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SEDIMENTS OF THE CENTRAL AND SOUTHERN STRAIT OF GEORGIA, BRITISH COLUMBIA

by

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ABSTRACT

A study of the distribution, dispersal and composition of surficial sediments in the Strait of Georgia, B.C., has resulted in the understanding of basic sedimentologic conditions within this area. The Strait of Georgia is a long, narrow, semi-enclosed basin with a restricted circulation and a single, main, sediment source. The Fraser River supplies practically all the sediment now being deposited in the Strait of Georgia, the bulk of it during the spring and summer freshet. This river is building a delta into the Strait from the east side near the south end. Ridges of Pleistocene deposits within the Strait and Pleistocene material around the margins, like bedrock exposures, provide local sources of sediment of only minor importance. Rivers and streams other than the Fraser contribute insignificant quantities of sediment to the Strait.

Sandy sediments are concentrated in the vicinity of the delta, and in the area to the south and southeast. Mean grain size decreases from the delta toward the northwest along the axis of the Strait, and basinwards from the margins. Silts and clays are deposited in deep water west and north of the delta front, and in deep basins northwest of the delta. Poorly sorted sediments containing a gravel component are located near tidal passes, on the Vancouver Island shelf area, on ridge tops within the Strait, and with sandy sediments at the southeastern end of the study area. The Pleistocene ridges are areas of non-deposition, having at most a thin veneer of modern mud on their crests and upper flanks. The southeastern end of the study area contains a thick wedge of sandy sediment which appears to be part of an earlier delta of the Fraser River. Evidence suggests that it is now a site of active

submarine erosion.

Sediments throughout the Strait are compositionally extremely similar, with Pleistocene deposits of the Fraser River drainage basin providing the principal, heterogeneous source. Gravels and coarse sands are composed primarily of lithic fragments, dominantly of dioritic to granodioritic composition. Sand fractions exhibit increasing simplicity of mineralogy with decreasing grain-size. Quartz, felspar, amphibole and fine-grained lithic fragments are the dominant constituents of the finer sand grades. Coarse and medium silt fractions have compositions similar to the fine sands. Fine silts show an increase in abundance of phyllosilicate material, a feature even more evident in the clay-size fractions. Montmorillonite, illite, chlorite, quartz and felspar are the main minerals in the coarse clay fraction, with minor mixed-layer clays and kaolinite. The fine clay fraction is dominated by montmorillonite, with lesser amounts of illite and chlorite.

The sediments have high base-exchange capacities, related to a considerable content of montmorillonite. Magnesium is present in exchange positions in greater quantity in Georgia Strait sediments than in sediments from the Fraser River, indicating a preferential uptake of this element in the marine environment. Manganese nodules collected from two localities in the Strait imply slow sediment accumulation rates at these sites. Sedimentation rates on and close to the delta, and in the deep basins to the northwest, are high.

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The considerable help, understanding and devotion of my wife Sue, who has withstood the disadvantages of being the wife of a graduate student and can still smile, has been a major factor in the successful completion of this thesis.

FRONTISPIECE

Floccule structure within a glauconite pellet

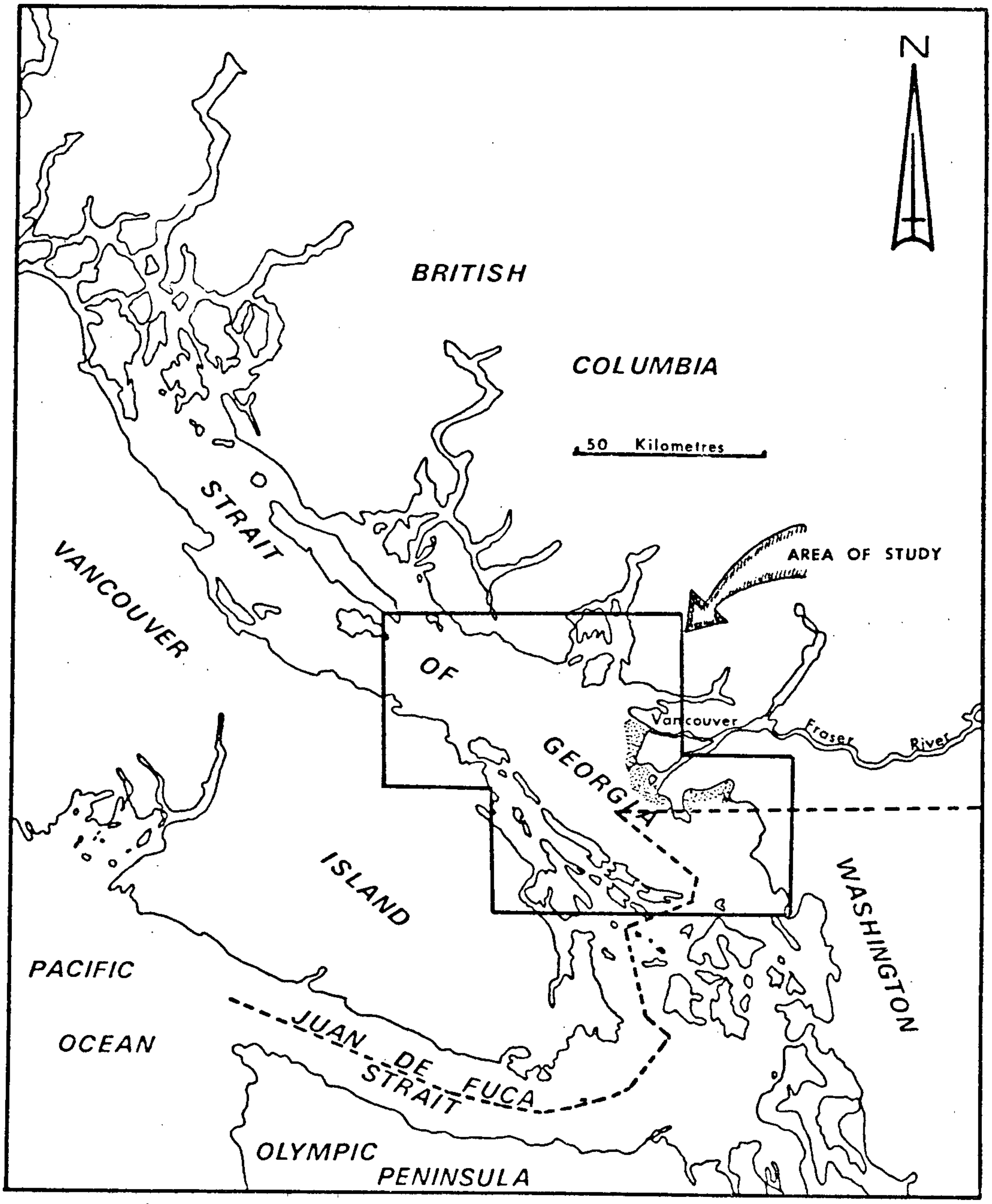


FIGURE 1: *Location of the study area in southwestern British Columbia, Canada, and northwestern Washington, U.S.A.*

for transportation, sport and recreation, as well as for disposal of sewerage, garbage and other waste material.

The long axis of the Strait of Georgia extends in a north-westerly direction from the U.S. San Juan Islands in the south to Quadra Island in the north, between latitudes 40°50'N and 50°00'N, a distance of some 225 kilometres (Figure 1). Access to the open Pacific Ocean is achieved in the south by way of Juan de Fuca Strait, through the partial barrier of the Canadian Gulf Islands and the U.S. San Juan archipelago. To the north connection with the Pacific is made through numerous narrow channels.

Of the total length of the Strait, only the southern 110 kilometres between latitudes 48°50'N and 49°26'N are included in this study, which covers the area extending from Alden Ridge in the south to Ballenas Islands in the north. Within this area the Strait has an average width of 28 kilometres, varying between 17½ kilometres just south of Texada Island to 35 kilometres between Valdes Island and Point Grey. Topography in the Strait varies considerably from the smooth fan of sediments of the Fraser River delta that extends almost completely across the Strait, to the rugged region of steep-sided banks and ridges separating deep, flat-floored basins in the north (see map, Figure 2). Tabular summaries of the dimensions and parameters of the Strait of Georgia are available in Waldichuk (1957), Mathews, Murray, and McMillan (1966) and Tiffin (1969).

High mountains of the Vancouver Island Range to the west are separated from the Strait by a broad, low-lying, emergent portion of the Georgia Depression (Holland, 1964). On the east side, north of Burrard Inlet, the Mainland Coast Range rises almost directly above the

Strait, being separated in only a few places by a narrow strip of lowland. South of Burrard Inlet the Strait is bordered by the extensive, low-lying, flattish expanse of the Fraser Lowland.

Names of geographic features referred to throughout the text are given in Figure 2.

1.2 GEOLOGIC SETTING

A generalised geological sketch map of the area surrounding the Central and Southern Strait of Georgia is presented in Figure 3.

The area lies in the "...western part of the 'Paleozoic-Mesozoic Cordilleran volcanic orogenic belt' or Pacific engeosyncline..." (Danner, 1968, p.2). It is part of a long, linear structural depression that extends from the Gulf of California in the south through the Great Valley of California, Willamette Valley Oregon, Puget Sound Washington, Georgia Depression British Columbia, to Dixon Entrance Alaska, where it seems to disappear. A large part of this depression is near to or below sea-level, but is actually inundated only in British Columbia and part of the Washington and California sections. The Strait of Georgia is the submerged portion of the Georgia Depression (Holland, 1964) which extends along the coast of British Columbia between Vancouver Island and the Mainland. Emergent portions of Georgia Depression flank the Strait on either side, and are known as the Georgia Lowland on the mainland side and the Nanaimo Lowland along the east coast of Vancouver Island.

The Georgia Lowland forms a narrow strip ranging from four to eighteen kilometres in width and representing in large part an elevated Tertiary erosional surface (Holland, 1964, p.36). South of Burrard Inlet the Georgia Lowland is called the Fraser Lowland, a large,

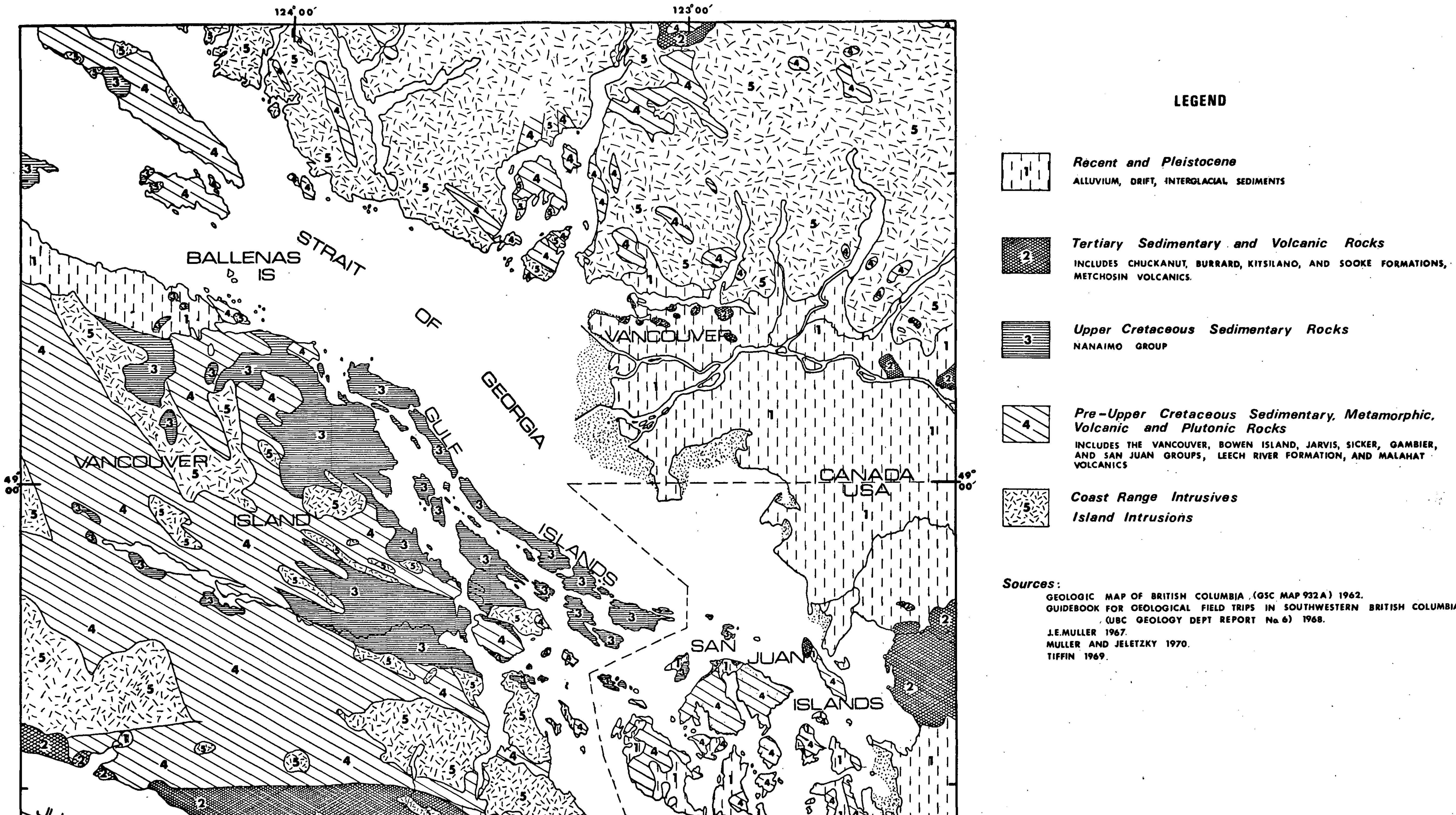


Figure 3: *GEOLOGICAL SKETCH MAP OF THE AREA AROUND THE CENTRAL AND SOUTHERN STRAIT OF GEORGIA, BRITISH COLUMBIA, CANADA, AND WASHINGTON, U.S.A.*

triangular-shaped feature of low relief believed to be largely depositional in origin (Holland, 1964). The Nanaimo Lowland is a post-Cretaceous erosional feature that has been modified locally by glacial erosion and deposition of a mantle of glacial and fluvioglacial material. It is underlain by a thick sequence (5,000 feet to 10,000 feet) of marine and non-marine Upper Cretaceous strata of the Nanaimo Group (Clapp, 1912, 1913, 1914, 1917; Usher, 1952; Muller and Jeletzky, 1970) deposited in two basins which were separated by two uplifted ridges of pre-Mesozoic rocks that trend northward from the Nanoose area on Vancouver Island (Muller and Jeletzky, 1967).

