Processes of Heavy Mineral Concentration on the High Energy Coast of North-Eastern Queen Charlotte Islands, British Columbia, Canada.

by

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ABSTRACT

Beaches on the eastern coasts of Queen Charlotte Islands are dominated by black sand deposits. This study is located within the intertidal zone between latitude $54^0$06.56' and $54^0$07.62'N. Accretion and erosion measurements, and wind speed and direction data were analyzed daily during the study period. A total of 51 samples for longshore (Ls), cross-shore (Cs), depth within sediments (Ds) and relict sediment samples (Rs) were collected and analyzed for heavy mineral content, mean grain sizes and degrees of sorting. Identification of individual heavy minerals were also performed on selected heavy mineral fractions.

The heavy minerals within mature textured environments showed a general increase in bulk concentrations from fore-shore to back-shore, alongshore from south to north and with depth. The samples mean grain sizes consequently decreased for both longshore and cross-shore transects but increased with depth. Heavy mineral concentrations are enhanced within zones of accentuated erosion. Erosion was accentuated as a result of increased wave energy due to wave refraction, direction of approach of swell waves to the coast, beach profile and shoreline configuration.

The heavy mineral fraction consists predominantly of the opaques (including magnetite), amphiboles, garnet and epidote. The concentrations of magnetite, non-magnetic opaques and garnet showed similar trends as the bulk heavy minerals while the concentrations of ampiboles and epidote increased from back-shore to fore-shore relative to the bulk heavy mineral content. The sorting processes were more effective in separating magnetite, non-magnetic opaques and garnet from light minerals (quartz and feldspars) and least effective in epidote and amphiboles. Among the four processes of placer formation (Suspension, shear, entrainment and transport sortings), entrainment and transport are identified as the most significant processes resulting to these placer deposits. The formation of these placer deposits was most influenced by the densities and grain sizes of individual minerals.

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I. Introduction.

Heavy minerals are chemically stable and phyically durable grains of high specific gravity (> 3.0 g/cm^3). Exploration and mining of certain of these minerals had been largely limited to the terrestrial environment due their economic value and easy accessibility. Due to ever-growing demands on land use and depletion of some of these terrestrial mineral deposits, offshore minerals are gaining importance. Consequently research on the mineral potential of the continental shelf, for placers has grown because they are easier to mine, require less capital expenditure on research and development, and have lower risk as compared to deep sea mineral research and mining.

Placer deposits form by mechanical concentration of heavy minerals, subsequent to weathering, transport and deposition, given conducive conditions will form placer deposits. Concentration on beaches due to wave and longshore currents have formed economic deposits which have and are now being exploited in many countries. For example, beaches and nearshore areas of western coasts of southern Africa are mined for diamonds; Indonesia, Thailand and Burma are major producers of offshore tin; and gold is mined in Nome, Alaska (Sutherland, in Press).

The exploration of some of these deposits has involved a lot of money, time and energy while others were discovered out of sheer luck. Many placer deposits are yet to be discovered because the processes of formation are not yet well understood. Recently research has been undertaken to determine the processes of concentration by using flumes, and field research focused particularly on Oregon beaches (Komar and Wang, 1984, Li and Komar, 1992, Lupke, 1980). These studies determined four processes responsible for heavy mineral concentrations on the beaches: suspension, shear, entrainment and transport sorting. It is, therefore, important to examine the significance of these models in other areas.

1. Objectives

This study looks into the applicability of these models to the eastern Queen Charlotte Islands, focusing on heavy mineral deposits of Graham Island (Fig. 1). It discusses the surficial changes in mineralogy and sediment texture alongshore and across-shore, and with depth within the intertidal zone of a 2.1 km stretch of coast North of Cape Fife (Fig. 2). The distribution is then correlated with the diurnal measurement of net accretion and erosion, geomorphology and direction of approach of swell waves. This knowledge will help in the siting and subsequent possible exploitation of these transient placer deposits. Knowledge of the sites of concentrations could be extrapolated to the understanding of alluvial and heavy mineral deposits in other marine settings.

2. Continental Margin Placer Distributions.

Four factors are responsible for continental margin placer formation and distribution including (1) Sources for the minerals, (2) Transport mechanism, (3) concentration processes and (4) preservation.

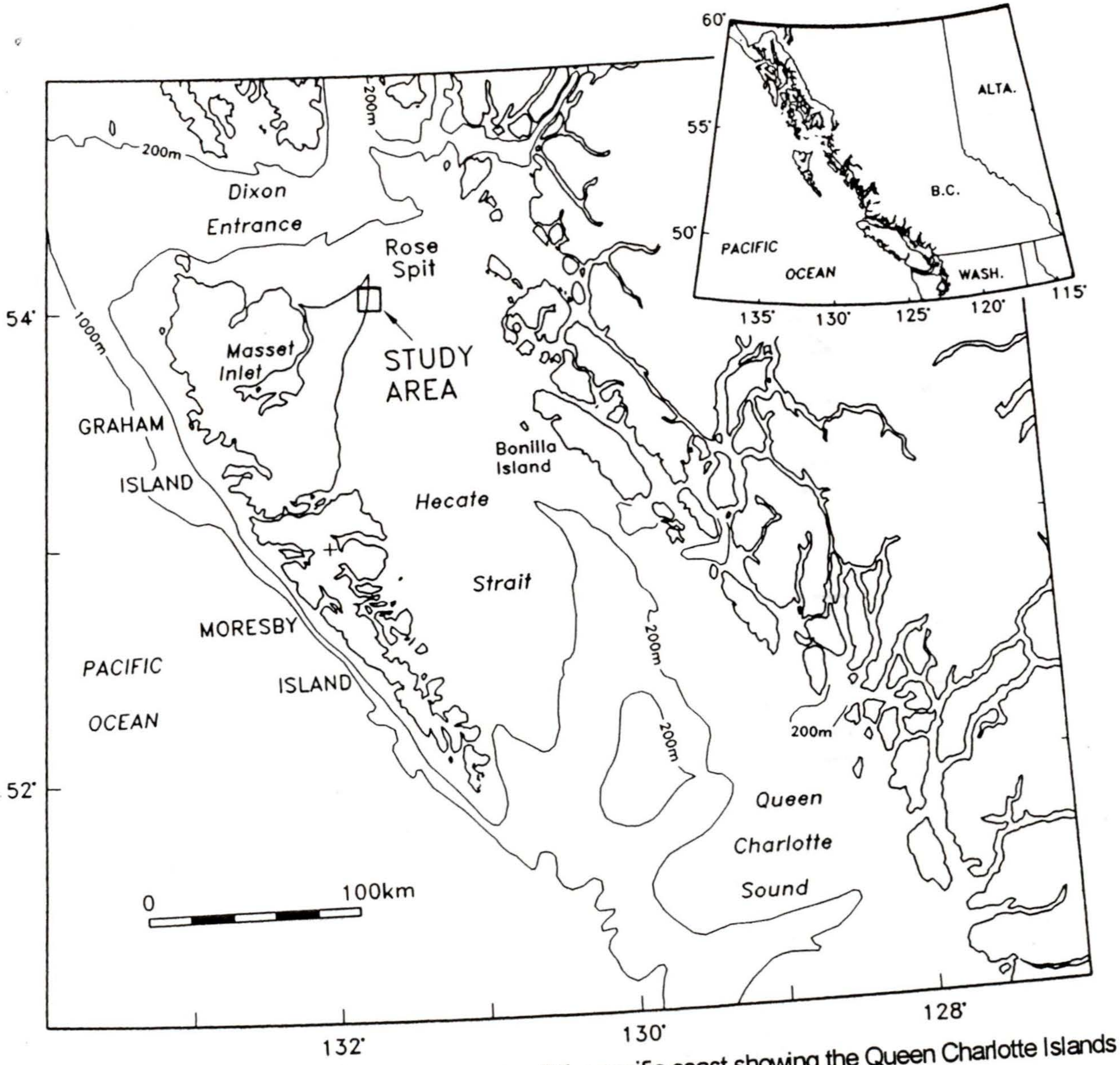

Fig. 1. The nothem Canadian continental margin off the pacific coast showing the Queen Charlotte Islands and location of the study area.

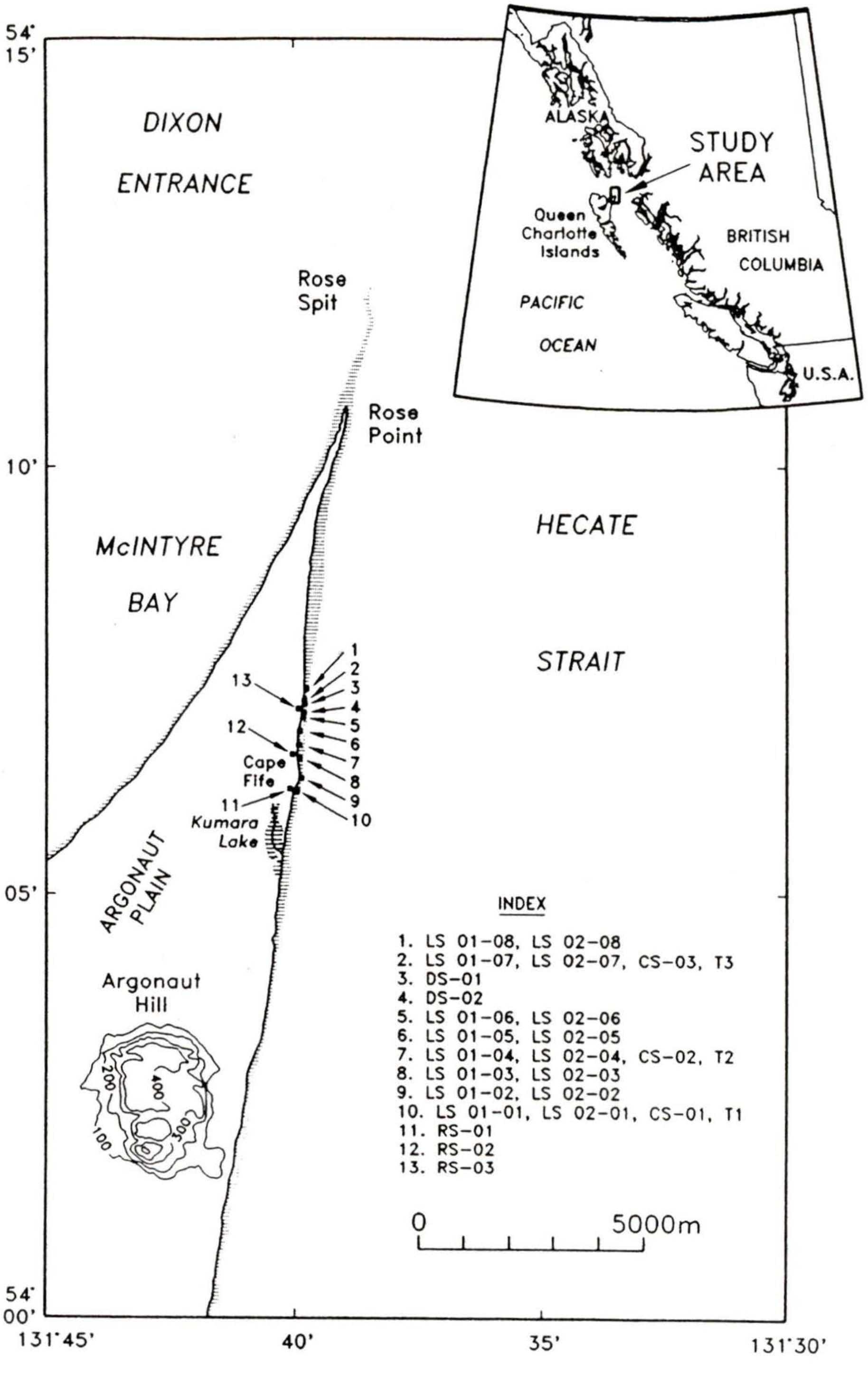

Fig. 2. The study site along the eastern coast of Graham Island showing sampling locations. T=Accretion/Erosion transects, Ls=Longshore transects, Cs=Cross-shore transects, Ds=Depth sampling, Rs=Relict samples

2.1 Sources

Sources of marine placer minerals may be primary and/or secondary, and could lie within the continental margin (exposed underwater within the could lie within the continental margin (exposed underwater within the continental shelf or crop out at the shoreline) or lie well inland from the margin (Clifton and Luepke, 1987). Primary sources are basically the rocks where the minerals crystallized. Within these rocks, the heavy minerals occur predominantly as disseminated grains but may also occur on a mineable scale. Secondary sources include sedimentary deposits that bear heavy minerals. The source rocks for the most common heavy minerals are outlined in Table.1 below.

Table 1: Selected heavy minerals and their source rocks after (Kunzedoff, 1986).

Rocks	Heavy minerals present
Granites, grano-diorites, rhyolites (acid rocks)	Magnetite, monazite, tourmaline, zircon, cassiterite, hornblende.
Basalts, dolerites, gabbros (basic rocks)	Chromite, ilmenite, leucoxene, magnetite, rutile, zircon, hornblende
Metamorphic rocks	Garnet, leucoxene, magnetite, tourmaline, epidote
Pegmatites	Monazite, tourmaline, zircon
Hydrothermal veins	Cassiterite, pyrite, wolframite, gold, platinum.

2.2 Transport

Due to the physical and/or chemical resistance of heavy minerals, and because of their different hydraulic properties from the light minerals (sp. gr. < 3.0 g/cm^3), weathering and erosion of source rocks and subsequent transport concentrate heavy minerals into potential placer deposits. Table 2 shows heavy minerals of possible economic interest classified according to their stability. Placer minerals can be classified into three groups according to their physical and hydraulic characteristics which are influenced by their specific gravity (US Congress, 1987):

i) heavier heavy minerals (sp. gr. > 6.0 g/cm^3)
ii) lighter heavy minerals (sp. gr. 4.2 - 6.0 g/cm^3)
iii) precious minerals (sp. gr. 3.0 - 4.1 g/cm^3)

For distant sources, mechanisms are required to transport the minerals to the coastal zone. Four mechanisms of transport have so far been established:

i) fluvial processes
ii) glaciers
iii) landslides
iv) wind

Rivers are the most widespread method by which minerals are delivered to the coast. Their competence depends mainly on the stream gradient and volume of discharge. Because of the high specific gravity of the heavier heavy minerals, they are difficult to entrain and are therefore deposited and concentrated mainly within stream channels near their source rocks except where the source is close to the coast. Lighter heavies and light minerals tend to concentrate within the marine environment because they are more readily transported over greater distances.

Despite high-grade placer deposits within some formerly glaciated areas (e.g. Cassiterite-bearing "morainic debris" in Bolivia (Sutherland, 1985)), the glacial environments are quite unfavourable to the development of placers. This is due to its tendency to disperse minerals rather than to concentrate them. Glacial processes and landslides introduce heavy minerals, including coarse and heavier heavy mineral grains to the continental shelf during glacio-eustatic lowstands of the sea or by ice-rafting (Clifton and Luepke, 1987). Wind is also an important process in some arid and semi-arid coastal settings. The absolute amount of heavy minerals supplied to the coast through these different sources and transport modes are of less significance to the resulting beach placer (Sutherland, In Press). This is due to various factors that influence heavy mineral concentrations which are described below.

2.3 Concentration Processes on the beach

Beaches have been recognized as important sinks (depositional environment) for heavy minerals (Clifton and Luepke, 1987). These heavy minerals must be concentrated into a placer deposit before it arouses economic interest. Four theories have been suggested that could explain the processes through which heavy minerals are concentrated:

TABLE 2. Heavy minerals of possible economic interest classified by stability. Specific gravity in parentheses (taken from Clifton and Luepke, 1987).

