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Grain-Size, Heavy-Mineral, and Geochemical Analyses of Sediments from the Chuckchi Sea, Alaska

By GRETCHEN LUEPKE and EDWARD C. ESCOWITZ

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Grain-Size, Heavy-Mineral, and Geochemical Analyses of Sediments from the Chukchi Sea, Alaska

By Gretchen Luepke *and* Edward C. Escowitz

Abstract

The heavy-mineral assemblage in sediments of dredge and box-core samples from the Chukchi Sea, Alaska, is dominated by pyroboles. Other minerals occurring in measurable amounts include ilmenite and chromite, garnet, magnetite, and epidote. Minerals of economic value—ilmenite, leucoxene, chromite, rutile and zircon—constitute an average of about 23 percent of the heavy minerals in the analyzed sediments and an average of about 0.05 percent of the bulk samples. The overall scarcity of economic mineral species, extremely low total heavy minerals in the sediments, and generally thin sand cover of the sea floor show that the economic placer potential for the coastal area of the Chukchi Sea northeast of Cape Lisburne is negligible.

INTRODUCTION

As part of the U.S. Geological Survey (USGS) effort to assess the potential for placer deposits on the continental shelves in the Exclusive Economic Zone, the present study examines the sediments of the coastal northeastern Chukchi Sea off northern Alaska (fig. 1). Because no metallic-mineral lodes or valuable placer deposits exist anywhere on the Alaskan coast adjacent to the Chukchi Sea (Cobb, 1973), it has been speculated that the Chukchi Sea is an unlikely place for placers (Clifton and Luepke, 1987). However, no systematic analysis of the economic placer potential of the Chukchi Sea has ever been attempted, and no descriptions of heavy minerals from the Chukchi Sea have been previously published.

The Chukchi Sea is a broad shelf that is icebound for approximately 9 months of the year. The sea floor in the northern part has a thin veneer (2 to 5 m) of unconsolidated sediments, mostly sand and gravel, that covers well-indurated bedrock; in the southern part, the unconsolidated sediments are as thick as 11 m (Grantz and others, 1982). In the study area, the sands and gravels are relict and contain essentially no silt or clay (McManus and others, 1969). Substantial gravel accumulations occur near Cape Lisburne, and smaller accumulations occur near Icy Cape. Sand is concentrated beneath the main course of the Alaska coastal current from Point Hope to Point Franklin (Grantz and others, 1982). This current could act as a concentrating mechanism for placers.

The Alaskan coast bordering the Chukchi Sea is part of the Arctic Coastal Plain geomorphic province, primarily a low-lying tundra dotted with lakes. The foothills of the Brooks Range border the coast northeast of Cape Lisburne for about 137 km. The Utukok River, with its mouth at Icy Cape, drains the westernmost Brooks Range; all other rivers in the coastal area represent local drainages. The geology of the area is almost uniform. The Pliocene and Pleistocene Gubik Formation, consisting of mostly marine cross-bedded gravel, sand, silt, and clay, underlies the coastal plain in the study area from Skull Cliff to beyond Point Barrow. Permian and Triassic clastic and carbonate rocks, which are exposed in cliffs at Cape Lisburne (Beikman, 1980), are the primary source for the relict gravels immedately offshore (McManus and others, 1969). Cretaceous sedimentary rocks are exposed along the remainder of the coast and at Skull Cliff under the Gubik Formation (Beikman, 1980).

Acknowledgments

We thank Mark Brown for the sample processing to concentrate the heavy minerals and Robert Oscarson for SEM and EDAX analysis.

METHODS

Samples used in this study were taken during a cruise aboard the National Oceanographic and Atmospheric Administration ship *Discoverer* in August 1985. Four dredge and six box-core samples were collected with a 40-cm-diameter pipe dredge and a Reineck-type box corer, respectively. The pipe dredge was completely filled during sampling, so no winnowing of material was

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evident. The box corer samples a 31×22×60-cm^3 segment of sea floor (Barnes and others, 1986). The samples were taken to study bedforms and biology in the area beneath the Alaska coastal current. This focus also allowed the samples to be taken commonly in lag gravels, where any heavy minerals were likely to be concentrated.

Sample locations are shown on figure 1. The locations, water depths, size fractions, and groupings of samples are given in table 1. Two composite samples were made by combining two and three of the box-core samples, respectively, on the basis of their nearly identical locations. Combination of box-core samples for heavy-mineral analysis ensures a sample large enough to reduce the possiblility of a particle-sparsity bias that can result when a limited number of grains significantly influences the concentration of an economically important mineral species (see Clifton and others, 1969).

The resulting samples were analyzed for their grain size, heavy-mineral, and geochemical content of the heavy-mineral fraction. A flow chart for sample processing is given in figure 2. The gravel-size (>2.0 mm) material in the samples was removed on shipboard and studied separately (Barnes and others, 1986). R.L. Phillips is preparing visual descriptions of the box-core and dredge samples.

The sand samples (grain size 0.062 to 2.0 mm) were sent to Reston, Virginia, where a repository subsample (average weight 575 g) of each sample was

