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**HEAVY MINERAL CONCENTRATION IN A MARINE SEDIMENT
TRANSPORT CONDUIT, BERING STRAIT, ALASKA**

by

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CONTENTS

INTRODUCTION	1
REGIONAL SETTING	2
MATERIALS AND METHODS.....	3
RESULTS	5
Heavy Mineral Deposition in the Bering Strait Area	5
Heavy Mineral Composition.....	8
Mineralogy.....	9
DISCUSSION	10
Sediment Transport	10
Marine Placer Deposition	12
Potential for a Subeconomic/Economic-Scale Deposit	12
Comparative Examples of Marine Placer Sands.....	13
CONCLUSIONS	13
ACKNOWLEDGMENTS	13
REFERENCES	14

FIGURES

Figure	1. Cape Prince of Wales and Bering Strait area.....	3
	2. Sampling the seafloor with a split Shelby tube sampler and screw-on extension pipes.....	4
	3. Beach and nearshore sample locations.	6
	4. Percent heavy mineral concentration contained in marine sediments, Bering Strait.....	7
	5. Enhanced satellite view of the eastern Bering Strait and high-altitude enlarged view of Prince of Wales Shoal area.....	11

TABLES

Table	1. Sieve analysis of offshore sand, Prince of Wales Shoal.....	8
	2. Summarized analyses of 52 heavy mineral concentrates from the Bering Strait.....	8
	3. Summarized analyses of major oxides in heavy mineral concentrates from the Bering Strait.	8
	4. Concentration of minerals with specific gravity greater than 7, using tin as an elemental tracer in beach and dune features, Prince of Wales Shoal.....	9

APPENDIX

Appendix A	Sample Map Number –Sample Field Number cross reference	15
B	Percent Heavy Mineral Concentrations	16
C	Table of Elemental Analyses of Heavy Mineral Concentrates	18
D	Major Oxide Analyses of Heavy Mineral Concentrates after lithium borate fusion at Chemex Labs.....	22

HEAVY MINERAL CONCENTRATION IN A MARINE SEDIMENT TRANSPORT CONDUIT, BERING STRAIT, ALASKA

by
James C. Barker¹, John J. Kelley², and Sathy Naidu²

ABSTRACT

A reconnaissance investigation in the Bering Strait shows that a series of marine processes transport offshore sediment northward and northeast of Cape Prince of Wales, which forms the eastern Bering Strait headland. As a result, marine sands are hydraulically sorted, with the heavy mineral fraction becoming concentrated within and just north of the high-energy strait while lighter fractions are winnowed and transported farther north–northeast. Upon exiting the Bering Strait, fine-sized sorted sand is transported by diverging currents to form the 35-km-long Prince of Wales Shoal and northeast to form barrier islands along more than 100 km of coastline.

A succession of present and past sediment-accumulation processes in the northern Bering Sea and continuing marine sediment transport, climatic, littoral, and eolian processes are present. Heavy mineral concentrations in excess of eight percent by weight occur over several km² immediately northeast of the strait in the area bounded to either side by the diverging currents. Neither the northern extent nor thickness of the heavy mineral concentration have yet been determined. Data from shallow seafloor cores show that the shoal, as well as sediment delivered eastward to the beach, are depleted in the heavy mineral fraction. Sediment delivered onshore continues to be driven by littoral and eolian processes, particularly by dune progressions, forming the extensive Shishmaref spit and barrier islands along the northwest Seward Peninsula coast.

The minerals of potential economic interest include titanium as ilmenite, anatase, rutile, and titanite; lesser rare-earth minerals monazite and xenotime, plus zircon, and trace to accessory columbite, wolframite, and cassiterite. Trace to anomalous levels of gold and platinum metals are also found in assays of the heavy mineral splits of seafloor samples.

The heavy minerals are mostly derived from sediments reworked during multiple late Quaternary to Holocene transgressions of the Bering Land Bridge (Beringia). These glacial and paleofluvial sediments originated in the expansive and highly mineralized metallogenic provenances of the eastern Chukotka (Russia) Peninsula and the Seward (Alaska) Peninsula, as well as erosion of several drowned bedrock terranes. Closer to the Bering Strait, sediment is derived from the well-known western Seward Peninsula tin district where cassiterite has been historically mined from both placer and lode deposits.

INTRODUCTION

As the only waterway connection between the Pacific and Arctic oceans, the Bering Strait is a dynamic focus of marine geological processes leading to massive-scale transport of sediments and their sorting by grain size and specific gravity (sp.gr.). With the regional presence of source rock containing resistant, economic heavy minerals and a Holocene sediment transport conduit process in active operation, the Bering Strait was consequently chosen to study its marine placer potential. It was theorized that during ice advances, the present western Seward Peninsula and the eastern Chukotka Peninsula contributed sediment including economically important heavy minerals to the continental shelf (Beringia). Conversely, during the interglacial periods the drift deposits were subject to reworking by fluvial systems and eventual rising sea levels. Marine currents present in the eastern Bering Strait were deemed sufficient to transport large quantities of sediment, and initial field observations suggested sorting by at least grain size was occurring as part of the deposition forming the Prince of Wales Shoal.

The objective of this study was to identify the presence of placer heavy mineral concentrations in or north–northeast of the Bering Strait, and make a preliminary assessment of the processes by which they formed relative to the regional geological setting.

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Previous work by Creager (1963) cited the 1958 U.S. Navy data describing northward currents of more than 200 cm/sec. He described currents through the eastern Bering Strait as the most significant cause of sediment transport onto the continental shelf underlying the Chukchi Sea. The major driving force for the intense northward flow as described by Naidu (1988) is the constraining of that flow through the narrow, relatively shallow channel between the Bering and Chukchi seas. The sea surface slopes down to the north; the normal summer sea level is about 0.5 m lower in the Chukchi Sea than in the northern Bering Sea.³

Marine placer gold concentrations have been observed along the south coast of the Seward Peninsula since the 1901 gold rush at Nome. Nelson and Hopkins (1972) confirmed the presence of particulate gold in the northern Bering Sea. Nelson (1969; oral commun., 1982) discussed studies of cassiterite in the offshore between Lost River and Cape Prince of Wales, and noted seafloor black sand accumulations visible from underwater camera scans along the coastline.

Between 1979 and 1991, author J.C. Barker, then with the U.S. Bureau of Mines (USBM), undertook investigations and sampling of the seafloor, beaches, and eolian features between Wales and Little Diomed Island, and across the Prince of Wales Shoal. Approximately 80 beach, dune, and seafloor samples were collected. Assistance was provided by the Institute of Marine Science of the University of Alaska Fairbanks and the University of Mississippi Marine Minerals Technology Center. The work is briefly summarized in Barker and others (1990). Additionally, mineralogical study of the heavy minerals in USBM beach samples is described by Woo (1989). The USBM was closed by the U.S. Congress in the early 1990s and the unprocessed samples, field notes, and files were archived. A draft report of findings was prepared but was not completed or published. In 2005, the U.S. Minerals Management Service (MMS) provided a grant to the University of Alaska Fairbanks School of Fisheries and Ocean Sciences to reopen the project and report on the findings. Those findings are contained in this report.

REGIONAL SETTING

The Bering Strait is a very remote waterway between Chukotka Peninsula (Russia) and the Seward Peninsula, Alaska (United States). It is well known by the Eskimo residents for its adverse weather and dangerous currents. Within the strait are the prominent Diomed Islands that straddle the border as well as the International Date Line.

A highly mineralized belt of metasedimentary rocks extends across the Bering Strait region, and granitic plutons (some with associated tin occurrences) underlie highlands such as Cape Mountain, which forms the prominent western tip of North America (fig. 1), as well as, Kougarok, Potato Mountain, Lost River, Ear Mountain, the Diomed Islands, and the East Cape of Chukotka (Hudson and Arth, 1983, Hudson and Reed, 1997, Mulligan, 1959, 1966; Mulligan and Gnagy, 1965) (fig. 1). Placer tin as cassiterite with accessory lithophile minerals have been prospected or mined from nearly all streams that drain the western Seward Peninsula. Lode tin prospects, mostly contact-metamorphic deposits in limestone roof pendants overlying the intrusive rocks, occur at most of these locations (Sainsbury, 1972), as well as Erulen and Chaantal on Chukotka (Nokleberg and others, 1993).

Farther to the east and southeast are the gold districts in the Port Clarence and Nome areas. Glaciation and interglacial fluvial systems have transported particulate gold to the marine environment along the south of the Seward Peninsula (Moore and Welkie, 1976). The widespread intrusive and metasedimentary rocks of the Chukotka and Seward peninsulas, as well as exposed bedrock islands and shallow seafloor bedrock outcroppings in the northern Bering Sea, are also host to common accessory heavy minerals such as magnetite, zircon, and titanium minerals, all of which are, or have been, reworked by late Quaternary transgressions.

Glaciation has played an important, though not fully understood, role in regionally exposing mineralized terrane, eroding and dispersing the sediments. Nelson and Hopkins (1972) summarized Pleistocene glacial advances that derived and entrained sediment from the highlands of the western Seward Peninsula and deposited glacial drift up to 5 km beyond the present shoreline. Six glacial episodes are recorded in the mountains and uplands of southwestern Seward Peninsula (Hopkins, 1967). Extensive glaciation on the Chukotka Peninsula extended as far as the present northern Bering Sea. The Chukotka glaciation carried large amounts of till eastward to the Chirikov Basin during low sea level stands and formed what is presently a mappable submarine paleomoraine extending 225 km to the northeast from northwest of St. Lawrence

³Since the completion of this investigation in the early 1990s more recent, government-funded, scientific investigations have focused on the northward flow and characteristics of Bering seawater through the Straits, and effects of that water as it mixes with the Arctic Ocean water. Moored sub-sea stations in and north of the Bering Strait are now maintained to continuously collect data, which are annually downloaded. For more information on present research we refer the reader to: <http://psc.apl.washington.edu/HLD/Bstrait.html>