STABLE	**MODERATELY STABLE**
Epidote (3.38 - 3.49)	Andalusite (3.2)
Anatase (3.9)	Ilmenite (4.5 - 5.0)
Barite (4.5)	Marcasite (4.8 - 4.9)
Brookite (3.9 - 4.1)	Pyrolusite (4.7 - 4.8)
Cassiterite (6.8 - 7.1)	
Chromite (4.3 - 4.6)	
Columbite (5.3 - 7.3)	
Corundum (4.0 - 4.1)	
Diamond (3.5)	
Fluorite (3.2)	
Garnet (3.5 - 4.3)	
Gold (15.0 - 19.3)	
Kyanite (3.5 - 3.7)	
Leucoxene (3.5 - 4.5)	
Magnetite (5.2 - 6.5)	
Monazite (4.9 - 5.3)	
Platinum group (14 - 19)	
Scheelite (5.9 - 6.1)	**UNSTABLE**
Rutile (4.2 - 4.3)	
Sillimanite (3.2)	Apatite (3.2)
Spinel (3.5 - 4.0)	Pyrite (5.0 - 5.1)
Staurolite (3.6 - 3.7)	Pyrrhotite (4.6 - 4.7)
Topaz (3.4 - 3.6)	
Tourmaline (3.0 - 3.3)	
Wolframite (7.0 -7.5)	
Xenotime (4.5 - 4.6)	
Zircon (4.2 - 4.9)	

1) suspension sorting
2) shear sorting
3) entrainment sorting
4) transport sorting

2.3.1 Suspension sorting

Suspension sorting is the fractionation of mineral grains of different settling velocities into different levels off the bed in a turbulent, open-channel flow, and their subsequent separation into different deposits (Slingerland, 1984). Stokes determined the relationship between grain density (ρ'), grain size (D), and the terminal settling velocity (V_{lam}) for mineral grain in a laminar setting:

$$V_{lam} = C_D \{(\rho' - \rho) g D^2 / \mu\} \quad ....(1)$$

Where C_D is the coefficient of drag, ρ the fluid density and μ the fluid viscosity for sediment up to 100 μm. Rubey (1933) hypothesized that various minerals would be transported and deposited according to their settling velocities. Subsequent studies, however, have found that light and heavy minerals are not always in settling equivalence (Slingerland, 1984; Li and Komar, 1992 and Peterson et al., 1986).

Komar and Wang (1984), Li and Komar (1992) described fractionation of mineral grains in the nearshore, with grains of high and near equivalence settling on the beach and low settling velocity grains carried offshore. The near equivalence settling velocities would thereby produce an inverse relationship between grain size and density according to Stoke's model. The development of beach placer, therefore, depend predominantly on the relative abundance of hydraulically equivalent sizes of heavy minerals that reside on the beach relative to their light mineral counterparts (Sutherland, In Press). Li and Komar (1992a) observed an increase in settling velocities away from Columbia River mouth for both the light and heavy minerals to about 5 to 10 km on Long Beach Peninsula. Beyond this point there is a decrease in settling velocities. Komar and Wang (1984) also noted a slight increase in settling velocities from backshore to foreshore. Since minerals of higher settling velocities should deposit close to the river mouth, Li and Komar (1992a) concluded that sorting by differential settling was not the dominant process of concentration close to the river. Li and Komar (1992a) also found that the hydraulic ratio, which is the weight percent ratio of heavy to light mineral of equivalent settling velocities, decreases with transport distance. The rate of decrease is proportional to the effective difference in density between the heavy and the light minerals. They also performed a flume experiment to study selective sorting in bedload transport using settling equivalent samples. The result showed an increase in concentration of the heavies relative to the original mixture and a decrease in the transport direction.

Samples from Assateague Beach, Virginia, determined that the settling velocity ratios of light to heavy minerals for both swash advance ("Ins") and retreat ("Outs") at the plunge points, plot close to the equal line with no difference in heavy mineral concentration (Slingerland, 1984). In the upper swash, the "Ins" plot close to the equal line and are less heavy mineral rich than the "Outs" which plot away from the equal line.

These observations and the limited range of particle settling velocities in the nearshore eliminate differential settling as a key process in heavy mineral concentration. Ruling out differential grain settling rates other processes must remain to effect heavy mineral concentration.

2.3.2 Shear Sorting

Shear sorting is the separation of grains into different horizons within a concentrated granular dispersion due to dispersive pressure acting on grains in either subaqueous or subaerial flow (Slingerland, 1984 and Bagnold, 1954). Bagnold (1954), hypothesized that dispersive pressure in a grain flow would be higher on larger grains than smaller ones at any given horizon resulting to a migration of larger grains towards the surface. This mechanism enables grains of equivalent dispersive pressure to reside together at a single horizon within an inertial grain flow. Sallenger (1979) used Bagnold's hypothesis to derive a dispersive equivalent relationship for a single horizon assuming Bagnold's hypothesis to be correct for grains of mixed sizes and density:

$$D_H \approx D_L (\rho_L / \rho_H)^{1/2} \quad \text{.........} \ (2)$$

Where D_H is the diameter of a heavy grain of density ρ_H which will reside with a light mineral of diameter D_L and Density ρ_L . Heavy mineral grains would therefore be smaller than associated light grains.

Sallenger (1979) did flume and beach foreshore sampling by sequentially applying pieces of adhesive tape to the sediment surface, thereby obtaining samples approximately one grain size. He then analyzed the grain sizes and concentration of heavy minerals of S.G. < 2.9 g/cm^3 and 3.1-3.3 g/cm^3 of each sample. He also analyzed the concentration of the entire heavy mineral suite (S.G. > 2.9 g/cm^3) separated using heavy liquid. The mean grain size for each fraction plotted against its relative vertical position in the deposit yielded an inverse grading for both heavy and light fractions, and at any given horizon, the heavy minerals are considerably finer than the associated light grains. The percent by weight of all heavy minerals (S.G. >2.9 g/cm^3) and the 3.1 - 3.3 g/cm^3 fraction were plotted versus relative depth. Heavy minerals generally increased with depth within a lamination.

Peterson et al. (1986) noted an inverse grading of the light minerals and an increase in heavy mineral concentration from the surface of Otter Rock, Oregon, beach-face laminations which may have formed due to grain shear. Komar and Wang (1984) analyzed the dispersive equivalence on the Oregon coast which they noted to be out of equivalence.

2.3.3 Entrainment Sorting

Entrainment sorting is the segregation of grains due to differences in their critical static force, the force required to initiate movement. This mode of sorting has been considered by many as one of the key processes in heavy mineral concentration (Komar and Wang, 1984; Slingerland, 1984; Li and Komar, 1992a; Day and Fletcher, 1991; Li and Komar, 1992b; Komar and Li, 1984 and Barrie et al., 1988). A grain movement is initiated when the moment of fluid-drag force (shear stress) exceeds the moment of a grain's weight (Li and Komar, 1992). An examination of these two opposing forces within a sand size population consisting of various grain sizes and densities yielded the relationship below (Komar and Wang, 1984):

$$\tau_t = k\,(\rho_s - \rho)\,gD\,\tan\Phi \quad \ldots\ldots\ldots (3)$$

The angle Φ in equation (3) is defined as the angle between the vertical of a grain and the line which connects its center to the pivot point with neighbouring grain (Komar and Wang, 1984). For non-uniform mixtures, the Φ value depends on a grain's size relative to the surrounding roughness as expressed by the empirical relationship below (Komar and Wang, 1984):

$$\Phi = 61.5\,(D/K)^{-0.3} \quad \ldots\ldots\ldots\ldots (4)$$

The threshold flow stress (τ_t) necessary for grain entrainment therefore depends on the following variables: grain diameter (D), grain density (ρ_s) and bottom roughness (K) (Slingerland, 1984; Komar and Wang, 1984 and Li and Komar, 1992). Li and Komar's (1992) and Slingerland's (1984) flume experiments established that in sediments of near equal grain sizes, the smaller grains which are nestled between the larger grains are more difficult to entrain than their counterparts due to large reactive angles through which they have to be rolled, and also because they project lower into the velocity profile than the larger grains. The critical shear stress falls to a minimum for grains slightly larger than bed roughness (K) and then rises again for grains much larger. Here instead of entrainment, the finer grains get plucked through the vortices of the larger grains. As the ratio of grain size (D) to bed roughness (K) decreases, threshold stress (τ_t) increases as seen from equation (3) and (4) (Li and Komar, 1992). This is explained by Slingerland (1984), to be due to pore pressure reduction with increase in roughness and "hiding factor" of smaller grains between the crevices of larger grains. Since density and size of beach minerals are inversely related, the high density minerals will therefore require higher entrainment stress than low density mineral grains due to their relatively finer sizes, and consequently form a lag deposit. Komar and Wang (1984) computed threshold stresses (τ_t) for the principal minerals of Oregon coast for a range of grain sizes. They determined an increase in threshold stress required to entrain finer grains within individual mineral species and for higher density minerals.

2.3.4 Transport Sorting

Transport sorting is the fractionation of mineral grains due to their differential transport rates under a given flow stress (Slingerland, 1984). This sorting is considered to be the principal mode of placer formation since it includes entrainment and suspension sorting (Slingerland, 1984). Day and Fletcher (1991), Komar and Wang (1984), Slingerland (1984) and Li and Komar (1992) used Einstein's bedload formula, due to its consideration of the probability of particle movement, to determine the degree of transport sorting. They noted the influence of bed roughness and flow stress (frictional velocity) to transport rates and settling velocities.

Li and Komar (1992) and Slingerland (1984) noted an increase in transport rates of mineral grains as the flow stress increased. The lag of heavy minerals behind the lights decreased, with an increase in flow stress for each level of roughness, and a decrease in bed roughness for each flow stress. This is due to consequent decrease in transport rate ratio of light to heavy minerals. Komar and Wang (1984) observed a similar influence of flow stress on minerals of the heavy fraction. The transport rates of light mineral grains are relatively faster than denser grains and their ratios, light to heavy grains, are proportional to the difference in their densities. Slingerland (1984) documented a decrease of the settling velocity ratios of magnetite to quartz in transport with increasing flow stress for any roughness and a decrease followed by an increase with increasing roughness for any flow stress.

Li and Komar (1992) analyzed changes in the concentration factor (CF) (percentage ratio of each mineral fraction in the placer to its lowest percentage in a transect (longshore or cross-shore)), to transportation rates. Their study showed a progressive decrease in concentration factor with increasing transportation rate. CF determines the degree to which a mineral is concentrated in the placer. The light minerals which have the highest transport rates correspond to the lowest CF value.

Marine heavy minerals accumulating under the influence of contemporary processes described above form modern deposits (Beach placer deposits) (Solomon et al., 1990 and Clifton and Luepke, 1987). Heavy mineral enrichment on the beach-face is more effective during storms. During these periods, these concentrations may be transported from the beach by high onshore winds during low tide and deposited in eolian landforms above high tide (Force, 1991).

2.4 Preservation

Placer deposits formed and preserved under oceanographic environments different from their present marine setting (e.g. emergent or submergent deposits) form relict placer deposits (Clifton and Luepke, 1987 and Solomon et al., 1990). There are two major factors that influence the distribution and preservation of these placers: (1) Fluctuation of sea level, and (2) Tectonic forces.

2.4.1 Fluctuation of Sea level

Sea level plays a great role in heavy mineral preservation. As sea level falls, rivers extend their channels and cut down to lower base level . During this period, the nearshore alluvial sites are flushed of their sediments that had accumulated in them during the preceding periods of high relative sea levels. The hydraulic conditions required for offshore heavy mineral concentration fall within a critical water depth, (i.e. constructive zone for Queen Charlotte Sound lies between 100 and 140m depth for coarse to fine sand respectively (Barrie et al., 1988)). Slow sea level changes shift this point back and forth. A slow regression with a subsequent rapid transgression favours the preservation of placers formed during regression, as sediment reworking and distribution are minimal (Clifton and Luepke, 1987 and Solomon et al., 1990). For example the glacial and siliciclastic Quaternary sediments deposited on the Cook Bank, north of Vancouver Island during a sea level low (at least 95m) at 10.5 k.a. (thousand years ago) were concentrated by the paleo-hydraulic conditions. During the rapid sea level rise in early Holocene, these deposits were preserved (Barrie, 1990). In Mozambique, an extensive deposit of ilmenite associated with zircon and rutile had developed along a submerged beach ridge between 50 and 60 m (Long and Amos, 1992). Heavy minerals formed within streams crossing an exposed shelf during a sea level lowstand may also be preserved during subsequent transgression. Slow sea level change , rise or fall, increases the probability of Modern autochthonous placer formation due to extensive sediment reworking.

2.4.2 Tectonic forces.

In tectonically passive margins which have existed for extended periods of time, (e.g. African coasts, eastern margin of North America), the potential for relict placers are high and may exist throughout its length as opposed to the active margins where the paleogeography can change markedly over a relatively short interval of time (e.g. western margin of Canada). In addition, local tectonics such as isostatic rebound in glaciated, terrains may form emergent relict placers on high latitude shelves.

Where tectonic uplift is nearly of the same rate as the sea level rise, for example the Oregon coast, the beach environment remains relatively stable in position and allows for prolonged reworking of the sediments (Komar and Wang, 1984). Modern deposits are, therefore, more enriched in heavy minerals relative to margins with marked difference in the rate of sea level rise and tectonic uplift.

Before implementing a survey, basic information about the prospect area is required. As a first step in assessing placer minerals, criteria were developed and listed according to their relative importance as outlined in Table 3 (Hale and McLaren, 1984; U.S. Congress, 1987).

3) Regional Setting

The study area is located on the eastern coast of Graham Island, the largest of the Queen Charlotte Island group (approx. 2500 sq. miles), within the intertidal zone between latitude $54^0$06.56'N and $54^0$07.62'N (Fig. 2). It is separated from the low lying Argonaut Plain to the west by sand dunes (north of the study area), which are oriented in a northwest direction and are up to 10m in relief (Harper, 1980), and by the unconsolidated Pleistocene bluff to the south. Immediately south of Cape Fife lies Kumara Lake. This Lake is now believed to have extended up to the northern part of Cape Fife (Conway, pers. comm., 1994). Graham Island is separated from the mainland Coastal mountains by Hecate Strait which is 300 m deep and 130 km wide at its southern end, and 20 to 80 m deep and 60 km wide at the north (Crawford et al., 1989). A shallow (30 m) bank, Dogfish Bank, extends over 50 km into Hecate Strait from the eastern shore of Graham Island (Fig. 3).

The sources of sediments to the beach are the large unconsolidated Pleistocene bluffs to the south of the study area and the raised dunes and beach material of the study area (Harper, 1980). There are very few minor rivers draining to the eastern shore, this contributing very little sediment from inland. The coastal bluffs and the dunes are significantly eroded during storms. During the study period, 1.5 m of erosion was measured at the Cape Fife site in a 12 hour period (southernmost portion of the study area). The absolute amount of

Table 3 Criteria important for a reconnaissance survey of the probable potential of a placer deposit (From Hale and McLaren, 1984).
+++ extremely favourable ++ very favourable + favourable

Criterion		Implication	
1.	Presence in marine sediments of interest	+++	Direct evidence
2.	Mineral presence in onland unconsolidated deposits close to the shoreline	+++	Alluvial sediments in seaward flowing watershed in glacial deposit
3.	Presence of drowned river channels and strandlines offshore of coastal host rocks	++	
4.	Occurrence in source rock close to shore	++ +	With seaward flowing watershed No watershed but previously glaciated with offshore ice movements
5.	Presence of unconsolidated sediments seaward of onland host rocks	+	

6. Evidence of preglacial regoliths and mature weathering of bedrock	+	Liberation of resistant heavy minerals from bedrock for subsequent transportation and concentration
7. Sea-level fluctuations:		
(i) Transgression	+	For preservation of relict fluvial placers now submerged.
(ii) Stable sea level	+	For formation of a contemporary beach placer.
(iii) Regression	+	For formation of contemporary river mouth placer.
8. High-energy marine	+	For formation of a contemporary placer
	-	For preservation of a relict placer
9. Previously glaciated	-	Glacial ice tends to scour out, disseminate or bury the heavy minerals.
	+	In some circumstances glaciation liberates heavy minerals and transport them to considerable distance to the offshore.
10. Ice cover	-	Generally the longer the ice-free period the greater potential to generate a marine placer.
11. Circulation pattern	+	
12. Climate	+	Important to the maturity of the mineral assemblage.