North of Burrard Inlet the Georgia Lowland is underlain by granitic intrusions of the Coast Crystalline Belt (Holland, 1964; Roddick, 1965) plus inliers of older rocks. To the south the crystalline basement lies under some 15,000 feet of late Cretaceous, Tertiary and Quaternary continental and marine sediments (Roddick, 1965; Hopkins, 1966; Mathews, Murray and McMillan, 1966). Apart from an inlier of probable Mid- to Upper- Cretaceous greywackes and argillites in the Garibaldi area (Mathews, 1958), there is no definitely known equivalent of the Nanaimo Group on the B.C. mainland. There is still some controversy as to whether the uppermost Nanaimo Group (Gabriola Formation) is Palaeocene rather than Late Cretaceous in age and therefore correlatable with the Burrard and Kitsilano Formations, or whether on the other hand the lower part of the Burrard Formation is Late Cretaceous in age (McGugan, 1962; Rouse, 1962; Crickmay and Pocock, 1963; Hopkins, 1966; Scott, 1967).

The Fraser Lowland, extending eastward from Georgia Strait as a broadly triangular reentrant, occurs in an area that was once the site of a structural depression known as the Whatcom Basin (Hopkins, 1966). This basin, which extended eastward from the coast to Laidlaw, B.C. then southwestward to Bellingham, Washington, is floored by Late Cretaceous rocks overlying crystalline basement, and is bounded to the south by Late Cretaceous to Early Tertiary continental sediments of the Chuckanut Formation. Hopkins (1966) did not regard either the Late Cretaceous or the Chuckanut to be part of the Whatcom Basin fill, but instead he related them to a once more extensive region of marine and continental sedimentation that included the area over which the Nanaimo Group now outcrops.

Knowledge of the rocks in the Whatcom Basin is largely restricted to information obtained from drill cores, augmented by scattered outcrops around the basin margin, road cuts, and some tunnels. A thick, luxuriant vegetative cover, deep weathering of surface material, and a thick mantle of Pleistocene deposits are severe restrictions to the accessibility and area of outcrops. The basin is filled with a thick sequence of continental deposits; no marine rocks have been identified from drill core or in outcrop. Tertiary sediments, and the underlying Cretaceous, lap on to the intrusive complex of the Coast Mountains (see Roddick, 1965), dipping southward toward the centre of the basin. To the east and south Tertiary rocks wedge out on pre-Tertiary metamorphic and ultrabasic rocks of Canadian and American Sumas Mountains, and upon the Palaeocene Chuckanut Formation. The thickness of sediment in the basin, the consistent basinward dips of strata from north and south rims of the basin, the thickening of beds and formations toward the centre of the basin, and the inclusion of younger strata that seem to wedge out to the north, south of Burrard Inlet (Roddick, 1965; Mathews, Murray and McMillan, 1966), suggest that persistent if intermittent subsidence and deposition took place throughout the Late Mesozoic and Tertiary. No Tertiary rocks similar to those of the Whatcom Basin occur on eastern Vancouver Island, and later Tertiary sediments, believed to be several thousand feet thick, are known only from drill-holes in the Fraser Lowland.

A descriptive summary and references to other stratigraphic analyses are given by Hopkins (1966) for the Tertiary formations in the Whatcom Basin. Roddick (1965) has presented a detailed account of the geology and petrology of the southern Coast Mountains. The geology of southeastern Vancouver Island has been discussed by Clapp (1921, 1913, 1914, 1917), Usher (1952), Muller (1967), and Muller and Jeletzky (1967, 1970).

Pleistocene deposits are both widespread and thick, locally reaching a cumulative thickness of 1700 feet (Johnston, 1923; Armstrong and Brown, 1954; Armstrong, 1956, 1957, 1960; Fyles, 1963; Armstrong et al., 1965). Late- and post- Pleistocene sediments, both of periglacial origin and modern river deposition, have accumulated locally to thicknesses in excess of 1000 feet (Mathews and Shepard, 1962). Since the end of the Pleistocene the Fraser River has constructed a delta extending westward into the Strait of Georgia some 16 miles from New Westminster (Mathews and Shepard, 1962).

The trend of the Strait is similar to that of the structures in the flanking rocks, especially on the western side in the Nanaimo Group. Muller (1967) advanced the idea that the pattern of faulting in the Nanaimo Group rocks might represent splays of one or more major faults along the east coast of Vancouver Island, the pattern being of numerous fault-bounded blocks tilted toward the northeast and downthrown to the southwest. Tiffin (1969) advocated a similar block-faulted origin for the southern Island slope ridges, although he considered the downthrown side to be to the northeast; i.e., opposite to that of Muller (1967). Faulting along the line of the Vancouver Island slope followed downflexing of the Strait of Georgia associated with the uplift of the Coast Mountains. Maximum depression of the basin axis occurred along the western side of the Strait. The dominance of faulting rather than folding in the Insular Belt (area west of the mainland coast) is advocated by Sutherland-Brown (1966), Muller (1967), and by Muller and Jeletzky (1967, 1970). Bedrock structures, probably fault-controlled, are visible in some of Tiffin's (1969) seismic profiles. The occurrence of fault-bounded blocks of Nanaimo Group sediments 5000 feet above sea-level in the Alberni and Cowichan areas (Fyles, 1963; Muller and Jeletzky, 1967) indicates that block-faulting may well have been the common structural feature of the Nanaimo Group rocks, but the direction of throw may not have been consistent. The available evidence supports the contention that the original control on the origin of the Strait of Georgia was tectonic.

1.3 GEOLOGIC HISTORY

Deciphering the geologic history of the area of the Strait is made difficult by the lack of outcrop and by the poor resolution of bedrock types in seismic profiles. Between the Late Cretaceous and Pleistocene much of the geologic record is blank. The outline of the

CORRELATION OF KNOWN PACIFIC NORTHWEST PALEOZOIC FORMATIONS

PERIOD SYSTEM		EPOCH-SERIES	VANCOUVER ISLAND SAN JUAN ISLANDS STRAIT OF GEORGIA	CASCADE MTS. OF B.C. & WASHINGTON (NORTH OF 48° 30')	B.C. INTERIOR: ASHCROFT-KAMLOOPS PRINCETON
PERMIAN	UPPER	OCHOAN			
		GUADALUPIAN	TRAFTON		MARBLE CANYON; UP. HARPER R.
	LOWER	LEONARDIAN	UPPER SICKER; UPPER CHILLIWACK	UPPER CHILLIWACK (WASH.) | (B.C.)	MIDDLE HARPER RANCH
		WOLFCAMPIAN			
PENNSYLVANIAN	UPPER	VIRGILIAN		PLANT-BEARING CLASTICS (WASH.) (B.C.)	
		MISSOURIAN	?		
	MIDDLE	DESMOINESIAN	LOWER SICKER		
		LAMPASAN-ATOKAN	MIDDLE CHILLIWACK (SJ) ?	? ?	? LOWER HARPER RANCH ?
	LOWER	MORROWAN	?	MIDDLE CHILLIWACK ? (WASH) ? (B.C.)	
MISSISSIPPIAN	UPPER	CHESTERIAN	NONE RECOGNIZED IN MAP AREA		
		MERAMECIAN			
	LOWER	OSAGEAN			
		KINDERHOOKAN			
DEVONIAN	UPPER	BRADFORDIAN			
		CHAUTAUQUAN			
		SENECAN	?	?	
	MIDDLE	ERIAN	PRESIDENT CHANNEL BEDS (S.J.)	LOWER CHILLIWACK	
	LOWER	ULSTERIAN			
PRE-DEVONIAN			? TURTLEBACK COMPLEX (S.J.)	SCHISTS OF VEDDER MT (B.C.) YELLOW ASTER COMPLEX (WASH.) ETC.	

TABLE 1: Stratigraphic relationships of known formations in the Lower Mainland, Northern Washington and Interior of British Columbia. From Danner (1968).

CORRELATION OF KNOWN PACIFIC NORTHWEST MESOZOIC FORMATIONS

PERIOD SYSTEM		EPOCH-SERIES	TEXADA IS. E.VANC IS. SAN JUAN IS. STRAIT OF GEORGIA	CASCADE MTS. OF B.C.-WASHINGTON NORTH OF 48°30'	B.C. INTERIOR: ASHCROFT-KAMLOOPS HOPE PRINCETON
CRETACEOUS	UPPER	DANIAN	LOWER CHUCKANUT ? (S.J); NANAIMO GROUP (T.IS., V.IS., S.J) ?	LOWER CHUCKANUT ?	
		MAESTRICHTIAN	CHEAKAMUS FM, COAST MTS ?; LOPEZ IS. PILLOW LAVAS GREYWACKES ?		
		SENONIAN			
		TURONIAN			PASAYTEN
		CENOMANIAN			GROUP (WASH) (B.C)
	LOWER	ALBIAN			KINGSVALE (B.C)
		APTIAN			SPENCE BRIDGE
		BARREMIAN			
		HAUTERIVIAN	?	? BROKENBACK	JACKASS
		VALANGINIAN	SPIEDEN FORMATION (S.J) ?	NOOKSACK / HILL FM ?	MT. / BREW-LILLOOET GROUP
		BERRIASIAN		PENINSULA FM (B.C)	GROUP
JURASSIC	UPPER	PORTLANDIAN		GROUP	DEWDNEY CREEK GROUP
		KIMMERIDGIAN		(WASH) / AGASSIZ	
		OXFORDIAN		PRAIRIE FM.	
		CALLOVIAN		KENT BILLHOOK MYSTERIOUS CREEK	ASHCROFT GROUP
	MIDDLE	BATHONIAN		(B.C) ?	
		BAJOCIAN		NOOKSACK / CHEHALIS VOLCANICS? HARRISON	LADNER GROUP / THOMPSON GROUP
	LOWER	TOARCIAN		VOLCANICS ? / LAKE (B.C) ?	?
		PLIENSBACHIAN		CULTUS FM.	
		SINEMURIAN			?
		HETTANGIAN	? PARSONS BAY	(WASH) (B.C)	NICOLA-PAVILION "TULAMEEN"
TRIASSIC	UPPER	RHAETIAN	? SEDIMENTS	? CULTUS	GROUPS
		NORIAN	SUTTON LS / MARBLE BAY-OPEN BAY	FM (B.C)	
		KARNIAN	FRANKLIN CREEK VOLCANICS (V.IS.) / TEXADA VOLCANICS (T.IS. ST.G.) / HARO FM (S.J) ?		(B.C)
	MIDDLE	LADINIAN			?
		ANISIAN			
	LOWER	SCYTHIAN			

Table 1 . . . . continued.

CORRELATION OF KNOWN PACIFIC NORTHWEST CENOZOIC FORMATIONS

EPOCH-SERIES	STAGE-AGE CALIFORNIA	VANCOUVER ISLAND SAN JUAN ISLANDS	CASCADE MTS. OF B.C. & WASH. NORTH OF 48°30'	B.C. INTERIOR ASHCROFT-KAMLOOPS PRINCETON
PLIOCENE	SAN JOAQUIN		PRE-SEYMOUR IN PART ?	
	ETCHEGOIN		SEDIMENTS OF	PLATEAU BASALT
	JACALITOS		FRASER DELTA	
MIOCENE				DIATOMITE
	NEROLY			
	CIERBO			
	BRIONES			
	TEMBLOR			
	VAQUEROS	? SOOKE FM. (V.I.S.)		
	BLAKELEY	LOWER		
OLIGOCENE		BLAKELEY	HANNEGAN VOLCANICS	
	LINCOLN	CARMANAH-FM		
	KEASEY		? ?	
EOCENE	TEJON		HUNTINGDON GROUP (WASH.)(B.C.) / KITSILANO (B.C.)	
	TRANSITION BEDS		BURRARD (B.C.)	KAMLOOPS GROUP / TRANQUILLE BEDS; PRINCETON GROUP
	DOMENGINE	? METCHOSIN (V.I.S.)		
	CAPAY			
PALEOCENE	MEGANOS	(S.J.) CHUCKANUT	CHUCKANUT (WASH.)	
	MARTINEZ			

Footnotes:

1. The terms: Trafton, President Channel and Lower, Middle and Upper Harper ranch are informal stratigraphic names as yet not formally defined. The term "Trafton" replaces "Stillaguamish" previously assigned to these rocks but now recognized from earlier use as a Pleistocene stratigraphic unit. The divisions of the Sicker Group and Chilliwack Group are based on present knowledge of fossil zones in rocks mapped as belonging to these groups. Middle Pennsylvanian fusulinids have been identified in limestone from the Ballenas Islands by Charles Ross (J. Muller, Oral communication).