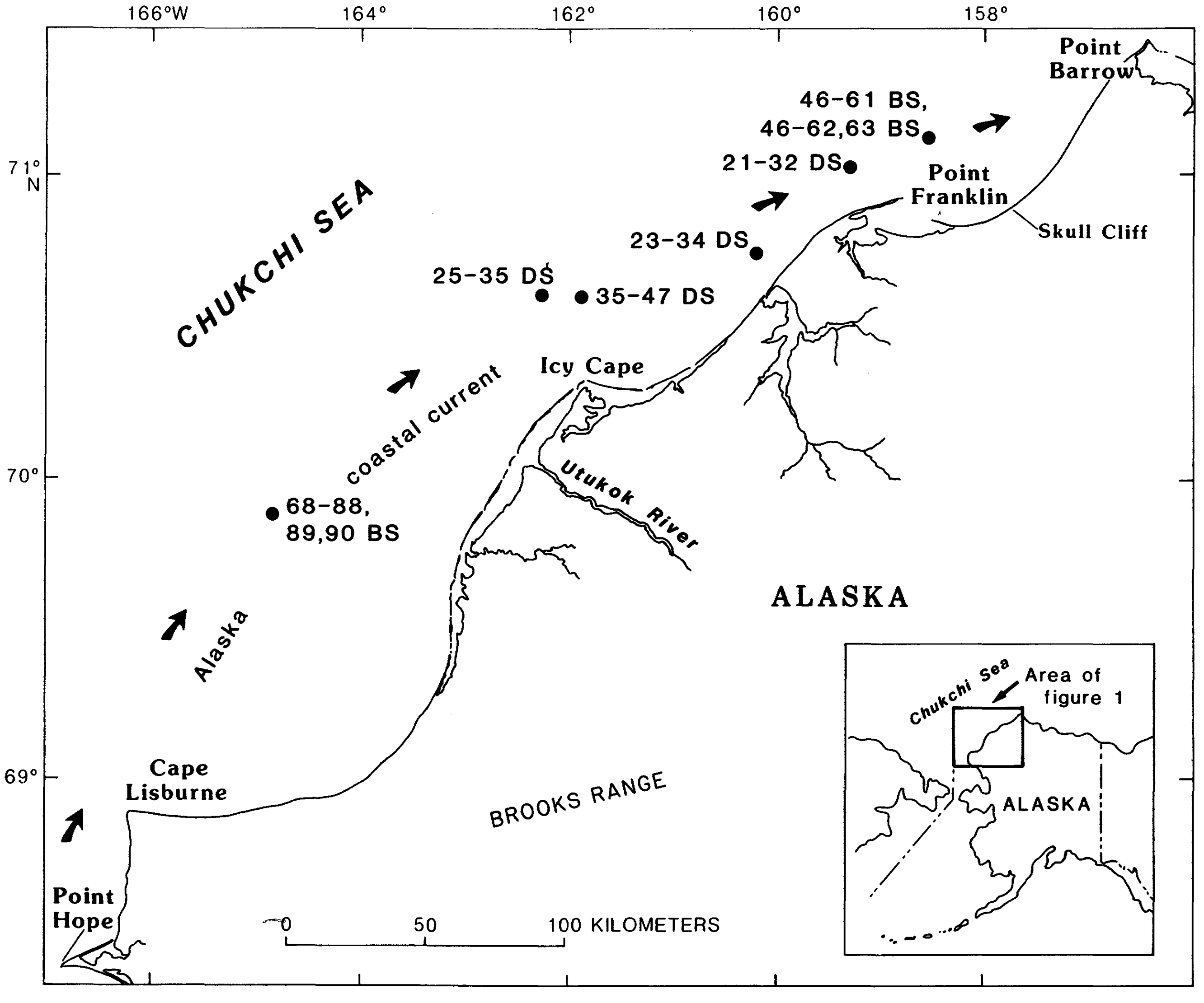

Figure 1. Index map of the Chukchi Sea, Alaska, showing sample locations for this report. Sample numbers include type of sample (BS, box-core; DS, dredge). Arrows indicate primary direction of the Alaska coastal current. Drawn from National Oceanographic and Atmospheric Administration (NOAA) National Ocean Survey Chart 16005 (Cape Prince of Wales to Point Barrow, 1980, scale 1:700,000).

Table 1. Locations, water depths, size fractions, and groupings of samples taken from the Chukchi Sea, Alaska

[Braces indicate samples combined for heavy-mineral analysis. DS, dredge sample; BS, box-core sample; *, presence of silt and clay detected with rapid sediment analyzer (see fig. 3); —, value not calculated because it would be statistically meaningless]

Sample number	Latitude [1] N.	Longitude [1] W.	Water depth (m)	Weight percent of sample: Gravel (>2.0 mm)	Sand (2.0–0.062 mm)	Silt and clay [2] (<0.062 mm)
21–32 DS	71.015	159.267	60	48.9	51.1	0
23–34 DS	70.728	160.202	30	18.7	81.3	*
25–35 DS	70.608	162.390	42	0	100	0
35–47 DS	70.593	161.902	41	6.9	93.1	0
46–61 BS	71.103	158.483	35	<0.1	99.9	*
46–62 BS	71.108	158.482	37 }	0	100	0
46–63 BS	71.118	158.482	38 }			
68–88 BS	69.902	164.792	38 }			
68–89 BS	69.900	164.778	38 }	<0.1	99.9	0
68–90 BS	69.900	164.773	38 }			
Minimum value				0	51.1	0
Mean value				—	89.3	—
Maximum value				48.9	100.0	*
Standard deviation				—	18.2	—

[1]Latitude and longitude expressed in degrees to the nearest thousandth.
[2]All samples contained <0.1 percent silt.

separated. From the remaining volume of each sand-sized sample, ranging in weight from about 8,000 g to nearly 22,000 g, heavy minerals were removed, following the wet-milling process described in Luepke and Grosz (1986). After the wet-milling process, the heavy-mineral concentrates were further purified using a Magstream Model 1000E separator. This device, which uses ferrofluids as the separating medium, replaces heavy liquids in the concentration process (Urbanski and others, 1987).

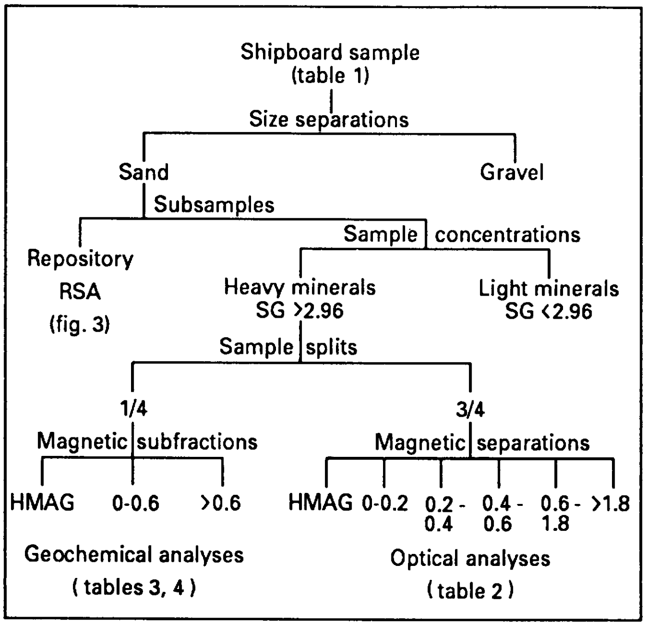

Figure 2. Flow chart for processing of samples from Chukchi Sea, Alaska. RSA, rapid sediment analyser; SG, specific gravity; HMAG, hand-magnet separation; electromagnetic separation numbers in amps.

The repository samples and heavy-mineral concentrates were then returned to the USGS Marine Geology sedimentation laboratory in Menlo Park, California. Grain-size analyses were made from a split of about 0.7 grams from each of the repository samples, using a rapid sediment analyzer (RSA) (Thiede and others, 1976). Settling velocities for the sand-sized particles are calculated from the equations of Gibbs and others (1971).

A quarter split of each heavy-mineral fraction was taken: half for geochemical analyses and half for repository. The analytical split was separated by magnetic techniques (Luepke and Grosz, 1986) into three paramagnetic subfractions: one strongly magnetic (separable by hand magnet or = 0 amp), and two separable by an electromagnet set at 0.6 amp. A D-C arc 3-mm grating spectrograph was used to test for 64 minor elements by inductively coupled argon plasma– atomic emission spectrometry (ICAP-AES). This rapidanalysis method yields semiquantitative data (Lichte and others, 1987).