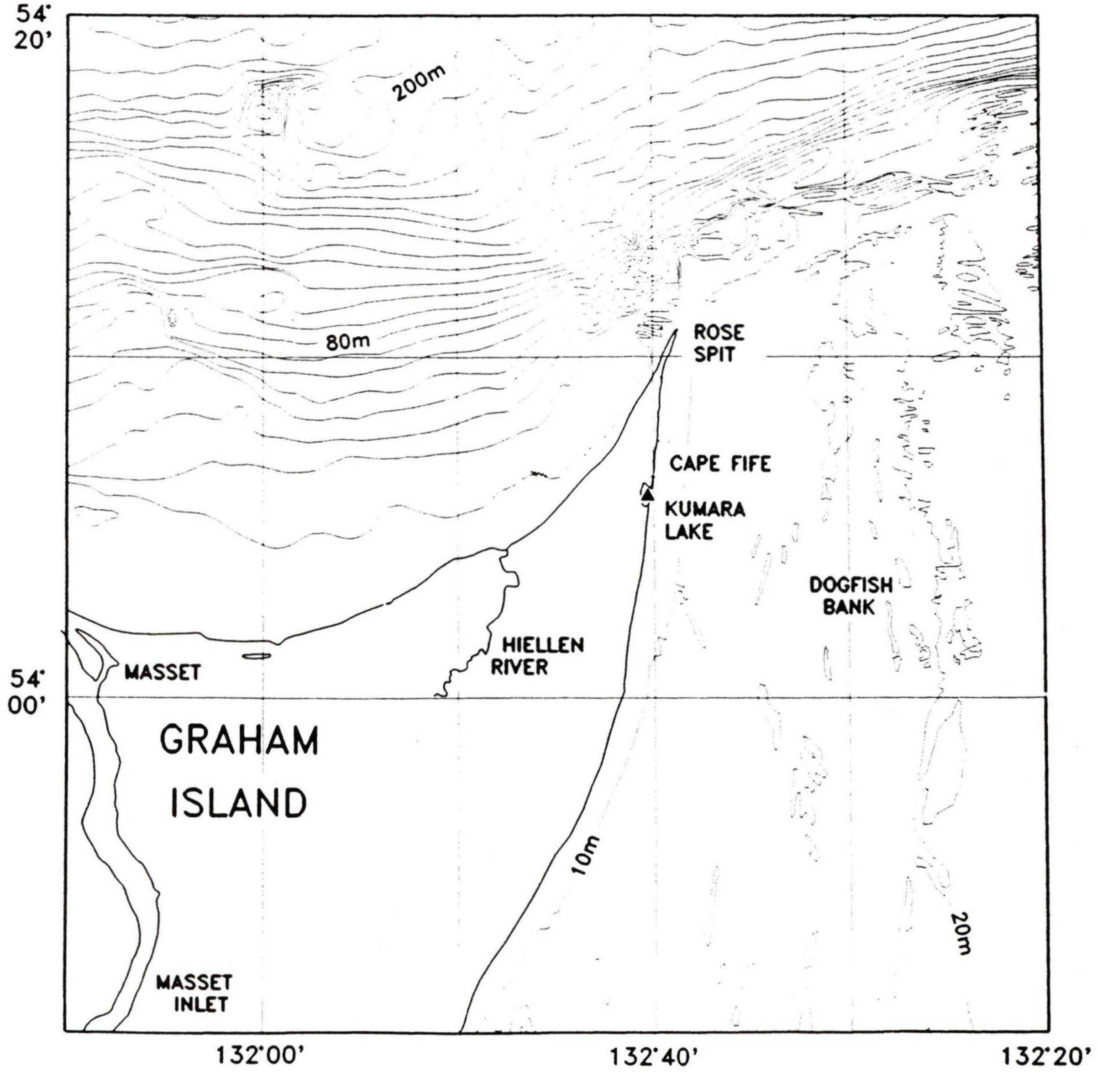

Fig. 3. The bathymetry of the eastern coast of Graham Island showing Dogfish Bank.

heavy minerals supplied to the coast through these different sources and transport modes is of little significance to the resulting beach placer (Sutherland, In Press). This is due to the various factors that influence heavy mineral concentrations which are described below. The eroded sediments are consequently dispersed by the strong wind patterns and the associated local waves generated (Harper, 1980). Oblique off-shore bars are common.

The Island's climate is generally mild, with only minor extreme weather changes. The central and eastern parts receive considerable rainfall, about 15cm annually (Mandy, 1934). In early summer, the weather is frequently cloudy but is interspersed with many sunny days (Mandy, 1934). The driest period of the year is around August, and fall months are the wettest. Snow does not lie on the ground for any length of time in the winter (Mandy, 1934).

4) Previous Work

Considerable and diverse research has been conducted on the Queen Charlotte Islands and its neighbouring continental shelf. The work most relevant to this study is related to the bedrock geology of Graham Island and the Quaternary geology of Queen Charlotte Islands.

Blaise et al. (1990) examined samples from Cape Ball on eastern and Mary Point on northern Graham Island to study the extent and time of maximum Late Wisconsinan glaciation on the western coast of Canada. The data indicate a glacial peak between 21 and 16 ka, a period during which the Cordilleran ice lobes coalesced with the valley and piedmont glaciers from western Queen

Charlotte mountains. To determine the environments of deposition during deglaciation on Dogfish Bank within north-central shelf of Hecate Strait, three core sites were selected within various seismographic units for vibrocoring aboard CSS John P. Tully in June, 1991. Barrie et al. (1993) analyzed the samples paleoecologically and compared some results to Cape Ball samples of the same age. The results indicate a subaerial exposure of Dogfish Bank and a cold environment which supported terrestrial non-arboreal plants.

South of the study area, piston core samples and high resolution seismic profiles recovered from Queen Charlotte Sound on the central continental shelf of western Canada were studied for the purpose of establishing the geochronology of Late Quaternary sedimentation (Luternauer et al., 1989). They established five post-glacial sedimentation units overlying the glacial till. Clague et al. (1982b) analyzed samples collected from eastern Graham Island in order to establish a chronology for late Quaternary sea-level changes.

Barrie and Emory-Moore (1994) undertook research within an extensive zone on the east coast of Graham Island encompassing the present study area. This was to determine the processes acting to generate the rich auriferous black sand on the shore and the possible existence of these minerals offshore. They collected surficial samples within the intertidal zone and analysed mean grain sizes of each bulk samples and their heavy minerals content. The results showed an increase in heavy mineral concentration and fining of grain sizes landward within the intertidal zone. Longshore variation in texture and heavy mineral concentration showed no systematic trend. This is probably due to external factors that increases the erosive energy in certain locations.

II. Geological Setting

1) Bedrock geology

Graham Island and much of Hecate Strait are underlain predominantly by two Tertiary rock formations; the Masset and Skonun Formations. The Masset Formation is a non-marine, Late Oligocene to Earliest Pliocene suite of calc-alkalic volcanic rocks with minor sediment intercalations (Hickson, 1991). It is conformably overlain in part by the Skonun Formation to the east but shallows and eventually outcrops extensively in the west. It consists of mafic through felsic flows and pyroclasts of aphyric to feldsparphyric texture (Hickson, 1991). The mafic units are dominant on eastern Graham Island and consist of multiple flows with thin interflow breccias. The rocks of this unit contain cumulate nodules (up to 8 cm) of anorthosite and pyroxenite, and megacrysts (up to 3 cm) of plagioclase and pyroxene. It is also dominated by plagioclase phenocrysts, but pyroxene occurs infrequently and olivine is rare (Hickson, 1991). Felsic volcanic rocks are predominantly welded pyroclastics with minor lava flows. They dominate western Graham Island and plagioclase is the only phenocryst phase that is consistently present; quartz, pyroxene, k-feldspar and opaques are rare (Hickson, 1991). The most abundant rock type of the Masset Formation, aphanitic basalts containing 20-35 wt% pyroxene (principally augite), 5-10 % Iron oxides and 0-30 % Olivine (Sutherland, 1968).

The Skonun Formation consists of Miocene-Pliocene sandstones, mudstones, conglomerates and coal (Hickson, 1991). It occurs throughout northeast Graham Island, Hecate Strait and Queen Charlotte Sound, beneath a cover of Quaternary sediment (Higgs, 1991). Deposition of Skonun strata on Graham Island began sometime in the interval of 15-11Ma, or Middle to Late Miocene under alternating marine and non-marine conditions (Higgs, 1991). The marine environment is all shallow water and the sediments contain bivalve shells, gastropods, Ophiomorpha burrows, and dispersed pebbles and cobbles of volcanic, plutonic, metamorphic and sedimentary rock types. The pebbles and cobbles are believed to be ice-rafted dropstones probably supplied by icebergs from glaciers of the ancestral (Miocene) mountains of Moresby Island or from the mainland coast ranges (Higgs, 1991). The dropstones were deposited in most cases under a strong tidal current (Higgs, 1991).

2) Quaternary Geology

The Queen Charlotte Islands have been glaciated several times during the Pleistocene period. During this period, the Islands' glaciers were restricted and of very short duration, based on stratigraphic and paleoecological evidence (Barrie et al., 1993 and Clague et al., 1982b). During the last Late Wisconsinan glacial episode, the Queen Charlotte mountains supported ice caps and a network of valley and piedmont glaciers which coalesced with the Cordilleran ice lobes on the eastern and northern Graham Island during the glacial peak between 21 and 16 ka (Clague et al.,1982b and Blaise et al., 1990). Deglaciation of the shelf commenced after 16 ka and was complete by 13 ka

(Blaise et al., 1990). The mainland coast consequently underwent isostatic depression while the coast of Graham Islands experienced emergence, a result of a collapse on the mainland coast.

The lowland of eastern Graham Island is underlain mainly by thick Quaternary sediments consisting of marine and glaciomarine mud, outwash sand, and till (Clague et al., 1982b and Blaise et al., 1990). The glacial sediments consist of the upper till deposited by local piedmont glaciers extending eastward from western mountain ranges of Graham Island (Blaise et al., 1990 and Clague et al., 1982b). The till is conformably underlain by outwash sand deposited sometime after 23 ka, partly from the meltwater streams issuing from the advancing Hecate ice lobe before the site was subsequently overridden by ice (Blaise et al., 1990). The sand is conformably underlain by interstratified laminated mud and sand with foraminiferal assemblages indicative of a much colder climate than present deposited between 28 and 23 ka (Clague et al., 1982b and Blaise et al.,1990).

The glacial till described above is overlain by postglacial sediments deposited towards the end of Pleistocene to Holocene time (Clague et al., 1982b; Blaise et al., 1990 and Barrie et al., 1993). The unit immediately overlying the till consists of sand and minor interbedded silt, gravel and diamicts deposited sometime after 16 ka (Clague et al., 1982b and Blaise et al., 1990). The sand and silt are due to the erosion of lowland hills with subsequent deposition on subaerial surfaces by running water and mass wasting. Erosion was probably triggered by instability of the slopes after deglaciation (Clague et al., 1982b). This unit (sand and silt) is overlain by terrestrial woody peat deposited between 12 and 9 ka (Clague et al., 1982b). Above this unit is the Holocene marine sandy mud and silty sand sediments deposited between 9 and 8.5 ka (Clague et al., 1982b). Directly underlying the land surface and overlying the marine sand described above is the terrestrial woody peat.

In Hecate Strait, on Dogfish Bank, three facies were noted to overlie the Late Pleistocene till (Barrie et al., 1993). The upper facies immediately below the surficial sediments consists of sandy gravel with shell fragments and burrows. This facies was deposited after 10.5 ka, the onset of rapid transgression on the western coast, and abruptly overlies the interbedded and trough-cross-bedded sands and stiff silty sand which alternate up to the Wisconsinan till (Barrie et al., 1993). This facies was deposited during the deglaciation period probably under similar processes as interbedded sand and silt from the Cape Ball section (Barrie et al., 1993 and Clague et al., 1982b). It contains no marine indicators but posses abundant non-arboreal plant macrofossils. Two AMS dates of 13.8 and 13.2 ka were obtained from two depths within this facies (Barrie et al., 1993). In some areas the upper Facies (sandy gravel facies) is underlain by indurated clay.

Hecate Strait stratigraphy shows glaciomarine mud deposits with ice-rafted debris overlying the Wisconsinan till. The ice-rafted debris was deposited during deglaciation and terminated with the complete retreat of the shelf glacier

(Barrie et al., 1993). The glaciomarine mud contains equal proportions of sand, silt and clay (Barrie et al., 1993). During deglaciation on eastern Graham Island, before 13.7 until 10.5 ka, the shoreline was below the present mean level (Clague et al., 1982b and Barrie et al., 1993). Dogfish Bank supported mainly non-arboreal plants (e.g. dwarf shrub tundra, mosses and willows) between 13.5 and 13.0 ka, a period where at least 31m of sea level lowering had occurred. The sediments are free of foraminifera, ostracods and shells, and with the presence of bryophytes in some areas supports the concept of subaerial exposure of Dogfish Bank and existence of glacial refugia on Queen Charlotte Island (Clague et al., 1982b and Barrie et al., 1993). The rate of sea level lowering climaxed after 13.0 ka resulting in a coarse reversely graded sandy mud unit that overlies the glaciomarine deposit (Barrie et al., 1993). This lag sequence terminated about 10.5 ka with a sharp contact due to abrupt changes in the conditions that caused the lag (Barrie et al., 1993). This unit is overlain by peat at places. The rapid isostatic crustal forebulge of the mainland shelf with subsequent collapse on the Queen Charlotte shelf due to complete retreat of the Cordilleran ice resulted in a rapid transgression (7 to 10 cm/yr rise in sea level) that began about 10.5 ka, reaching its present position about 10 to 9.5 ka (Clague et al., 1982a). This abrupt transgression brought about the sharp contact between the sandy mud and the transgressive sequence (Luternauer et al., 1989a; Barrie et al.,1993). Transgression continued over the lowlands of Graham Island reaching up to about 15 m above the present levels between 8.0

and 7.5 ka. (Clague et al., 1982a). Sedimentation during this period resulted in olive, clay-rich mud. The transgression was followed by a regression culminating between 6.0 and 5.0 ka and is still continuing (Clague et al., 1982a,b). The above clay-rich mud unit is overlain by Holocene sandy gravel.

III. Oceanographic Setting

Hecate Strait lies within Queen Charlotte Basin and is bounded to the south by Queen Charlotte Sound and to the north by Dixon Entrance. For the purpose of this study, an understanding of the oceanography of Hecate Strait is required in order to understand sediment dynamics within the study area.

1) Wind patterns and Wave Climate

The weather patterns on the northern coasts of British Columbia are related to the relative strength and location of two major air pressure systems over the Pacific: the Aleutian Low centered over the Bering Sea and Gulf of Alaska, and the North Pacific High off California (Juszko et al., 1985). With the former predominant in winter and the latter in summer, these patterns result in generally strong south to southeasterly winds in the winter and weaker west to northwesterly winds in the summer. The winds are greatly influenced by the steering effect due to the mainland's mountainous coastlines and local topographic sheltering (Juszko et al., 1985; Thomson, 1981). The wind patterns therefore neither simulate in direction nor speed of the offshore winds which generate swell waves. The largest mean and maximum wind speeds are generally during winter. Seakem Oceanographic Ltd. conducted a wave measurement program on Queen Charlotte Sound from the fall of 1982 to the spring of 1984. On Hecate Strait, the closest data to the study area were collected from Bonilla Island. Seakem measured a mean speed of 9.5 m/s and maximum speed of 30 m/s during winter which closely relates to the historical mean speed of 9.1 m/s and maximum speed of 40 m/s, both in a modal S.E. direction. During field work, on the 8th of February 1994, winds at the study site gusted at 23.16 - 26.77 m/s from S.E. and later dropped to 15.44 m/s for an eight hour period before calming down (Conway and Barrie, 1994).

The northwest Pacific Margin experiences one of the most severe wave conditions in the world, especially during winter. There are limited direct data of the wave climate in Hecate strait. A general seasonal pattern prevails of calm, summer weather (June, July and August), rapid increase in storm frequency and strength (late September through October) and a more gradual decrease in storms in the spring from April to June (Juszko et al., 1985). During an exploratory drilling carried out by Shell Canada Ltd. in the late ninteen sixties, waves of greater than 18 m significant height, with a maximum height of 27 to 30m during an October storm, were recorded (Juszko et al., 1985). Severe waves on the northern British Columbia coasts are generated by two storm types: (1) Large scale, deep low-pressure system which moves eastward over the Gulf of Alaska to produce strong south to southeasterly winds due to the tightening of the isobars between the coastal mountains and the open ocean (Juszko et al., 1985), and (2) smaller center over the Gulf of Alaska which deepens rapidly when it approaches the coast (Juszko et al., 1985). Hecate Strait which is less open to swell waves than Dixon Entrance and Queen Charlotte Sound, experiences less severe significant wave heights but has the greatest occurrence of large waves. This is phenomenon probably due to the trajectory of storms causing severe conditions and/or larger local fetches in this area (Juszko et al., 1985). Given the wind strength within the Basin, winds blowing up or down Hecate Strait may generate wave conditions with significant heights of 3-6 m and significant periods of 7-9 seconds due to maximum local fetch of 277.8 km associated with the complete length of Hecate Strait.

2) CurrentS

During winter a prevailing northward current exists along the eastern side of Hecate Strait and a pressure driven southward bottom flow occurs along the southwestern portion of the Strait due to pile-up of water at the north end of Hecate Strait when wind blows from the south (Crawford et al., 1988). North of Moresby Island all wind-driven currents flow towards the north on Dogfish Bank because the wind stress can easily penetrate to bottom in the shallow water there (Crawford et al., 1989). In winter, the water column in Hecate Strait is almost homogeneous with a typical temperature of 5 to 6^0 C and salinity of 32 to 33 ppt due to downwelling and mixing of the warm water blown from the south by the southeast wind (Crawford et al., 1989). Dogfish Bank waters are the warmest in the Strait due to its shallow depth (Crawford et al., 1989). Due to the homogeneity of Hecate Strait waters in winter, the wind-forced circulation tends to be uniform in direction through the water column and currents are generally strongest at the surface. Speeds are greatest in November, reaching values of 38 cm s^{-1} in northern Hecate Strait and 24 cm s^{-1} in mid Hecate Strait (Crawford et al., 1989). The waves and currents in winter in northwestern Hecate Strait move sediments to the Northeast, building up Rose Spit and eroding the northeastern shore of Graham Island (Crawford et al., 1989).