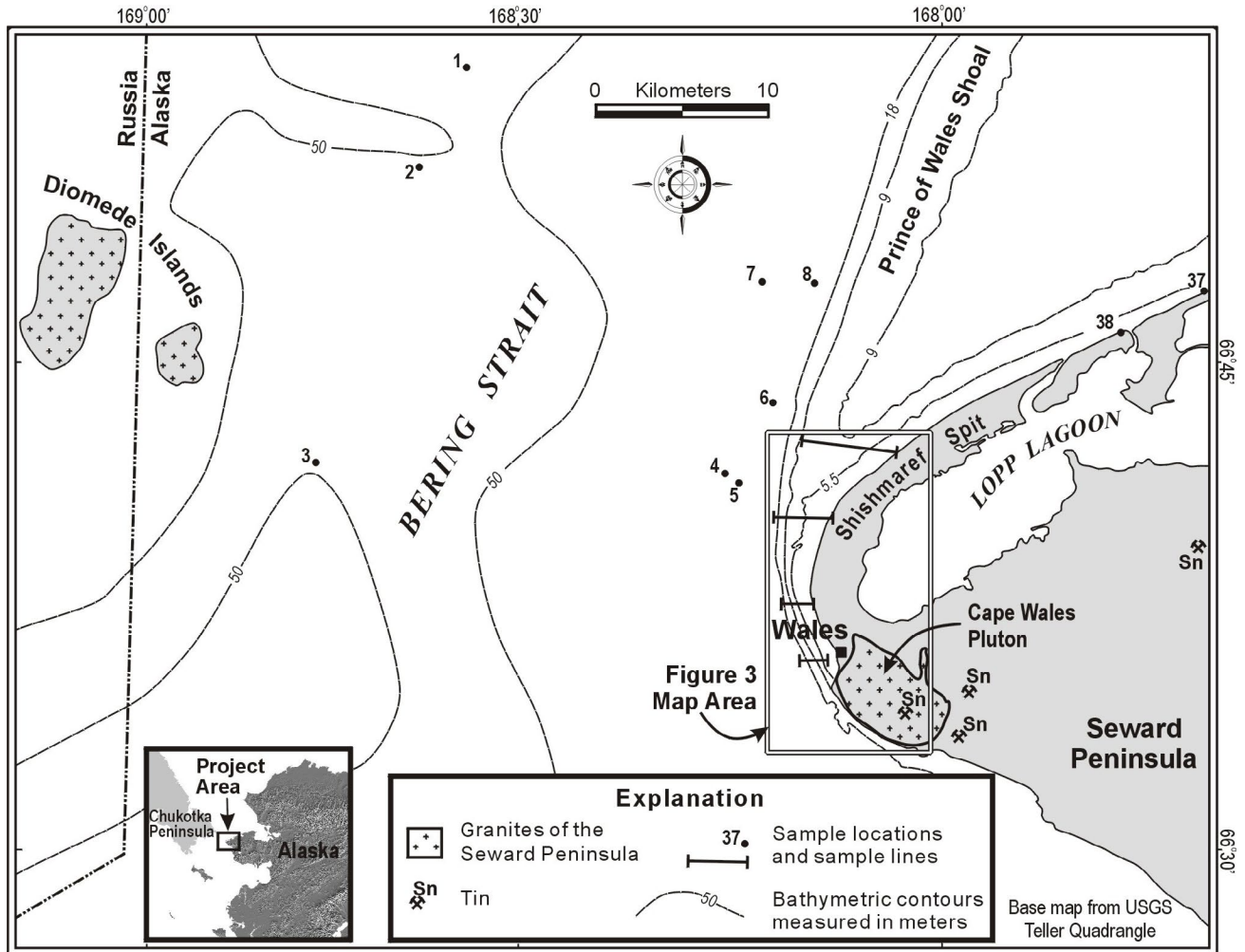


Figure 1. Cape Prince of Wales and Bering Strait area.

Island to the Bering Strait (Nelson and Hopkins, 1972; Nelson, 1982). They proposed glacial drift from the west to be the principal source of gold in the sediments of the northern Bering Sea.

As recently as the beginning of the Holocene the Beringia region was dry land. Interglacial periods resulted in varying sea levels. Beach gravels were found (this study) at 15–20 m water depth off Wales village; they extend north along the base of the shoal, suggesting a shoreline prior to the most recent rise in sea levels. Stillstands about 30 m above the present sea level are noted in several creeks draining Cape Mountain where the placer pay streaks are abruptly terminated and beach gravel and sea shells are found near bedrock (Mulligan, 1959, 1966; Mulligan and Gnagy, 1965).

Marine placer resource development has figured prominently in the economy of the Seward Peninsula and historically several deposits have been mined in the Nome area. During the 1980s offshore dredging for placer gold was undertaken with a bucket ladder dredge known as the Bima, which during the years 1987–1989 produced just over 100,000 oz gold (3.1 metric tons) (Barker and others, 1990). Since 1901, the Nome beach has been famous for its gold. Gold is still mined from the beach. Onshore, the elevated strand lines are the source of most of the nearly 5 million oz (155 metric tons) of historic gold production in the Nome district. Smaller-scale offshore gold placer mining was also reported near Bluff and Solomon in the past. In recent years there have been efforts to develop apparent lode sources of placer gold such as the nearby Rock Creek deposit. Recent rises in the value of gold and many other minerals has generated renewed industry interest in the historic mining districts of the Seward Peninsula region.

MATERIALS AND METHODS

Field studies were conducted during both summer and winter conditions. In 1979 and 1985, onshore geologic mapping and mineral assessment were performed in the Cape Prince of Wales to Kougarok area. The studies initially included 15 sample stations along 10 km of the beach and active dune area of the Shishmaref spit that specifically targeted natural black sand

concentrations. Sand samples (map numbers 60–74) consisted of two 14-inch pans (0.006 m^3) reduced to a concentrate of about 30 g. Heavy mineral samples of sufficient volume were split: the first half was analyzed for tin by x-ray fluorescence (XRF) and examined by scanning electron microscope (SEM); the second half was later made available to the U.S. Geological Survey for mineralogical examinations using optical and x-ray diffraction techniques and reported in Woo (1989).

Offshore samples were collected in 1987 and 1990. Sample stations 01–08 were collected with a Van Veen grab sampler from the *R/V Surveyor*. All other offshore samples were collected from sea ice by drilling holes through the ice and lowering a split Shelby tube sampler coupled with threaded extension pipes to the sea floor and driving the apparatus with a sledge hammer (figs. 2A and B). Sample site 43, over the west edge of the shoal, was too deep at 23 m to reach with the extension tubes and consequently a snapper grab sampler was used. Otherwise, seafloor cores 0.3 to 0.9 m in length, each weighing 1–2 kg, were collected with the Shelby tube. Cores were quickly transferred onsite to plastic bags before they froze. The sample barrel was lowered back into the water to clean any frozen sample remaining on the tube. A total of 43 offshore samples were collected; 40 were later recovered from archive in 2005 and analyzed in this study. Data from three additional samples similarly processed in 1990 are also included. All samples referred to in this report are listed in appendix A with their corresponding map number.



Figure 2A and 2B. Sampling the seafloor with a split Shelby tube sampler and screw-on extension pipes; water depth approximately 10 m. Pressure ridge in background marks edge of shorefast ice and western edge of Prince of Wales Shoal; sample 43, near the pressure ridge in photo, was at 23 m depth.

A second set of nine beach samples was collected at random from the lower swash zone of the beach along the Shishmaref spit. These samples were taken to represent the sediment being delivered from offshore to the beach. Sampling intentionally avoided local concentrations of black sand seen frequently in the upper- to back-beach zone and as winnowed patches between the dunes to the rear of the beach.

Locations of sample sites on the ice were determined by a combination of distance measurements with a thread chain and careful triangulation to prominent topographic features to the east and west. Samples collected from the *R/V Surveyor* were positioned by Loran C. At the time of sampling, GPS was not yet available and Loran navigation was not possible at the sample stations on the sea ice closer to shore due to interference by Cape Mountain and nearby hills.

All offshore and lower swash zone samples were dried in the laboratory and sieved at 20 mesh (0.84 mm) to remove shell material. Where oversize gravel was present it was weighed, described, and archived. Samples were later split and weighed. Splits from several samples were tested with electromagnetic separation, and a shaking table. Results of these separation tests were inconclusive and therefore suspended. Larger samples would have been required for further testing. Ultimately all offshore samples were processed by methylene iodide heavy liquid, specific gravity 3.2, retaining an unprocessed one-quarter split for archive. The results of these separations and the calculated percent heavy mineral concentrate are provided in attached appendix B.

The prepared heavy mineral concentrates were then analyzed as tabulated in the appendices; a suite of 38 elements were analyzed by inductively coupled plasma (ICP)–mass spectrometry (ICP-MS, laboratory code ME-MS81) methods (appendix C). Additional samples were analyzed by fire assay–inductively coupled plasma (FA-ICP) for Au, Pt, and Pd (appendix D). Where sufficient heavy mineral sample remained, the major oxide suite was later analyzed by x-ray fluorescence (XRF) (appendix D). Originally a few samples (SP 28640 through SP 26847, appendix C) were analyzed by neutron activation (NAA) and XRF at Bondar-Clegg in 1990; all remaining samples and pulps of some of the original samples were analyzed under contract with ALS Chemex, Vancouver, BC, in 2006.

Three offshore samples believed to be representative of the larger group of samples were further studied by X-ray diffraction (XRD). Study of samples 11, 19, and 30 was done at the USBM Reno Metallurgical Center in 1990 (see discussion page 9). Mineralogy of four natural black sand concentrate samples (map numbers 61, 62, 63, and 65) were examined by scanning electro-microprobe

RESULTS

HEAVY MINERAL DEPOSITION IN THE BERING STRAIT AREA

Heavy mineral concentrations can be expected at any of several specific stages in the high-energy marine sediment transport and sorting conduit that begins south of the Bering Strait and continues into a lower-energy coastal regime to the north and northeast of the strait. Of particular interest is sorting that is observed to occur over the shoal, resulting in (1) the silt to fine sand fractions carried northward by the reduced currents as suspended turbidity seen in satellite images, and (2) winnowed lighter sand transported to the beach. Observations were noted during several winter and summer periods of field work.

The glacial-marine sand and gravel lag deposits in the Bering Strait consist of subangular to subrounded material that was found to contain 2 percent or less heavy mineral weight fraction in the minus 20 mesh size fraction (figs. 3 and 4). Samples contain as much as 40 percent plus 20 mesh (0.84 mm). Nearing the Prince of Wales Shoal the seafloor begins to rise from 40 m depth to about 20 m; bottom currents orient subparallel to the base of the shoal and diminish in velocity. Organic-rich muds are either mixed with or overlie fine-sized, well-rounded ancient beach gravel at several sample sites. Samples contain a 3–4 percent heavy mineral fraction in this stage. Continuing east, water depths decrease to about 10 m over the top of the shoal and the seafloor is composed of silty sand, giving way to clean, well-sorted sand that contains 4 percent or more heavy minerals.