2. New age assignments for the Ladner Group and Dewdney Creek Group are based on the work of James Coates in the Manning Park area.

Table 1 . . . . continued.

Table 1: QUATERNARY RECORD

CLIMATIC TRENDS (approximate dates)	
Alpine glaciers slowed recession and advance	1950 A.D.
Alpine glaciers general and rapid recession	1920-1950 A.D.
Alpine glaciers slow recession	1850-1920 A.D.
Alpine glaciers maximum recent extent	1650-1850 A.D.
Cool period	1550-1700 A.D.
Warmer period	900-1000 to 1200-1300 A.D.
Cold period	500 B.C.
Xerothermic (Warm-Dry)	3-4000 to 5-6000 BP
Climatic Optimum (Warm-Moist)	6000-8000 BP

STRATIGRAPHY		BRITISH COLUMBIA	WASHINGTON
Mount St. Helens Ash (1802) eruption			
Mount St. Helens Ash about 500 years ago			
Mount Rainier Ash 2,000-2,300 years ago			
Mount St. Helens Ash about 3,000 years ago			
Mount Mazama Ash about 6,600 years ago			
Post Glacial		Salish Group	Post Glacial Sequences
WISCONSIN GLACIATION — FRASER GLACIATION	SUMAS STADE 10,000 to 11,000 ±	Sumas Drift (Lowland) local	Sumas Drift (Lowland) local
	EVERSON INTERSTADE 11,000 to 13,000 ±	Whatcom glaciomarine	Bellingham glaciomarine
Glacier Peak ash (12,000 years ago)		Newton stony clay	Deming sand
		Cloverdale sediments	Külshan glaciomarine drift
	VASHON STADE 13,500 to 18,000 ± (Lowland)	Surry Drift (Lowland)	Vashon Drift (Lowland)
	EVANS CREEK STADE 17,000 to 21,000 ± (Alpine)		Evans Creek (Drift (Alpine)
OLYMPIA INTERGLACIATION 15,000 to 50,000 ± (Cool and moist - Pine, spruce, fir pollen)		Quadra sediments	Kitsap Formation
SALMON SPRINGS GLACIATION Greater than 50,000		Semiamu Drift (age unknown) Dashwood Drift (Van.Is. age unknown)	Salmon Springs Drift
PUYALLUP INTERGLACIATION STUCK GLACIATION ALDERTON INTERGLACIATION ORTING GLACIATION		Glacial and interglacial sequences in drill holes	Sequences in Southern and Southeastern Puget Sound

Table 1 . . . . continued.

geologic history presented here has been compiled from Snavely and Wagner (1963), Danner (1965, 1968), Sutherland-Brown (1966), Hopkins (1966), Roddick (1966), Mathews (1968), and Tiffin (1969). Table 1, taken from Danner (1968), summarises stratigraphic relationships in the area.

The oldest rocks in the area belong to the Sicker Group, which comprises 8,000 to 10,000 feet of altered basaltic flows, breccias, and tuffs, locally intercalated and interfingering with greywacke, argillite and chert. The Sicker Group is overlain by about 1,000 feet of crinoidal and cherty limestones of ?Late Pennsylvannian or Early Permian age. A period of mild uplift and local erosion is suggested for the remainder of the Permian and the Early Triassic: no rocks of this age have been identified in the area. From the Mid-Triassic to the Late Triassic (Mid Karnian) rapid sinking and eruption of 10,000 feet of sodic basalt flows and pillow lavas of the Karmutsen Formation occurred. Extrusion of lava seems to have stopped in the Late Triassic, to be followed by deposition of between 400 and 3000 feet of limestones over most of the area. This limestone is preserved in isolated patches over much of Vancouver Island and on Texada Island. Sedimentation continued into the Early Jurassic, and was succeeded by explosive eruption of porphyritic andesite agglomerates and tuffs of the Bonanza Formation. Most of the Middle and Late Jurassic and Early Cretaceous was a period of general non-deposition and possibly erosion. The future site of Georgia Strait is believed to have been a tectonic highland at this time, and most of Vancouver Island and Georgia Strait continued to be exposed and eroded until the Santonian, when basal conglomerates of the Upper Cretaceous Nanaimo Group were deposited in a depression (a downwarped or downfaulted trough) called the Georgia Seaway (Sutherland-Brown, 1966). Deposition of 5,000 to 10,000 feet of alternating marine shales and marine and non-marine sandstones, some coal measures and conglomerates, followed and continued throughout the Late Cretaceous.

General withdrawal of the sea from the area occurred sometime in the uppermost Cretaceous or earliest Palaeocene. Marine sediments are missing from the sequence of ?Late Cretaceous to Eocene rocks in the Whatcom Basin and there are no sediments of this age on the southeast coast of Vancouver Island. The early Tertiary is represented in the southern tip of Vancouver Island by some 7,500 feet of submarine pillow basalts (Metchosin Volcanics), although this sequence appears to be related to a petrographic province to the south (in Western Washington and Oregon, see Snavely and Wagner, 1963). Tertiary marine sedimentation seems to have been restricted to the west coast of Vancouver Island. Snavely and Wagner (1963) depict a Mid Tertiary shoreline crossing southern Vancouver Island and entering Washington near Bellingham on their palaeogeographic reconstructions of Tertiary history. Sutherland-Brown (1966) suggests this shoreline extended from Kyoquot to Sooke on Vancouver Island, where Oligocene and Early Miocene marine sediments overlap older rocks and have a distinct shoreline conglomerate at the base of the section.

Within Whatcom Basin ?Late Cretaceous to Late Eocene non-marine conglomerates, sandstones, shales, and some lignites and coals, were deposited in alluvial plain environments. Material was derived from the growing Coast Ranges and Vancouver Island mountains, although floral evidence suggests that the growing uplands were much lower than at present. Local vigorous uplift may have occurred to provide a source for conglomerates. Roddick (1966) tentatively concluded that relatively little uplift of the Coast Mountains occurred in the Early Tertiary, but most has occurred since the Pleistocene. He cites as evidence that although coarse conglomerates occur in the Tertiary, marine Upper Cretaceous rocks intruded by quartz diorites are found in the Garibaldi area at an elevation of 6,000 feet. Pliocene plateau basalts of the central interior of the Province of British Columbia rise gradually from 2,500 feet to 8,500 feet in the Coast Mountains. In both cases the amount of uplift indicated is about 6,000 feet, and the younger basalts place a limit in the time of uplift.

How far across the Strait of Georgia Tertiary continental sedimentation extended is not known. Mathews (1968) considers the Strait of Georgia to have been a subsiding basin in which several thousand feet of clastic sediment accumulated. However, definite answers cannot be obtained from seismic records, and Tertiary rocks are unknown from the east coast of Vancouver Island.

Hopkins (1966) suggests that deposition of Tertiary rocks slowed or ceased by the end of the Eocene or earliest Oligocene. During the Miocene orogenic activity in western Washington and Oregon produced a number of more or less isolated, closed basins with local accumulation within them of continental sediments. By the Late Pliocene and Pleistocene, general uplift of the Coast Mountains and Cascade Mountains added to the clastic sediments carried to the area.

Pleistocene stratigraphy of the Lower Fraser Valley has been described by Armstrong and Brown (1954), Armstrong (1956, 1957, 1960), and Armstrong et al. (1965). Up to 2,000 feet of older Pleistocene and Pliocene sediments have been recorded in drill holes (Danner, 1968).

Over these occur the interglacial sands and clays that make up the Quadra sediments (see Table 1) at Point Grey; similar sediments at Point Roberts to the south are believed by Danner (1968) to be older than the Point Grey beds. Extensive deposits of outwash, till and glaciomarine drift, and interglacial alluvial sediments occur above an erosion surface cut on Quadra sediments.

Pleistocene deposits with chaotic and stratified internal structures are recorded in seismic profiles across the Strait (Tiffin, 1969). Some of these deposits have been correlated tentatively with Pleistocene deposits on nearby land (e.g. McCall Ridge Unit and Point Grey series). Mathews (1968) suggested that the entire Georgia Depression was at one time filled with Pleistocene sediments but Tiffin (1969) found no evidence of debris of Pleistocene age in the floor of Ballenas Basin on the west side of the Strait.

During each of the major glacial episodes ice advanced southward and southwestward into the Strait of Georgia, flowing out to sea by way of the present Juan de Fuca Strait. Ice thickness in the Strait of Georgia reached at least 5,000 feet (Roddick, 1965; Mathews, 1968; Glacial Map of Canada, 1958). At least two (Fyles, 1963: Vancouver Island) or three (Armstrong _et al_., 1965: Vancouver and Fraser Lowland areas) major late advances of ice are known on land surrounding the Strait. Tiffin (1969), however, could not find clear evidence for the number of glacial advances that had taken place within the Strait, partly because of the rapid lateral and vertical facies changes exhibited by the Pleistocene deposits, and partly because the ice-deposited material, influenced by changing sea-levels, must have undergone some reworking and modification.

During the Late Pleistocene or early post Pleistocene, the thick wedge of sediment comprising Roberts Swell (see Figure 2) was deposited. This material appears to have come from the southeast and is believed to have been an older delta of the Fraser River, built at a time when the river discharged into the Strait from near Bellingham in the U.S. (Tiffin, 1969). Subsequently, at sometime shortly after the Sumas Stade, the Fraser River changed from its southerly course to its present one and commenced constructing its present delta. The growth of the delta and the dispersal of sediments in the Strait were influenced, and often directed, by Pleistocene and older deposits. Ponding of sediments occurred behind such upstanding features as Roberts Reef, Fraser Ridge, Finger Ridge and the section of McCall Ridge between McCall Bank and Point Grey, until such times as these barriers were buried and sediment dispersal could continue unimpeded. The present distribution of sediments in Georgia Strait reflects both the early influence, and the continued existence, of some of these older ridges and Pleistocene deposits.

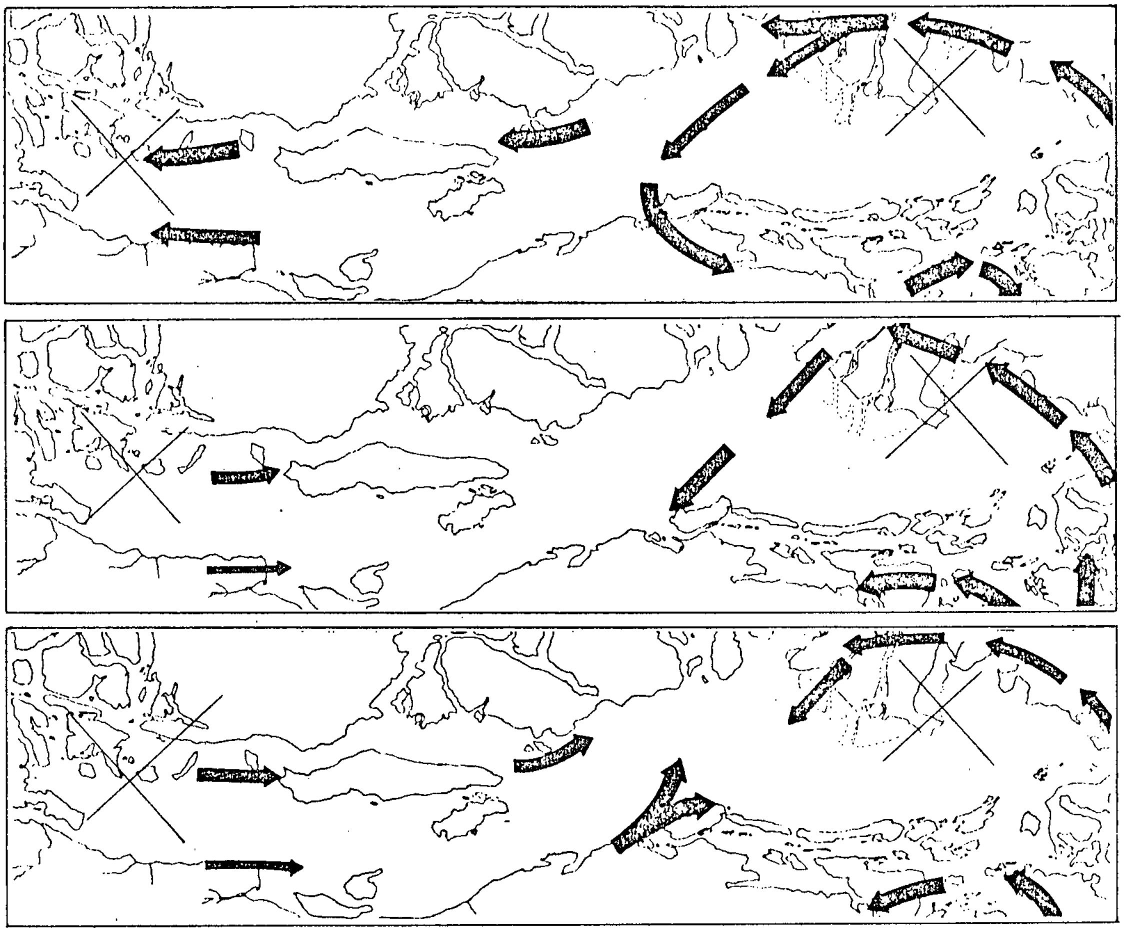
1.4 CLIMATE

Surface wind circulation on the Pacific coast is directly related to the proximity of a semi-permanent high-pressure cell in the eastern Pacific Ocean centred at approximately 30°N, 145°W. Prevailing winds in summer resulting from this cell are northwesterly. The slight weakening and southward migration of this high-pressure cell in the winter, coupled with the development and intensification of a low-pressure cell in the Aleutian area, causes a reversal of wind directions in the winter. Prevailing winds on the Pacific coast are southeasterly in autumn and early winter, shifting to southerly and southwesterly by the late winter.