Transport in northern Hecate Strait is mainly to the south in summer. Surface circulation during this period is strongly influenced by buoyancy flux and by topographically controlled eddies and the water mass is more stratified with salinity values of 31 to 34 ppm and temperatures between 5 and 13^0 C. (Crawford et al., 1989).

IV. Field and Analytical Methods

1) Field Methods

The field survey was undertaken over 10 days between 31st of January and 9th of February 1994. During this period, measurement of accretion and erosion of the beach, and sediment sampling was undertaken. Fifty-one samples were collected, using a spatula. Four types of samples were collected; Longshore samples (Ls), Cross-shore samples (Cs), Depth samples (Ds) and Relict samples (Rs). The samples were bagged and labelled, and a description of field observations and location of the samples noted in the field book. Sample sites are shown in Figure 2.

1.1 Accretion and Erosion measurement

To measure the daily accretion or erosion within the study area, brass rods were graduated and four rods driven into the sand in each of the three transects T1, T2, and T3. Transect T1 coincided with the cross-shore transect Cs 01 in the southern-most part of the study area, T2 coincided with Cs 02 in the mid portion and T3 coincided with Cs 03 in the northern-most portion (Fig. 2). The readings were taken daily during low tides. The diurnal net accretion and erosion measurements alongshore and across-shore were collected to enable the determination of the direction of longshore current and to compare the relative net accretion or erosion between two successive rods and transects. The results of these measurements will be related to texture and heavy mineral distributions.

1.2 Longshore sampling

Two longshore transects each consisting of eight samples and different beach morphology were collected from mid-beach on two days. The samples were collected at intervals of 300 m, starting from Cape Fife point (southern limit) to approximately 2.1 km north (Fig. 2). Rectangular areas of approx. 0.03 m width (width of a spatula) by 5 m (Ls 01) and by 3.7 m (Ls 02) lengths oriented normal to the shore, were sampled during low tide. The length reduced the effect of cross-shore sorting. The depth was restricted to approx. 1 - 1.5 cm, so as to represent contemporaneous samples formed during the last high tide. The samples weighed approx. 1.5 kg for Ls 01 and 0.6 kg for Ls 02. At rip current zones, which simulate fluvial environments, erosion is enhanced and sometimes the stress level may exceed threshold stress required to entrain all heavy minerals leaving only cobbles and boulders behind. Sampling of these zones was avoided.

1.3 Cross-shore sampling

Nineteen samples from three cross-shore transects Cs 01, Cs 02, and Cs 03 were collected. Cs 01 consists of four samples collected at an interval of 15m. Cs 02 lies 0.9 km north of Cs 01 and consists of six samples collected at a similar interval. Cs 03 is 1.8 km north of Cs 01 and consisted of nine samples, the first eight samples were collected at an interval of 5 m and the last sample at 10 m in the foreshore. A square area of approximately 10 cm by 10 cm was sampled and to similar depths as longshore samples.

1.4 Depth sampling

Fourteen samples were collected from two locations (Fig. 2), each consisting of seven samples. Sampling was done by successively scraping of approximately one grain layer. Each sample weighed approximately 10 grams.

1.5 Relict sampling

Three grab samples were collected from the unconsolidated Pleistocene bluff to the south of the study area (Rs-01 and Rs-02) and sand dunes to the north (Rs-03) (Fig. 2). This was done to determine the concentration of heavy minerals in the source.

2) Analytical Methods

2.1 Sample Preparation.

The samples were first oven dried overnight at a temperature of 40° C prior to dry sieving through a #10 mesh (4 mm) to remove gravels and wet sieving through a #230 mesh (0.063 mm) to remove fines and salts. Two subsamples were then obtained from each bulk sample of the sand fraction using a mechanical splitter. One of the subsamples, weighing between 120 and 200 grams, was dry-sieved at 1/2 Φ interval with an upper cut-off of 2 Φ (4 mm) and a lower cut-off of 4 Φ (0.063mm) in order to determine the texture of the bulk sample. Textures of samples obtained with depth, Ds 01 and Ds 02, were analyzed using a 2-m long settling tube. This is because the samples were too small to sieve. The second subsample, weighing between 3 and 6 grams, was utilized in the separation of light and heavy minerals.

2.2 Heavy Mineral Separation Procedure

The sand for the heavy mineral separate was placed in a plastic centrifuge tube (10 cm long, 2 cm diameter) and thoroughly shaken to disaggregate any adhered mineral grains. Sodium polytungstate, a non-toxic heavy liquid of specific gravity 2.96 g/cm^3, was then added. A vortex mixer was used to mix the sand grains and heavy liquid until no sand grains were present on the tube bottom (grains either suspended or floating on top of the heavy liquid). The plastic tubes were then inserted into a centrifuge and spun at 2000 rpm for 15 minutes which allowed a near complete separation of the light minerals from the heavy minerals (Carver, 1971). After spinning, the bottom portion where the heavy minerals settled, was dipped into liquid nitrogen for a period of 40 to 50 seconds to freeze the heavies and a small amount of liquid above them. The non-frozen portion containing light minerals was decanted into a coffee filter and the light minerals thoroughly washed. The frozen heavies were then washed out of the tube with de-ionized water into a Whatman filter paper. A minimum of three washings with de-ionized water and four times with tap water ensured complete rinsing of the heavy grains. After rinsing, the separates were oven dried overnight at a temperature of about 40° C. The heavies were then brushed off the filter paper and weighed. The weight percentage, relative to the bulk raw sample, was then calculated.

Magnetite grains were then extracted from a pre-weighed bulk heavies (total heavies in each sample). The magnet was wrapped in a tracing paper in order to minimize loss due to strong adherence of the grains to the magnet. The magnetites were then weighed and their percentage relative to the bulk heavies calculated.

The non-magnetic minerals from each sample were then mounted on microscope slides using Canada Balsam. Three hundred grains per sieve fraction were optically identified and counted under a petrographic microscope. Percentages were then determined for different mineral grains (Appendix B).

2.3 Data analysis

After sieving, the mean grain sizes of the bulk samples were computed from the graph's cumulative weight percentages of sand fractions collected from each sieve plotted against their respective sieve aperture sizes, using Folk's graphic mean formula (M) (Folk, 1974):

$$M = (\Phi_{16} + \Phi_{50} + \Phi_{84}) / 3 \ldots\ldots\ldots (5)$$

This formula was preferred since it accounts for skewed curves and is a better measure than median measurement.

The degree of sorting, a measure of the spread in grain sizes of a sample, was obtained from Folk's inclusive graphic standard deviation formulae (σ) (Folk, 1974):

$$\sigma = ((\sigma_{84} - \sigma_{16})/4) + ((\sigma_{95} - \sigma_{5})/6.6) \ldots\ldots\ldots (6)$$

2.4 Oceanographic analysis

Oceanographic data for wind speeds, directions and tidal levels of eastern Graham Island were obtained from Rose Spit weather station and analyzed for the study period. Wind speed and direction data were obtained hourly between the 30th of Jan. and the 9th of Feb. Tidal data were only obtained during low and high tides. Average wind speeds and directions between high and low tide periods prior to sample collections during subsequent low tides were calculated (Table 4). These data are used to determine the effect of wave stress and its direction of approach to the beach and therefore to the longshore distributions of heavy minerals.

3) **Sources of Error.**

The rate of sedimentation would influence the beach concentration of heavy minerals. The non-uniformity of bluff erosion would, therefore, affect the pattern of heavy mineral distribution. To reduce the magnitude of this effect, a short distance of 2.1 km was studied. This short distance reduces the effect of variation in swell wave energy. Sampling of zones within the vicinity of obstacles would as well affect the pattern of concentration, hence much effort was made to avoid these zones. For the analysis of each distribution pattern (longshore, cross-shore and depth), the sampled depth ought to be uniform. As discussed below, heavy mineral concentration varies with depth. Any slight inconsistency in sampling would, therefore, contaminate the result, so the sediments were sampled carefully. Errors could also arise from individual mineral identification and counting, so counting was done twice on two different locations on each slide and the results averaged.

Table 4: Data of average wind direction and speed during the study period indicating maximum speed. * Dates, between high and low tide preceding sample collections, providing averaged data. ** Sample collection dates.

Average Wind Direction and Speed during the study Period.		
Date	Average Direction	Average Speed m/s
31st Jan. - 1st * Feb. (1st)**	15	1.54 (Max. 2.57)
1st Feb. - 2nd Feb. (2nd)	310	2.21 (Max. 3.60)
2nd Feb. -3rd Feb. (3rd)	340	3.65 (Max. 5.66)
3rd Feb. - 4th Feb. (4th)	350	3.60 (Max. 8.24)
4th Feb. - 5th Feb. (5th)	302	3.60 (Max. 10.29)
6th Feb. - 7th Feb. (7th)	50	10.29 (Max. 14.93)
7th Feb. - 8th Feb. (8th)	120	10.29 (Max. 26.77)

V. Results

1) Accretion and Erosion

During the study period, some rods were lost either due to excessive erosion at their sites, possible burial, or anthropogenic disappearance. These rods were replaced and measurements taken. The highest water level during high tide within nearly the entire period were below the upper rods in transects T2 and T3. On the 6th of February no data could be collected due to bad weather. These problems may reduce the strength of the results, nevertheless, some trends are still evident from the data obtained.

The accretion and erosion results of the beach-face indicate a relatively greater erosion within the lower quarter than the upper quarters in transects T2 and T3 (Table 5). In transect T1, the lower quarter is generally more accretionary than the lower quarters of transect T2 and T3. Transect T2 is generally more erosive in the lower quarter than transect T3. If we go by these patterns, the trends may imply the probable amount of erosion of the lost rods, especially within the lower quarters of transects T2 and T3. For example, the erosion within the lower quarter of T3 between 7th and 8th probably exceeded 45 cm relative to the previous days reading since lower quarter is generally more erosive than its upper quarters and that of T2 was therefore much more since it's lower quarter is generally more erosive than that of T3. These two inferences, erosion at T2 and T3 which exceeded the previous length below surface, would explain rod loss at these sites (Table 5). The erosion on T1 at the upper quarter was probably less than 10 cm since the upper quarter is generally more accretive than the third quarter. From data averaging, transect T2 is relatively more erosive and less accretive than transects T1 and T3 (Table 5; Fig. 4). This averaging of transect data is not very representative due to some of the problems outlined above. Except for the rod losses, the data obtained on the 8th of February are free of the error sources outlined. From the observations made above, the data affirm an enhanced erosion within transect T2 relative to T1 and T3. Transect T1 is the most accretive and least erosive.

During conditions of high energy storm waves sediments are eroded from the beach and transported offshore (Plate 1). These sediments return to the beach during fair-weather conditions when the incident waves have relatively low steepness (Komar, 1976).

2) Grain Size Distribution.

A general increase in mean grain size of longshore distributions from the northern to the southern limit of the study area was observed (Fig. 5). Significant differences in both field and analytical observations were noted for grain sizes of Ls 01 and Ls 02. Ls 01 was sampled on the 1st of February when the wind approached from an average direction of 15° at an average speed of 1.54 m/s. The field observations of the Ls 01 beachface environment showed a more size segregation and coarser grain sizes than the Ls 02 beachface environment. Ls 02 was sampled on 7th of February when the wind gusted from an average direction of 50^0 at an average speed of 10.29 m/s. The wind velocity and direction determines the amount of energy imparted to the waves and their direction of approach to the beach respectively (Komar, 1976). Relatively coarse sand and gravels were noted within the Ls 01 environment while medium sand was typical of the newly accreted Ls 02 environment. In the analytical observations, similar results were obtained. Ls 01 samples show coarser sand (0.332 - 0.518 mm) than Ls 02 (0.346-0.406) samples. The grain size distribution

Plate 1. Study area after a storm. All the beach sediments have been eroded away leaving cobbles and gravels behind.

Table 5: Accretion and Erosion measurement. (-) Erosion relative to previous measurement. (+) Accretion relative to previous measurement. (**L**) lost rods. (50) lost and replaced rods. (Aver.) average for the accretion measurement.

Tran-sects	Rods	31st	Accre	1st	Accre	2nd	Accre	3rd	Accre
Trans T3	Rod 1	50	0	50	0	50	0	50	0
	Rod 2	50	+4	54	+2	56	+3	59	+1
	Rod 3	50	+4	54	+3	57	-3	54	+6
	Rod 4	50	-7	43	-8	35	-3	32	-5
	Aver.		+1		-3		-3		+2
Trans T2	Rod 1					50	0	50	0
	Rod 2					50	+4	54	+1
	Rod 3					50	0	50	+5
	Rod 4					50	-7	43	-7
	Aver.						-3		-1
Trans T1	Rod 1			50	+1	51	+5	56	0
	Rod 2			50	+4	54	+2	56	+10
	Rod 3			50	-10	40	-6	34	-2
	Rod 4			50	0	50	+14	64	—
	Aver.				-5		+15		+8

Tran-sects	Rods	4th	Accre	5th	6th	Accre	7th	Accre	8th
Trans T3	Rod 1	50	0	50	NO	0	50	-3	47
	Rod 2	60	0	60		+4	64	-45	19
	Rod 3	60	+4	64	D	—	L 50	-22	28
	Rod 4	27	-4	23	A	+1	24	—	L
	Aver.		0		T	+5		-70	
Trans T2	Rod 1	50	0	50	A	0	50	-18	32
	Rod 2	55	0	55		+8	63	-40	23
	Rod 3	55	0	55	CO-	—	L 50	-28	22
	Rod 4	36	-4	32	L	-1	31	—	L
	Aver.		-4		L-	+7		-86	
Trans T1	Rod 1	56	0	56	E	+2	58	—	L
	Rod 2	66	+2	68	C	-28	40	-23	17
	Rod 3	32	+4	36	T	—	L 50	+9	59
	Rod 4	L	—	L 50	E	+19	69	-10	59
	Aver.		+6		D	-7		-24	

of Ls 02 are nearly uniform with slight coarsening towards the south. The difference in mean grain sizes between the two transects, Ls 01 and Ls 02, increases to the south (Fig. 5). At the northern limit, the sample mean size of Ls 02-08 exceeds that of Ls 01-08. Between the southern limit and approximately 1km from the southern limit, the two environments show a decrease in grain size and the location of the two minima points are out-of-phase. This location coincides with the zone of enhanced erosion (T2) discussed above.

The cross-shore distributions of grain sizes indicate an increase from the upper shore-face to the lower shore-face and are pronounced for samples collected both during fair and stormy conditions (Fig. 6). Cs 02 shows the finest mean cross-shore grain size followed by Cs 03 and Cs 01 being the coarsest. Cs 03 show a reduction in grain size near the lower shore-face limit . This zone coincides with the increased erosion zone within the last quarter of transect T3, discussed above.

Ds samples (samples collected with depth) show drastic decrease in mean grain sizes from the surface samples to the second layer samples. Ds 01 showed no clear trend within the subsequent layers, while Ds 02 showed an increase of grain size with depth (Fig. 7).

3) Concentration

The concentration of bulk heavy mineral population for longshore samples from the study area, Ls 01 and Ls 02, does not seem to possess any definite trend if it were not for some probable external influences described below. In general, the concentrations are observed to decrease in the transport direction from the northern to the southern limit (Fig. 8). Ls 01 shows greater concentration than Ls 02 except in the northern limit. Within about 1 km distance from the southern limit, the concentration of the heavies is significantly higher for both Ls 01 and Ls 02.

Magnetic separation and microscopic examination of heavy mineral fractions of the sand samples identified the opaque and non-opaque minerals. The opaque mineral suite consist of magnetite (separated using hand magnet) and intergrown of hematite and ilmenite all of which are common minerals of the Masset Formation (Barrie and Emory-Moore, 1994; Hamilton and Dostal, 1993). The non-opaque suite include garnet, amphiboles, epidote, sphene, rutile, zircon and other altered minerals (Appendix B). Light mineral fractions consist of quartz and feldspars. The surficial concentration of magnetite ranges between 0.1 and 31 wt% of the heavy mineral fraction. While the TiO_2 content of magnetite rarely exceeds 0.5 wt%; that of hematite is very high, ranging from 10 to 25 wt% (Barrie and Emory-Moore, 1994). The replacement of Fe_2O_3 in a free hematite by TiO_2 cannot exceed 1-2 wt% (Deer et al., 1977), hence the high content of the hematite grains probably reflects the presence of ilmenite or rutile intergrowth (Barrie and Emory-Moore, 1994).