Wave action, particularly during storms, and northeast-directed water currents intermingle to sort and transport sand both northeast and east–southeast from the shoal to the surf zone and the beach. The process is poorly understood at present. A confused sea and divergent currents over the transition regime are coincident with the slightly deeper seafloor depression between the shoal and surf zone. Intersecting wave trains are present in most aerial photography and satellite imagery. The heavy mineral content in samples of the seafloor across the shoal increases incrementally to more than 8 percent. The lighter sand is winnowed eastward and deposited on the beach, where prevailing southwest winds transport sand as a progression of numerous dunes paralleling the rear of the active beach. Heavy mineral content of the beach samples, except where concentrated in the upper swash zone or within the dune progression, is generally less than 2 percent.

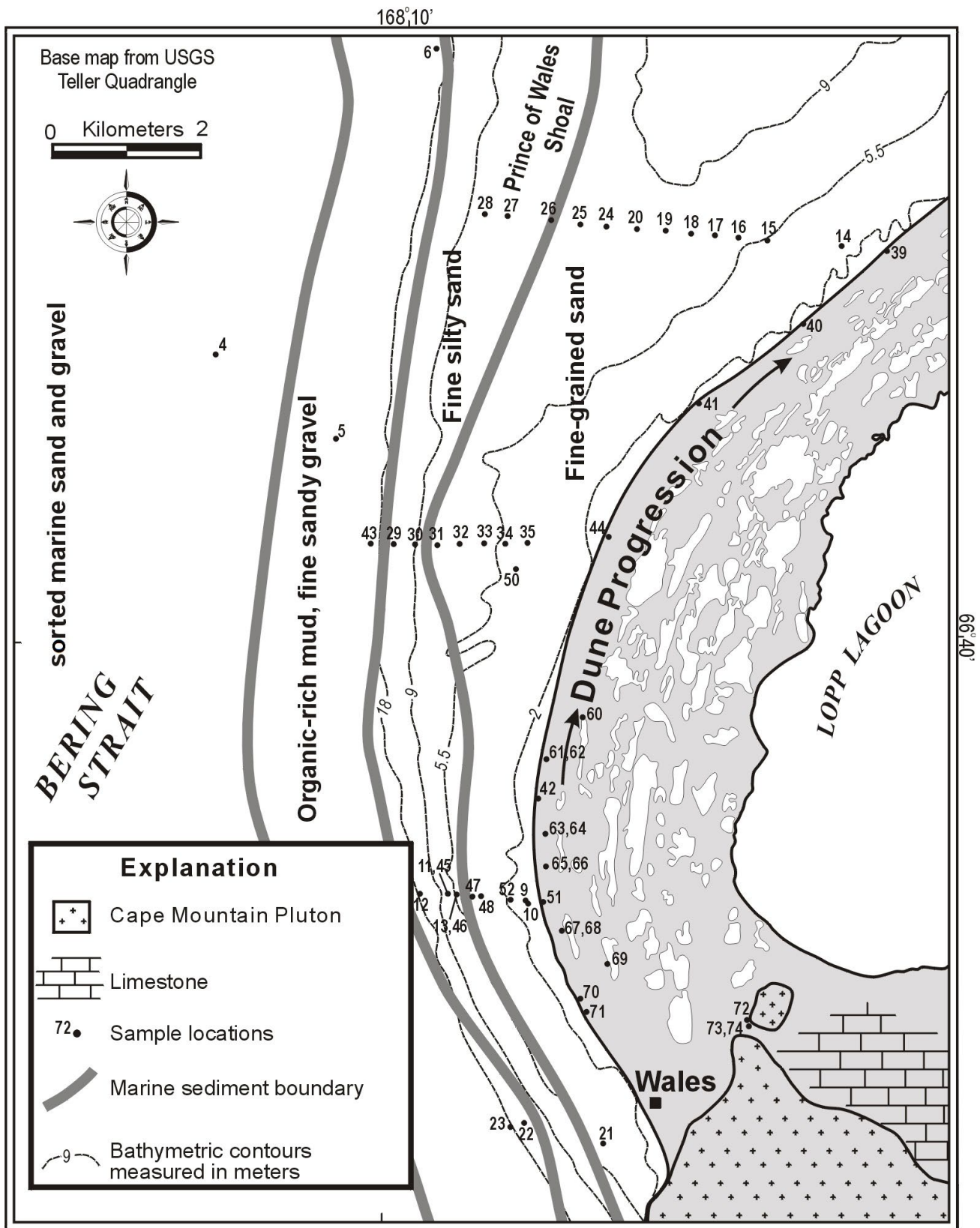


Figure 3. Beach and nearshore sample locations.

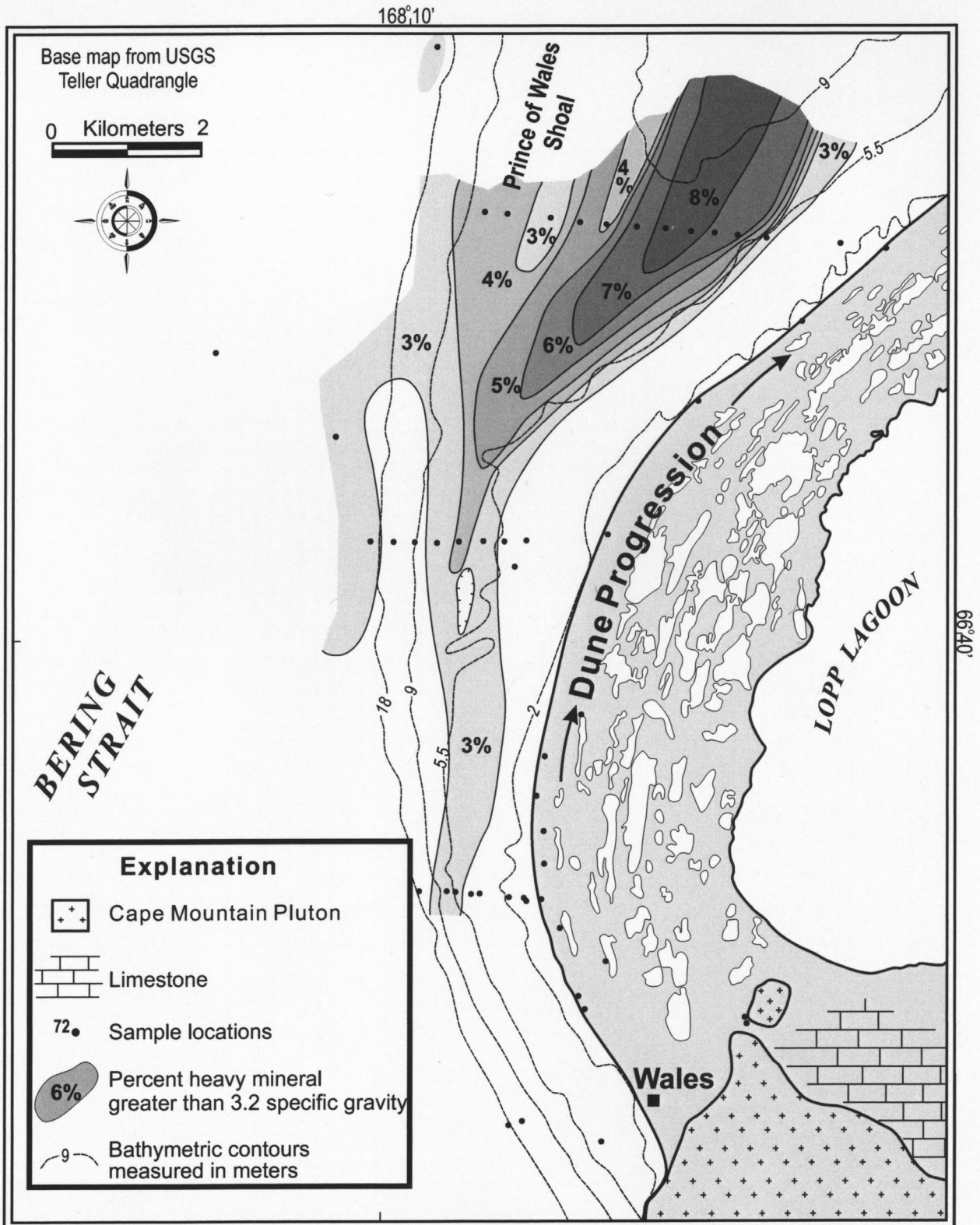


Figure 4. Percent heavy mineral concentration contained in marine sediments, Bering Strait.

The seafloor sediment across the shoal is uniformly well sorted fine sand found to mostly pass a 100 mesh (150 µm) screen. Sieve analyses of raw sand splits from the northern sampling line across the shoal are summarized below (table 1).

HEAVY MINERAL COMPOSITION

The analyses of heavy mineral composition in 52 samples from the Bering Strait area were treated as two populations. The first group includes 42 samples from offshore, and the second includes the nine samples from the lower swash zone. The beach swash zone samples collected in 1990 should not be confused with the 1985 beach and back beach pan concentrate samples analyzed for tin and reported separately. In each of these two populations the heavy mineral composition does not vary markedly from one site to another, although the percent of heavy minerals present in samples varies zonally as discussed

Table 1. Sieve analysis of offshore sand, Prince of Wales Shoal

Sieve Size		North Shoal Line, Sample Numbers, fraction weight in grams					Analysis	
mesh size	Opening µm	Sample 18	Sample 20	Sample 24	Sample 25	Sample 26	Σ fraction grams	% pass
-20 + 70	+212	1.74	8.86	6.76	11.99	7.33	36.68	1.9
-70 + 100	-212 +150	34.61	175.16	89.58	103.54	137.35	540.24	27.99
-100 + 140	-150 +106	158.82	288.04	138.46	252.93	149.47	987.72	51.17
-140 + 170	-106 +90	28.19	45.36	21.43	34.67	33.63	163.28	8.46
-170 + 200	-90 +74	20.45	29.66	15.67	26.84	21.72	114.34	5.92
-200 + 230	-74 +63	8.00	13.35	6.64	14.53	9.71	52.23	2.71
-230	-63	4.39	9.19	5.17	11.01	5.97	35.73	1.85
TOTALS		256.2	569.62	283.71	455.51	365.18	1930.22	

Table 2. Summarized analyses of 52 heavy mineral concentrates from the Bering Strait.

Element	Offshore Average, PPM	Swash Zone Average, PPM
Au	0.160 ^b	0.001
Au (1990) ^a	0.270	
PGE (Pt + Pd)	0.03	0.01
Cr	3,632	5,611
ΣREE+Y	1,388	1,165
Nb	100.4	86.1
Sn	45	28
Ta	9.1	7.3
U	15.42	11.04
W	15	16
Zr	3,316	2,467

^a Sample map numbers 01 through 08 were assayed at Bondar-Clegg Ltd., 1990, using multi-element analyses by 4-acid digestion/ICP; Sn, La, Ce, Y, Nb, Cr, and Zr analyzed by XRF; Au by fire-assay-ICP. Remaining samples and pulps of sample map numbers 01 through 03 and 07 analyzed by ALS Chemex (2006) using lithium meta-borate fusion and ICP procedure; Au, Pt, and Pd assayed by fire-assay-ICP procedure PGM-ICP23.