(A)

(B)

(C)



Surface wind patterns in the Strait of Georgia during (A) winter, October–March, (B) spring transition, April–May, and (C) summer, June–September (Extended from Harris and Rattray, 1954).

FIGURE 4: Surface wind circulation in the Strait of Georgia at different times of the year (from Waldichuk, 1957, p.417).

Within the Strait of Georgia this general picture is strongly modified by the presence of the mountains and by the local wind patterns in Juan de Fuca Strait, Puget Sound and the Fraser Valley. The result (Figure 4) is a closed, anticlockwise circulation for the southern part of the Strait (south of a line between Nanaimo and Vancouver, and north of the Olympic Peninsula) in winter, with a shift to generally easterly or southeasterly winds throughout the Strait during spring, and a rather confused pattern in summer, with prevailing southwesterly or southeasterly winds in the southern parts and northwesterlies at the northern end. Wind records kept by the Meteorological Office at Vancouver International Airport show that prevailing winds at the airport are, on the basis of percentage frequency from each direction, almost always easterly. The monthly data for the years 1964 to 1972 suggest the average prevailing winds for each month, except one or twommonths in summer, are easterly blowing at 6 to 8 miles per hour. However, the data also shows that westerly winds are generally stronger, if of shorter duration, and these winds will be the important ones controlling movement of sediment on the delta, and erosion of coastal regions on the east side of the Strait.

Precipitation, mostly as rain, is moderate and increases from west to east. The western margin of the Strait is in the rain shadow of the Vancouver Island Mountains, and receives an average of 40 inches of precipitation per year. In Burrard Inlet the average amount of precipitation per year is 60 inches. The wettest period is from October to February, averaging 6 to 8 inches per month; the driest, July and August, averaging less than 1 inch per month.

Air temperatures seldom fall below freezing, and never stay that low for any length of time. Warm air from the Pacific tends to moderate temperatures in the Strait, resulting in average winter values of 2°C (January and February), with an increase after mid-February to average values of 13°C in May and 18°C in July and August, with midday temperatures often reaching 24°C.

1.5 OCEANOGRAPHIC CHARACTERISTICS

A comprehensive analysis of the physical oceanographic characteristics of the Strait of Georgia is available in Waldichuk (1957). This study was based on data collected over a period from 1949 to 1951, taken to be representative of the seasonal variations of 1950, and augmented by data from other oceanographic surveys in 1930 to 1932 and 1952 to 1953. A brief review will be given here, drawn mainly from Waldichuk (1957), of those oceanographic factors considered to be of importance to the dispersal and distribution of the Recent sediments in the Strait of Georgia.

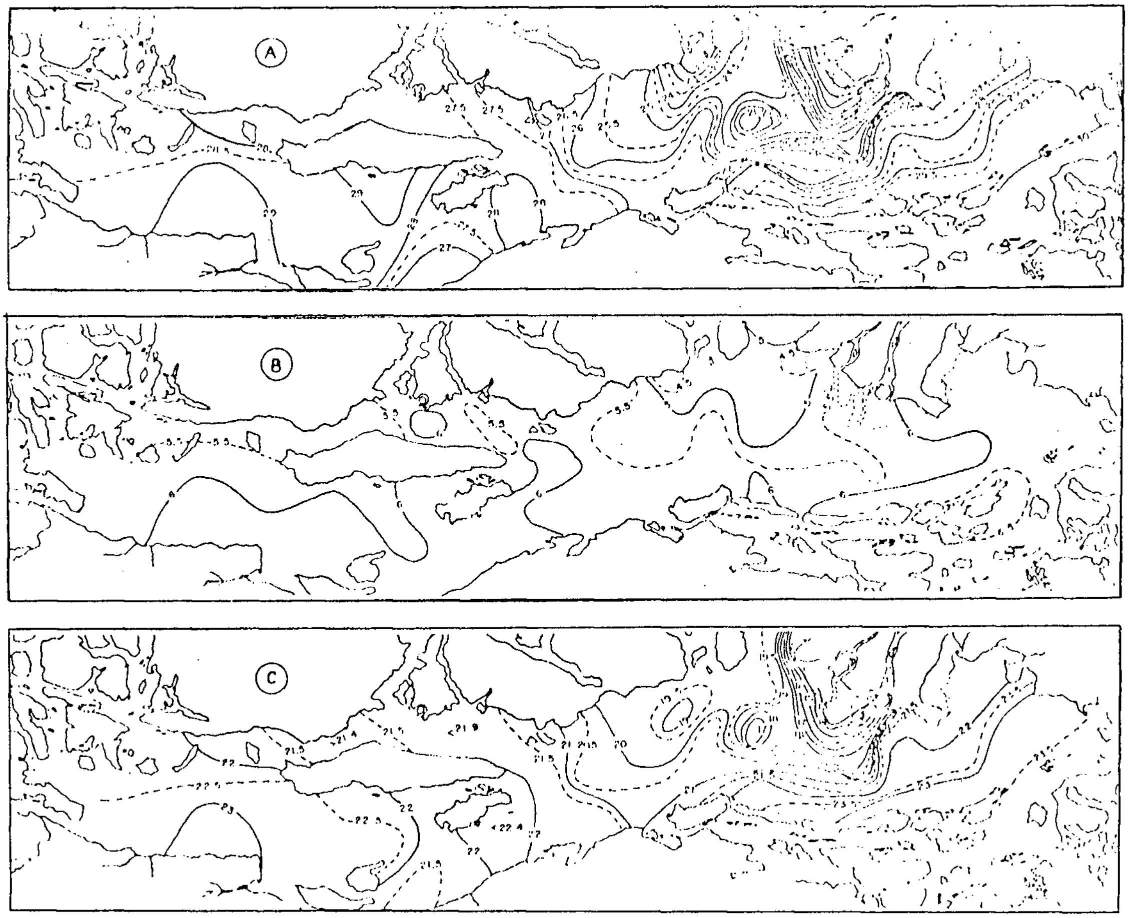
Waldichuk (1957) considered the Strait of Georgia to be an oceanographically unique feature. In contrast to other B.C. fjords its axis runs parallel to the coast, the freshwater inflow is lateral rather than from one end, and there is a connection to the open ocean at both ends. It is neither as steep-sided nor as narrow as many of the B.C. fjords, but its great depth and obvious origin as a glacially eroded and modified deep valley contrasts sharply to the estuaries of the coastal plain of the eastern U.S.A.

The rate of freshwater input greatly exceeds that of evaporation, and although the Strait receives water from many sources the Fraser River is the most important, contributing some 80% of the total freshwater input into the Strait. This tremendous, localised influx of low-salinity water greatly complicates the oceanography of the Strait, creating a highly stratified situation with mixing and entraining of sea-water near the river mouth. Inflow of sea-water is mainly from the south, the effect of the northern outlets - Discovery Passage and Johnstone Strait - is very small and may be neglected when considering water movement: especially water movement in the Central and Southern Strait. Intense vertical mixing of the entire water column occurs in the San Juan Archipelago - Gulf Islands area. The stratification patterns and fresh-water distributions are further complicated by effects due to changing tides and seasons (see Waldichuk, 1957; and Figures 5, 6, and 7).

1.5.1 CIRCULATION

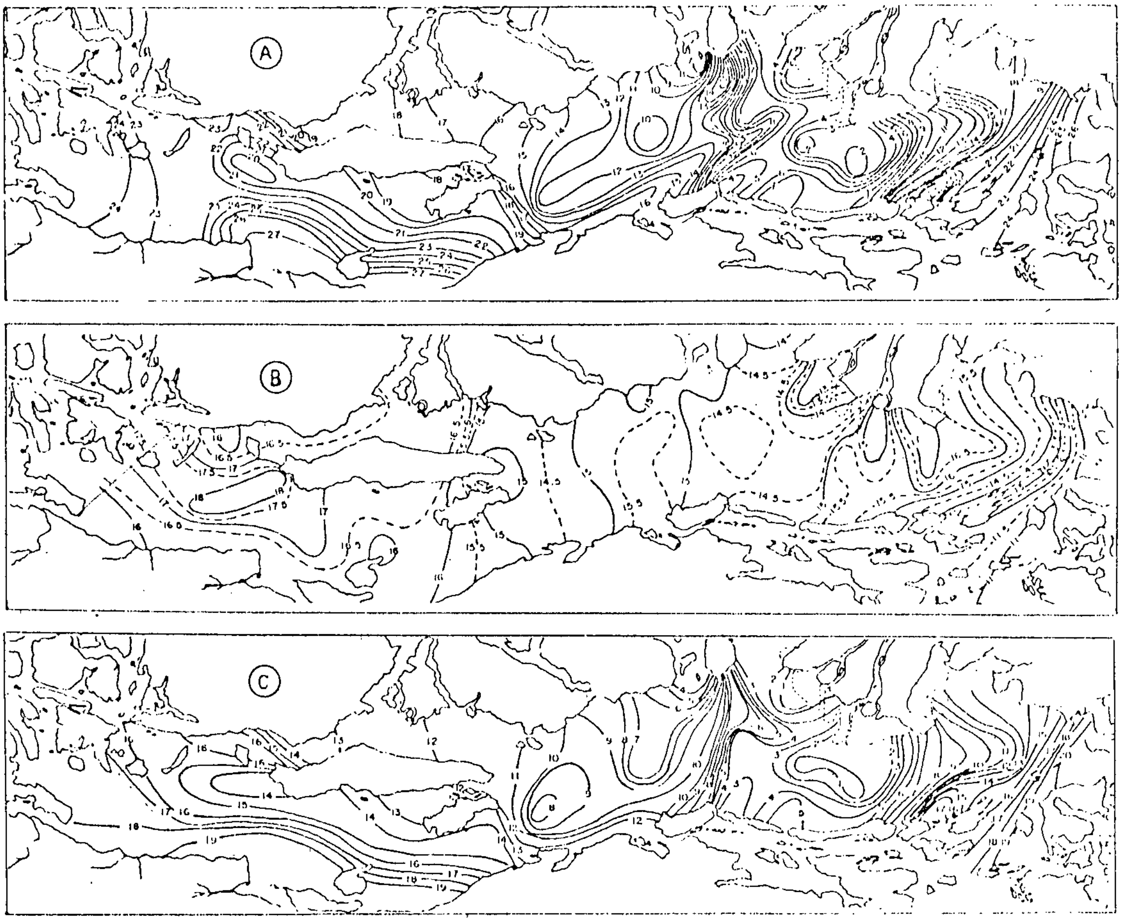
The main factors responsible for moving water masses and determining the distribution of water properties in the Strait of Georgia include tides, river runoff, winds and salinity gradients. Modifying these factors are the directive influences of topography, with Coriolis and centrifugal forces assuming minor roles.

