. 377-422.

Robinson, F. M., and Collins, F. R., 1959, Core test, Sentinel Hill area and test well, Fish Creek area, Alaska: U.S. Geol. Survey Prof. Paper 305-I, p. 485-521.

Robinson, F. M., and Yuster, S. T., 1959, Test wells, Simpson area, Alaska: U.S. Geol. Survey Prof. Paper 305-J, p. 523-568.

Silverberg, Norman, 1972, Sedimentology of the surface sediment of the East Siberian and Laptev Seas: Unpubl. Ph.D. thesis, University of Washington, 134 p.

Walker, H. J., 1974, The Colville River and the Beaufort Sea-some interactions, p. 513-540 (with discussion), In: The coast and shelf of the Beaufort Sea, J. C. Reed and J. E. Sater, eds., Arctic Inst. of North America.

Wiseman, W. J., Jr., Suhayda, J. N., and Hsu, S. A., 1974, Characteristics of nearshore oceanographic environment of Arctic Alaska, p. 49-64, In: The coast and shelf of the Beaufort Sea, J. C. Reed and J. E. Sater, eds., Arctic Inst. of North America.

Wiseman, W. J., Jr., and others, 1973, Alaska Arctic coastal processes and morphology: Louisiana State Univer. Coastal Studies Inst. Tech. Rept. 149. 171 p.

List of Figures

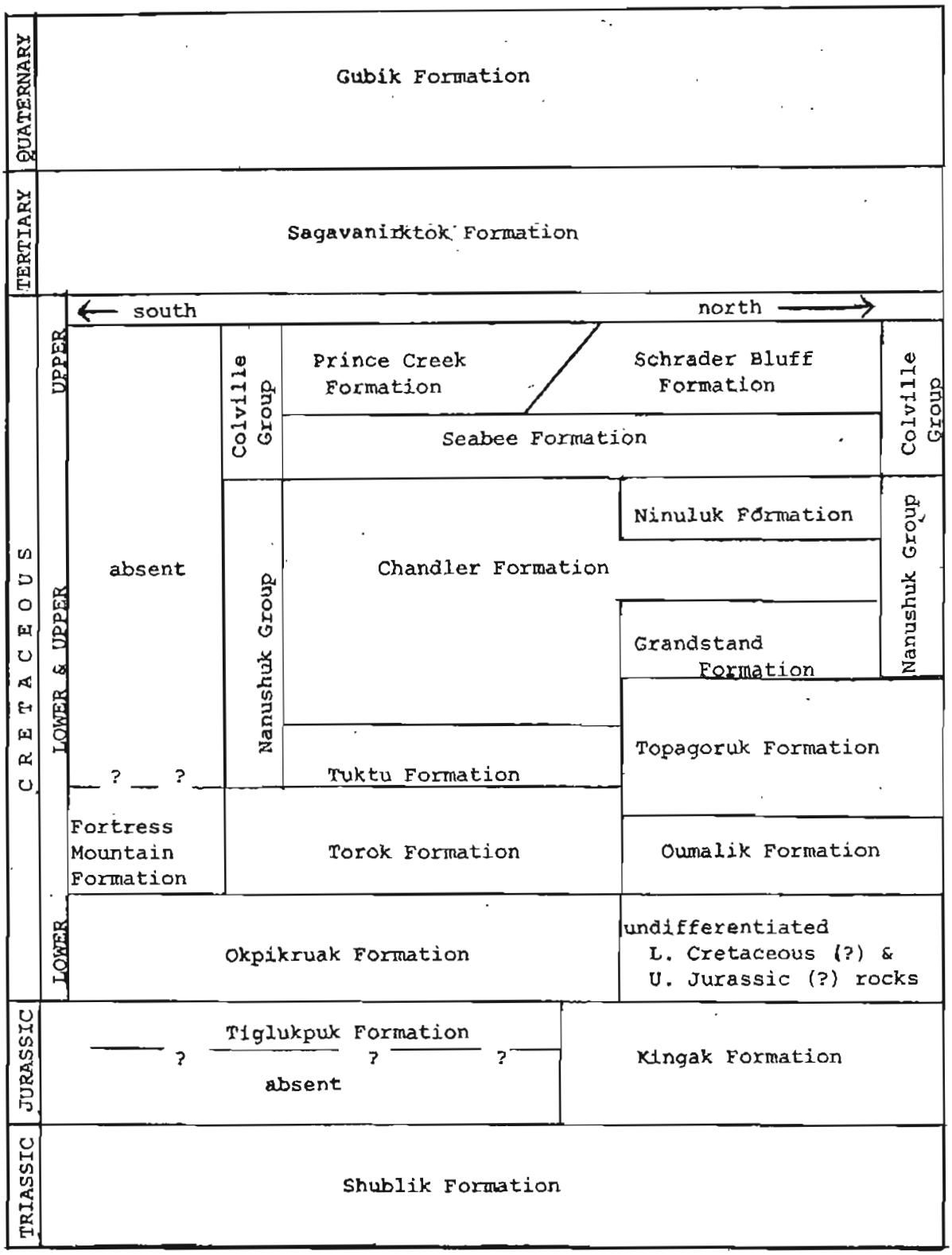

Figure 2. Generalized stratigraphic column of Cenozoic and Mesozoic rocks of Alaska's North Mlope (Colville River region). (After Gryc and others, 1956, p. 212, fig. 2).