^b Excludes highly anomalous sample 29, which contains 15.2 ppm Au

Table 3. Summarized analyses of major oxides in heavy mineral concentrates from the Bering Strait.

Oxide	Offshore Average, %	Swash Zone Average, %	Comments
Cr ₂ O ₃	0.55	0.91	Analyses by x-ray fluorescence
TiO ₂	8.68	7.21	Analyses by x-ray fluorescence
ZrO ₂	0.45	0.33	Calculated on basis of atomic weight
RE ₂ O ₃ ^a including Y ₂ O ₃	0.2440	0.1475	Calculated on basis of atomic weight

^a REE atomic weight assumed to be 79% of RE oxide molecular weight for conversion

above. There are, however, obvious variations in the heavy mineral composition between the offshore and the swash zone sediment. The averages or ranges of economic elements present in the Bering Strait are summarized in tables 2 and 3.

A comparison can be made of the heavy mineral composition between the offshore and the lower swash zone sediments. Precious metals are essentially absent in beach samples, and REE+Y, TiO₂, ZrO₂, and accessory metals of Nb and Sn are markedly lower. Conversely, it is noted that Mn and Cr are enhanced in the beach samples. Excepting the concentration of Cr in the swash zone, the data suggest the heavy-end mineral suite (sp.gr. >4) is being sorted and concentrated offshore. Manganese is likely occurring as oxide coatings on lighter silicate minerals that are not amenable to concentration. Cause of the increased Cr in the swash zone remains unclear; however, there is no apparent correlation with the PGE values.

In the heavy mineral fraction, sample 29 contained 15.2 ppm Au, approximately 0.45 oz Au/ton. This assay was too anomalous to include in the calculation of the average gold content of the sample dataset but it is important as it indicates that gold is present as discrete grains. This situation creates a “nugget effect” for sampling, which indicates that it will be difficult to resample a given site and replicate the assay. For instance, duplicate splits of samples 01, 02, and 03 originally assayed for gold in 1990 and re-assayed in 2006. The earlier results were 0.091, 0.258, and 0.067 ppm Au, respectively, as compared to 2006 assays of 0.454, 0.113, and 1.715 ppm Au. These findings are consistent with sampling results by Nelson and Hopkins (1972) in the northern Bering Sea. They reported that the bulk of the gold in offshore relict gravel from glacial drift consisted of flakes 1 mm or larger in diameter. Consequently, future sampling should attempt to mitigate the problem by pre-concentrating larger volumes of the heavy minerals and color counts to better evaluate the actual gold and possibly the PGE content and characteristics.

The gold values in heavy mineral concentrates of the three samples within the minus 50 m depth Bering Strait channel (fig. 1) average 0.761 ppm as compared to 0.160 ppm Au for the entire dataset. The data indicate gold is more highly concentrated in the heavy mineral fraction of relict lag gravel present in the channelway.

MINERALOGY

Several beach concentrates, (samples 61, 62, 63, and 65) were analyzed by the USBM for preliminary mineralogy by SEM/microprobe in 1985 and 1986. Samples for mineralogical examination were derived from naturally-occurring black sand concentrations in the upper swash zone, layers up to 8 cm thick in the storm bank of the back beach, and lag accumulations behind dune progression (table 4). Three samples, 72, 73, and 74, were collected from sites near the base of Cape Mountain and are influenced to an unknown degree by Holocene fluvial processes. Each sample as noted in the table, consisting of one or two 14-inch pans (equivalent 0.003 to 0.006 m³), was concentrated on site by panning. The purpose of these samples was to specifically examine the heavier mineral fraction of specific gravity 7.0 or more by examining the recovery as grams of Sn per m³ of elemental tin in the sampled feature. Consequently, considerable loss of the minerals with specific gravity

Table 4. Concentration of minerals with specific gravity greater than 7, using tin as an elemental tracer in beach and dune features, Prince of Wales Shoal (Sn analyses by XRF at Chemex Labs).

Sample	Sn (ppm)	Sample vol., m ³	Concentrate (g)	g Sn per m ³	DESCRIPTION
60	1,100	0.006	21.52	4.16	Channel sample to 20 to 50 cm depth in upper swash with disseminated and banded black sand
61	77	0.006	58.54	6.53	Channel sample 20 to 50 cm deep in upper swash
62	1,400	0.006	43.76	10.1	Pit sample between dunes, back beach
63	179	0.006	82.84	2.38	Channel sample to 45 cm depth in swash, 10 cm black sand
64	120	0.006	29.75	0.59	Pit sample between dunes, back beach, disseminated black sand
65	1,240	0.003	58.19	23.75	10 cm band black sand exposed in upper swash
66	56	0.003	31.55	0.59	Pit sample, disseminated black sand in back beach
67	760	0.003	20.57	5.34	Pit in coarse sand in upper swash
68	65	0.006	25.21	0.3	Pit sample between dunes, back beach
69	100	0.006	12.77	0.24	1.0 m deep pit in ancient beach line
70	390	0.006	16.31	1.08	From dune face, back beach area
71	650	0.004	18.35	2.97	Rafted semi-consolidated sand block, back beach
72	2,960	0.006	15.46	7.72	From 30 cm gravel on clayey sand layer
73	2,480	0.006	35.46	14.25	Gravel outwash at base of slope to Cape Mountain
74	3,440	0.006	12.74	7.13	Fluvial layering in outwash, slope to Cape Mountain

between 3.5 and 4.5, such as chloritoid, epidote, garnet, zircon, and ilmenite, was expected during field panning. The presence of tin, which occurs as cassiterite (sp. gr. 7), provides a qualitative indication of the intensity of ongoing sediment transport and concentration processes. Analyses were done by X-ray fluorescence for tin and showed a range of 56 to 3,440 ppm Sn. The 12 samples of the upper swash and back beach average 511 ppm Sn, while the three samples near Cape Mountain averaged 2,960 ppm Sn. The highest concentration of elemental tin, as a measure of grams Sn per m³, however, occurs in heavy mineral bands in the upper swash zone, sample 65.

Microprobe analyses performed in 1986 by the USBM's Reno Research Center identified individual grains of interest. Tungsten values are attributed to wolframite, although a few grains of scheelite were also present. The rare-earth elements are contained in monazite and xenotime. Some monazite was found to contain elevated Th, some is Nd-rich, and other monazite grains are of normal composition and lacked reportable Th. Similar variation in composition was noted in wolframite grains. A few grains of allanite and cassiterite were also identified. Chromite, zircon, ilmenite, sphene, and magnetite, some titaniferous, are present. No rutile was found and no gold or platinum grains were observed. Overall, the grains are subrounded to subangular.

Three offshore samples were examined by x-ray diffraction (XRD) in 1990. Samples 11 and 30 represent the outer west slope of the Prince of Wales Shoal, composed of fine, silty sand; sample 19 is from the top of the shoal and consists of fine, well-sorted sand. Samples were a one-quarter split of the original sample and were concentrated by tetrabromothane (sp. gr. 2.95). The weight percent of heavy minerals was 3.8 percent in sample 11, 12.3 percent in sample 19, and 2.3 percent in sample 30. The heavy mineral suite was dominated by chloritoid, epidote, and a form of TiO₂ (either rutile or anatase). Other heavy minerals present in minor or trace amounts included zircon, titanite, ilmenite, hematite, augite, and almandine. Chromium and rare-earth elements were detected in an emission spectrographic scan but were not identified using XRD.

DISCUSSION

SEDIMENT TRANSPORT

Figure 1 shows a trough-like feature leading through the strait from the Chirikov Basin in the northern Bering Sea as a 50-m-deep channel (adapted from the NOAA marine chart). Seafloor within the trough is a transgressive lag of sand and gravel; subangular to well-rounded gravels and cobbles occur at sample sites 1–3 (fig. 1). Intensifying north-directed currents and sediment transport develop in proximity to the Bering Strait. The major driving force for the intense northward flow as described by Naidu (1988) is the relatively narrow and shallow channel between the Bering and Chukchi seas. The sea surface slopes down to the north; the normal summer sea level is about 0.5 m lower in the Chukchi Sea than in the northern Bering Sea. Variations and brief reversals occur, however, from certain combinations of atmospheric pressure centers and regional wind distribution.

Since the last glacial period, transgressive sea levels and accompanying beach erosional processes have reworked sediments in the Chirikov Basin (the former Beringia coastal plain). The postglacial development of strong bottom currents (reports of up to 225+ cm/sec in the eastern Bering Strait) have subsequently reworked and transported sediment northward as proposed by Creager (1963). Surface currents approximately 250 cm/sec were visually estimated from the edge of late winter shorefast ice overlying the western edge of the Prince of Wales Shoal during this study. Passing north through the strait, the current direction is controlled by the western base of the shoal. These currents, laden with turbidity, are apparent in satellite imagery of the Bering Strait region (fig. 5).

Particularly strong bottom currents as represented by turbidity also follow the bathymetry along the mineralized southwest coast of the Seward Peninsula to converge with north-trending flow in the eastern strait area. Currents have been sufficient to scour the seafloor and locally expose bedrock, and the percent of heavy mineral in relict sediment correlates directly with current velocity (Nelson, 1982; 1985, personal communication).