Tidal effects in the Strait of Georgia are at a maximum near the Fraser River mouth, and decrease to the north. With ebbing tides the fresh-water flow is in the same direction as that of the tide and tongues of muddy water extend across the Strait, even as far as or into Active Pass. Flooding tides on the other hand result in a rapid flow of water northward along the shore, which tends to shear off lobes of river water leaving clouds of brackish water moving independently under the influence of wind and tides (Waldichuk, 1957). Flooding tidal currents



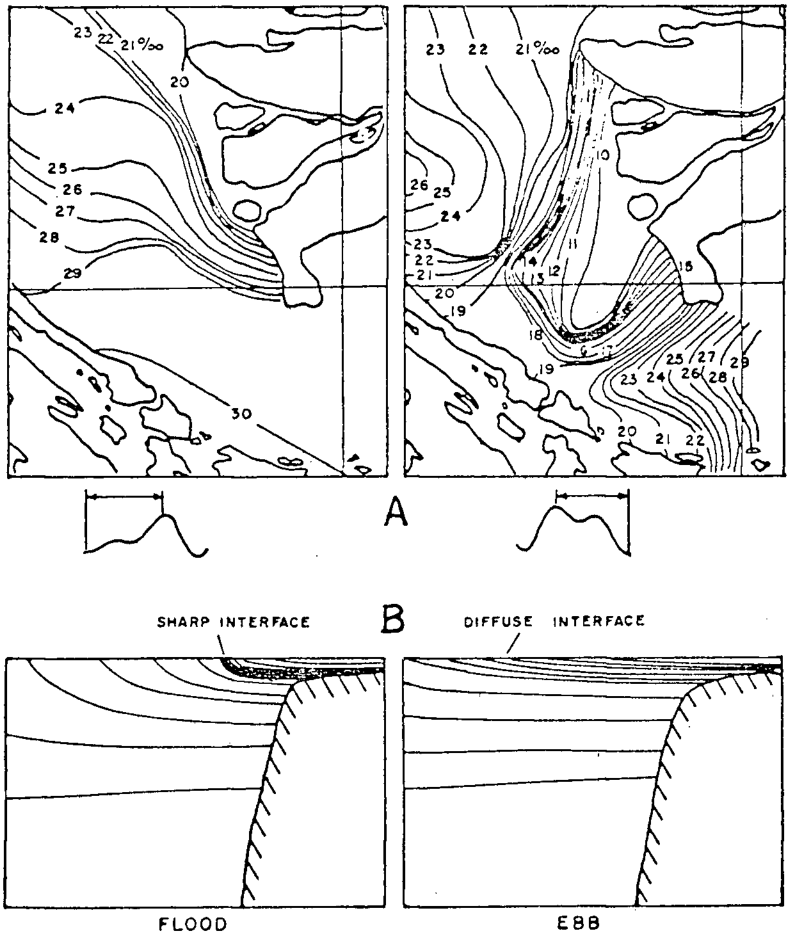
Distribution of properties at the surface in the Strait of Georgia, February 1950. (A) salinity, (B) temperature, (C) density (σ_t).

FIGURE 5: Distribution of salinity, temperature and density measurements in the Strait of Georgia, February 1950 (from Waldichuk, 1957, p.353).



Distribution of properties at the surface in the Strait of Georgia, June 1950. (A) salinity, (B) temperature, (C) density (σ_t).

FIGURE 6: Distribution of salinity, temperature and density measurements in the Strait of Georgia, June 1950 (from Waldichuk, 1957, p.358).



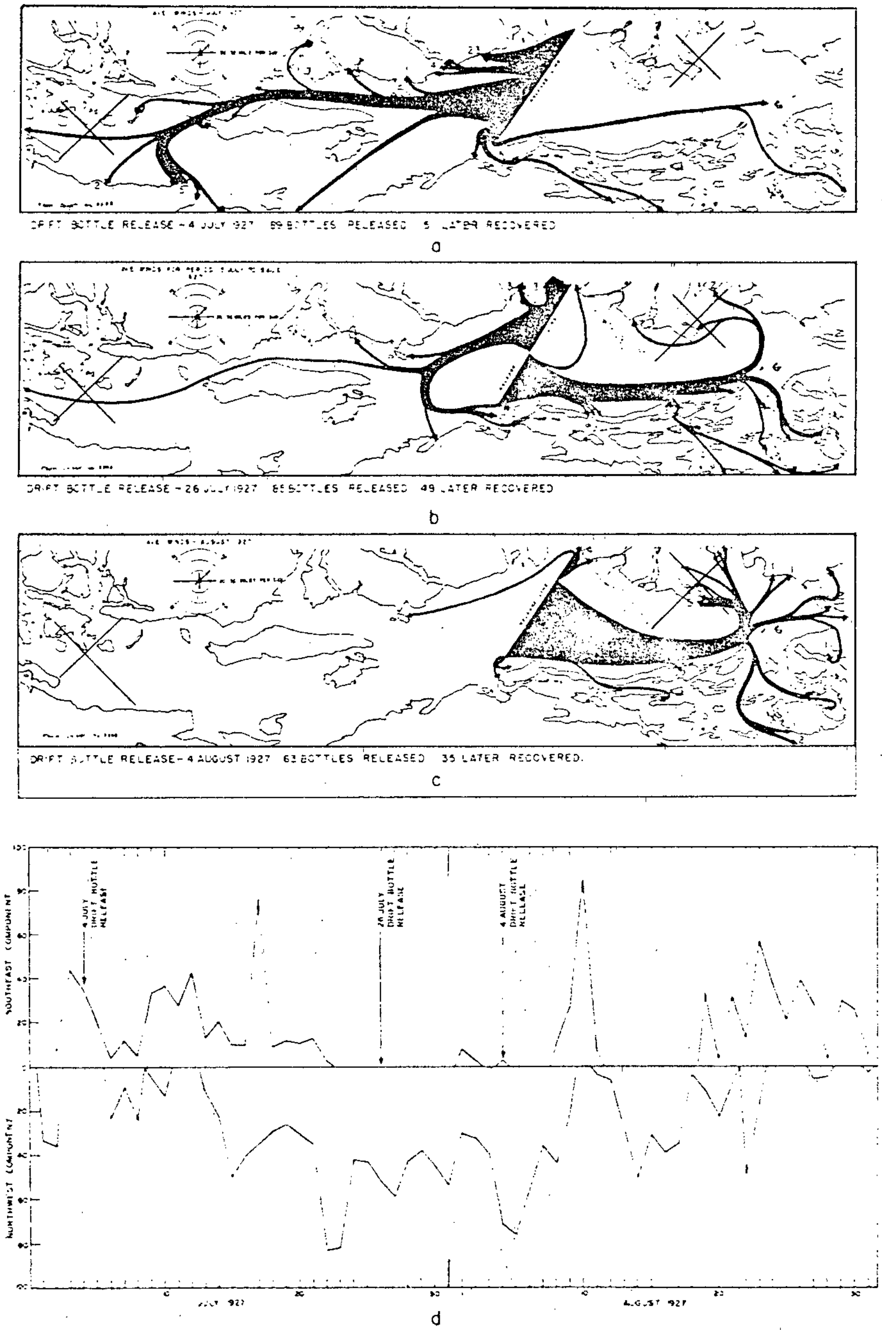
(A) Salinity distribution at the surface on flood and ebb stages of the tide off the Fraser River estuary. (Observed on survey, 1–8 December 1949.) (B) Schematic sections of salinity distribution off the Fraser River estuary on flood and ebb stages of the tide.

FIGURE 7: Salinity distributions on flood and ebb tides (from Waldichuk, 1957, p.366).

are generally stronger and of longer duration on the eastern side of the Strait than on the west, while the reverse is true for ebbing tides. Since the flood tides tend to set in a northerly direction, this combined tidal flow, augmented by Coriolis effects, topographic influences and the closed anticlockwise wind pattern, tends to produce a general anticlockwise water circulation within the Strait. Departures from this general picture do occur however. Even during ebb tide a northward movement of silty water from the river mouth into Burrard Inlet and beyond may be seen on air photographs and is indicated by current measurements monitored continuously for one year (Dr. S. Tabata, Fisheries Research Board of Canada, oral comm., 1972) and casual observation.

Johnston (1921), comparing old and new soundings of the Fraser River delta, and Mathews and Shepard (1962), in a similar type of study, found indications of heavier silting on the northern side of the delta than in other areas. Tiffin's (1969) studies in the Strait indicated that active sedimentation is occurring only to the north of Sand Heads. Salinity measurements (Waldichuk, 1957) support the concept of northward transport of water along the eastern side of the Strait, with low-salinity water from the Fraser River veering to the right almost as soon as it enters the Strait of Georgia (see Figures 5, 6 and 7). LaCroix and Tully (1954) offer evidence of a general, overall northward flow of water through the Strait besides the general anticlockwise circulatory pattern.

Surface currents in the Strait are neither as well known nor as clearly understood as might be expected. Available information is limited to surface-current studies made with drift-bottles (Waldichuk,



Patterns of drift bottle recoveries from releases on a line across the Strait of Georgia and associated winds during the summer 1927.

FIGURE 8: Circulation patterns in the Strait of Georgia determined by surface drift-bottle recoveries (from Waldichuk, 1957, p.388).

1957) or free-floating current followers (Giovando and Tabata, 1970; Tabata et al., 1971). and to a few studies made with current meters over varying lengths of time at different anchor stations (Pickard, 1956; Huggett, 1966; Tabata et al., 1970; Tabata et al., 1971). Interpretation of direct current studies, whether made by surface drifter or stationary meters, is complicated by the effects that short-term factors such as winds, tides, yawing of the ship, etc., have on the measurements.

Recent shallow- and surface-current studies made in the Strait include those of Giovando and Tabata (1970), Tabata et al. (1970), Tabata et al. (1971) and Tabata et al. (unpubl.; oral comm. Tabata, 1972). Tabata et al. (unpubl.) report on the results obtained from moored instruments that recorded continuously for a period of over one year. Three mooring sites were situated along a line between Valdes Island and the Iona Island sewage outfall channel. Of considerable importance are the consistent, persistent easterly currents recorded at the surface and 50 metres depth at the station in mid-Strait (Figure 9).

Giovando and Tabata (1970) used free-floating current-followers to determine current velocities and direction of flow of Fraser River water subsequent to its entrance into the Strait of Georgia. They found that water from South (Main) Arm enters the Strait as a surface jet which undergoes little lateral spreading and, if there is no significant wind drift, may retain its entrant direction for some time (e.g. high-water slack to next low-water). The surface water may move in a variety of ways in the Strait:

(i) persistent northward movement on ebb as well as flood tides to or near to the mainland shore west of Howe Sound.

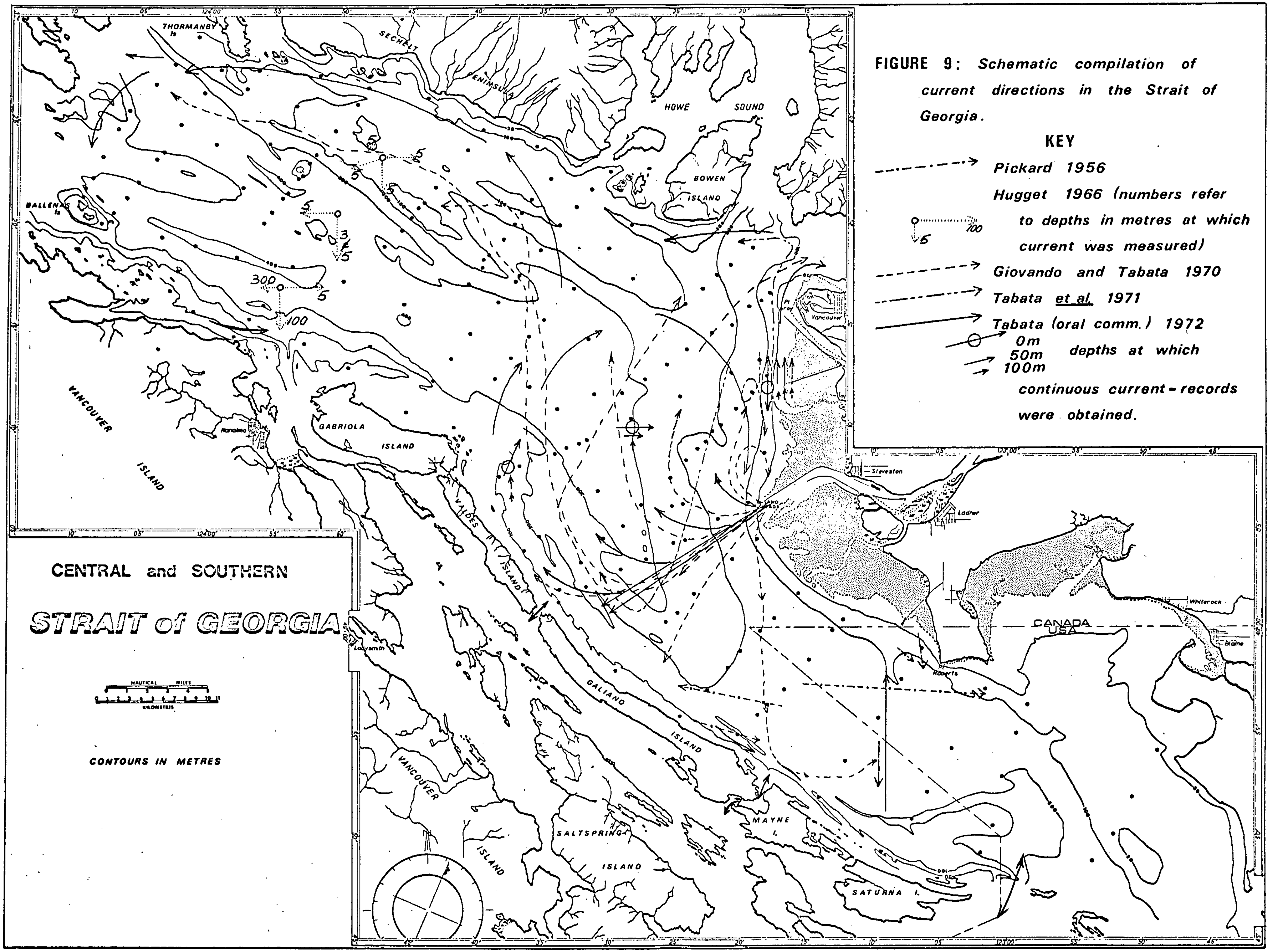


FIGURE 9: Schematic compilation of current directions in the Strait of Georgia.