The remaining three-quarters split of each heavy-mineral fraction was separated into six paramagnetic subfractions: strongly magnetic, 0.0 to 0.2, 0.2 to 0.4, 0.4

to 0.6, 0.6 to 1.8, and >1.8 amp. Each magnetic fraction was weighed and examined using binocular and petrographic microscopes. Long-wave and unfiltered shortwave ultraviolet illuminations were used with other optical properties to detect zircon and monazite, respectively. X-ray diffraction was used to check the bulk mineralogy of a representative aliquot of each subfraction. Selected mineral grains were examined using a scanning electron microscope (SEM), and an energy dispersive X-ray analyzer (EDAX), to aid in confirming mineral identification.

RESULTS

Grain-Size Analysis

Gravel percentages range from 0 to nearly 50 percent (table 1). The grain-size distribution histograms for the sand-sized fractions are shown in figure 3. Except for samples 21–32 DS, 46–61 BS, and 46–62, 63 BS, which have bimodal grain-size distributions, the sands of the remaining samples are well sorted. The mode peak of the well-sorted samples and the primary mode peak of the bimodal samples fall in the medium-sand range (0.125 to 0.250 mm, around 2.0 or 2.5ϕ). Only two histograms, 23–34 DS and 46–61 BS, show any material in the silt-size range (<0.062 mm, or <4ϕ).

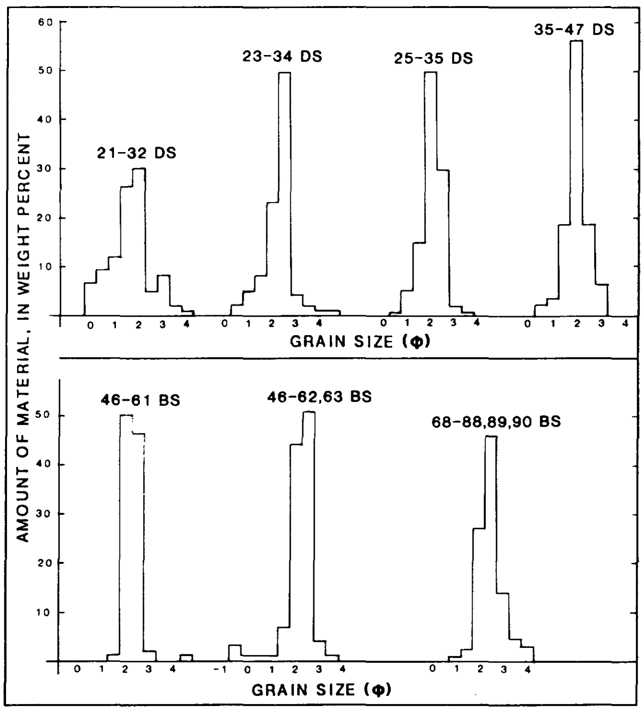

Figure 3. Histograms of grain sizes in samples from Chukchi Sea, Alaska.

Heavy-Mineral Content

The weight percentages of heavy minerals identified in the sediments (table 2) were calculated according to the method described in Luepke and Grosz (1986). Minerals identified include magnetite, ilmenite + chromite, leucoxene, garnet, epidote group, pyroboles (pyroxenes and amphiboles), sphene, apatite, zircon, and rutile. Minerals occurring only in trace amounts include mica, kyanite, staurolite, chloritoid, tourmaline, limonite, anatase, pyrite, hematite, corundum(?), andalusite(?), and beryl(?). A bright aqua-blue mineral, tentatively identified as the beryl variety aquamarine, was noted in samples 21–32 DS and 46–61 BS. An unknown, pale-pink mineral (rhodonite?) was also seen; according to EDAX analysis, it contains manganese.

Minerals designated as "Others" are altered grains that cannot be precisely identified. The dusty appearance of these grains, especially when the overall grain size was fine to very fine (<0.125 mm), is attributed to extreme weathering. From EDAX analysis, titanium appears to be a minor constituent of many of these grains.

The ratio of pyroxenes to amphiboles in all samples is at least 2:1 and commonly more; the ratio of clinopyroxene to orthopyroxene is about 5:1. These ratios are based on point counts of grain mounts. Pyroxenes identified in grain mounts include augite, diopside, and hypersthene; amphiboles include green and blue-green hornblende, with rare brown and basaltic hornblende and glaucophane. The epidote group includes both epidote and clinozoisite.

Magnetite percentages show the greatest variability. Magnetite inclusions are common in both garnet and hypersthene grains. Limonite occurs occasionally as a coating on other grains. Zircon constitutes from about 1 to 3 percent of the heavy-mineral fraction; grains are mostly colorless, but some are pink. Rutile and sphene occur from trace amounts to about 1 percent of the heavy-mineral fraction.

Differentiating between ilmenite and chromite grains is commonly difficult. For this reason, ilmenite and chromite percentages are combined in table 2. However, geochemical data in tables 3 and 4, combined with X-ray and EDAX analyses, show that ilmenite is probably the more common of the two.

Apatite in the Chukchi Sea sediments has two distinct forms, clear and black; the black variety is more common. Black apatite was found primarily in the 0.6- to 1.8-amp fraction. Both varieties were confirmed by EDAX. The presence of the rare-earth elements cerium and lanthanum was noted in one black apatite grain; this grain was anomalous in that it also contained high levels of strontium and aluminum and low levels of calcium and iron. Although no other black apatite grains examined displayed these elements, this analysis may be indicative

Table 2. Heavy-mineral analyses of dredge (DS) and box-core (BS) samples from the Chukchi Sea, Alaska

[S.G., specific gravity; EHM, economic heavy minerals; C, heavy-mineral concentrate; T, total sample; Tr, trace (<0.1 in EHM/T column, <0.5 in other columns); —, value not calculated because it would be statisically meaningless]