The concentration of magnetites within the heavy mineral fraction of Ls 02 shows a similar trend to that of the bulk heavies relative to sample weight (Fig.9). Within the concentrations of individual dominant heavy minerals

(Appendix B), on the northern section, the concentration of garnet in Ls 02 exceeds that of the opaques, followed by the amphibole and last the epidote concentration (Fig. 10). The concentrations of the magnetite, garnet and the opaques decrease to about 1 km point from the northern limit (near the end of longshore bar (Fig. 2)) followed by a general increase to the southern limit while that of the amphibole generally increases from north to south. The concentration of epidote is variable with a slight increase to about 1.5km from the southern limit followed by a decline. There is a marked difference in concentration between amphibole and epidote which is not in line with their hydraulic properties.

In cross-shore samples, Cs 01, Cs 02 and Cs 03, the concentrations of heavies decrease with distance from backshore to foreshore (Fig. 11). Within the beachface, especially across-shore, distinctive colours of opaques (black), garnet (pink), epidote (avocado green), and quartz-feldspar (tan) were observed. Diversion from the normal trend of the bulk concentration is observed in the last quarter of transects Cs 02 and Cs 03 from the upper shoreface, showing a magnified concentration. This zone coincides with the zone of enhanced erosion at the lower quarter in transects T2 and T3, and to the reduced mean grain sizes at these two locations. In mid-beach, approx. 25 m from the shore-face, among the dominant heavy mineral concentrations in Cs 03 (Fig. 12 and 13), a similar

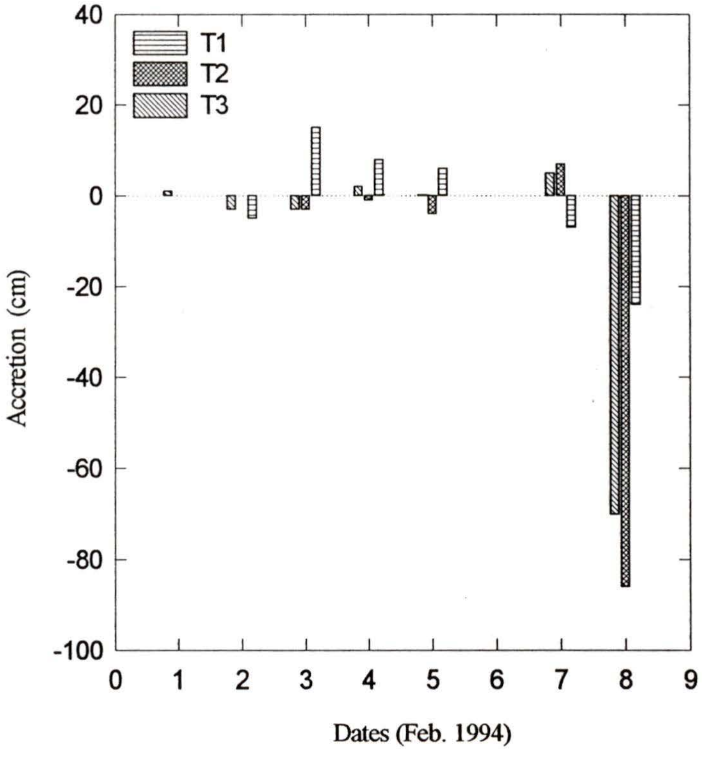

Fig.4 Graph of accretion versus erosion over the period of observations

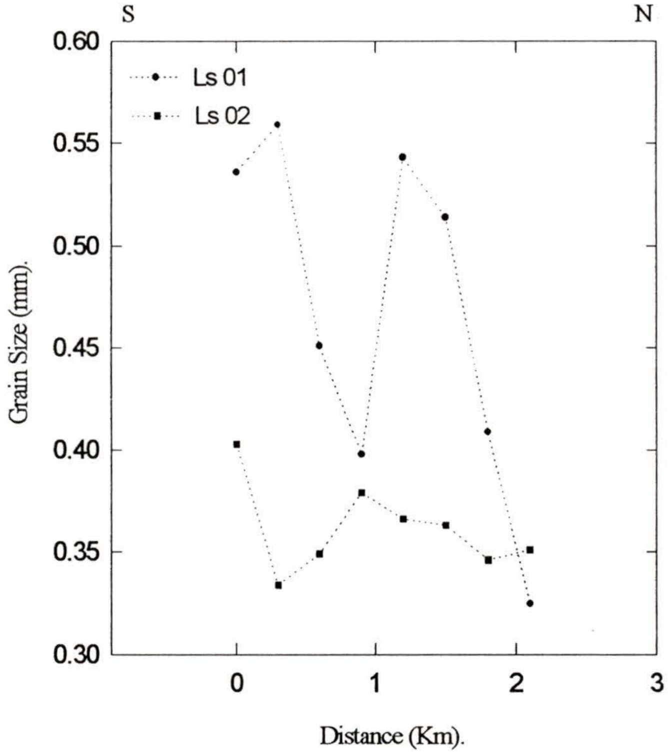

Fig. 5 Longshore mean grain size distributions for Ls 01 and Ls 02 plotted against distance.

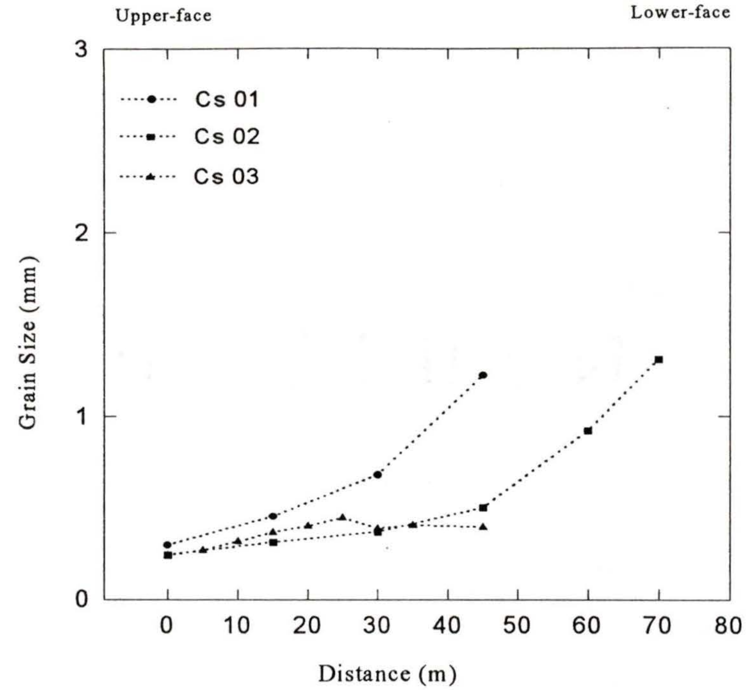

Fig. 6 Mean grain size distributions of Cs 01, Cs 02 and Cs 03 plotted against their respective cross-shore distance

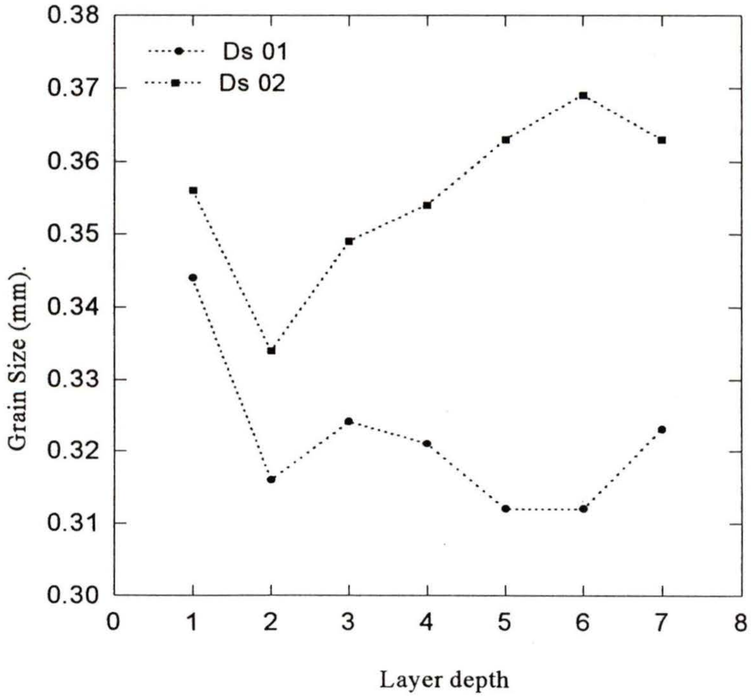

Fig. 7 Mean grain size of individual layer depths obtained using settling tube.

distribution of individual mineral concentrations, garnet-opaque-amphibole-epidote, as in the northern section of Ls 02 samples, is observed. The amphiboles in the study area mainly consist of pale-dark green common hornblende. Hornblende has a density ranging between 3.02-3.45 g/cm^3 which is similar to that of epidote (3.38-3.49 g/cm^3) (Deer et al., 1977). This similarity would provide a near equivalent hydraulic behaviour as noted in Cs 03 (Fig. 13). Amphiboles and epidote both show a gradual increase in concentration with distance across-shore but with the amphiboles having a slightly higher rate. It is important to note that the increase in concentration of the amphiboles and the epidote in the transport direction is relative to the non-magnetic heavy mineral fraction and not the bulk sample. Given the bulk sample, the concentration would decrease with transport distance. The similarity of some of the light heavy minerals', for example amphiboles, hydraulic behaviour relative to their heavy mineral counterpart to light minerals relative to bulk samples has been noted by many researchers (e.g. Ruby, 1933; Li and Komar, 1992; Komar and Wang, 1984). The magnetite, opaques and the garnet show a general decline in concentration from the upper to the lower shore-face samples.

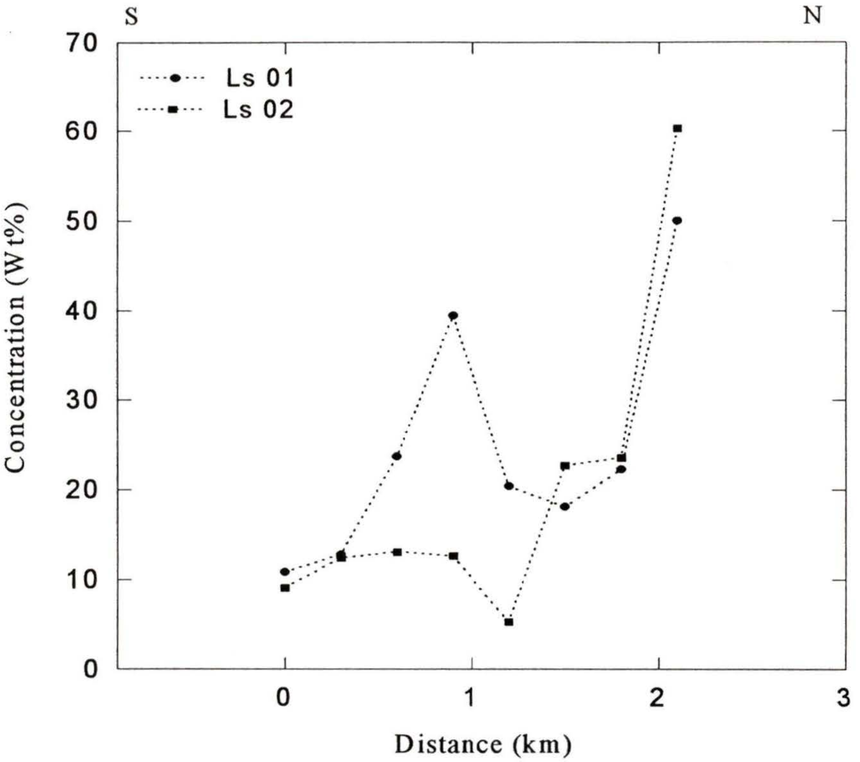

Fig. 8 Changes in bulk heavy mineral concentrations of Ls 01 and Ls 02 with longshore distance.

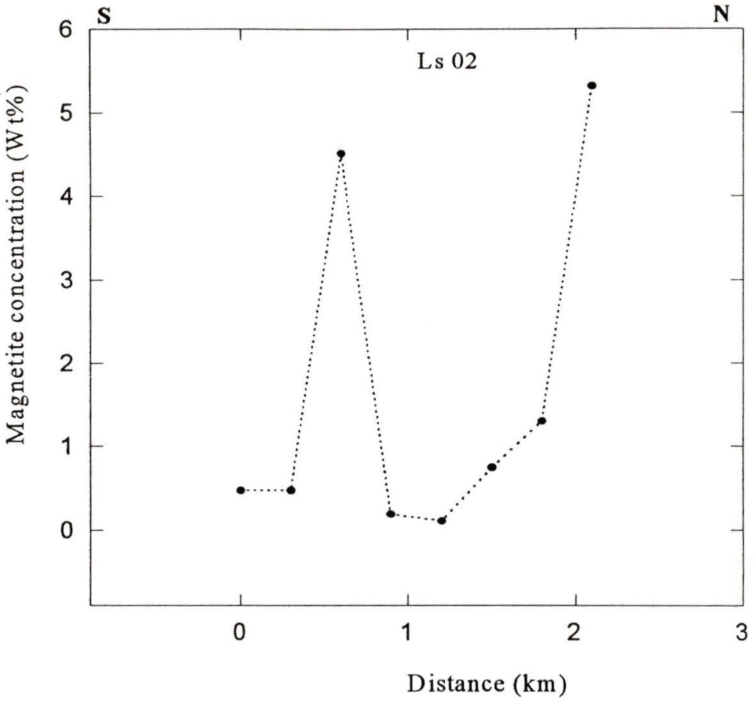

Fig. 9 Wt% distribution of magnetite in Ls 02 samples plotted relative to their position between the southern and the northern limit.

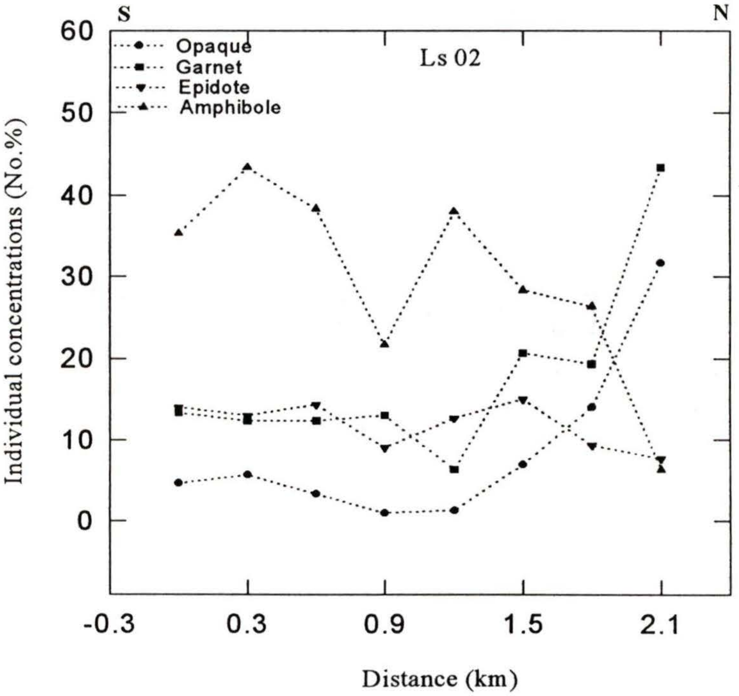

Fig. 10 Concentrations of prominent individual heavy mineral within Ls 02 plotted against their longshore distance.