Subsequently the movement may be westward to mid-Strait, then northwestward, rather than immediately northwestward along the mainland shore;

(ii) flow northward and eastward toward the mainland shore between Burrard Inlet and South Arm;

(iii) westward movement to the vicinity of the Gulf Islands over a time interval that may encompass several tides;

(iv) water entering the Strait on early stages of an ebb tide can, if wind effects are negligible, sometimes be moved southward;

(v) water entering the Strait at low-water slack, during intermediate values of run-off at least, appears to turn northward immediately, and appears to undergo persistent northerly movement.

Surface current speeds up to three to five knots are common at times of strong ebb tidal flow associated with the freshet. Current velocities in the open Strait are generally in the order of one to two knots when there is no strong wind influence. The smallest velocity value obtained by Giovando and Tabata (1970) was 0.2 knot. Water entering the Strait from South Arm contributes to the formation and extension of a plume of river water north of the Arm. Extension of this plume much to the south is believed to be controlled by wind drift and tidal action.

Tabata et al. (1971) reported on a number of observations of current movements conducted over relatively short time intervals (less than one week). They point out that the conclusions that can be drawn from their study are valid only if the measurements are uncontaminated by lower frequency oceanographic events. Other evidence

(Tabata et al., 1970) suggests that significant oceanographic variability with time scales greater than one week do occur elsewhere in the Strait. Of primary concern for this (Tabata et al., 1971) study was the determination of current movements around the Iona Island sewage outfall, through which treated effluent is released to the Strait via an open channel that extends almost to the western edge of Sturgeon Bank. Current movements were monitored by dye-studies, free-floating current-followers and, occasionally, meters. North of the outfall channel and in a zone extending to about two miles offshore, current movement was predominantly northward. Ebb tidal effects were masked except for a slowing of the northward current's velocity, although large flood tides sometimes induced an easterly flow. The northward flow eventually extends around Point Grey and may move eastward into Burrard Inlet. Westward of the northward moving stream, surface layer velocities indicated an overall southerly, although variable, flow. The net southerly movement occurs for periods of a few days at least and had not been observed before. Tabata et al. (1971) suggest that it may be the manifestation of a large clockwise eddy in the central Strait, whose persistence and frequency are not known. Its presence conflicts with previously-held ideas that have been postulated for current flow in the Strait. Occasional southward movement of surface water from the Fraser in the Strait of Georgia is indicated by Tabata et al. (1970) and Giovando and Tabata (1970).

Little or no current velocity information is available from the central Strait on or near to banks and ridges. Some mud obviously does get deposited and trapped in these places, but if the sedimentation rate was the same on the banks as it is in the deep basins, then no relict boulders or gravels should be found at the surface, and no

FIGURE 10

FIGURES 10 and 11: Living animals and gravelly deposits as yet unburied by modern muddy sediments. 115 ft (35 m.) depth, Halibut Ridge. (Photo: Mr R.D. MacDonald, Geology Dept, U.B.C.)

FIGURE 11

FIGURE 12

FIGURES 12 and 13: Views to the southwest across the Strait of Georgia from near Sand Heads (Sand Haeds light visible in Figure 12) showing demarkation between silty water from Fraser River discharge and "clear" oceanic water of Georgia Strait. July, 1971.

FIGURE 13

sedentary attached life-forms such as sponges or corals be present (see Figures 10 and 11). Consequently, it is suspected that currents of sufficient strength to prevent deposition of hemipelagic material (but not necessarily strong enough to cause erosion) exist around the tops and flanks of many of the ridges. Diver observations by Mr. R.D. MacDonald, Geology Dept., U.B.C., on Halibut Bank tend to confirm this suspicion.

The "tide line" demarkation of silty water from "clear" Georgia Strait water was explained as due to compression of isohalines by the flooding tide by Waldichuk (1957). Tabata et al. (1971) provide evidence from dye studies suggesting that the "tide line" marks a shear zone between two distinct water masses, one flowing north (the silty one), and the other south.

1.5.2 FRESHWATER BUDGET

The largest source of fresh water for the Strait of Georgia is from stream runoff. This runoff is of two types: stored - from streams with headwaters in regions of winter snow; or direct - from streams whose discharge depends on the local rainfall.

By far the most important contributor of freshwater to the Strait is the Fraser River. It is a stream of the stored runoff type and reaches its peak discharge in late June or early July. Its low discharge period is from February to April, during which time the coastal drainage area is the only significant contributor of fresh water to the Strait.

The Fraser River, contributing some 80% of the total runoff into the Strait, drains an area of 85,600 square miles upstream from Hope, B.C., and a further 4,500 square miles of area downstream from

Hope. Of the three main river mouths the greatest volume of water enters the Strait via South Arm. North Arm passes only 10 to 15% of the total outflow, while Canoe Pass has not been a significant channel for some years. Mathews, Murray and McMillan (1966) summarise information available to that date on the Fraser River, its bed and suspended loads, flow rates, etc. Pretious (1969, 1972) and Tywonink (1972) provide more recent information on the sediment loads transported by the Fraser River.

Glacial streams, such as the Squamish River at the head of Howe Sound, are primarily of the stored runoff type. Peak discharge may occur up to one month later than that of the Fraser River. Rivers flowing into the Strait from Vancouver Island such as the Cowichan, Chemainus, Nanaimo, Puntledge and Campbell are predominantly of the direct runoff type, and peak runoff closely follows periods of high precipitation. These rivers are generally of little importance in supplying anything other than suspended or dissolved materials to Georgia Strait. They discharge into basins behind the partial barrier of the Gulf Islands or into shallow bays.

Waldichuk (1957) suggests that the inlets bordering the Strait of Georgia (e.g. Bute, Toba, Burrard, Saanich and Howe Sound) can be treated as separate oceanographic entities which have little effect on the characteristics of the Georgia Strait waters, while they themselves are influenced greatly by conditions in the Strait of Georgia. They are usually "silled" somewhere along their length, the sills providing effective traps for bed-load sedimentary material. Probably the only contirbution they can offer to the Strait is to further dilute its surface waters and to provide some suspended sediment during freshet times. Even then it appears that this material is masked by sediment from the Fraser River.

1.6 PREVIOUS STUDIES

Geological investigations in the Strait of Georgia have, until comparatively recently, been restricted to detailed studies of areas bordering the Strait. Johnston's (1921, 1922, 1923) studies of the Fraser River delta were for a long time the only source of information available on the Recent sediments of the Strait. Mathews and Shepard (1962) duplicated some of Johnston's work in an effort to establish growth rates and sediment dispersal patterns, among other things, for the Fraser River delta. During their survey they located, described and attempted to explain some anomalous, rounded hills occurring near the foot of the delta front. These hills have been more extensively studied by Tiffin et al. (1971) who confirmed earlier suggestions (Tiffin, 1969; Mathews and Shepard, 1962) that they may have been produced by sliding or slumping of material down the delta front.

The tidal flats at Boundary Bay are described in a publication by Kellerhals and Murray (1969). Garrison et al. (1969) report on the early diagenetic cementation of sands by low-magnesium calcite in the channels of the Fraser River.

More general investigations within the Strait include those of Waldichuk (1954, 1957), who gave a brief and very generalised description of the bottom sediments in the Strait, and Cockbain (1963a, 1963b) who produced, as an adjunct to his foraminiferal studies, a report and map of the distribution of sediments within the Strait. In neither case were the sediments studied in any detail. No detailed study of the geology or structure of the Strait had been made until 1969, when

Tiffin (unpublished Ph.D. thesis, Institute of Oceanography and Dept. of Geophysics, University of British Columbia) completed a survey of the Central and Southern parts of the Strait using continuous seismic-reflection profiling techniques.

Mathews, Murray and McMillan (1966) summarised fully the information available to that date on the Fraser River and the nature, quantity and seasonal variability of its load. They also summarised available knowledge of the setting, geomorphology, sediment distributions and sedimentation rates of the Strait of Georgia and areas adjacent to it (Boundary Bay, Howe Sound, Saanich Inlet, Pitt Lake).

1.7 SAMPLING PROCEDURES

1.7.1 SHIPBOARD

Sampling was carried out during January, 1970, from the Canadian Naval Auxiliary Vessel (CNAV) LAYMORE. A total of 358 Peterson and La Fond - Dietz grab samples, 28 large Kullenberg gravity cores and 12 small Phleger cores were collected. Fifteen camera stations were occupied, using 50 or 100 foot rolls of black-and-white film in an Edgerton, Germeshausen and Grier underwater camera with strobe unit. The ship's officers were responsible for navigation and for locating sampling sites. Most of the latter was accomplished by radar and visual fixes.

Immediately upon retrieval all samples were described in terms of colour (against the G.S.A. rock colour chart), texture, and macrofaunal content.

1.7.2 LABORATORY

Samples were analysed for grain-size distributions by combined sieve and pipette techniques, and petrographic and X-ray diffraction examinations were utilised to determine the mineralogy. Other characteristics determined included organic carbon and calcium carbonate contents, cation exchange capacities, oxalate-extractable inorganic oxides and hydroxides, and exchangeable base concentrations. More detailed descriptions of the methods of sample treatment and analysis are given in the appropriate sections.

Of the 358 grab samples collected, only 187 were subjected to mechanical size-analysis because of the rather uniform nature of the sediments over a fairly large area of the Strait; a feature recognised in the early, visual examination of samples immediately after their retrieval.

Within the text samples are referred to by a single number e.g. 123, although full identification is 70-1-123, referring to I.O.U.B.C. cruise number 70-1. Core samples are indicated by a "C" following the sample number e.g. 123C. Samples collected from the Fraser River, near Ruby Creek 12 miles east of Aggassiz, B.C., are prefixed "FR". Location of sampling sites in the Strait of Georgia is shown on Figure 2.

CHAPTER 2

BATHYMETRY

2.1 INTRODUCTION:

The bathymetry and topographic features of the study area are shown in Figure 2, which was interpolated from charts constructed by Tiffin (1969). Canadian Hydrographic Service charts and field sheets, and a detailed echo-sounding survey conducted by Cockbain (1963a) in the region of the Strait north of the Fraser River delta, provided the data from which the contours could be drawn. Contours are missing from areas where there is little information, but their omission does not affect this study, which is concerned with the deeper rather than the marginal areas of the Strait. Positions of contours are believed to be accurate to within 0.5 kilometres (Tiffin, 1969).

Nine cross-sections are presented in Figures 14 and 15, and one longitudinal section, extending from Sturgeon Bank on the Fraser Delta to Ballenas Islands at the north end of the study area, is given in Figure 16. Vertical exaggeration on the profiles is x25.8. 1:1 scale profiles are indicated by the dashed lines on some of the exaggerated figures.

Water depths on the Strait reach a maximum of 433 metres, which is considerably greater than the depths usually encountered on the nearby continental shelf, but not much greater than the depths of some of the mainland fjords. Off Barkley Sound the shelf attains a maximum depth of 236 metres, with an average depth for the shelf of 200 metres (Carter, 1970). The shelf break in Queen Charlotte Sound occurs between 183 and 275 metres (Luternauer and Murray, 1969). The percentage distributions of depths in the Strait are:

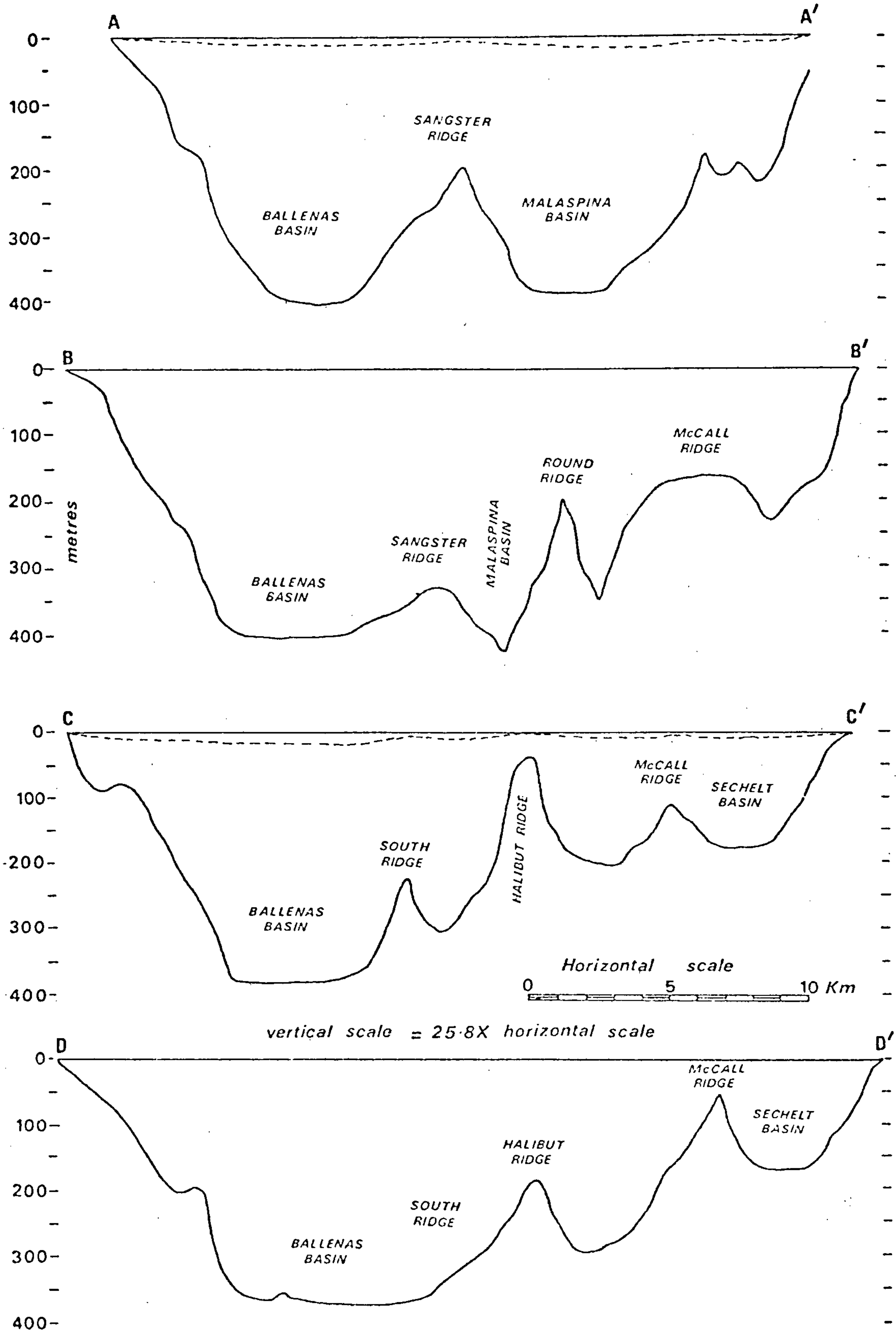


Figure 14: *Profiles across the Strait of Georgia showing bottom topography on an exaggerated scale. Dashed line on sections* AA′ *and* CC′ *are at 1:1 scale. Positions of sections are given in figure 2.*