Sample number	Weight percent of sample having S.G. >2.96	Weight percent of minerals having S.G. >2.96													EHM/C[5], sum of percentages	EHM/T[5], weight percent
		Magnetite	Illmenite + chromite	Leucoxene	Mica	Garnet	Epidote group[1]	Pyroboles[2]	Sphene	Apatite	Zircon	Rutile	Trace minerals[3]	Others[4]		
21–32 DS	0.08	11.4	15.8	3.1	Tr	12.0	7.4	44.0	Tr	0.6	2.5	[6]Tr	0.5	1.7	21.7	0.01
23–34 DS	.23	3.2	17.2	3.3	Tr	13.1	10.9	38.6	0.8	1.0	2.8	0.9	Tr	8.0	24.2	.04
25–35 DS	.20	6.9	15.0	4.0	Tr	8.4	8.3	49.1	Tr	1.4	1.3	Tr	Tr	4.6	20.7	.03
35–47 DS	.24	11.5	17.6	3.0	Tr	12.6	8.6	34.6	.5	1.7	3.0	[6].8	Tr	6.0	24.4	.04
46–61 BS	.47	3.8	13.0	.9	Tr	12.9	8.0	54.4	Tr	1.7	1.4	.6	Tr	2.6	15.9	.06
46–62,63 BS	.36	5.9	14.1	1.3	Tr	14.5	9.9	45.7	.5	1.3	1.4	1.1	Tr	3.9	17.9	.05
68–88,89,90 BS	.39	3.6	21.0	1.0	0.5	6.2	8.7	45.7	Tr	.9	3.2	1.1	Tr	7.7	26.3	.08
Minimum value	.08	3.2	13.0	.9	Tr	6.2	7.4	34.6	Tr	.6	1.3	Tr	Tr	1.7	15.9	.01
Mean value	.28	6.6	16.2	2.4	—	11.4	8.8	44.6	.4	1.2	2.2	.7	—	4.9	21.6	.04
Maximum value	.47	11.5	21.0	4.0	.5	14.5	10.9	54.4	.8	1.7	3.2	1.1	.5	8.0	26.3	.08
Standard deviation	.13	3.6	2.6	1.3	—	3.0	1.2	6.5	.2	.4	.8	.3	—	2.1	3.7	.02

[1]Includes epidote and clinozoisite.

[2]Pyroxenes plus amphiboles.

[3]Most samples show traces of kyanite, staurolite, chloritoid, tourmaline, and limonite; some show pyrite, hematite, corundum(?), beryl(?), and andalusite(?).

[4]Altered minerals that cannot be positively identified.

[5]Ilmenite + chromite, leucoxene, rutile, and zircon.

[6]Anatase seen in this sample.

of the possible variability in composition of the black apatite.

Geochemical Analysis

Results of geochemical analyses for each magnetic subfraction of each sample are given in table 3; the cumulative statistics for all samples in each magnetic range are given in table 4. The statistics within ranges in table 4 are divided into two categories: (1) major elements, with values in percent, and (2) minor elements, with values in parts per million. The detection ranges for each of the 64 elements sought are given in table 3.

The geochemical data generally support the optical determination of mineral assemblages. For example, sample 68–88,89,90 BS, which ranks first in ilmenite + chromite as determined optically, also ranks first in titanium and chromium concentrations determined by emission spectrography. In the other six samples of this study, the rank order of the spectrographically determined titanium and chromium concentrations also parallels that of the optically determined ilmenite + chromite.

Some variance is expected from strict correlation because titanium is present in other minerals such as leucoxene, rutile, and sphene. EDAX data indicate that many of the pyrobole minerals also contain titanium. Sample 46–62,63 BS, which ranks first in concentrations of rutile and sphene, ranks second in overall titanium concentration. This sample has the most mature heavy-mineral assemblage (high percentage of stable unaltered heavy minerals) and has a primary mode in the fine-sand (approx. 2.5ϕ) size range in the grain-size distribution (fig. 3).

Although monazite was not detected with the unfiltered short-wave ultraviolet light, the presence of detectable amounts of cerium, lanthanum, yttrium, yttterbium, and thorium in the >0.6-amp geochemical fraction of all samples may imply its presence. The total would, however, be only trace amounts in the total heavy-mineral fraction. The detectable amount of silver in each sample is puzzling and cannot be immedately explained.

Attempts to find patterns or trends in the heavy-mineral and geochemical distributions were generally unsuccessful. The samples may be too few and too widely spaced to detect any trends. However, the lack of any noticeable difference in such widely scattered samples would seem to indicate a true lack of variability. The large variety of minerals identified in the northeastern Chukchi Sea indicates an overall immaturity of sediments. This mineral variety and immaturity has also been noted in Beaufort Sea sediments east of Point Barrow (Luepke, 1975). Coastal erosion of the Gubik Formation is probably the major source for sediments in both the Beaufort and Chukchi Seas. The lack of nearby sources of economic heavy minerals is the primary reason for lack of heavy-mineral placers in the Chukchi Sea north of Cape Lisburne.

CONCLUSIONS

After the removal of gravel, the mean grain size of samples examined for this study is within the medium-sand range (0.125 to 0.25 mm). The sand varies from poorly to well sorted. The Alaska coastal current effectively removes most silt- and clay-size material.

The economically important heavy minerals identified in the Chukchi Sea samples are ilmenite, chromite, leucoxene, zircon, and rutile. On the basis of geochemical analyses, monazite may be present but only in trace amounts. The weight percentages of the economically important minerals (EHM/T column, table 2) in the samples of sediments of the Chukchi Sea constitute only a trace amount of whole samples, ranging from 0.01 to 0.08 percent, or about 20 to 26 percent of the heavy-mineral fraction (EHM/C column, table 2). Equally important, no bulk sample contained more than 0.5 percent heavy minerals. Among the more important economic elements, no gold, tungsten, tantalum, uranium, or platinum-group elements were detected in any sample. On the basis of the samples analyzed, the potential for significant economic heavy-mineral concentrations in the Chukchi Sea north of Cape Lisburne appears to be negligible.

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TABLES 3 and 4

Table 3. Emission spectrographic analyses of samples from the Chukchi Sea, Alaska

[Analyst, Carol J. Skeen; plate recorder, William B. Crandell. Samples separated by hand magnet (HMAG) and electromagnet (<0.6 amp and >0.6 amp) H, exceeds upper limit of detection; E, occurrence of unresolved interference]