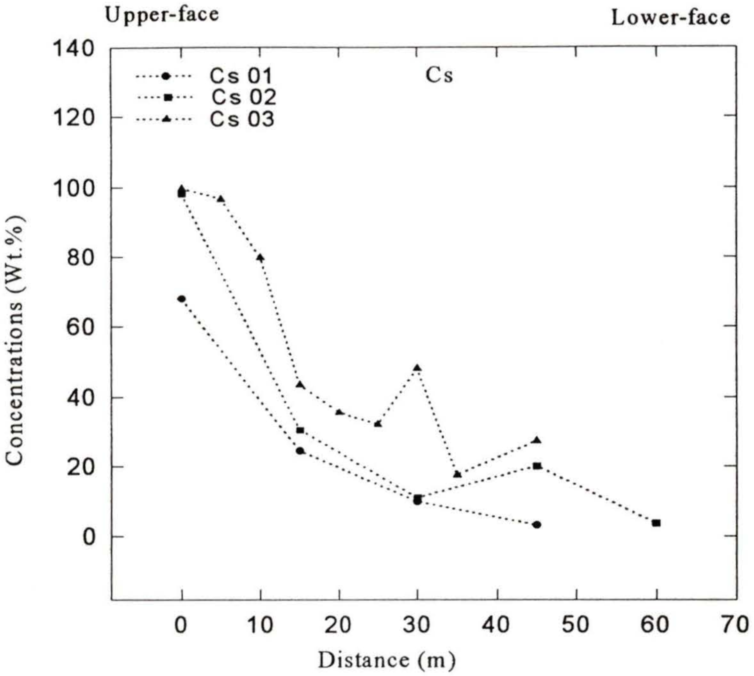

Fig.11 Heavy mineral distributions of cross-shore samples plotted against their respective distance from the upper-shore face

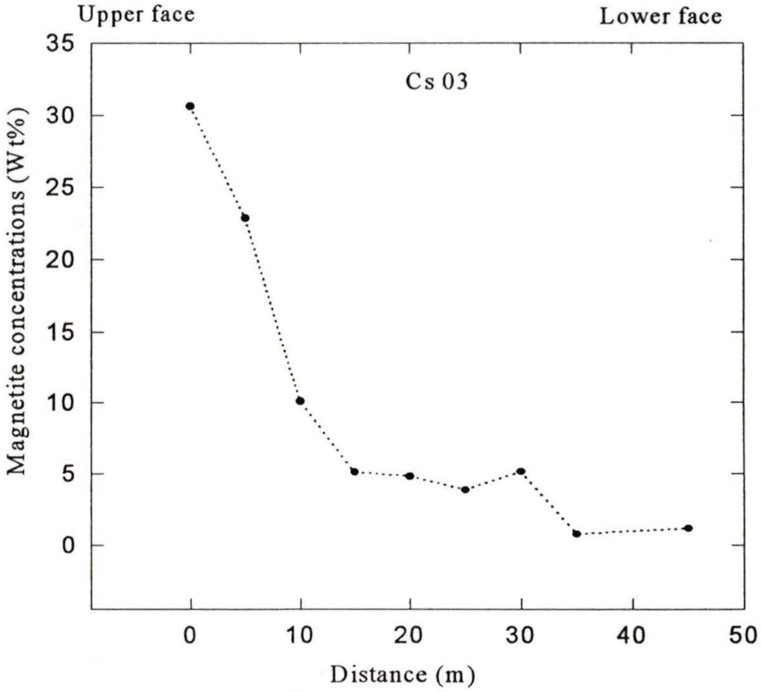

Fig. 12 Magnetite distributions within cross-shore distance of transect Cs 03.

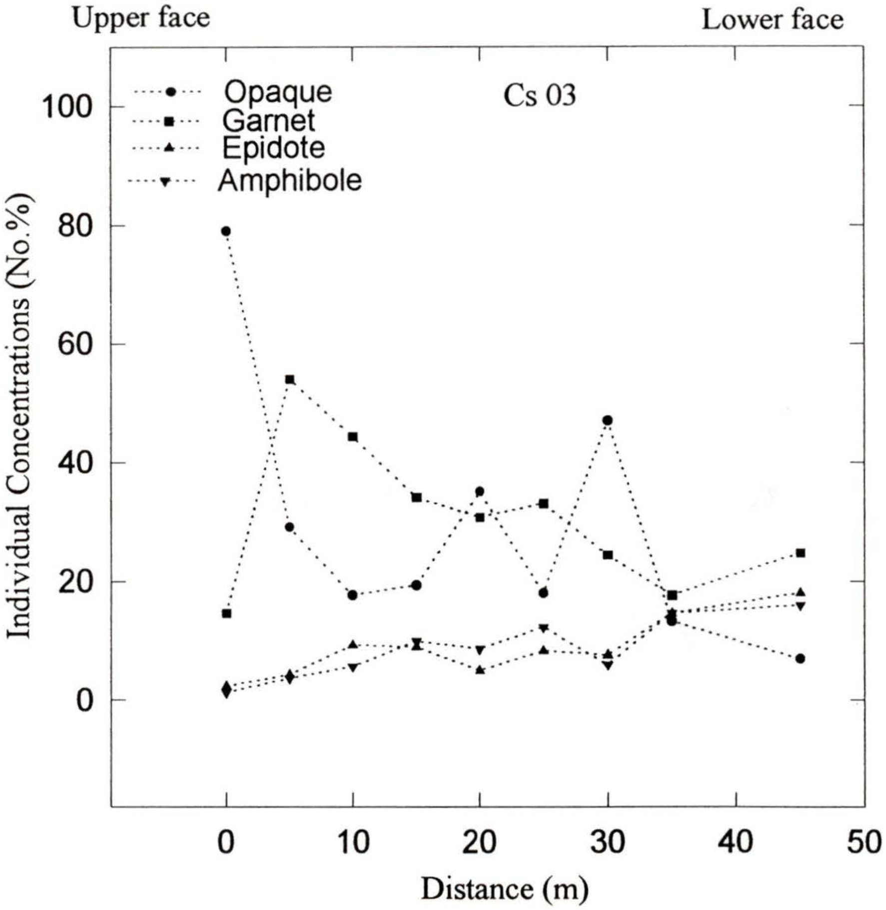

Fig. 13 Concentrations of prominent individual heavy minerals of transect Cs 03 versus their cross-shore distance.

Field observations around isolated clasts within the beachface showed an anomalously high concentration of heavy minerals relative to the background, especially on the flanks of the obstacles. Sorting by density is again evident from the distinctive colours in the backwash transport direction away from the clasts. The clasts therefore exert a considerable influence on sediment transport and consequently heavy mineral concentration. Sampling of these zones were therefore avoided in order to reduce anomalous results.

In the analysis of the change of concentration with layer depth, the concentrations of the bulk heavies show an increase between the surface and the second layer of Ds 01 but is nearly the same within subsequent layers. That of Ds 02 shows a constant increase between subsequent layers with depth (Fig. 14). Within individual minerals, magnetite, opaques and garnet become increasingly abundant with depth (Fig. 15 and 16). The near equivalence property is noticed in Ds 02, but here the amphiboles show a gentle decline in concentration while the epidote show a nearly constant concentration with depth.

Trenches dug in the study zone shows a thick deposit of heavy minerals that underlie laminations of light and heavy minerals (plate 2) and changes in heavy mineral distribution with depth (plate 2 and 3). Individual laminations in plate 2 show a gradational increase in concentration of heavy minerals with depth.

4) Sorting.

From Figures 17 a, b, and c compared to Figures 8 (Ls 01), 11 (Cs 03) and 14 (Ds 02) respectively, it is evident that the variation in heavy mineral concentrations is dependent on the degree of sorting of the samples. The concentrations of heavy minerals is higher in a well sorted sediment than in a poorly sorted sediment.

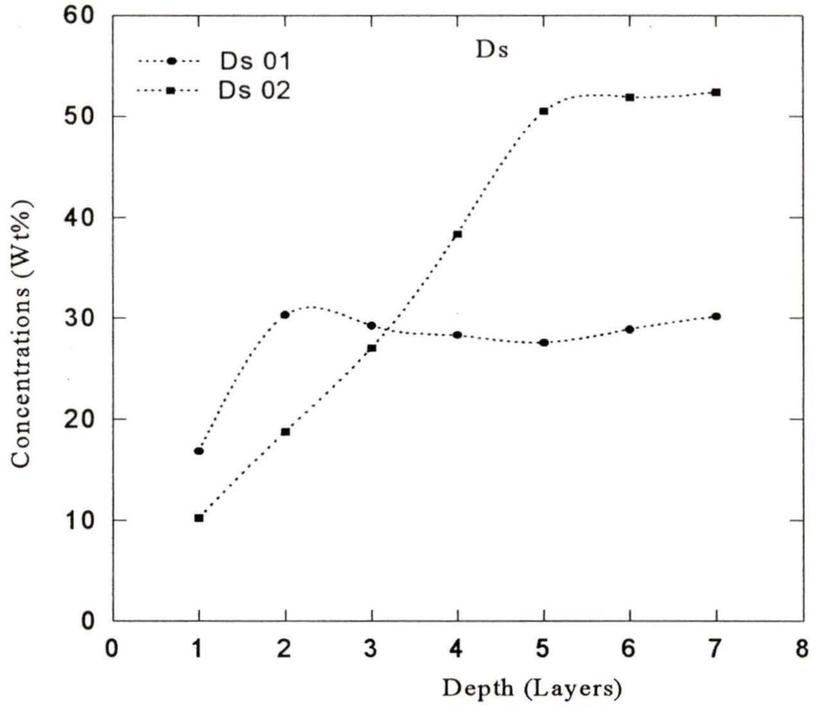

Fig. 14 Bulk concentrations of heavy minerals plotted against their layer depth.

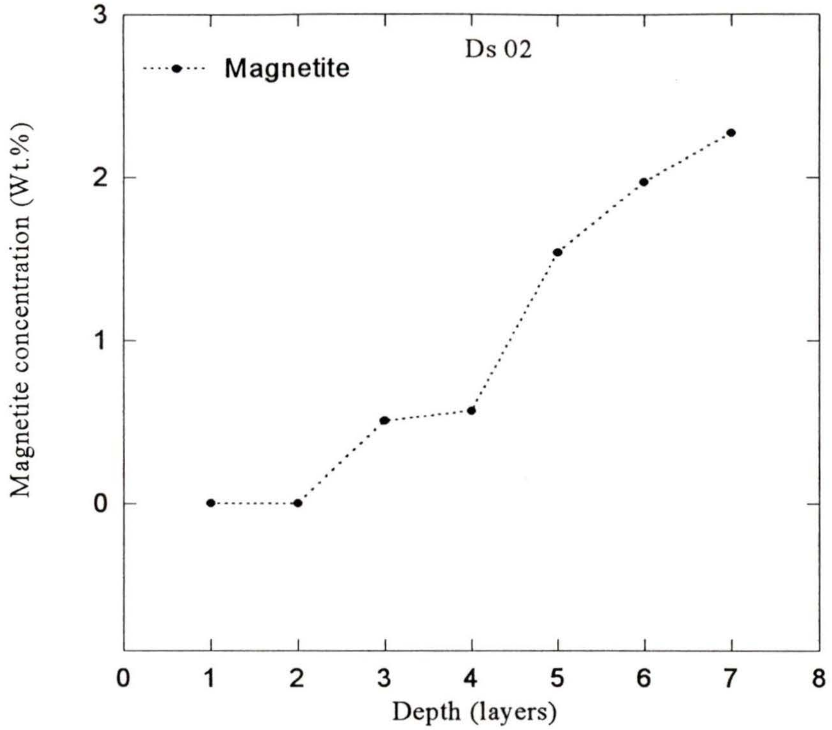

Fig. 15 Magnetite concentrations of Ds 02 samples versus layer depth.

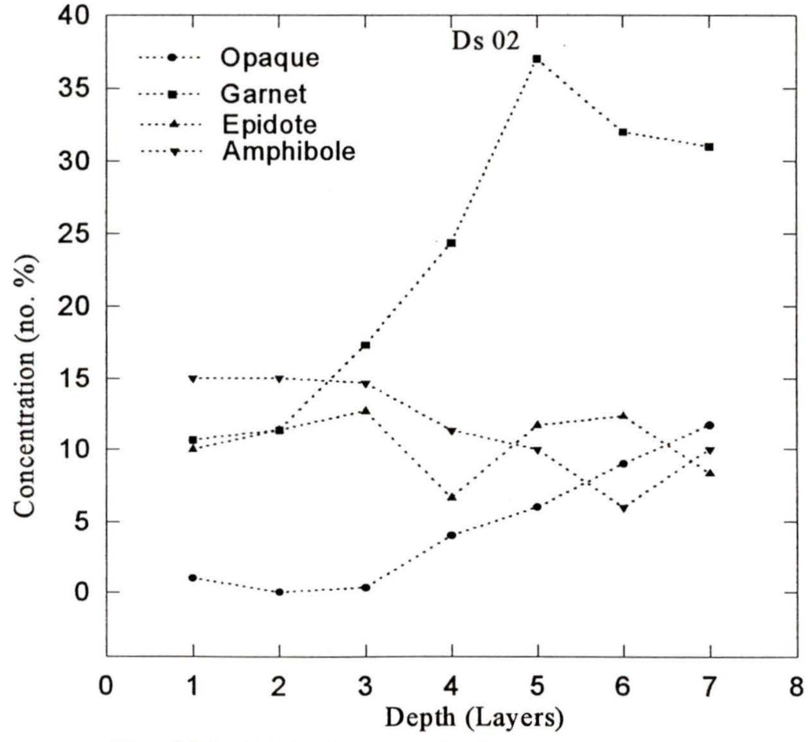

Fig. 16 Individual concentrations of dominant heavy minerals plotted against layer depth

The inverse proportionality between heavy mineral concentrations and mean grain size of the bulk samples (Fig. 19) consequently influences the proportionality between mean grain size of the bulk sample to sorting value. The results show that the relative abundance of heavy minerals increases with the degree of sorting. In an immature and less erosive environment, LS 02, there is no clear correlation between the degree of sorting, to heavy mineral concentrations and to grain sizes. The results shown in Figure 17b suggest that the effect of size and density in the segregation of beach sand are mutually exclusive. In addition to size, sorting is dependent on density of the sediment particles. A decrease in the degree of sorting is also caused probably by the entrapment of the finer grains between the voids of coarser grains which increases with distance across-shore.

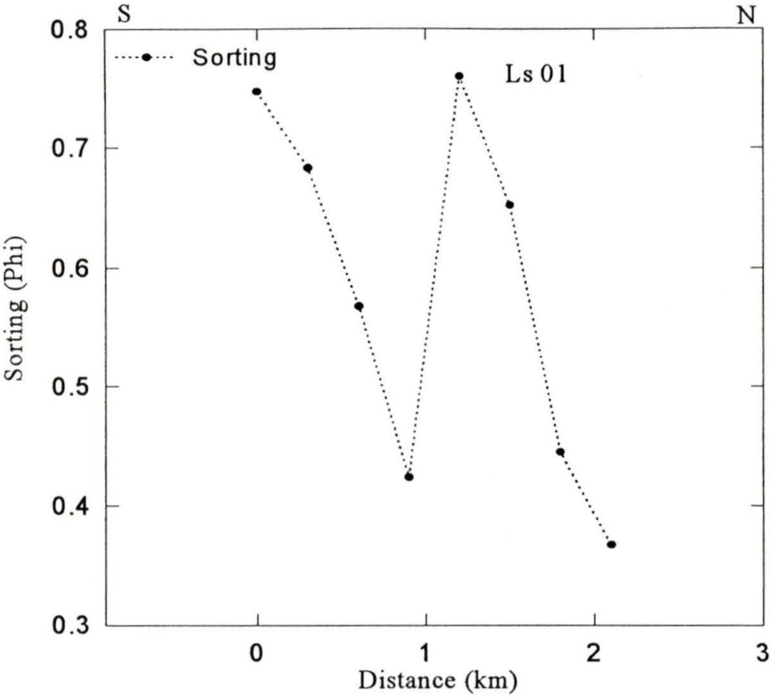

Fig. 17a Sorting (Phi) of Ls 01 plotted against longshore distance.

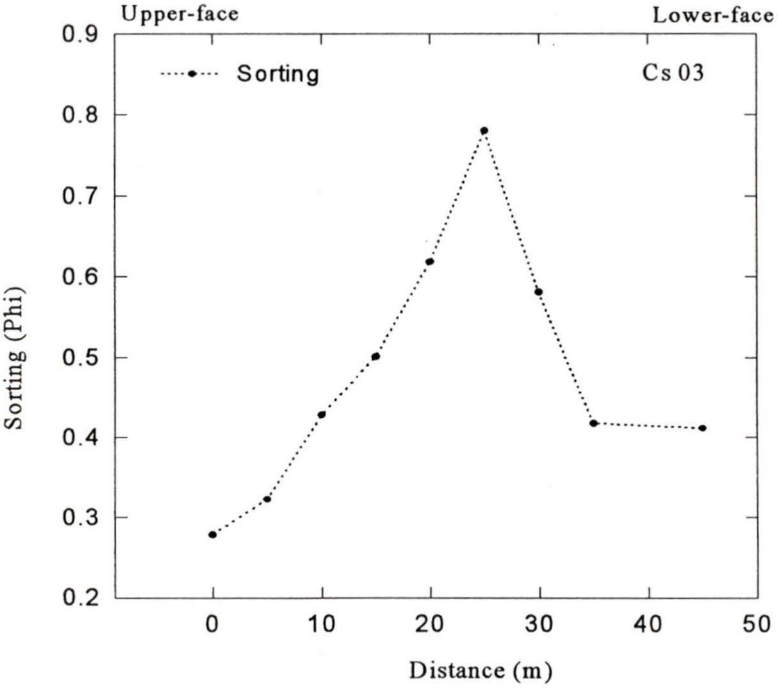

Fig. 17b Sorting (Phi) within transect Cs 03 versus cross-shore distance.