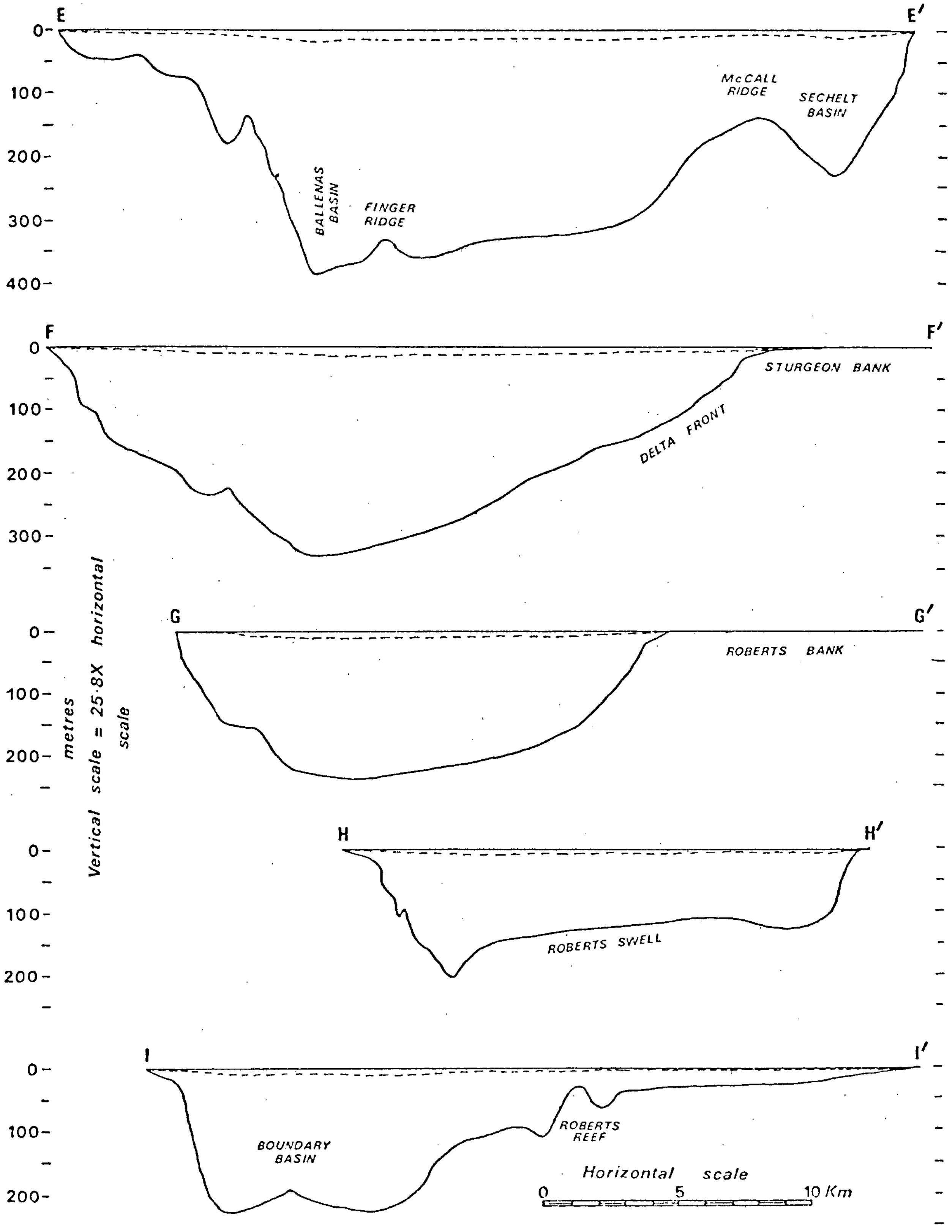


Figure 15 : *Profiles across the Strait of Georgia showing bottom topography on an éxaggerated scale. Dashed lines represent a 1 : 1 scale. Positions of sections are shown in figure 2.*

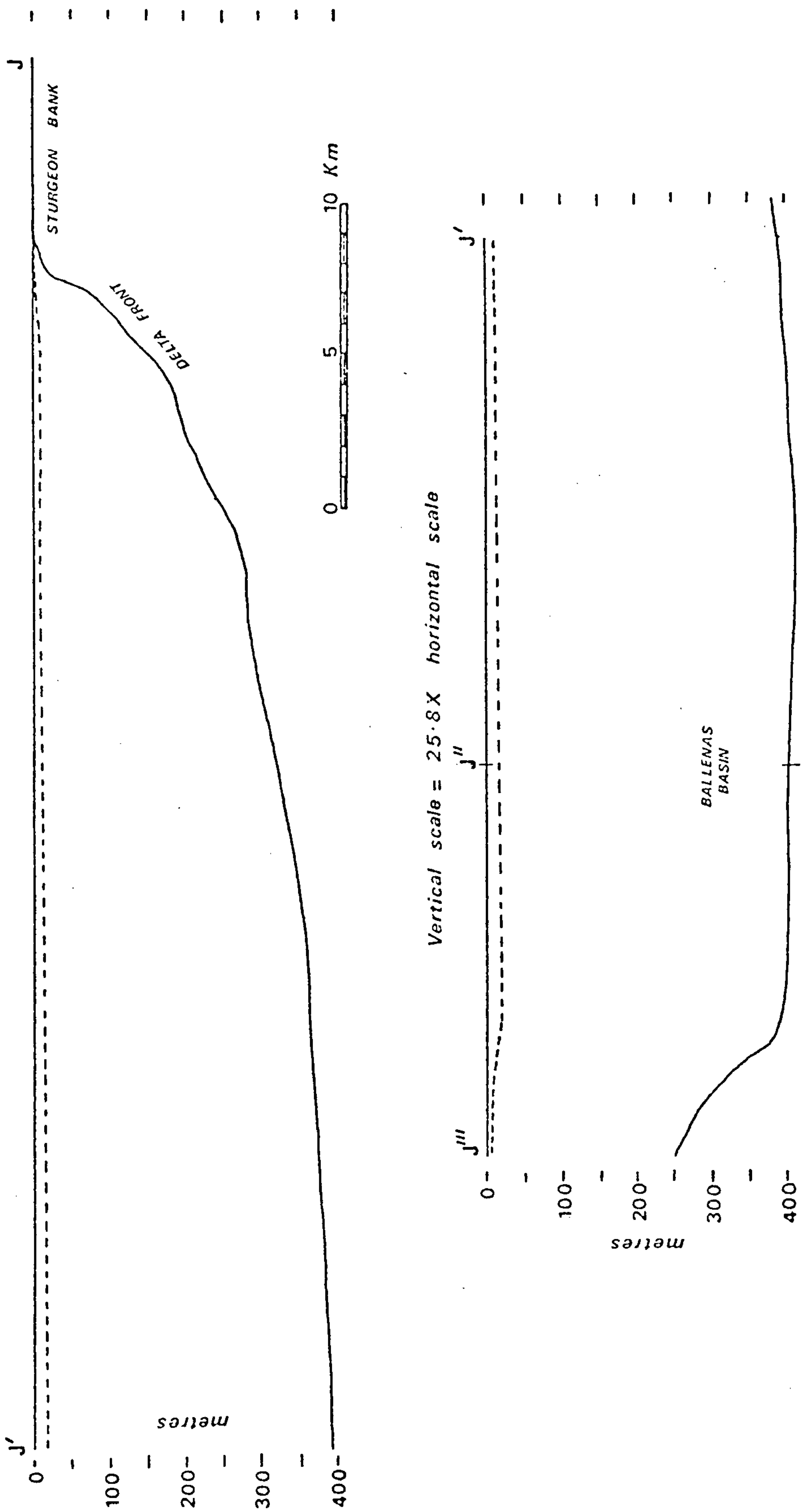


Figure 16: *A profile along Ballenas Basin from Sturgeon Bank to the low rise between Sangster Ridge and Ballenas Islands. True 1:1 scale is represented by the dashed line. Location of this section is shown in figure 2.*

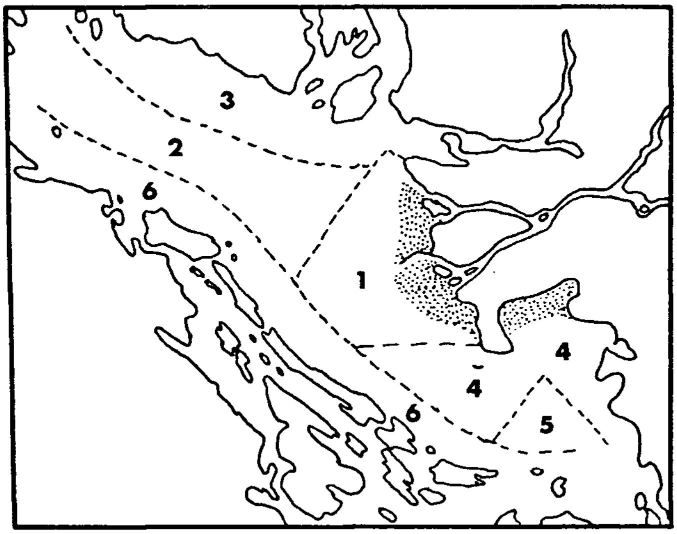
	Km^2	% total area
Total study area	3780	100
Area deeper than 36.6m. (20fm)	2800	75
Area deeper than 183m. (100fm)	1640	44
Area deeper than 366m. (200fm)	367	10

2.2 PHYSIOGRAPHIC SUBDIVISIONS

It is very often useful to unite, under a single name, individual features or areas which are sufficiently unique or distinctive that reference to them or description of them may be facilitated by such a grouping. That such a subdivision of Georgia Strait into distinctive areas should have been done is at once apparent from inspection of the bathymetric chart (Figure 2).

Waldichuk (1954, 1957) subdivided the Strait into areas characterised by the nature of the bottom-sediments and the physical characteristics of the water masses in the Strait. Cockbain (1963a), and later Mathews, Murray and McMillan (1966), recognised areas of the Strait characterised by distinctive morphologies. Although the subdivisions recognised by Cockbain (1963a) and by Mathews, Murray and McMillan (1966) are similar, the latter extended the area of their survey to include the regions of the Strait west and south of the Fraser Delta.

Tiffin (1969) distinguished six subdivisions that could be recognised by their unique combinations of morphologic, bathymetric, geological (structural) and geophysical characteristics. The regions are (see Figure 17): the Fraser Delta; Area of Deep Basins; Elevated Area of Ridges; Roberts Swell and Nearby Mainland Shelf; Boundary Basin and Alden Ridge; and the Island Slope. A detailed and comprehensive account of the structure, stratigraphy, and probable history of each region is given by Tiffin (1969).



1 *Fraser Delta Area.*
2 *Area of Deep Basins.*
3 *Elevated Area of Ridges.*
4 *Roberts Swell and Mainland Shelf.*
5 *Boundary Basin and Alden Ridge.*
6 *Island Slope.*

FIGURE 17: *Subdivisions of the Strait of Georgia into areas of distinctive morphology. (After Tiffin, 1969).*

2.3 DISCUSSION:

The following discussion is largely a description of the bathymetric features of the Strait, (see also Figure 2). The adjectives "steep," "wide," "high" etc., refer to the apparent topography as shown on the exaggerated scale cross-profiles. In true scale, slopes are much less pronounced (Figures 14, 15 and 16).