Element	Sample 21–32 DS			Sample 25–35 DS			Sample 23–34 DS			Sample 35–47 DS		
	HMAG	<0.6 amp	>0.6 amp	HMAG	<0.6 amp	>0.6 amp	HMAG	<0.6 amp	>0.6 amp	HMAG	<0.6 amp	>0.6 amp
Ag (ppm)	2.0	0.9	2.8	1.5	$9.6x10^{-1}$	1.4	2.1	$8.8x10^{-1}$	5.9	1.9	$7.7x10^{-1}$	5.0
Al (pct)	5.6	5.7	1.1	2.8	7.8	1.2	3.3	7.6	3.0	5.2	5.5	2.1
As (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Au (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
B (ppm)	$5.1x10^{1}$	$1.8x10^{2}$	$9.4x10^{1}$	L	$4.2x10^{2}$	$1.4x10^{2}$	$2.0x10^{2}$	$4.4x10^{2}$	$7.4x10^{1}$	$7.2x10^{1}$	$3.3x10^{2}$	$8.9x10^{1}$
Ba (ppm)	$2.5x10^{2}$	$2.5x10^{2}$	$6.9x10^{3}$	$1.3x10^{2}$	$2.8x10^{2}$	$1.3x10^{4}$	$8.6x10^{1}$	$1.7x10^{2}$	$1.4x10^{4}$	$9.7x10^{1}$	$2.5x10^{2}$	$2.1x10^{4}$
Be (ppm)	L	L	5.3	L	L	L	L	L	1.8	L	L	L
Bi (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Ca (pct)	4.3	6.9	3.8	2.4	$1.0x10^{1}$	4.2	2.3	8.3	9.8	3.2	7.9	6.2
Cd (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Ce (ppm)	L	$5.6x10^{2}$	$4.8x10^{2}$	L	$5.0x10^{2}$	$9.9x10^{2}$	L	$4.1x10^{2}$	$1.1x10^{3}$	L	$5.8x10^{2}$	$7.9x10^{2}$
Co (ppm)	$4.6x10^{1}$	$3.3x10^{1}$	6.8	$4.2x10^{1}$	$3.7x10^{1}$	6.6	$6.0x10^{1}$	$4.8x10^{1}$	$1.0x10^{1}$	$5.9x10^{1}$	$3.5x10^{1}$	7.1
Cr (ppm)	$1.9x10^{3}$	$1.7x10^{4}$	$6.3x10^{2}$	$1.7x10^{3}$	$1.8x10^{3}$	$3.2x10^{2}$	$2.9x10^{3}$	$2.9x10^{3}$	$4.4x10^{2}$	$3.1x10^{3}$	$2.5x10^{3}$	$2.1x10^{2}$
Cu (ppm)	$3.3x10^{1}$	$1.1x10^{1}$	$1.4x10^{1}$	$7.0x10^{1}$	$6.9x10^{1}$	$2.3x10^{1}$	$3.5x10^{1}$	$3.2x10^{1}$	L	$7.1x10^{1}$	$7.8x10^{1}$	$5.4x10^{1}$
Dy (ppm)	L	L	E	L	L	E	L	L	E	L	L	E
Er (ppm)	L	L	E	L	L	E	L	L	E	L	L	E
Eu (ppm)	L	4.7	9.9	L	L	9.0	L	L	$2.0x10^{1}$	L	L	$1.5x10^{1}$
Fe (pct)	H	$1.4x10^{1}$	1.2	H	$1.7x10^{1}$	1.3	$2.0x10^{1}$	$1.6x10^{1}$	1.1	H	$1.5x10^{1}$	1.0
Ga (ppm)	E	$1.5x10^{1}$	4.5	E	$1.7x10^{1}$	6.8	$2.5x10^{1}$	$3.2x10^{1}$	6.5	E	$1.8x10^{1}$	4.3
Gd (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Ge (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Hf (ppm)	L	L	$1.0x10^{3}$	L	L	$3.0x10^{2}$	L	L	$1.3x10^{3}$	L	L	$1.7x10^{3}$
Ho (ppm)	L	L	L	L	L	$1.3x10^{1}$	L	L	L	L	L	$3.3x10^{1}$
In (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Ir (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
K (pct)	$4.7x10^{-1}$	$2.7x10^{-1}$	$2.6x10^{-1}$	$4.1x10^{-1}$	$3.1x10^{-1}$	$2.2x10^{-1}$	0.4	0.3	$3.5x10^{-1}$	$3.7x10^{-1}$	$3.1x10^{-1}$	$2.0x10^{-1}$
La (ppm)	$3.7x10^{1}$	$2.2x10^{2}$	$1.7x10^{2}$	L	$2.0x10^{2}$	$1.7x10^{2}$	$3.7x10^{1}$	$1.8x10^{2}$	$4.7x10^{2}$	$3.2x10^{1}$	$2.2x10^{2}$	$3.4x10^{2}$
Li (ppm)	E	L	L	E	E	L	E	E	L	E	L	L
Lu (ppm)	L	L	L	L	L	L	L	L	$2.6x10^{1}$	L	L	$2.1x10^{1}$
Mg (pct)	4.6	9.1	$6.8x10^{-1}$	3.5	8.4	$6.9x10^{-1}$	3.8	7.5	$5.7x10^{-1}$	3.8	6.0	$5.5x10^{-1}$
Mn (ppm)	$1.3x10^{4}$	$8.1x10^{3}$	$2.0x10^{2}$	$9.2x10^{3}$	$6.2x10^{3}$	$3.6x10^{2}$	$1.2x10^{4}$	$7.0x10^{3}$	$3.9x10^{2}$	$1.1x10^{4}$	$5.9x10^{3}$	$1.8x10^{2}$
Mo (ppm)	E	2.6	L	E	3.2	L	5.8	2.0	L	E	4.3	L
Na (pct)	$3.1x10^{-1}$	$2.7x10^{-1}$	$2.4x10^{-1}$	$2.6x10^{-1}$	$3.7x10^{-1}$	$2.4x10^{-1}$	$2.9x10^{-1}$	$4.2x10^{-1}$	0.3	$2.5x10^{-1}$	$2.8x10^{-1}$	$2.7x10^{-1}$