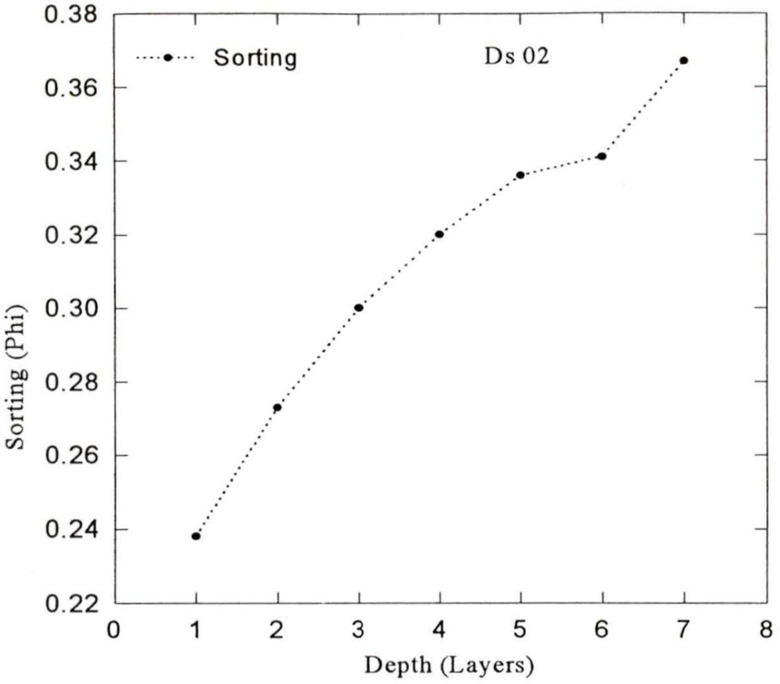

Fig 17c Sorting (Phi) of Ds 02 samples versus layer depth

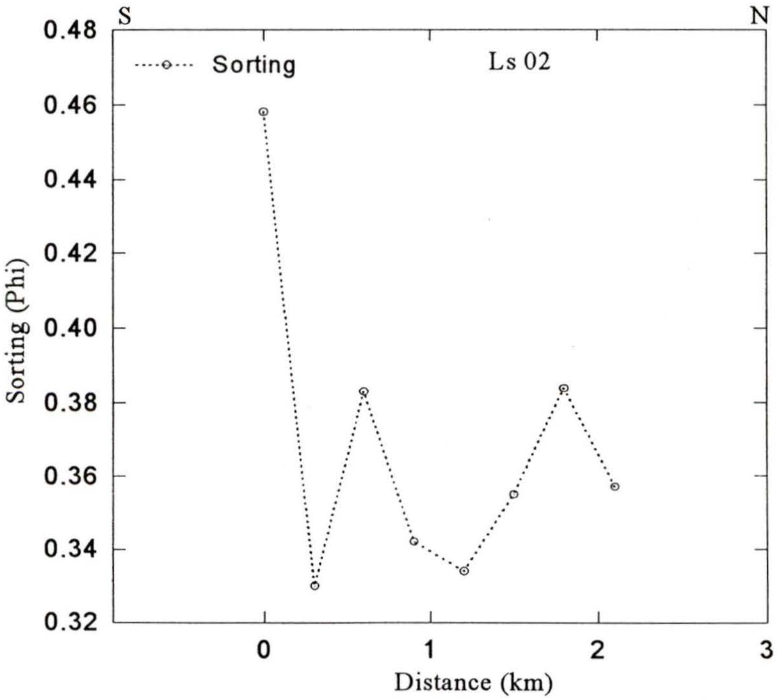

Fig. 18 Variation in the degree of sorting with longshore distance of Ls 02

VI. Discussion

1) Accretion and Erosion

Wave energy along the coast may be accentuated or reduced due to wave refraction by irregular bottom topography, or shoreline configuration (Peterson et al., 1986). In the case of increased energy, either the obliqueness of wave approach to the beach-face is increased, thereby increasing the longshore current velocity and shear stress, or wave convergence results in a localized enhanced wave energy (Komar, 1976). In areas of reduced energy, the waves are either diffracted, reducing the wave energy impacting the beach-face or the swell waves are less oblique to the coast (Komar, 1976).

Enhanced erosion in the last quarters of transects T2 and T3 are probably caused by the steep gradient of their foreshores, and the amplified erosion on transect T2 relative to T1 and T3 could be due to the shoreline configuration at this point or refraction of the incident swell waves, consequently increasing the obliqueness of the waves to the beach-face. This refraction could be caused by the > 1 km shore-attached bar building offshore off the southern section. Accentuated erosion at these points are also evident in plots of Figures 5, 6, 7, 8, 10, and 11 of bulk heavy mineral concentrations, magnetite concentrations and grain sizes versus cross-shore and longshore distances.

Diversions from the normal trend of concentration are observed in Ls 01, Ls 02 and Cs 03, and reduced grain sizes observed in Ls 01, Ls 02, Cs 02 and

Cs 03 as discussed in sections 2 and 3 of this chapter. Enhanced heavy mineral concentration at T2 could also be due to high concentration in the unconsolidated to semi-consolidated relict source which underlies mud sediments presumed to be of Lake Kumara origin and overlies cobbles which are of Pre-Kumara formation but marine (Pers. comm., K. Conway). In either of the environments, lake or marine, the sediments were pre-concentrated by hydraulic processes and preserved. This does not explain the enhanced erosion at transect T2, hence shoreline configuration or wave refraction may be the major factor.

2) Grain Size Distribution.

The grain size distributions within longshore and cross-shore directions transects are a result of selective sorting of beach sediment due to waves and currents operating on the beach-face. The degree of sorting depends on three factors based on field observations: (1) wave climate, (2) geomorphology and (3) time as discussed below.

Ls 01 environment shows a more segregated beach sand and coarser mean grain sizes, both in field and analytical results than Ls 02 despite the low average wind speed of the day and hence less intense waves. This is consistent with increased beach erosion due to high shear stress as a result of increased obliqueness of waves. On the 7th of February, the sediments were transported back to the beach-face but because of low current stress, more time was required to achieve an equivalent sorting level to the Ls 01 environment.

Because the sediments at Ls 02 are at an earlier stage of sorting, grain size distributions are nearly uniform with slight coarsening towards the south, except within an enhanced erosive zone at transect T2, probably due to refraction. Within this zone, the bulk grain size is reduced due to re-entrainment of the larger grains by the amplified current stress. This zone migrates back and forth within the 1km distance north of Cape Fife, as seen from the two grain size minima points in Figure 8 that are out-of-phase, depending on the angle of swell waves to the coast and the condition of the waves (wave height and period). The difference between mean grain size of Ls 01 and Ls 02 samples increases to the south due to high rate of dilution of Ls 01 by larger grains entrained and transported from the north.

The cross-shore grain size segregation during both fair and storm conditions are pronounced due to the greater energy of the backwash currents as a result of the beach profile. As in Ls 01 relative to Ls 02, the mean grain size of Cs 03 is coarser than Cs 02 (Fig. 6) due to increased erosion that leaves behind coarser light mineral grains which are difficult to entrain, hence increasing the bed roughness. The increased bed roughness influences the concentration as discussed below (Chapter VI, Section 3). Reduced grain sizes on the foreshores of transects Cs 02 and Cs 03 (Fig. 6) may be due to increased erosion, as explained in accretion and erosion, because of increased inclination of the profile.

Dispersive pressure, as outlined by Sallenger (1979), acts on larger grains perpendicular to the shear direction creating laminations of heavy mineral concentrations. The laminations are one of the common features seen within a cross-section of many beach sands (Komar, 1976; also see Plate 2). According to Sallenger's (1979) model each lamination would thereby be inversely graded. Komar (1976) observed that beach laminations dominantly consist of finer dark heavy minerals in their basal zones and coarse tan (quartz and feldspar) in the upper zones and that the transition in grain size is gradual. The results obtained from this study (Fig. 7), show no trend for Ds 01 and normal grading for Ds 02. This result in Ds 02 is hard to substantiate due to the increase in heavy mineral concentration discussed in the concentration results below.

3) Concentrations

Heavy mineral distribution for both longshore and cross-shore samples is dependent on the wave and longshore current energy, and on bed roughness (Day and Fletcher, 1991; Slingerland, 1984). Because of differing entrainment stress and transportation rates required by minerals with different grain sizes and subsequently densities, beach minerals are sorted with the heavy minerals forming concentrations behind the lights. The critical shear stress required for the entrainment of coarse grains is very high and these clasts are either left undisturbed or, in case of disturbances during high stress, they get deposited first forming a framework with large voids (Day and Fletcher, 1991). High stress required is probably due to their ability to shed eddies, hence reducing the drag force (Li and Komar, 1992).

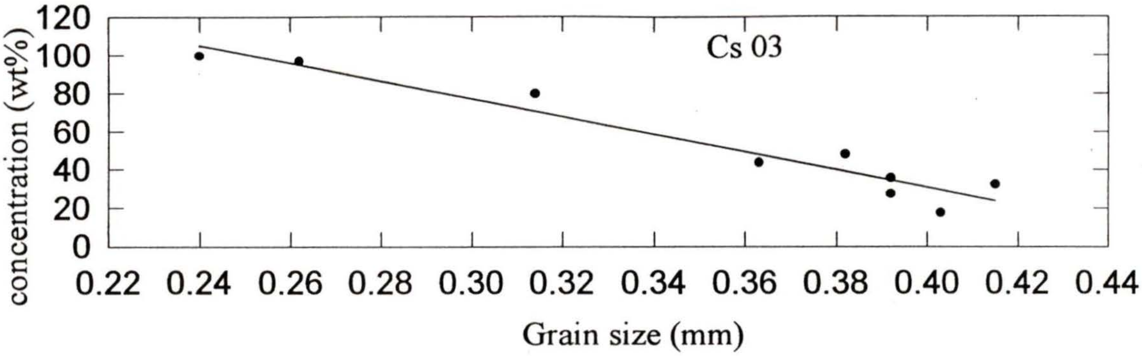

Fig.19 A graph of bulk heavy mineral concentrations within cross-shore samples of transect Cs 03 plotted against mean grain size of the bulk sample (heavy + light minerals).

During high energy conditions, therefore, the bed roughness is high as seen in Ls 01 and Cs 03 (Fig. 5 and 6). At this point the transport rate ratios of the lights to the heavies of sand size is high as outlined in Chapter I section 2.3.4 above.This lag of the heavy minerals behind the lights results in preferential enrichment of the heavies by interstitial entrapment between the framework clasts.

The denser minerals are more effectively trapped than the less dense heavy minerals (Day and Fletcher, 1991). As the stress falls or during fair-weather when sediments are transported back to the beach, the voids get filled with sandy sediments reducing bed roughness relative to the stormy weather environment (e.g. Ls 02). This results in a low transport rate ratio of the lights to the heavies, hence poor selective sorting of the heavy minerals (low concentration in the fair-weather environment).

Longshore samples decrease in heavy mineral concentrations from the northern to the southern limit due to greater stress in the north which decreases gradually to the south. As the stress decreases, light minerals entrained from the north are deposited hence diluting the heavy mineral concentrations toward the south. In cases of increased stress, due to factors outlined above under accretion and erosion (at transect T2), the lights are re-entrained and transported further south. This enhanced stress at transect T2 increased the concentration of heavies at this zone (Fig.8). Due to greater stress and higher

Plate 2. A trench within the study zone shows laminations of heavy and light minerals underlain by thick deposit of heavy minerals.

bed roughness on Ls 01 environment than Ls 02, the heavies are more segregated from the lights as a result of increased transport rate ratios between the lights and the heavies. Consequently, the entrapment of the heavies between the interstices of the coarser grains makes it difficult for them to be entrained, hence a lag concentration forms behind the lights. Ls 01 is therefore, on average, more enriched in heavy minerals than Ls 02 (Fig.8). The higher concentration of Ls 02 relative to Ls 01 in the northern section is probably due to caused increased erosion due to the presence of a boulder. Otherwise it is hard to explain. The shear stress in the Ls 02 environment is probably just enough to entrain the amphiboles and light minerals from the north re-depositing them to the south (Fig.10). The decline in the concentration of individual heavier minerals may be due to dilution. At the point of enhanced erosion, T2, the amphiboles are re-entrained hence the low concentration at this point. The amphiboles in the study area mainly consist of pale to dark green common hornblende with density ranging between 3.02-3.45 g/cm^3, which is similar to that of epidote (3.38-3.49 g/cm^3) (Deer et al., 1977). This should provide a near equivalent hydraulic situation. But Ls 02 shows a marked difference in concentration between amphibole and epidote. This may be due to its immaturity in sorting. It should be realized that although the amphiboles and epidote show increases in concentration to the south, these are percentages of the heavy mineral fraction and not of the bulk sample. The concentration of these minerals with respect to the bulk sample is expected to decrease to the south due to dilution by the lights (quartz and feldspars).

In cross-shore samples, the weight percent concentrations of heavies in Cs 03 samples plotted against the bulk mean grain size show an inverse relationship (Fig.19). This is also evident within Cs 01 and Cs 02 samples (Figs.6 and 11). The mean concentrations in Cs 01, Cs 02 and Cs 03 increases from south to north but the mean grain size of Cs 03 exceed that of Cs 02. The high concentration is therefore probably due to the hiding factor of heavies within the coarser light mineral interstices. An increase in concentration within the lower quarter of Cs 02 and Cs 03 transects may be due to an increase in the inclination of the profile. The amphibole and the epidote in Cs 03 show near equivalent hydraulic properties (e.g. their concentrations are nearly equal and both increase to the lower shoreface at nearly the same rate) (Fig.13).

Exceptionally high concentrations of heavy minerals above background exist within the neighbourhood of clasts as a result of flow separation on their upper-face (Best and Brayshaw, 1985). Due to this separation, flow velocities are accelerated or decelerated in certain zones within the vicinity of the clast. On the upper-face of the clast, the flow velocity is decelerated. Greatest velocity is achieved at the obstacle's flanks due to flow convergence at these points. The enhanced flow velocity is subsequently followed by a rapid deceleration at the lower-face of the obstacle before converging back to background flow velocity (Best and Brayshaw, 1985). The rapid deceleration on the lower-face sorts the heavy and the light minerals at least according to density as observed from the distinctive colours away from the obstacle. The light minerals which require low entrainment stress are further transported downstream leaving the heavies behind.

Shear sorting on each lamination would result in heavy minerals migrating to the basal zone. Repeated shearing of beach sediment, as described in section 2.3.2, may result in a placer deposits as seen from the common association of placer deposit beneath laminations (Komar, 1976; see also Plate 2). The data obtained from the study indicate an increase in bulk concentration from the first to the second layer in Ds 01 and relatively constant in subsequent layers (Fig. 14). This could be due to immaturity of the beach sediment during its collection period. Ds 02 shows an increase in concentration with depth which could be due to shear sorting. This result is supported by the increase in individual heavy mineral concentrations of the magnetite, opaques, garnet and epidote, and a decrease in amphibole concentrations with depth relative to the heavy mineral fraction (Fig. 14 and 15). Light minerals would decrease in concentrations with depth due to increase in bulk heavy mineral concentrations with depth. The laminations would, therefore, show a gradual contrast between dark and light zones, but the interface between adjacent laminations would be sharply delineated (Plate 2).

4) <u>Sorting</u>

The sorting result shown in Figure 17a, b and c suggest that the effects of size and density act together in the segregation of beach sand. In addition to size, sorting is dependent on density of the sediment particles. A decrease in the degree of sorting is also caused probably by the entrapment of the finer grains in the voids of coarser grains which get which increase with distance across-shore. Minerals of significant difference in density from the lights (e.g. magnetite, opaque and garnet) are deposited between 0 - 30m distance from the upper shore-face in Cs 03 while those of near equivalent size, (light heavies, amphiboles and epidote, and the light minerals, quartz and feldspar), deposited beyond 30m distance. This increases the degree of sorting in these areas (>30m) despite an increase in bulk heavies concentrations (Fig.11 and 17b). In an immature and less erosive environment, Ls 02, there is no clear correlation between the degree of sorting to heavy mineral concentrations and grain sizes (Fig.18). This could only be inferred to be due to its immaturity but hard to substantiate since weaker trends are evident within the grain size, bulk heavies and individual heavies concentrations. This weaker trend should have been evident within the sorting trend. The greater difference between the concentrations of the amphiboles and epidotes also support immaturity. Sallenger's (1979) hypothesis of vertical sorting of grains by density and size due to dispersive pressure exerted on them could not be accounted for by the sorting results. This hypothesis calls for a near equivalent degree of sorting or an increase with depth since larger grains provide voids for the entrapment of finer grains, subsequently decreasing the value of sorting.