Heavy-Mineral Trends in the Beaufort Sea -- Gretchen Luepke

Errata

Table 4 - Hornblende should be listed under -- average S.G. = 3.0-3.49

p. 15 - last paragraph should read as follows:

Density ratios for 26 samples were plotted against depth (fig. 6). In depths greater than 20 m, D.R. values exceed 0.8 only once and never exceed 0.9. In water shallower than 20 m, nine samples have D.R. greater than 0.8, and two near the mouth of the Sagavanirktok exceed 1.7. Although some samples from water depths less than 20 m have low density-ratio values, the highest values occur only in shallow water. In other words, the greatest range of density-ratio values is seen in samples from water depths less than 20 m.

Please correct your copy of OF 75-667

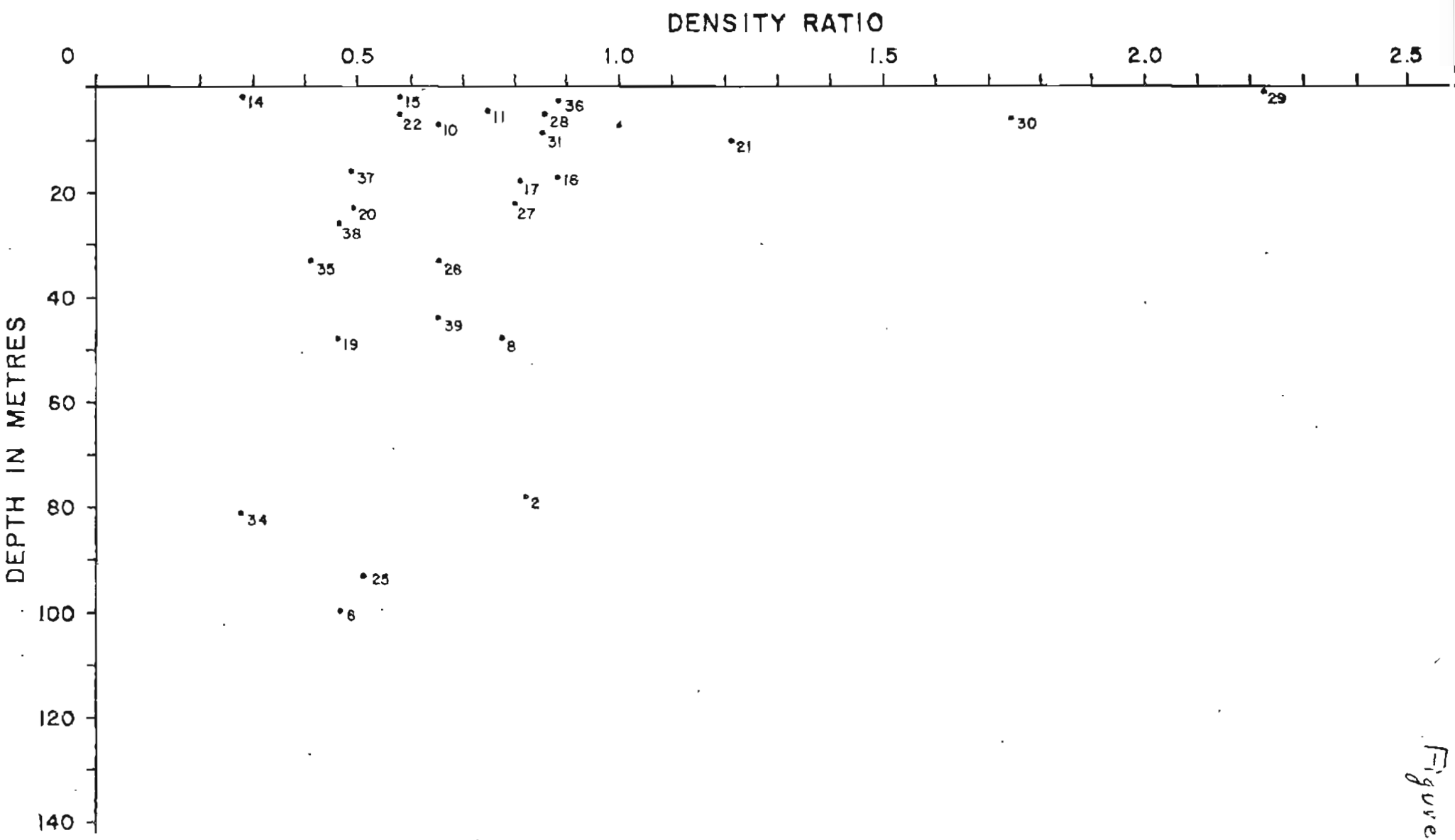
DENSITY RATIO
0
0.5
1.0
1.5
2.0
2.5
DEPTH IN METRES
20
40
60
80
100
120
140
14
15
22
10
11
36
28
31
30
29
21
37
17
16
20
27
38
35
26
39
19
8
2
34
25
6

Figure 6.