Nb (ppm)	$3.3x10^{1}$	$2.1x10^{1}$	$2.4x10^{2}$	$6.9x10^{1}$	$2.9x10^{1}$	$2.2x10^{2}$	$4.1x10^{1}$	$3.9x10^{1}$	$3.5x10^{2}$	$5.0x10^{1}$	$3.7x10^{1}$	$5.4x10^{2}$
Nd (ppm)	L	$2.2x10^{2}$	$1.4x10^{2}$	L	$2.1x10^{2}$	$2.1x10^{2}$	L	$1.5x10^{2}$	$3.0x10^{2}$	L	$2.4x10^{2}$	$1.9x10^{2}$
Ni (ppm)	$1.6x10^{2}$	$1.2x10^{2}$	$2.9x10^{1}$	$9.2x10^{1}$	$1.2x10^{2}$	$2.6x10^{1}$	$1.4x10^{2}$	$1.4x10^{2}$	$3.7x10^{1}$	$1.4x10^{2}$	$1.1x10^{2}$	$3.0x10^{1}$
Os (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
P (pct)	L	L	2.5	L	L	3.5	L	L	3.1	L	L	3.2
Pb (ppm)	$3.8x10^{1}$	$4.3x10^{1}$	H	$3.4x10^{1}$	$2.3x10^{1}$	$3.6x10^{1}$	$2.8x10^{1}$	$3.3x10^{1}$	$5.3x10^{1}$	$2.6x10^{1}$	$4.4x10^{1}$	$2.9x10^{1}$
Pd (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Pr (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Pt (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Re (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Rh (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Ru (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Sb (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Sc (ppm)	$3.7x10^{1}$	$3.6x10^{1}$	$1.8x10^{1}$	$2.8x10^{1}$	$5.0x10^{1}$	$1.1x10^{1}$	$1.7x10^{1}$	$3.6x10^{1}$	$3.6x10^{1}$	$3.6x10^{1}$	$3.9x10^{1}$	$2.8x10^{1}$
Si (pct)	$1.3x10^{1}$	$2.2x10^{1}$	$1.8x10^{1}$	$1.3x10^{1}$	$2.2x10^{1}$	$1.9x10^{1}$	$1.6x10^{1}$	$1.9x10^{1}$	$1.7x10^{1}$	$1.3x10^{1}$	$1.8x10^{1}$	$1.8x10^{1}$
Sm (ppm)	L	$2.5x10^{1}$	L	L	$2.3x10^{1}$	$7.9x10^{1}$	L	$2.2x10^{1}$	L	L	$2.7x10^{1}$	L
Sn (ppm)	E	$1.1x10^{1}$	$4.0x10^{1}$	E	9.6	$5.1x10^{1}$	$2.5x10^{1}$	$2.4x10^{1}$	$1.1x10^{2}$	E	8.7	$3.7x10^{1}$
Sr (ppm)	$6.1x10^{1}$	$1.8x10^{2}$	$5.3x10^{2}$	$2.9x10^{1}$	$2.4x10^{2}$	$6.5x10^{2}$	$2.7x10^{1}$	$2.7x10^{2}$	$1.3x10^{3}$	$5.1x10^{1}$	$2.0x10^{2}$	$1.5x10^{3}$
Ta (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Tb (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Th (ppm)	L	$1.2x10^{2}$	$1.4x10^{3}$	L	L	L	L	L	$2.2x10^{3}$	L	L	$2.0x10^{2}$
Ti (pct)	3.9	$8.1x10^{-1}$	2.3	2.0	1.0	3.6	1.2	1.3	9.8	5.1	1.1	9.0
Tl (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Tm (ppm)	L	L	$1.1x10^{1}$	L	L	7.6	L	L	$1.9x10^{1}$	L	L	$1.7x10^{1}$
U (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
V (ppm)	$3.0x10^{2}$	$1.6x10^{2}$	$1.6x10^{2}$	$2.5x10^{2}$	$1.9x10^{2}$	$2.0x10^{2}$	$1.9x10^{2}$	$2.3x10^{2}$	$2.4x10^{2}$	$5.6x10^{2}$	$2.2x10^{2}$	$2.1x10^{2}$
W (ppm)	L	L	L	L	L	L	L	L	L	L	L	L
Y (ppm)	$4.5x10^{1}$	$4.4x10^{1}$	$1.3x10^{2}$	$4.0x10^{1}$	$5.2x10^{1}$	$1.2x10^{2}$	$2.7x10^{1}$	$5.0x10^{1}$	$1.5x10^{2}$	$4.9x10^{1}$	$5.6x10^{1}$	$2.0x10^{2}$
Yb (ppm)	$1.3x10^{1}$	5.1	$1.9x10^{1}$	7.8	7.4	$1.8x10^{1}$	5.5	6.8	$6.5x10^{1}$	L	7.6	$5.9x10^{1}$
Zn (ppm)	$3.8x10^{2}$	$2.0x10^{2}$	E	$3.7x10^{2}$	$2.8x10^{2}$	E	$4.7x10^{2}$	$3.5x10^{2}$	E	$4.0x10^{2}$	$2.8x10^{2}$	E
Zr (ppm)	$2.8x10^{2}$	$2.5x10^{2}$	H	$3.2x10^{2}$	$6.8x10^{2}$	H	$8.8x10^{1}$	$4.6x10^{2}$	H	$3.0x10^{2}$	$4.1x10^{2}$	H