To the north, active large-scale sediment deposition resulting from energy loss in the north-directed currents forms the Prince of Wales Shoal. The shoal is a feature traceable in bathymetry at least 60 km north of the strait. As indicated by the turbidity plume, strong but northward-weakening currents follow the west slope of the shoal and continue to deposit sediment there. Bottom sediment on the western slope are composed of silty, fine sand (fig. 3). The present-day submarine Prince of Wales Shoal is likely continuing to build to the west and north as previously suggested by Creager (1963). Samples across the top of the shoal are composed of fine, sorted sand lacking the silt fraction, and are the product of the winnowing process. Visible in aerial and satellite imagery, a prominent area of confused sea marks the present-day divergence of northward and northeasterly currents. This feature is elongate and unexplored to the northeast, apparently controlled by a seafloor

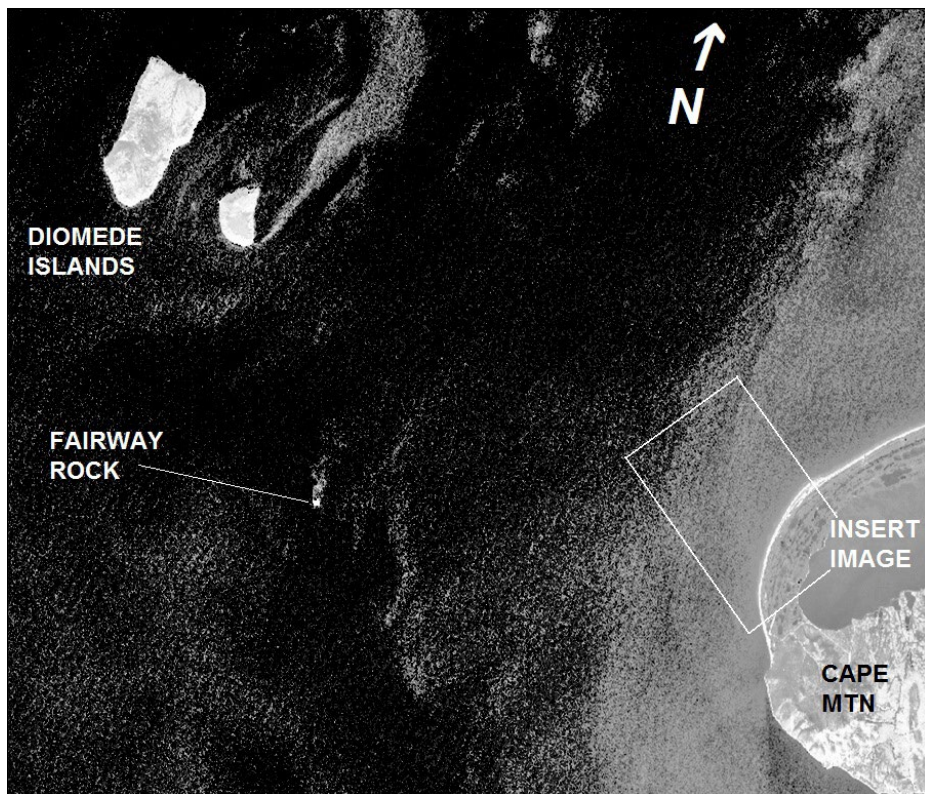


Figure 5. A. Enhanced satellite view of the eastern Bering Strait and high-altitude enlarged view of Prince of Wales Shoal area (note that orientation to north varies slightly between the two images). Plumes of suspended sediment depict currents: (1) along the southwest coast of the Seward Peninsula; (2) north from the Diomedes Islands and Fairway Rock; and (3) particularly prominent suspended sediment driven northward along the shoal. B. Note the confused sea and diverging wave trains that overlie the zone of sorting and concentration of heavy minerals seen in the high altitude enlargement.



depression between the diverging shoal and the nearshore shallow surf zone. Within this feature, poorly-understood shallow bottom currents and wave action are responsible for removal of the silt fraction from bottom sediments, concentration of heavy minerals, and continued winnowing of well-sorted fine sand that later is presented to the beach.

Nearshore and beach sediment transport continues to the north–northeast during the open-water period each year. A combination of northeast longshore beach transport and eolian transport of fine sand in the back beach drives a lengthy progression of dunes to the northeast and continues to remove sand from the present beach. Cumulatively, these processes have resulted in formation of the vast Shishmaref sand spit that extends at least 180 km along the entire northwest coast of the Seward Peninsula.

In summary, the sediment transport process is a net one-way sediment transport through the eastern Bering Strait that leads to sorting by grain size and specific gravity. Consequently, heavy mineral concentrations can be expected at specific stages within this high-energy marine environment that passes into a lower-energy coastal regime; at least some concentration of the heavy mineral fraction can be measured.

MARINE PLACER DEPOSITION

The data suggest limited gold concentrations may be found in placer accumulations on the flanks of the 50-m-deep channel, or in fine sediment deposition underlying sediment plumes to the north–northeast of Fairway Rock and northeast of Little Diomedea. Nelson and Hopkins (1972) concluded that coarse 1 mm or greater size Au was not being transported, but rather was concentrated in-place in relict gravels overlying lower-grade auriferous glacial drift. Our sample results for gold within the -50 m channel agree with this theory; however, present data also indicate gold is entrained with transported sand deposited on or immediately east of the shoal. Sporadic high gold values from the shoal, such as sample 29 with 15.2 ppm Au in the heavy mineral concentrate, indicate the presence of coarse-grained gold (defined as >1.0 mm). Beach samples, both those assayed and those panned in the field at Cape Prince of Wales are barren in gold, which indicates that the gold is too coarse and heavy to be transported beyond the shoal.

The overall composition of the heavy mineral suite was not found to markedly reflect a direct association to the local geology of Cape Mountain, nor the widely-occurring cassiterite deposits in the area that include placer tin deposits on streams that drain directly into Lopp Lagoon. Tin, although somewhat concentrated in black sand accumulations in the back beach and upper swash zones, is present at an average grade of only 45 ppm (tungsten at only 15 ppm) in offshore heavy mineral samples. Lopp Lagoon is situated directly behind the Shishmaref spit and it was expected that the cassiterite eroding into the lagoon would be present in the mineralogy of naturally-concentrated beach and nearshore sediments. The presence of only trace cassiterite in offshore samples, together with wolframite and rare-earth minerals more common than cassiterite, plus the distinct variations in the monazite and wolframite compositions, are evidence of multiple mineralized sources from more distant locations.

Development of tin-bearing strandlines along the base of Cape Mountain probably occurred but are buried by Holocene sand transported by presently active processes. This is evident at sample 22, at a depth of 13 m about 1.6 km west of Wales village, where a drowned beach comprises mixed local lithologies containing 25–30 percent granitic materials and vein quartz pebbles, mostly subrounded to subangular, suggesting a local source. The heavy mineral fraction contained 549 ppm Sn, 2,648 ppm REE + Y, and 58 ppm W, as compared to the average offshore values of 45, 1,388, and 15, respectively.

Nelson reported significant cassiterite in the offshore along the southwest coast of the Seward Peninsula. The presence of weak concentrations of tin in the upper swash zone and eolian concentrated beach samples from the Shishmaref spit indicate minerals with specific gravities greater than 6.5–8 have been largely sorted out earlier in the sediment transport conduit, probably nearer the south entrance to the Bering Strait. Therefore, these minerals are depleted or found in only trace amounts in shoal sediments. High-specific-gravity minerals (sp.gr. >7) are more likely to have been concentrated during earlier sea levels at elevations approximating the present depth of drowned beach lines (-15–20 m) found north of Cape Prince of Wales, such as near sample 22, or lower.

POTENTIAL FOR A SUBECONOMIC/ECONOMIC-SCALE DEPOSIT

The objective of this study was an initial reconnaissance of the sediment transport system present in the Bering Strait area to determine if marine processes may be sufficient to concentrate economically valuable heavy minerals in economically viable quantities. The data indicate that concentration is occurring in a multi-kilometer-scale area, but further sampling will be necessary to suggest the magnitude and grade of the potential resource present. The TiO₂ content of the more enriched sands over the Prince of Wales Shoal are subeconomic. However, the titanium is at least partially contained in an enhanced form of ilmenite altered to anatase. Detailed analyses of ilmenite are needed for further comment concerning economic viability.

The presence of gold and possibly trace platinum metals, rare-earth minerals, zircon, and the possible recovery of minor byproduct Sn–Ta–Nb–W (sp.gr. >7) also enhance the potential of a placer resource. Chromite may be a detriment, as it is normally penalized if not removed from a titanium concentrate.

COMPARATIVE EXAMPLES OF MARINE PLACER SANDS

Ilmenite, rutile, zircon, monazite, and several other minerals are commonly mined from marine sediment features where they have been concentrated by paleocurrents or modern inlet currents, beach, eolian, and dune processes, ancient beach lines, or drowned paleofluvial channels, all of which include sorting and winnowing of lighter mineral grains. The most common deposits are elongate strandlines that form from modern or ancient beach lines, typically found above present sea levels. There are many examples of such deposits on the east and west coastlines of Australia, India, Kenya, Malaysia, Egypt, Florida, and elsewhere (Force, 1986). The Nome gold placers are important ancient strandlines of this type. Other placers have formed by subaerial weathering of terrestrial mineralized bodies or by formation of eluvial placers at times of lower sea levels. Some of the best examples are Malaysia's offshore tin fields. Less common are placers that have concentrated from offshore marine processes only.

Economic grades of placer deposits vary widely and depend largely on the type and grade of products. For example, economic TiO_2 placer is more dependent on the ability of the concentrating plant to produce a 65 percent TiO_2 grade than on the original grade of elemental Ti in the placer sand. A lower "raw" sand grade of TiO_2 is possible if the Ti mineral is rutile or altered ilmenite that has sufficient Fe leached out of it and has an increased specific gravity from lattice collapse. The economics of a deposit are enhanced if sufficient ZrSiO_4 and/or monazite–xenotime are present and can also be produced. Most placer sand deposits that recover rare-earth elements generally recover a monazite product (Force, 1986; Attanasi and DeYoung, 1986). In the Bering Strait deposits the REE occur also in xenotime, which contains a higher percentage of the heavy, more valuable REE and Y.

There are few examples of marine placers with precious metals; the best are the Nome marine placers where a grade of 0.245 ppm Au in total processed gravel was mined by Dredges 5 and 6 on elevated strandlines, and 0.2 ppm Au in the seafloor gravel mined by the Bima dredge. No other mineral byproducts were recovered from these operations. Note that these grades are calculated over the entire mined sediment section, not just the heavy mineral fraction.

CONCLUSIONS

The marine sediment transport processes in the Bering Strait create dynamic net one-way transport but the processes remain poorly understood. We conclude that sedimentary processes in the Bering Strait are present that could create heavy-mineral placers containing minerals with titanium, zirconium, and rare-earth elements plus minor tin, tungsten, niobium, and precious metals. Further research is necessary to refine this assessment. For instance, titanium resource potential is highly dependent on mineralogical characteristics of the ilmenite present at Cape Prince of Wales. Gold is present in flake form perhaps >1.0 mm diameter, however, larger samples are required to mitigate the nugget-effect problem by pre-concentrating larger volumes of the heavy minerals.

Gold has been concentrated in lag-type gravel deposits in the channelways leading north to the Bering Strait. Data suggests gold to some degree is additionally entrained in transported sediments immediately north of the strait but has not been found in sediment arriving at the beach along the spit. Cassiterite concentrations are reported in seafloor sediments along the southwest coast of the Seward Peninsula and in economic fluvial placers on shore. In the Bering Strait cassiterite and other minerals, likely from local sources, with similar specific gravity may be concentrated in strandlines aligned with pre-Holocene drowned beach lines at depths of 15–20 m below present sea level. North of the strait tin is found in natural occurring heavy mineral concentrations along the Shishmaref spit but at only relatively low levels.