5) Summary

Rubey's (1933) concept of hydraulic equivalence is insufficient in accounting for grain-by-grain heavy mineral sorting on the beach-face at this site. The increase in heavy mineral concentrations within the vicinity of obstacles and the segregation of mineral grains into various colours as seen on the beach cannot be accounted for under this concept. Although sorting according to settling rates is insignificant in placer formation, it enhances the probability within the initial stages by depositing mineral grains of high and of nearly equivalent settling rates on the beach-face as noted by Komar and Wang (1984). This equivalence, therefore, results in an inverse relationship between density and grain sizes of beach minerals which are important properties in subsequent sorting processes.

According to Bagnold's (1954) and Sallenger's (1979) concept, heavy minerals are concentrated as a result of dispersive pressure acting on larger grains, creating inversely graded lamina. Heavy minerals would, therefore, reside within the basal layers of each lamina due to the inverse relationship between density and size of beach minerals. The degree of sorting would also be nearly equal or increase with depth. The results obtained in this study are contrary to this concept since the mean grain size of Ds 02 increases while its sorting degree decreases with depth. That of Ds 01 shows no clear trend due to sediment immaturity. Although this process was insignificant during this study, its role in placer formation could not be ruled out due the existence of many placer deposits beneath laminations. The increase in both concentration and grain sizes with depth of the maturely sorted Ds 02 samples is hard to account for. Where shear sorting processes are active, other concentration processes would still be required to remove the light minerals and subsequently form placer deposits.

Field observations and analytical results from this study point extensively to the significance of selective grain entrainment and differential transport in heavy mineral concentration. The distinctive colours of mineral grains across-shore and in the vicinity of obstacles are an indication of the role of grain size and density in heavy mineral concentration. Denser minerals which, consequently, have finer grain sizes require greater entrainment stress than their lighter counterparts to initiate their movement. This is essentially due to their low projection within the velocity profile. They therefore form deposits while the lighter minerals are transported further. In zones of accentuated erosion, where entrainment stress exceeds that required by light minerals which stand higher in the profile, heavy mineral concentrations stand higher. The distribution of epidote and amphiboles within cross-shore, longshore and depth samples are nearly the same due to their near equivalent densities and sizes, and consequently their hydraulic behaviours. Due to low densities relative to their heavier counterparts (magnetite, opaque and garnet), the physical concentration processes are not as effective in separating them from the lights. Their concentrations (epidote and amphiboles), therefore increase in the transport direction. The effect of density could also be deduced from the sorting curves. Without the influence of density, the degree of sorting would be nearly constant.

Apart from the physical properties of the minerals in transport, heavy mineral concentration is also controlled by external factors like bathymetry, wave climate and shoreline configuration. The bathymetry accentuates or reduces wave energy impacting the shore-line by refracting the swell waves. In cases of accentuated energy, the resulting waves are either more oblique or the flow accelerated due to wave convergence. Heavy mineral concentration is more effective during storms and periods of high energy than during fair weather. During the storm conditions on the 8th of February, the mean concentration of heavy minerals was higher than during other periods. Longshore current energy is also influenced by the obliqueness of wave approach to the shore. The more oblique the waves to the coast the greater the energy. Hence shoreline configuration would also influence the longshore current energy.

6) Placer Potential

No work was done to determine the potential of placer development in the study area. Following previous works and field observation during the study period, the following tentative remarks governing long- and short-term development of placer deposits on the study area can be made.

The eastern continental shelf of the Queen Charlotte Islands provides a conducive environment for the development of placer deposits. The climate, oceanography and the physiography of the region play a great role in achieving this development. As previously discussed, during the Pleistocene period a glacial refugium existed on Queen Charlotte Island. This limited the dispersal of previously worked sediments. During sea level fall in the Late Pleistocene, the nearshore areas were flushed of their sediment deposits. These sediments were subsequently concentrated in patches by shoaling waves and tidal currents on the continental shelf. During subsequent rapid sea level rise between 10.5 and 9.5 k.a., these concentrations were preserved forming relict placers. The fluvial channels that extended into the continental shelf were drowned by this rapidly transgressing sea (Fig. 20) (Barrie, 1994). The present fall in sea level scours these relict placers and reconcentrates them while less sediment is introduced by the small rivers. The eastern coast of Queen Charlotte Islands exist on a

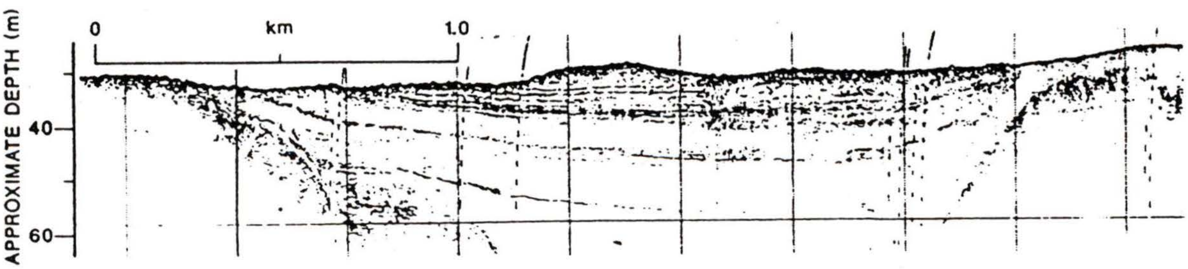

Fig. 20. Submerged river channel that flowed into the Continental Shelf during sea level low stand (from Barrie, 1994).

tectonically active margin. Nevertheless, the shelf has been relatively stable over a period of time since the tectonism is strike slip, hence non destructive. The reworking of the sediments has therefore existed for an extended period of time. It is also storm-dominated and open to swell waves hence the wave energy generated is sufficient for the erosion of source materials and selective sorting of the sediments. Modern placers should therefore be more enriched than relict placers due to the extensive period of reworking with limited terrestrial dilution. The light minerals are also easily broken down into finer grains and would eventually be carried offshore. There is therefore a possibility of placer potential within the submerged continental shelf and on Modern beaches.

Other than the four local processes (suspension, shear, entrainment and transport sorting) discussed above, a short-term (diurnal) development of placer deposits are also depended on three other local variables (Slingerland, 1984 and Luepke, 1980):

(1) Material availability

(2) The volume of material processed through time

(3) The flow strength

The availability of heavy minerals on the beach is principally governed by their presence at the source area(s). Samson (1984) reported a placer gold production in the early 1900s on the east coast of Graham Island which yielded up to 715 troy ounces. The gold was fine grained and probably transported from Alaska, from the mainland of British Columbia or from within the Queen Charlotte

Island, possibly from both (Barrie, 1994). Holland and Nasmith's (1958) documentation and the finding of this study indicate that the heavy mineral suite contains hematite and ilmenite, magnetite, garnet, quartz and feldspar, hornblende, epidote, zircon, staurolite, sphene, and rutile. The population density of these heavy minerals within the source will determine the general level of concentration on the beach. The two samples obtained from the unconsolidated Pleistocene bluffs indicate a concentration of between 16 and 22 wt%, and one sample obtained from the sand dunes contains approximately 14 wt% heavy minerals (Appendix A). Reconcentration of these relict sediments would yield a much higher concentration as observed from plate 3.

Plate 3. Heavy mineral concentrations within a trench cut on the beach face of the study area. It shows the effect of sedimentation rates to heavy mineral concentrations.

The rate of sedimentation may also influence the degree of sorting. When the rate is higher than that sufficient for the flow to sort, then only a weak concentration of the heavy minerals will occur. Plates 1 and 2 show the effect of changes in sedimentation rates on a beach to heavy mineral concentrations. The lighter units indicating low concentrations of heavy minerals were probably deposited during higher sedimentation rates than the darker units of heavy minerals. The lower rates of deposition within the darker units allowed enough time for the sediment to be sorted.

When shear stress required by beach sediment to initiate movement is exceeded by the local flow strength, all the minerals would be transported and re-deposited within a conducive environmental setting. The deposits are therefore transient.

vii. Conclusions

1. Modern beach sediment on the eastern Graham Island is derived mainly from nearby unconsolidated Pleistocene bluffs and dunes.

2. The heavy mineral component of the sediments consists predominantly of amphiboles, garnet, magnetite, non-magnetite opaques and epidote.

3. Placer development is affected by wave and current sorting. This is influenced by mineral properties, wave climate and physiography.

4. Mineral densities and sizes act together in the enrichment of heavy minerals.

5. Due to greater densities and small sizes of heavy minerals, and because of their ability to hide within the interstices of coarser grains, they require greater entrainment stress than the light minerals to initiate their movement. Dense minerals are therefore deposited away from the transport direction while light minerals that are easily entrained are transported further.

6. The distribution of amphiboles and epidote relative to the bulk heavy mineral concentrations resemble light mineral distributions due to their nearly equivalent densities and sizes to the light minerals.

7. Within zones of enhanced erosion, light minerals which are more exposed to the velocity profile are easily re-entrained leaving heavy minerals as lag deposits. Heavy minerals form in zones where erosion dominates over deposition.

8. Increased erosion of beach sediments could be caused by enhanced energy of incident swell waves. Incident angle of wave approach, bathymetry and shoreline configuration are as well important factors aiding to achieve this condition.

9. Among the four processes identified as resulting in heavy mineral enrichment, entrainment and transport sorting play the most significant roles. Suspension and shear sorting play some role but are insignificant relative to entrainment and transport sorting.

10. The eastern Coast of Queen Charlotte Island has a great potential for heavy mineral exploitation for modern deposits and probably for submerged relict deposits. However, the occurrence of modern deposits would be intermittent due to their transient nature.

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APPENDIX A

Samples	Gr. size(mm)	Conc. Hv. Wt%	Sorting(Phi)	Sorting(mm)
Ls 01-01	0.5590	10.8000	0.6830	0.6230
Ls 01-02	0.5360	12.7500	0.7470	0.5960
Ls 01-03	0.4510	23.6800	0.5680	0.6750
Ls 01-04	0.3980	39.4500	0.4240	0.7450
Ls 01-05	0.5430	20.3500	0.7600	0.5900
Ls 01-06	0.5140	18.0600	0.6520	0.6360
Ls 01-07	0.4090	22.2500	0.4450	0.7350
Ls 01-08	0.3250	50.0000	0.3670	0.7750
Ls 02-01	0.4030	9.0900	0.4580	0.7280
Ls 02-02	0.3340	12.3400	0.3300	0.7960
Ls 02-03	0.3490	13.0500	0.3830	0.7670
Ls 02-04	0.3790	12.5900	0.3420	0.7890
Ls 02-05	0.3660	5.2800	0.3340	0.7930
Ls 02-06	0.3630	22.6900	0.3550	0.7820
Ls 02-07	0.3460	23.5700	0.3840	0.7660
Ls 02-08	0.3510	60.2400	0.3570	0.7810
Cs 01-01	0.2950	67.9500	0.4610	0.7260
Cs 01-02	0.4510	24.4200	0.5980	0.6610
Cs 01-03	0.6780	9.8500	0.4940	0.7100
Cs 01-04	1.2230	3.2300		
Cs 02-01	0.2410	98.1700		
Cs 02-02	0.3100	30.4800		
Cs 02-03	0.3660	10.9600		
Cs 02-04	0.5000	19.9500		
Cs 02-05	0.9200	3.7900		
Cs 02-06	1.3100			
Cs 03-01	0.2380	99.5900	0.2780	0.8250
Cs 03-02	0.2660	96.7700	0.3220	0.8000
Cs 03-03	0.3140	79.8700	0.4280	0.7430
Cs 03-04	0.3630	43.5400	0.5010	0.7070
Cs 03-05	0.3980	35.5100	0.6180	0.6520
Cs 03-06	0.4440	32.0500	0.7800	0.5820
Cs 03-07	0.3870	48.0800	0.5800	0.6690
Cs 03-08	0.4030	17.4700	0.4170	0.7490
Cs 03-09	0.3920	27.2500	0.4110	0.7520

Samples	Gr. size(mm)	Conc. Hv. Wt%	Sorting(Phi)	Sorting(mm)
Ds 01-01	0.3440	16.8100		
Ds 01-02	0.3160	30.2800		
Ds 01-03	0.3240	29.1900		
Ds 01-04	0.3210	28.2500		
Ds 01-05	0.3120	27.4900		
Ds 01-06	0.3120	28.8200		
Ds 01-07	0.3230	30.1200		
Ds 02-01	0.3560	10.2300	0.2380	0.8480
Ds 02-02	0.3340	18.7500	0.2730	0.8280
Ds 02-03	0.3490	26.9900	0.3000	0.8120
Ds 02-04	0.3540	38.3300	0.3200	0.8010
Ds 02-05	0.3630	50.4800	0.3360	0.7920
Ds 02-06	0.3690	51.8900	0.3410	0.7890
Ds 02-07	0.3630	52.3700	0.3670	0.7750
Rs-01	15.7100			
Rs-02	21.9800			
Rs-03	14.4900			

APPENDIX B

Samples	Magnetite(wt%)	Opaque (no.%)	Garnet (no.%)	Amphibole (no.%)
Ls 02-01	0.4700	4.6700	13.3300	14.0000
Ls 02-02	0.4700	5.6700	12.3300	13.0000
Ls 02-03	4.5000	3.3300	12.3300	14.3300
Ls 02-04	0.1900	1.0000	13.0000	9.0000
Ls 02-05	0.1100	1.3300	6.3300	12.6700
Ls 02-06	0.7400	7.0000	20.6700	15.0000
Ls 02-07	1.2900	14.0000	19.3300	9.3300
Ls 02-08	5.3100	31.6700	43.3300	7.6700
Cs 03-01	30.6100	79.0000	14.6700	2.3300
Cs 03-02	22.8300	29.0000	54.0000	4.3300
Cs 03-03	10.0700	17.6700	44.3300	9.3300
Cs 03-04	5.1000	19.3300	34.0000	9.0000
Cs 03-05	4.8000	35.0000	30.6700	5.0000
Cs 03-06	3.8400	18.0000	33.0000	8.3300
Cs 03-07	5.1300	47.0000	24.3300	7.6700
Cs 03-08	0.7600	13.3300	17.6700	14.6700
Cs 03-09	1.1600	7.0000	24.6700	18.0000
Ds 02-01	0.0000	1.0000	10.6700	10.0000
Ds 02-02	0.0000	0.0000	11.3300	11.3300
Ds 02-03	0.5100	0.3300	17.3300	12.6700
Ds 02-04	0.5700	4.0000	24.3300	6.6700
Ds 02-05	1.5400	6.0000	37.0000	11.6700
Ds 02-06	1.9700	9.0000	32.0000	12.3300
Ds 02-07	2.2700	11.6700	31.0000	8.3300
Ls 02-01	14.0000	0.6700	0.0000	0.0000
Ls 02-02	13.0000	0.3300	0.0000	0.0000
Ls 02-03	14.3300	0.6700	0.3300	0.0000
Ls 02-04	9.0000	0.3300	0.3300	0.0000
Ls 02-05	12.6700	0.3300	0.0000	0.0000
Ls 02-06	15.0000	0.6700	0.0000	0.0000
Ls 02-07	9.3300	0.6700	0.0000	0.0000
Ls 02-08	7.6700	0.3300	0.0000	0.0000

Appendix B Cont..

Samples	Epidote(no.%)	Sphene(no.%)	Rutile(no.%)	Zircon(no.%)
Cs 03-01	2.3300	2.3300	0.0000	0.0000
Cs 03-02	4.3300	2.0000	0.0000	0.0000
Cs 03-03	9.3300	1.6700	0.3300	0.0000
Cs 03-04	9.0000	1.3300	0.3300	0.0000
Cs 03-05	5.0000	1.6700	0.0000	0.0000
Cs 03-06	8.3300	1.0000	0.3300	0.0000
Cs 03-07	7.6700	1.6700	0.0000	0.0000
Cs 03-08	14.6700	0.6700	0.3300	0.0000
Cs 03-09	18.0000	0.3300	0.0000	0.0000
Ds 02-01	10.0000	0.0000	0.3300	0.0000
Ds 02-02	11.3300	1.0000	0.3300	0.0000
Ds 02-03	12.6700	0.3300	0.6700	0.3300
Ds 02-04	6.6700	0.6700	0.6700	0.6700
Ds 02-05	11.6700	0.3300	0.6700	0.0000
Ds 02-06	12.3300	0.3300	0.6700	0.0000
Ds 02-07	8.3300	0.6700	1.6700	0.0000

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