by Mark Brown. pct, percent; ppm, parts per million; L, may not be present or is less than limit of detection (Thomas, 1979);

Sample 46–61 BS			Sample 46–62, 63 BS			Sample 68–88, 89, 90 BS			Detection limits	
HMAG	<0.6 amp	>0.6 amp	HMAG	<0.6 amp	>0.6 amp	HMAG	<0.6 amp	>0.6 amp	Low	High
2.4	1.1	4.1	2.0	1.4	4.6	2.4	2.1	4.8	0.10	10,000
3.2	4.4	4.9	3.5	7.4	4.1	5.7	8.1	3.9	.088	60
L	L	L	L	L	L	L	L	L	100.	10,000
L	L	L	L	L	L	L	L	L	6.8	1,500
2.0x10^{1}	4.3x10^{2}	3.0x10^{2}	6.2x10^{1}	4.8x10^{2}	1.2x10^{2}	1.4x10^{2}	4.6x10^{2}	1.6x10^{2}	3.2	460
6.2x10^{1}	3.1x10^{1}	3.2x10^{3}	2.3x10^{2}	2.8x10^{2}	5.0x10^{3}	1.5x10^{2}	2.4x10^{3}	1.7x10^{4}	1.5	32,000
L	L	1.1x10^{1}	L	L	2.6	L	1.0	2.1	1.0	680
L	L	L	L	L	L	L	L	L	10	6,800
3.0	7.1	1.3x10^{1}	4.7	1.1x10^{1}	1.3x10^{1}	6.7	1.1x10^{1}	1.4x10^{1}	.0014	10,000
L	L	L	L	L	L	L	L	L	32	10,000
L	8.3x10^{1}	1.1x10^{3}	L	2.6x10^{2}	1.1x10^{3}	2.7x10^{2}	1.2x10^{3}	1.7x10^{3}	43	20,000
7.2x10^{1}	3.2x10^{1}	1.1x10^{1}	6.7x10^{1}	4.7x10^{1}	1.1x10^{1}	5.9x10^{1}	3.6x10^{1}	1.5x10^{1}	1.0	22,000
3.0x10^{3}	1.7x10^{3}	7.6x10^{2}	2.4x10^{3}	2.4x10^{3}	3.3x10^{2}	H	3.0x10^{3}	9.1x10^{2}	1.0	6,800
6.4x10^{1}	8.1x10^{1}	4.6x10^{1}	6.8x10^{1}	4.7x10^{1}	5.3x10^{1}	5.4x10^{1}	4.8x10^{1}	L	1.0	1,500
L	L	E	L	L	E	L	5.3x10^{1}	E	22	1,000
L	L	E	L	L	E	L	L	E	4.6	1,000
L	L	2.0x10^{1}	L	L	2.2x10^{1}	L	1.7x10^{1}	2.8x10^{1}	2.2	1,000
H	7.7	3.0	H	1.9x10^{1}	1.3	1.7x10^{1}	7.0	2.7	.011	34
E	2.1x10^{1}	1.4x10^{1}	E	1.7x10^{1}	8.2	3.1x10^{1}	3.5x10^{1}	8.9	1.5	1,000
L	L	9.3x10^{1}	L	L	L	L	5.5x10^{1}	L	32	1,000
L	L	L	L	L	L	L	L	L	4.6	10,000
L	L	7.1x10^{2}	L	L	1.9x10^{3}	L	5.6x10^{2}	3.5x10^{3}	15	10,000
L	L	2.2x10^{1}	L	L	4.4x10^{1}	L	1.3x10^{1}	L	6.8	1,000
L	L	L	L	L	L	L	L	L	10	10,000
L	L	L	L	L	L	L	L	L	15	10,000
3.9x10^{-1}	2.4x10^{-1}	4.3x10^{-1}	4.4x10^{-1}	L	2.2x10^{-1}	4.0x10^{-1}	3.4x10^{-1}	3.8x10^{-1}	.082	13
3.8x10^{1}	3.3x10^{1}	4.7x10^{2}	1.8x10^{1}	7.7x10^{1}	5.0x10^{2}	7.0x10^{1}	3.6x10^{2}	7.9x10^{2}	10	10,000
E	8.0x10^{1}	L	E	E	L	E	L	L	68	32,000
L	L	L	L	L	L	L	L	L	15	1,000
3.7	8.9	2.8	4.4	9.7	1.3	4.4	6.3	1.9	.0036	50
1.1x10^{4}	8.3x10^{3}	8.4x10^{2}	9.4x10^{3}	7.6x10^{3}	3.7x10^{2}	1.5x10^{4}	4.9x10^{3}	5.2x10^{2}	1.0	460,000
E	L	L	E	5.3	L	7.6	3.9	L	1.0	1,000
2.8x10^{-1}	3.5x10^{-1}	4.4x10^{-1}	3.4x10^{-1}	2.6x10^{-1}	2.5x10^{-1}	5.3x10^{-1}	5.3x10^{-1}	L	.0029	11
1.3x10^{2}	1.3x10^{1}	3.1x10^{2}	5.6x10^{1}	6.2x10^{1}	6.6x10^{2}	4.9x10^{1}	1.0x10^{2}	5.9x10^{2}	6.8	1,000
L	L	4.2x10^{2}	L	6.3x10^{1}	2.9x10^{2}	L	2.4x10^{2}	5.4x10^{2}	32	10,000
1.8x10^{2}	1.0x10^{2}	5.4x10^{1}	2.0x10^{2}	1.6x10^{2}	3.6x10^{1}	1.4x10^{2}	1.2x10^{2}	5.8x10^{1}	1.5	15,000
L	L	L	L	L	L	L	L	L	15	6,800
L	L	4.4	L	L	3.2	L	9.4x10^{-1}	2.9	.16	16
4.4x10^{1}	2.3x10^{1}	7.5x10^{1}	5.2x10^{1}	2.3x10^{1}	5.0x10^{1}	2.7x10^{1}	6.6x10^{1}	6.1x10^{1}	6.8	1,000
L	L	L	L	L	L	L	L	L	1.0	4,600
L	L	L	L	1.2x10^{2}	L	L	L	L	100	1,000
L	L	L	L	L	L	L	L	L	2.2	10,000
L	L	L	L	L	L	L	L	L	10	10,000
L	L	L	L	L	L	L	L	L	2.2	10,000
L	L	L	L	L	L	L	L	L	2.2	10,000
L	L	L	L	L	L	L	L	L	68	10,000
3.8x10^{1}	2.5x10^{1}	3.0x10^{1}	3.4x10^{1}	5.4x10^{1}	3.9x10^{1}	3.5x10^{1}	3.9x10^{1}	5.8x10^{1}	1.0	10,000
9.1	2.3x10^{1}	2.0x10^{1}	1.3x10^{1}	2.5x10^{1}	1.9x10^{1}	1.6x10^{1}	2.4x10^{1}	2.2x10^{1}	.0099	73
L	L	2.6x10^{2}	L	L	L	L	L	L	10	1,000
E	1.7x10^{1}	1.2x10^{2}	E	L	6.8x10^{1}	2.6x10^{1}	3.3x10^{1}	1.7x10^{2}	4.6	10,000
4.4x10^{1}	4.2x10^{1}	5.9x10^{2}	4.1x10^{1}	2.2x10^{2}	1.7x10^{3}	7.6x10^{1}	6.7x10^{2}	1.8x10^{3}	1.0	320,000
L	L	L	L	L	L	L	L	L	320	10,000
L	L	L	L	L	L	L	L	L	32	1,000
L	L	1.5x10^{3}	L	L	6.7x10^{2}	L	L	2.5x10^{2}	46	10,000
1.2x10^{1}	5.7x10^{-1}	6.1	7.3	1.5	1.6x10^{1}	4.5	4.0	1.7x10^{1}	.0053	77
L	L	L	L	L	L	L	L	L	10	10,000
L	L	1.6x10^{1}	L	L	2.5x10^{1}	L	L	3.4x10^{1}	4.6	1,000
L	L	L	L	L	L	L	L	L	220	10,000
8.4x10^{2}	1.5x10^{2}	2.8x10^{2}	9.8x10^{2}	2.5x10^{2}	4.5x10^{2}	3.2x10^{2}	2.8x10^{2}	3.2x10^{2}	1.0	1,000
L	L	L	L	L	L	L	L	L	15	10,000
3.1x10^{1}	7.0x10^{1}	2.3x10^{2}	4.4x10^{1}	7.5x10^{1}	E	4.2x10^{1}	9.4x10^{1}	E	1.5	10,000
L	1.3x10^{1}	5.4x10^{1}	L	8.6	9.1x10^{1}	7.6	2.2x10^{1}	1.2x10^{2}	.15	1,000
4.4x10^{2}	1.9x10^{2}	E	6.3x10^{2}	2.2x10^{2}	E	3.9x10^{2}	2.2x10^{2}	E	10	10,000
6.6x10^{2}	5.4x10^{1}	H	3.8x10^{2}	2.0x10^{3}	H	1.4x10^{2}	2.2x10^{3}	H	3.2	22,000

Table 4. Statistics of major and minor elements detected in designated heavy-mineral fractions of samples from the Chukchi Sea, Alaska

[Elements detected by emission spectrographic analysis (table 3)]