If the shoal is being advanced to the west, as proposed on the basis of continued apparent sediment deposition north of the strait and associated rising Holocene sea levels, it would follow that buried concentrations of heavy minerals may be found at slightly increasing depths east and south of the present target area.

There can be no marine mineral resource established in the Bering Strait area if the valuable minerals cannot be efficiently recovered from the sediment. Separation of the heavy mineral fraction from very-fine-grained, sorted sand poses a beneficiation challenge. Further, the heavy minerals of value will have to be separated from one another for final processing. The presence of chromite is usually a penalty if not separated.

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APPENDIX A
Sample Map Number –Sample Field
Number cross reference

Map numbers 1-8, 37, 38 are portrayed in figure 1; sample numbers 36,49, 50 are not portrayed in any figure; and all other samples are portrayed in figure 3. Analyses for map numbers 1-52 appear in Appendices B-D; Analyses for map numbers 60-74 appear in table 4.

Map No.	Sample No.
01	SP 26840
02	SP 26841
03	SP 26842
04	SP 26843
05	SP 26844
06	SP 26845
07	SP 26846
08	SP 26847
09	SP 27024
10	SP 27025
11	SP 27026
12	SP 27027
13	SP 27028
14	SP 27029
15	SP 27032
16	SP 27033
17	SP 27372
18	SP 27373
19	SP 27374
20	SP 27375
21	SP 27376
22	SP 27378
23	SP 27379
24	SP 27380
25	SP 27381
26	SP 27382
27	SP 27383
28	SP 27384
29	SP 27385
30	SP 27386
31	SP 27387
32	SP 27388
33	SP 27389
34	SP 27390
35	SP 27391
36	SP 27394
37	SP 27395

Map No.	Sample No.
38	SP 27396
39	SP 27397
40	SP 27398
41	SP 27399
42	SP 27400
43	SP 27401
44	SP 27402
45	SP 27690
46	SP27691
47	SP 27692
48	SP 27693
49	SP 27696
50	SP 27697
51	SP 27698
52	SP 27699
53	Unused
54	Unused
55	Unused
56	Unused
57	Unused
58	Unused
59	Unused
60	SP 23964
61	SP 23962
62	SP 23963
63	SP 23960
64	SP 23961
65	SP 23957
66	SP 23958
67	SP 23289
68	SP 23288
69	SP 23293
70	SP 23285
71	SP 23287
72	SP 23290
73	SP 23291
74	SP 23292

APPENDIX B
Percent Heavy Mineral Concentrations

	Sample number	Weight of sample fractions (g)						% HMC
		Received splits	+1.7 mm	Archived	-1.7 mm			
					Heavy Liquid Separation S.G. 3.2			
					Total	Lights	HMC	
	23293	754.7	0.40	0.0	754.3	742.8	11.5	1.52
01	26840	760.8	1.7	0.0	759.1	752.0	7.1	0.94
02	26841	698.4	0.90	182.4	515.1	508.8	6.3	1.22
03	26842	735.5	2.90	150.7	581.9	574.2	7.7	1.32
07	26846	698.3	0.04	296.5	401.8	394.9	6.9	1.72
08	26847	715.8	0.00	317.6	398.2	394.9	6.9	1.72
09	27024	734.8	0.00	340.8	394.0	389.0	5.0	1.27
10	27025	787.3	1.40	175.9	610.0	602.9	7.1	1.16
11	27026	565.2	0.00	156.1	409.1	397.2	11.9	2.91
12	27027	773.8	1.30	0.0	590.4	579.4	11.0	1.86
13	27028	713.3	0.10	260.0	453.2	439.7	13.5	2.98
14	27029	795.3	1.60	240.9	552.8	543.0	9.8	1.77
15	27032	784.2	0.00	385.5	398.7	385.6	13.1	3.29
16	27033	752.0	0.00	200.3	551.7	513.1	38.6	7.00
17	27372	761.9	0.00	233.7	528.2	493.7	34.5	6.53
18	27373	718.4	0.06	270.9	447.4	409.7	37.7	8.43
19	27374	738.5	0.04	330.1	408.4	374.8	33.6	8.23
20	27375	734.6	0.04	338.2	396.4	366.2	30.2	7.62
21	27376	795.5	0.00	230.0	565.5	557.0	8.5	1.50
22	27378	741.9	0.02	277.0	464.9	459.4	5.5	1.18
23	27379	720.4	27.60	0.0	636.6	629.4	7.2	1.13
24	27380	766.3	0.08	117.2	649.0	622.0	27.0	4.16
25	27381	732.2	0.00	290.3	441.9	419.5	22.4	5.07
26	27382	832.2	0.05	206.0	626.2	607.8	18.4	2.94
27	27383	772.2	0.10	247.6	524.5	499.6	24.9	4.75
28	27384	762.1	0.30	213.5	548.3	523.2	25.0	4.56
29	27385	722.6	0.00	287.9	434.7	423.3	11.4	2.62
30	27386	756.6	0.00	408.6	238.0	342.6	5.4	1.55
31	27387	714.1	0.04	274.1	440.0	424.4	15.6	3.55
32	27388	765.0	0.50	372.9	391.6	372.8	18.8	4.80
33	27389	732.0	0.03	345.5	386.5	374.2	12.3	3.18
34	27390	797.3	0.10	251.3	545.9	533.7	12.2	2.23
35	27391	732.4	0.00	410.7	321.7	312.3	9.4	2.92
36	27394	720.5	0.10	240.8	479.6	462.0	17.6	3.67
37	27395	778.2	0.30	217.2	560.7	529.0	31.7	5.65
38	27396	729.7	0.00	296.0	443.7	437.7	6.0	1.35
39	27397	781.4	0.00	179.7	601.7	588.2	13.5	2.24
40	27398	699.7	0.00	280.9	418.8	413.4	5.4	1.29
41	27399	740.6	0.00	217.8	522.8	503.6	19.2	3.67
42	27400	777.2	0.00	221.4	555.8	543.8	12.0	2.16
43	27401	753.6	0.00	303.6	269.2	258.4	10.8	4.01
44	27402	770.1	0.00	326.9	443.2	433.8	9.4	2.12
45	27690	562.6	3.40	118.7	440.5	427.9	12.6	2.86
46	27691	653.3	0.07	260.1	393.1	378.4	14.7	3.74

APPENDIX B
Percent Heavy Mineral Concentrations
(continued)

	Sample number	Weight of sample fractions (g)						% HMC
		Received splits	+1.7 mm	Archived	-1.7 mm			
					Heavy Liquid Separation S.G. 3.2 ¹			
					Total	Lights	HMC	
47	27692	724.0	0.30	359.4	364.3	357.9	6.4	1.76
48	27693	720.4	0.00	369.1	351.3	343.7	7.6	2.16
49	27696	350.3	0.08	81.8	268.4	264.7	3.7	1.38
50	27697	745.7	0.04	359.5	386.2	367.9	18.3	4.74
51	27698	760.4	0.00	190.5	569.9	551.6	18.3	3.21
52	27699	783.0	1.10	284.8	497.1	491.0	6.1	1.23

¹Sample separations performed by Overburden Development Management, Nepean, Ontario, 2006, using methylene iodide

	Sample number	Heavy Liquid Separation S.G. 2.95 ²						% HMC
		Total	Lights	HMC				
01	26840	1515.7	1477.0	20.4				
02	26841	1705.3	1656.9	36.4			2.13	
03	26842	1783.7	1732.2	32.4			1.8	
04	26843	1227.9	1170.9	33.3			2.71	
05	26844	1544.4	1477.7	56.9			3.68	
06	26845	2537.8	2428.7	83.5			3.4	
07	26846	1295.1	1245.1	44.5			3.44	
08	26847	1971.3	1931.0	36.3			1.84	

²Sample separations performed by U.S. Bureau of Mines, Reno, Nevada, 1990 using tetrabromothane