A. Strongly paramagnetic/ferromagnetic heavy-mineral fraction separated by hand magnet

Element	Minimum	Maximum	Mean	Variance	Standard deviation
Major elements, values in percent					
Si	9.1	16.0	13.3	5.4	2.3
Al	2.8	5.7	4.2	1.6	1.3
Fe	17.0	24.0	22.4	8.0	2.8
Mg	3.5	4.6	4.0	0.2	.4
Ca	2.3	6.7	3.8	2.5	1.5
Na	.3	.4	.3	3.8x10^{-3}	6.2x10^{-2}
K	.4	.5	.4	1.1x10^{-3}	3.3x10^{-2}
Ti	1.2	12.0	5.1	13.2	3.6
Minor elements, values in parts per million					
Ag	1.5	2.4	2.0	9.6x10^{-2}	0.3
B	6.8	200.0	78.8	4.7x10^{3}	68.5
Ba	62.0	250.0	144	5.1x10^{3}	72.1
Co	42.0	72.0	57.9	114	10.7
Cr	1,700.0	6,800.0	3,114	2.9x10^{6}	1,714
Cu	33.0	71.0	56.4	267	16.3
Ge	4.6	15.0	6.1	15.4	3.9
Hf	15.0	150.0	92.1	5.2x10^{3}	72.2
La	10.0	70.0	34.6	361	19.0
Mn	9,200.0	15,000.0	11,514	4.2x10^{6}	2,039
Nb	33.0	130.0	61.1	1.0x10^{3}	32.4
Ni	92.0	200.0	150	1.2x10^{3}	34.6
Pb	26.0	52.0	37.1	107	10.3
Sc	17.0	38.0	32.1	55.1	7.4
Sr	27.0	76.0	47.0	304	17.4
V	190.0	980.0	491	9.7x10^{3}	311
Y	27.0	49.0	39.7	62.6	7.9
Yb	5.5	13.0	7.8	5.9	2.4
Zn	370.0	630.0	440	8.3x10^{3}	90.9
Zr	88.0	660.0	310	3.4x10^{4}	186

B. Moderately magnetic 0.0-amp to 0.6-amp heavy-mineral fraction separated by electromagnet

Element	Minimum	Maximum	Mean	Variance	Standard deviation
Major elements, values in percent					
Si	18.0	25.0	21.9	6.5	2.5
Al	4.4	8.1	6.6	2.0	1.4
Fe	7.0	19.0	13.7	21.2	4.6
Mg	6.0	9.7	8.0	2.0	1.4
Ca	6.9	11.0	8.9	3.1	1.8
Na	.3	.5	.4	9.5x10^{-3}	9.7x10^{-2}
K	.2	.3	.3	4.0x10^{-3}	6.4x10^{-2}
Ti	.6	4.0	1.5	1.3	1.2
P	6.8x10^{-2}	.9	.2	.1	.3
Minor elements, values in parts per million					
Ag	.8	2.1	1.2	0.2	0.5
B	180.0	480.0	391	1.1x10^{4}	105
Ba	31.0	2,400.0	523	6.9x10^{5}	832
Ce	83.0	1,200.0	513	1.2x10^{5}	351
Co	32.0	48.0	38.3	42.6	6.5
Cr	1,700.0	3,000.0	2,286	3.1x10^{5}	558
Cu	11.0	81.0	52.2	655	25.6
Dy	22.0	53.0	26.4	137	11.7
Er	4.6	100.0	18.2	1.3x10^{3}	36.1
Eu	2.2	17.0	4.7	30.4	5.5
Ga	15.0	35.0	22.1	64.1	8.0
Gd	32.0	55.0	35.3	75.6	8.7
Ge	4.6	15.0	6.1	15.5	3.9
Hf	15.0	560.0	141	4.1x10^{4}	202

B. Moderately magnetic 0.0-amp to 0.6-amp heavy-mineral fraction separated by electromagnet—*Continued*

Element	Minimum	Maximum	Mean	Variance	Standard deviation
Minor elements, values in parts per million—*Continued*					
Ho	6.8	13.0	7.7	5.5	2.3
La	33.0	360.0	184	1.1x10^{4}	107
Mn	4,900.0	8,400.0	6,871	1.6x10^{6}	1.3x10^{3}
Mo	1.0	5.3	3.2	2.1	1.5
Nb	13.0	100.0	43.0	874	29.6
Nd	32.0	240.0	165	7.4x10^{3}	86.2
Ni	100.0	160.0	124.3	395.2	19.9
Pb	23.0	66.0	37.1	235.8	15.4
Pr	100.0	150.0	110.0	366.7	19.2
Sc	25.0	54.0	39.9	92.5	9.6
Sm	10.0	32.0	24.4	56.3	7.5
Sn	4.6	33.0	15.4	100	10.0
Sr	42.0	670.0	260	3.8x10^{4}	195
Th	46.0	150.0	102	963	31.0
V	150.0	280.0	211	2.3x10^{3}	47.4
Y	44.0	94.0	63.0	309	17.6
Yb	5.1	22.0	10.0	33.6	5.8
Zn	190.0	350.0	249	3.3x10^{3}	57.3
Zr	54.0	2,200.0	865	7.5x10^{5}	867

C. Nonmagnetic >0.6-amp heavy-mineral fraction separated by electromagnet

Element	Minimum	Maximum	Mean	Variance	Standard deviation
Major elements, values in percent					
Si	14.0	22.0	18.3	6.2	2.5
Al	1.1	4.9	2.9	2.2	1.5
Fe	1.0	3.0	1.7	.7	.8
Mg	.6	2.8	1.2	.7	.9
Ca	3.8	14.0	9.1	19.2	4.4
Na	.2	.4	.3	7.7x10^{-3}	8.8x10^{-2}
K	.2	.4	.3	8.3x10^{-3}	9.1x10^{-2}
Ti	2.3	17.0	9.1	32.7	5.7
P	2.5	4.4	3.3	.4	.6
Minor elements, values in parts per million					
Ag	1.4	5.9	4.1	2.3	1.5
B	74.0	300.0	139.6	5.9x10^{3}	76.9
Ba	3,200.0	21,000.0	11,443	43.6x10^{6}	6.6x10^{3}
Be	1.0	11.0	3.5	12.9	3.6
Ce	480.0	1,700.0	1,037	1.4x10^{5}	371
Co	6.6	15.0	9.6	9.4	3.1
Cr	210.0	910.0	514	5.7x10^{4}	239
Cu*	14.0	54.0	38.0	269	16.4
Eu	9.0	28.0	17.7	46.5	6.8
Ga	4.3	14.0	7.6	10.9	3.3
Hf	300.0	3,500.0	1,487	10.9x10^{5}	1,045
La	170.0	790.0	416	4.7x10^{4}	216
Mn	180.0	840.0	409	5.0x10^{4}	223
Nb	220.0	660.0	416	3.2x10^{4}	178
Nd	140.0	540.0	299	2.0x10^{4}	140
Ni	26.0	58.0	38.6	158	12.6
Sc	11.0	58.0	31.4	233	15.3
Sn	37.0	170.0	85.1	2.5x10^{3}	49.8
Sr	530.0	1,800.0	1,153	3.0x10^{5}	551
Th	46.0	2,200.0	898	6.6x10^{5}	813
Tm	7.6	34.0	18.5	77.7	8.8
V	160.0	450.0	266	9.4x10^{3}	96.9
Y*	120.0	230.0	166	2.2x10^{3}	47.2
Yb	18.0	120.0	60.9	1.3x10^{3}	36.7

*Statistics based on 5 samples.

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