APPENDIX C
Table of Elemental Analyses of Heavy Mineral Concentrates

ANALYTICAL METHOD

SAMPLE DESCRIPTION	PGM-ICP23			Ag ppm	Ba ppm	Ce ppm	Co ppm	Cr ppm	Cs ppm	Cu ppm	Dy ppm	Er ppm
	Au ppm	Pt ppm	Pd ppm									
SP 26840	0.454	0.039	0.003	<1	246	784	32	2,400	0.92	10	49.5	32.1
SP 26841	0.113	0.034	<0.001	<1	212	786	32.6	1,800	1.26	10	47.9	31.2
SP 26842	1.715	0.023	0.001	<1	163.5	1,005	30.7	1,290	1.93	5	42.6	24.4
SP 26846	0.129	0.023	<0.001	<1	209	562	34.1	3,660	0.52	9	39.8	27.7
SP 27024	0.239	0.031	<0.001	<1	89.3	388	36.9	6,260	0.38	<5	32.1	24.6
SP 27025	0.017	0.021	<0.001	<1	107.5	381	35.1	4,880	0.38	<5	30.1	22
SP 27026	0.106	0.020	<0.001	<1	123	436	37.3	3,140	0.43	7	33.2	23.3
SP 27027	0.075	0.028	0.001	<1	112	416	36.2	3,770	0.49	6	30.3	21.8
SP 27028	0.026	0.030	0.003	<1	108	438	35	4,200	0.4	<5	32.4	23.8
SP 27029	0.005	0.032	0.003	<1	90.1	345	35.3	4,480	0.38	<5	27.2	19.6
SP 27032	0.175	0.042	0.003	<1	105	476	35.7	3,590	0.39	<5	32.6	23.2
SP 27033	0.008	0.009	0.004	<1	98.9	411	34.8	2,640	0.38	9	30.6	21.2
SP 27372	0.010	0.027	0.007	<1	115	418	35	3,080	0.4	<5	31.9	21.8
SP 27373	<0.001	0.014	0.001	<1	123	410	35.7	2,760	0.43	5	31.1	20.8
SP 27374	0.010	0.022	0.001	<1	152	462	34	2,800	0.45	<5	38.5	26.6
SP 27375	0.002	0.031	0.004	<1	115	521	33.8	3,560	0.37	<5	37.8	26.8
SP 27376	0.074	0.034	0.003	<1	133.5	423	36.5	5,450	0.34	<5	32.5	23.6
SP 27378	0.002	0.032	<0.001	<1	221	968	30	1,800	1.64	22	50.9	34.5
SP 27379	1.140	0.037	0.002	1	181.5	533	35.5	2,730	0.68	15	40.9	27.8
SP 27380	0.006	0.025	0.003	<1	151.5	448	35.6	2,800	0.41	<5	35.6	24.6
SP 27381	0.003	0.031	<0.001	<1	123.5	521	34.9	3,220	0.42	5	38.4	27.3
SP 27382	0.006	0.023	0.003	<1	122.5	441	34.7	3,160	0.39	<5	33.5	23.2
SP 27383	0.010	0.005	<0.001	<1	132	426	34.8	3,710	0.38	<5	35.4	25.2
SP 27384	0.010	0.025	0.001	<1	115	461	35	4,210	0.38	<5	34.1	24.6
SP 27385	^G 15.200	0.019	0.004	1	132	438	35.6	3,110	0.39	25	34	23.9
SP 27386	0.002	0.032	<0.001	<1	112	419	36.1	3,530	0.35	<5	31.5	22.5
SP 27387	1.300	<0.005	<0.001	<1	124	516	35.4	3,500	0.4	<5	33.1	23
SP 27388	0.013	0.034	<0.001	<1	119	456	35.6	3,750	0.39	<5	35.7	24.8
SP 27389	0.368	0.029	0.001	<1	105.5	401	35.7	3,350	0.36	6	30.4	21.5
SP 27390	0.007	<0.005	0.002	<1	107.5	431	36.1	3,430	0.35	<5	32.7	22.4
SP 27391	0.011	<0.005	<0.001	<1	100.5	392	36.1	3,480	0.35	<5	31.8	22.5
SP 27394	0.003	<0.005	<0.001	<1	85	410	34.8	6,550	0.64	<5	32.4	24.3
SP 27395	<0.001	0.012	<0.001	<1	81.3	366	35.4	5,690	0.47	5	29.7	22.8
SP 27396	0.004	0.027	<0.001	<1	81.7	336	36.6	7,340	0.48	<5	28.9	21.9
SP 27397	0.002	0.029	<0.001	<1	91.4	347	33.6	3,790	0.58	<5	28	19.3
SP 27398	0.002	0.037	0.001	<1	94.9	324	34	4,220	0.5	<5	26.1	19.4
SP 27399	0.001	<0.005	<0.001	<1	102.5	386	35.2	5,690	0.45	<5	29.7	21.9
SP 27400	<0.001	<0.005	<0.001	<1	96.9	329	33.7	3,140	0.45	<5	28.1	19.2
SP 27401	0.016	<0.005	<0.001	2	203	544	34.4	2,860	0.49	101	42.1	28
SP 27402	<0.001	<0.005	<0.001	<1	97.4	401	34.2	6,170	0.43	<5	30.6	22.8
SP 27690	0.001	0.023	<0.001	<1	118	470	31.4	4,380	0.42	14	35.7	26.3
SP 27691	<0.001	0.023	<0.001	<1	126.5	447	32.8	4,270	0.44	7	32.8	24.1
SP 27692	0.008	0.034	0.002	<1	112	358	35.1	4,050	0.41	10	28.4	20.2
SP 27693	0.004	0.065	0.003	<1	109.5	381	35.1	3,750	0.41	5	27.9	19.6
SP 27696	0.003	0.042	0.001	<1	97	377	34.5	4,020	0.38	7	31.1	22.2
SP 27697	0.003	0.041	0.132	<1	92.4	402	35.5	5,700	0.34	5	31.8	23.5
SP 27698	<0.001	<0.005	<0.001	<1	121	679	23.3	7,910	0.83	<5	45.5	34.6
SP 27699	<0.001	0.025	<0.001	<1	116	277	30.7	7,080	0.52	<5	22.9	18
Analyses Completed by Bondar-Clegg 1988												
	Au ppm (NAA)			Ag ppm (NAA)	Ba ppm (NAA)	Ce ppm (NAA)	Co ppm (NAA)	Cr ppm (NAA)	Cs ppm (NAA)			
SP 26843	1.320	NA	NA	<8	1,100	555	<14	1,700	6.6	NA	NA	NA
SP 26844	0.049	NA	NA	<5	210	400	42	3,390	3.1	NA	NA	NA
SP 26845	0.085	NA	NA	<10	<280	350	<17	2,180	<1.9	NA	NA	NA
SP 26847	nd	NA	NA	<5	310	330	39	1,600	2.3	NA	NA	NA

APPENDIX C
Table of Elemental Analyses of Heavy Mineral Concentrates
(continued)

ANALYTICAL METHOD

SAMPLE DESCRIPTION	ME-MS81											
	Eu ppm	Ga ppm	Gd ppm	Hf ppm	Ho ppm	La ppm	Lu ppm	Mo ppm	Nb ppm	Nd ppm	Ni ppm	Pb ppm
SP 26840	8.99	20.1	57.4	90.3	10	367	4.76	4	193.5	371	66	36
SP 26841	9.19	19.6	57.2	93.9	9.53	360	4.62	5	181	385	65	29
SP 26842	9.64	18.2	63.8	73.3	7.88	507	3.31	5	205	460	61	20
SP 26846	7.61	22.7	42.8	116	8.4	282	4.43	2	95.4	260	128	22
SP 27024	5.03	21.8	30.1	94.7	7.18	192	4.28	2	101	174	124	16
SP 27025	5.09	22.1	29.3	70.2	6.49	189	3.59	2	86.5	173	138	22
SP 27026	6.39	23.7	34.9	87.8	7.03	214	3.79	2	98.4	205	164	22
SP 27027	5.64	22.6	31.2	70.7	6.43	201	3.45	2	89.4	188.5	152	17
SP 27028	5.74	22.3	32.8	90.8	6.97	220	4	2	96.5	202	138	18
SP 27029	4.63	22.8	25.7	57.2	5.8	172.5	3.25	<2	81.4	154	142	16
SP 27032	6.81	23.3	36.6	97.7	6.88	236	3.96	<2	100.5	220	150	19
SP 27033	6.04	23.8	32.7	62.1	6.39	202	3.32	<2	90.1	188	148	18
SP 27372	6.41	22.8	34.4	78	6.62	204	3.52	2	91.2	199	149	19
SP 27373	6.26	23.6	32.5	66.4	6.36	201	3.28	<2	85.9	190.5	156	19
SP 27374	7.33	23.5	38.8	83.7	8.17	226	4.31	<2	82.6	215	146	20
SP 27375	7.42	23.3	40	97.5	8.04	257	4.44	<2	80.7	241	128	19
SP 27376	5.34	21.7	31.7	89.5	6.88	210	4.02	<2	93.6	192.5	131	18
SP 27378	11.5	20.7	66.5	76.4	10.3	449	5.38	8	93.4	493	73	21
SP 27379	7.68	23.5	42.6	93.7	8.34	265	4.39	2	96.1	253	138	23
SP 27380	6.83	23.9	36.7	82.8	7.46	224	3.9	<2	96.6	208	158	20
SP 27381	7.26	23.6	40.4	100.5	8.22	259	4.53	<2	89.4	240	136	20
SP 27382	6.35	24.2	34.5	83.6	6.93	218	3.67	<2	92.2	205	142	19
SP 27383	6.44	24	34.7	96.2	7.55	212	4.22	<2	93.2	196.5	139	19
SP 27384	6.3	23	35.4	108	7.28	227	4.22	<2	95.6	211	126	17
SP 27385	6.49	23.7	35.3	84.2	7.09	218	3.81	2	98.3	203	154	102
SP 27386	5.99	23.8	32.8	78.9	6.65	207	3.65	<2	93.5	190.5	148	26
SP 27387	7.1	23.9	37.1	95.1	7	258	3.84	<2	94.7	241	144	20
SP 27388	6.38	23.6	36.4	87.9	7.43	223	3.96	<2	99.1	210	144	21
SP 27389	5.92	23.6	31.1	74.3	6.48	197.5	3.43	<2	90	188	153	19
SP 27390	6.06	23.6	33.3	74.3	6.71	212	3.57	<2	96	198.5	152	18
SP 27391	5.84	23.1	32.1	76.1	6.66	191	3.45	<2	90.5	182.5	148	17
SP 27394	5.35	24.7	32.5	71.8	6.98	187	3.79	2	92.6	198	100	6
SP 27395	4.87	26.6	28.6	41	6.46	176.5	3.49	2	87.7	162	126	14
SP 27396	4.75	26.6	27.6	46.1	6.27	160	3.34	<2	79.9	154.5	120	14
SP 27397	4.73	24.6	28.8	39.5	5.68	166.5	2.89	<2	80.2	156	142	10
SP 27398	4.66	25.1	27.5	39.2	5.69	151	2.72	<2	80.3	147.5	136	14
SP 27399	4.88	22.8	31.3	66.4	6.26	181.5	3.32	<2	91	177	129	16
SP 27400	4.68	24.3	29.4	28.2	5.73	159	2.61	<2	75.8	151	140	16
SP 27401	7.8	27.1	46	101	8.29	264	3.87	2	102.5	247	137	29
SP 27402	4.99	24.2	32.6	73.4	6.6	190	3.39	<2	94.3	181.5	120	22
SP 27690	6.46	24.4	39.2	120	7.56	224	3.9	<2	100.5	219	199	17
SP 27691	6.37	24.1	37.5	105.5	7.02	211	3.6	<2	95.7	207	136	18
SP 27692	5.05	23.6	30	78.3	5.88	168	3.07	<2	91.3	162	170	29
SP 27693	5.29	25	31	67.7	5.69	184	2.84	3	86.7	172.5	188	17
SP 27696	5.43	22.5	33.1	94.2	6.42	179.5	3.48	2	96.7	174.5	225	14
SP 27697	5.63	23.4	34	111	6.8	192	3.76	<2	101.5	181	136	11
SP 27698	5.93	20.8	51.3	191.5	9.73	319	5.36	<2	93.4	301	38	14
SP 27699	3.67	17.6	21.9	80.6	5.14	132	3.1	15	69.9	123	106	9
	Analyses Completed by Bondar-Clegg 1988											
	Eu ppm (NAA)			Hf ppm (NAA)		La ppm (NAA)	Lu ppm (NAA)	Mo ppm (NAA)	Nb ppm (XRF)		Ni ppm (NAA)	
SP 26843	8	NA	NA	72	NA	367	<3.5	<6	71	NA	100	NA
SP 26844	6	NA	NA	107	NA	261	<3.8	<3	69	NA	140	NA
SP 26845	7	NA	NA	92	NA	255	<4.1	<7	100	NA	140	NA
SP 26847	5	NA	NA	58	NA	218	<2.9	<3	51	NA	170	NA

APPENDIX C
Table of Elemental Analyses of Heavy Mineral Concentrates
(continued)

SAMPLE DESCRIPTION	ANALYTICAL METHOD										
	Pr ppm	Rb ppm	Sm ppm	Sn ppm	Sr ppm	Ta ppm	Tb ppm	Th ppm	Tl ppm	Tm ppm	U ppm
SP 26840	99.8	9.8	68.8	62	187.5	19.6	8.24	104.5	<0.5	4.77	28.1
SP 26841	102	10.9	70.8	86	161.5	16.9	8.31	126	<0.5	4.65	30.7
SP 26842	127	13.1	80.6	57	166	19.3	8.26	129	<0.5	3.53	27.6
SP 26846	70.5	8	50.4	30	295	8.4	6.36	59	<0.5	4.29	17.25
SP 27024	47.5	4.6	32.5	24	247	9.1	4.78	39	<0.5	3.99	15.25
SP 27025	46	5.1	32.5	23	282	7.9	4.56	36.3	<0.5	3.51	12.15
SP 27026	54.2	5.8	39.9	29	318	8.8	5.48	41.5	<0.5	3.64	13.5
SP 27027	50.8	5.7	35.4	25	292	8.1	4.9	38.7	<0.5	3.38	12.35
SP 27028	54.1	5.6	37.4	28	295	8.8	5.14	40	<0.5	3.77	13.45
SP 27029	41.4	4.9	28.3	18	274	7.2	4.18	31.9	<0.5	3.15	10.15
SP 27032	58.4	5.5	41.2	19	302	9.3	5.47	46.1	<0.5	3.69	15.05
SP 27033	50.2	5.2	35.9	15	328	8	5.04	36.8	<0.5	3.24	11.4
SP 27372	51.8	5.9	38.1	14	315	8.3	5.18	40	<0.5	3.36	13.4
SP 27373	50.4	6.2	35.9	14	330	7.7	5.04	37.9	<0.5	3.25	11.95
SP 27374	56.6	6.4	42.6	24	351	7.2	6.08	42.3	<0.5	4.13	17.15
SP 27375	63.7	5.8	45.1	32	316	6.8	6.06	51.3	<0.5	4.18	16.55
SP 27376	52	4.6	36.3	52	260	9.4	5	42.5	<0.5	3.78	15.35
SP 27378	129	13.2	87.9	549	243	12.5	9.18	83	<0.5	5.2	20.1
SP 27379	66	8.8	48	62	310	9.8	6.56	51.1	<0.5	4.33	24.2
SP 27380	55.3	6.2	40.3	23	335	9	5.78	45.3	<0.5	3.83	14.65
SP 27381	64	6.1	45.6	25	323	7.5	6.23	48.8	<0.5	4.3	16.3
SP 27382	54.1	6	39.4	21	316	8.4	5.28	39.9	<0.5	3.5	13.35
SP 27383	51.9	6.2	38.1	16	318	8.1	5.59	41	<0.5	3.94	15
SP 27384	55.9	5.8	39.9	18	297	9.9	5.47	44.8	<0.5	3.91	16.4
SP 27385	54	5.8	38.9	179	318	9.2	5.42	42.2	<0.5	3.61	14.6
SP 27386	51.2	5.4	36.8	18	296	8.5	5.12	40.2	<0.5	3.53	13.05
SP 27387	63.8	5.7	45.4	18	313	8.4	5.49	49.9	<0.5	3.58	14.7
SP 27388	55.6	5.6	39.4	18	312	9.2	5.7	43.1	<0.5	3.83	16.1
SP 27389	49.5	5.2	36.2	21	300	7.9	4.91	36.9	<0.5	3.26	12.5
SP 27390	52.8	5.1	37.9	20	303	8.7	5.17	41.5	<0.5	3.46	13.35
SP 27391	48.5	5.5	35.1	20	294	8.1	5.1	36.9	<0.5	3.4	12.15
SP 27394	48.3	4.7	37.4	33	201	7.9	4.77	30.5	<0.5	3.61	11
SP 27395	40.8	4.6	30.1	20	310	7.2	4.48	28	<0.5	3.31	8.4
SP 27396	38.1	4.8	29	22	274	7	4.29	24.4	<0.5	3.21	8.4
SP 27397	39.2	5.7	30	16	290	6.8	4.19	25	<0.5	2.74	8.62
SP 27398	36.8	5.5	29.1	17	282	6.6	4.14	24.8	<0.5	2.72	8.56
SP 27399	43.6	5.4	33.7	24	274	7.6	4.69	32	<0.5	3.26	10.4
SP 27400	37.6	5.5	29.7	16	296	6.5	4.29	28.1	<0.5	2.64	7.74
SP 27401	61.4	8	47.9	23	370	8.1	6.68	46.7	<0.5	3.82	15.7
SP 27402	44.5	5.1	34.2	20	276	8	4.67	30.9	<0.5	3.24	13.45
SP 27690	53.3	6.2	42.4	27	290	7.9	5.64	39.1	<0.5	3.71	17.4
SP 27691	50.9	6.2	40.5	21	293	7.3	5.19	38.3	<0.5	3.37	13.65
SP 27692	40.7	6.4	31.3	30	276	7.3	4.42	31.6	<0.5	2.97	11.45
SP 27693	42.5	5.3	32.9	19	301	7.1	4.41	31.2	<0.5	2.78	10.15
SP 27696	43.2	6.8	35	30	279	8.1	4.87	36.4	<0.5	3.14	12.3
SP 27697	45.1	5.1	35.5	18	269	8.6	5.05	34.4	<0.5	3.4	13.45
SP 27698	76.2	7.7	55.3	88	229	8	7.21	79.6	<0.5	4.84	22.8
SP 27699	30.9	10.6	23.3	20	199.5	6.1	3.35	23.8	<0.5	2.73	9.66
	Analyses Completed by Bondar-Clegg 1988										
		Rb ppm (NAA)	Sm ppm (NAA)	Sn ppm (NAA)		Ta ppm (NAA)	Tb ppm (NAA)	Th ppm (NAA)			U ppm (NAA)
SP 26843	NA	<33	61.3	30	NA	10	7.5	52.4	NA	NA	12
SP 26844	NA	<14	45.3	16	NA	10	7.6	49	NA	NA	16
SP 26845	NA	<38	44.5	9	NA	8.7	7	47.1	NA	NA	14
SP 26847	NA	<14	39.1	nss	NA	7.9	6.8	38	NA	NA	12

APPENDIX CTable of Elemental Analyses of Heavy Mineral Concentrates
(continued)**ANALYTICAL METHOD**

SAMPLE DESCRIPTION	V	W	Y	Yb	Zn	Zr
	ppm	ppm	ppm	ppm	ppm	ppm
SP 26840	503	14	272	30.2	596	3,440
SP 26841	531	24	259	29.4	288	3,670
SP 26842	522	12	212	21.8	234	2,800
SP 26846	301	16	227	27.1	205	4,350
SP 27024	256	14	196	25.4	192	3,600
SP 27025	283	12	178	22.1	180	2,660
SP 27026	345	8	195	23.4	184	3,370
SP 27027	309	9	176	21.8	180	2,710
SP 27028	278	7	193.5	24.6	188	3,580
SP 27029	280	6	157.5	20.1	172	2,230
SP 27032	302	8	188	23.9	183	3,750
SP 27033	344	7	173	21.3	172	2,350
SP 27372	328	6	181.5	21.8	170	2,980
SP 27373	325	7	173.5	20.8	172	2,590
SP 27374	337	45	223	27.2	175	3,400
SP 27375	304	12	221	26.5	175	3,900
SP 27376	265	16	193	24.4	180	3,400
SP 27378	479	58	295	34.5	215	2,880
SP 27379	330	22	231	27.5	197	3,540
SP 27380	341	11	202	24.1	180	3,080
SP 27381	341	7	230	27.8	185	4,000
SP 27382	327	9	197	22.9	182	3,280
SP 27383	325	7	210	25.7	182	3,820
SP 27384	317	17	205	25.8	190	4,210
SP 27385	351	100	196	23.9	193	3,260
SP 27386	320	13	186.5	22.1	184	3,050
SP 27387	322	11	197.5	23.2	182	3,740
SP 27388	322	7	202	24.7	182	3,330
SP 27389	335	15	177.5	21.3	176	2,900
SP 27390	323	9	186	22.1	177	2,930
SP 27391	317	8	186	22.2	178	2,980
SP 27394	255	9	195.5	26.8	217	2,820
SP 27395	304	12	183.5	24	182	1,515
SP 27396	259	16	174	23.6	190	1,645
SP 27397	333	7	159	19.8	166	1,435
SP 27398	306	12	161	20.3	168	1,445
SP 27399	322	11	181	24.1	184	2,470
SP 27400	344	8	157.5	19.6	165	993
SP 27401	364	17	236	27.9	191	3,560
SP 27402	297	11	188	24	194	2,670
SP 27690	297	10	212	27.9	182	4,410
SP 27691	317	9	196.5	25.9	177	3,900
SP 27692	308	11	163	20.9	180	2,820
SP 27693	310	7	162	19.65	172	2,450
SP 27696	296	6	180	24	178	3,470
SP 27697	281	6	189.5	25.4	180	4,000
SP 27698	299	58	271	37.1	158	7,210
SP 27699	144	6	143.5	20.4	161	2,940
		W	Y	Yb	Zn	Zr
		ppm	ppm	ppm	ppm	ppm
		(NAA)	(XRF)	(NAA)	(NAA)	(NAA)
SP 26843	NA	<70	nss	20	590	3,800
SP 26844	NA	<40	189	23	210	5,300
SP 26845	NA	<81	175	18	240	4,500
SP 26847	NA	<38	nss	17	270	2,400

APPENDIX D
Major Oxide Analyses of Heavy Mineral Concentrates
(continued)

Table B. Analyses by X-ray Fluorescence

SAMPLE NUMBER	SiO₂ %	Al₂O₃ %	Fe₂O₃ %	CaO %	MgO %	Na₂O %	K₂O %	Cr₂O₃ %	TiO₂ %	MnO %	P₂O₅ %	SrO %	BaO %
SP 26840	37.10	10.85	21.40	12.90	6.03	0.34	0.27	0.37	9.31	0.88	0.23	0.02	0.03
SP 26841	35.80	9.66	19.90	13.50	5.87	0.36	0.26	0.22	8.47	0.84	0.30	0.02	0.03
SP 26842	39.50	7.17	18.95	17.70	7.20	0.44	0.29	0.15	7.44	0.70	0.47	0.02	0.02
SP 27025	37.10	13.20	18.60	13.95	7.48	0.35	0.13	0.69	6.86	0.72	0.18	0.03	0.01
SP 27378	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS
SP 27379	33.50	12.60	18.65	11.30	6.86	0.32	0.20	0.35	8.52	0.57	0.49	0.04	0.02