Johnston (1921, 1922, 1923) and Mathews and Shepard (1962) have described the Fraser River Delta in considerable detail. Within the scope of the present study the area referred to as the Fraser River Delta is that portion of the delta seaward from the extensive tidal flats that have developed around the river's mouth. The delta front extends some 27 kilometres from Point Grey to Point Roberts, with active sedimentation most noticeable west and north of Sand Heads. Tidal flats extend some 9 kilometres from the land to the edge of the upper delta slope. Foreset beds now almost reach the opposite side of the Strait. The upper part of the delta front forms a smooth slope of between $3^1/_2$ to $1^3/_4{}^{\circ}$ down toward the floor of the Strait. Further from the river mouth the gradient decreases to 1° or less and the slope merges with bottomset beds of the northern deep basins. The only disruption to the smooth slope of the delta front is caused by a protruding ridge top (Fraser Ridge) northwest of Sand Heads that is believed to possess a Cretaceous or Tertiary bedrock core (Mathews and Shepard, 1962; Tiffin, 1969). At present it is almost buried by delta sediments, but it stands 370 metres above the pre-delta basin floor (Tiffin, 1969), indicating that not only was pre-delta relief in the area considerable, but also that deltaic sedimentation has been very heavy.

To the west of Sand Heads, near the base of the delta slope, is a group of small, rounded hillocks with a relief of 15 to 30 metres. First located by Mathews and Shepard (1962) and described in more detail by Tiffin et al. (1971), they are attributed to sliding or slumping of material from higher on the delta front.

South of Canoe Pass the tidal flats become increasingly narrow and the gradient of the upper delta slope increases markedly. Seawards a smooth, featureless, flattened, dome-shaped topographic high called Roberts Swell appears (section H-H', Figure 15) between 100 and 150 metres below the surface. Roberts Swell is a depositional feature composed of Late or post-Pleistocene sediments, but is not related to the present delta of the Fraser River although modern delta sediments overlie it on the north (Tiffin, 1969).

The southwestern margin of Roberts Swell is a U-shaped, marrow valley that changes in character from north to south. Its northern portion is smooth-floored, U-shaped in section and not particularly steep-sided. To the south it becomes more V-shaped, deeper and supports quite steep flanks. It is cut deeply into Roberts Swell sediments at its southern end, where it swings from a southeasterly to an easterly trend before widening and merging with Boundary Basin. Tiffin's (1969) seismic survey indicates that it has changed from a northward sloping to a southward sloping valley as a result of sedimentation raising the level of the floor in the north (to about 185 metres below sea level), and erosion incising it deeper in the south (to over 220 metres below present mean sea level at one spot west of Boundary Basin).

The roughly triangular depression of Boundary Basin occurs to the southwest of Roberts Swell. Its floor is rather more irregular than that of the deep basins to the north, and like the southern end of

Trincomali Trough it appears to be eroded into Roberts Swell sediments. Tiffin was led to this conclusion because of the possibility of joining reflecting horizons across Boundary Basin, the existence of truncated reflectors in the Roberts Swell unit, and because the power necessary to or responsible for eroding sediments in this area can be provided by tidal currents in the vicinity of Boundary Pass (up to and exceeding 2.5 metres/sec.). The basin increases in depth toward Boundary Pass, where the deepest point occurs (269 metres), and the southeastern margin slopes steeply up toward Alden Bank, which rises to within a few metres of the surface at its shallowest point, and slopes gently down on its eastern side into a shallow depression between it and the mainland coast.

The steep slopes above Roberts Swell are continued to the southeast around a long narrow ridge that extends to the southeast from Roberts Peninsula at between 25 and 70 metres depth. This structure, Roberts Reef, is believed to be composed of Pleistocene sediments. Between Roberts Reef and Alden Ridge the head of Boundary Basin rises more gently and smoothly to the north.

East of Point Roberts and Roberts Reef is the broad, almost flat-floored, shallow (up to about 30 metres) expanse of Boundary Bay. The extensive tidal flats on the north side of Boundary Bay are built, as is much of the floor of the shelf, on a now inactive segment of the Fraser River Delta which was constructed at a time when the river flowed out of, or at least had a distributary into, this region.

The term shelf is used to indicate a zone close to land that slopes basinward at a low angle. The shelf break, which can occur at any depth in this area, is then the outer margin of the shelf where the gradient increases suddenly. The steep zone between the shelf break and the basin floors is referred to as the slope. The shelf or slope on the northeastern side of the Strait is referred to as the Mainland shelf or slope, and on the southwestern side as the Island shelf or slope. Shelf or slope terms are virtually meaningless in the region of the delta, although the term slope is used in a loose way to refer to the upper (steeper) or lower (less steep) slopes of the delta front.

The Mainland shelf is well-defined in the southeast, but in the northwest it is either narrow or missing entirely. Instead the slope extends from the shoreline to the floor of the Strait. The Island shelf is clearly developed in the region of Nanoose Harbour, Nanaimo Harbour, and along the eastern sides of Gabriola and Valdes Islands.

South and north of Gabriola Reefs the Island slope has a different character. In the south the slope is characterised by numerous ridges, all trending in a southeasterly direction, paralleling each other and bedrock structures on the Gulf Islands. On the upper portions of the slope the ridges may form rocky shoals or islets. North of Gabriola reefs the slope is smooth and unbroken by ridges, tends to be steeper than in the south, and to be oversteepened in the lower portions beneath the recent sediments of Ballenas Basin (Tiffin, 1969), a feature not evident to the south. In the south the ridges are close together, but tend to become more widely spaced approaching Gabriola Reefs. The trend of the ridges, and the change in their spacing from south to north, is similar to the pattern of faulting displayed in the Nanaimo Group sediments on the adjacent Gulf Islands. North of Gabriola reefs the change in character of the slope may be attributed to a change in the nature of the bedrock, although Tiffin could not conclude this definitely from the nature of the seismic records.

Extending northwest from, and merging with the lower parts of, the Fraser Delta and situated on the west side of the Strait is an area occupied by two deep basins. These basins were named Ballenas and Malaspina by Cockbain (1963a). Within the study area the basins are separated over much of their length by Sangster Ridge, although near the eastern end of Malaspina Basin only a low col that exists between the eastern end of Sangster Ridge and South Ridge separates the two. The col is less than 20 metres above the basin floor at this junction.

Ballenas Basin, the larger of the two, extends some 65 kilometres in a northwesterly direction from Valdes Island in the south to Ballenas Islands in the north. For the most part the floor of the basin is wide (4 to 6 kilometres) and flat, sloping gently to the northwest. Depths are greater than 360 metres over most of the basin, with a maximum of 423 metres. The southeastern end of Ballenas Basin appears to have been protected from encroaching delta foreset sediments by a bedrock ridge (Finger Ridge: Tiffin, 1969). On the southern side of this ridge water depths reach more than 380 metres. The northwestern margin of Ballenas Basin is a low ridge joining Ballenas Islands to Sangster Ridge. The bottom rises gently up from the basin floor to this ridge, which also serves to separate Ballenas Basin from Hornby Basin (in the northwest, but outside this study area).

Malaspina Basin extends northeastward of Ballenas Basin beyond the limits of the study area. The portion investigated shows a more irregular floor than that of Ballenas Basin, and a narrower, more V-shaped profile. Water depths in Malaspina Basin are shallower, on an average, than in Ballenas Basin although the deepest spot in the Central and Southern Strait (433 metres) occurs in Malaspina Basin at the base of Round Ridge.

Sangster Ridge consists of two parts. The western part, which connects to Ballenas Islands via a low saddle and to the platform of Lasqueti Island, is an east-southeast trending hump that rises to within 200 metres of the surface. It is believed, from seismic records and from dredging, to be of morainal origin (Tiffin, 1969). The eastern part of the ridge is much smaller and consists of several separate hills rising from a low base. It is considered to have a different origin from the main, western, portion of Sangster Ridge; Tiffin (1960) considers it to be part Pleistocene material and partly of igneous instrusive origin.

In the northeastern side of the Strait the bedrock floor slopes up toward the mainland coast (see seismic profiles in Tiffin, 1969) and a number of northeast-southwest trending ridges are developed on this elevated sloping platform. Round Ridge is a steep-sided, narrow, conical feature situated on the north slope of Malaspina Basin and believed to comprise intrusive igneous rocks. On the northeast side of Ballenas Basin is South Ridge, a relatively inconspicuous feature consisting of 2 separate peaks of limited height.

On the northeast side of South Ridge, rising slowly at first then abruptly above it, is the much more prominent structure of Halibut Ridge, which rises to within 23 metres of the surface at its shallowest point. Halibut Ridge is a long, narrow feature sloping gently to the northwest and southeast along its length, and to the northeast where a wide valley separates it from McCall Ridge. McCall Ridge is the most extensive of all the ridges in the Central and Southern Strait of Georgia. It trends some 35 kilometres in a northwest-southeast direction parallel to Halibut Bank and the mainland coast, and striking towards but offset to the west from Point Grey.

The 175 metre deep, flat-floored Sechelt Basin separates McCall Ridge from the steeply inclined mainland slope of Sechelt Peninsula. The southeastern end of this basin has been cut by a deep valley that slopes down to the floor of Queen Charlotte Trench some 75 metres below. Queen Charlotte Trench trends in a northeasterly direction toward Howe Sound but is prevented from providing an open connection to Howe Sound at basin floor level by a sill west of Bowen Island (Mathews, Murray and McMillan, 1966).

CONCLUSION:

The Strait of Georgia can be subdivided, on the basis of morphology, bathymetry and structure into distinctive regions. A broad grouping is suggested from the description of the various areas. A line between Queen Charlotte Trench and Porlier Pass separates the Strait into two regions whose bottom topography is quite distinct, and is related primarily to Pleistocene (in the northwest) or Holocene (to the southeast) deposition and/or erosion.

Southeast of the line mentioned above, the Strait has a smooth topography associated with active and rapid deposition of sands and muds from the Fraser River. The Roberts Swell feature, likewise a broad, smooth area of deposition, is also believed to have been formed by the Fraser River, at a time when the Fraser entered the Strait from a more southerly point than at present. Boundary Basin has a smoother outline than the topography to the north.

To the northwest the topography reflects a complex interplay of bedrock structure, erosion by ice, and deposition of Pleistocene glacial and interglacial sediments. It is an area of extreme relief (from the 400+ metres depth of the deep basins to the 23 metre shoal of Halibut Ridge) and rugged topography, although smoothing of the topography is slowly being accomplished by deposition and accumulation of hemi-pelagic sediments - the bottomset or pro-delta muds introduced by the Fraser River.

CHAPTER THREE

LITHOLOGY

3.1 INTRODUCTION

Within this chapter lithologic attributes of the sediments are described and discussed. The results of the size analysis of 187 Strait of Georgia bottom-sediment samples are presented and explained. From the results of these analyses, and the observations recorded when samples were first collected, maps have been constructed of sand distributions, and of facies based on the proportions of sand (plus gravel):silt:clay in each sample. The granulometric data was submitted to factor analysis and the results of this are discussed, particularly in relation to the question of distribution and dispersal of sediments.

The cores examined showed a remarkable uniformity in colour and in texture, both among cores and within a single core. With the exception of one, there was no evidence of bedding in any core. A mottled appearance to the internal surface of split cores, and the occurrence of what can be identified as burrows and mounds on the sea floor in the area of some of the core sites (still visible even in the very poor quality photographs obtained) suggests bioturbation by bottom-dwelling organisms is an important process in homogenising the sediments. Accumulation of clays and fine silts by settling from suspension is also an important factor in producing non-laminated sediments. X-ray diffraction analysis of the mineralogy in 10 subsamples taken at the surface, 10, 20, 40, 80, 150, 176, 180, 200 and 230 cm. along the length of one core indicated a similar mineralogy throughout, with no systematic variations. Microscopic examination of smear slides confirmed this finding, and permitted recognition of diatoms and some radiolarian skeletons as well.

3.2 LABORATORY METHODS

Size analyses were performed by conventional sieve and pipette techniques (Krumbein and Pettijohn, 1938). Samples were homogenised prior to subsampling in case settling of particles or fluid migration had occurred between the times of collection and of analysis. Two subsamples were taken, one being dried to constant weight at 120°C and used to calculate water content of the sediment. The other was shaken in distilled water for two hours to remove soluble sea salts. The material was centrifuged and the supernatant liquid evaporated. Usually this would result in an estimation of the salt content of the sample, but for many of the Georgia Strait sediments the supernatant was discoloured a translucent or transparent, pale brownish, brownish green or greenish olive colour, even after 1½ to 2 hours centrifuging at 2800 rpm. X-ray diffraction of the residue after gentle heating toward dryness indicated that the material may be in part poorly crystalline clay mineral matter, but most of it is likely to be colloidal and dissolved(?) organic matter. Oxidation of the residue with 30 percent hydrogen peroxide often removed much of the discolouration.

The centrifuged sediment was mixed in a milk-shake blender for 10 to 15 minutes with a 5 gram per litre solution of CALGON (trade name for sodium hexametaphosphate), which was found to be an effective dispersing agent. The mixture was then washed through a 230-mesh (62 micron) sieve, thoroughly washed with dispersant solution, and the sub-sieve solution collected in a settling tube. The settling tube was made up to one litre with distilled water, and was placed in a water-bath to come to a steady temperature. Thorough stirring of the contents of the tube and inspection of it next day revealed whether flocculation had taken place or whether the dispersing procedure had been successful. If it was not, the sample was centrifuged, washed, centrifuged again, then redispersed in fresh dispersant.

The fraction remaining on the 230-mesh sieve was washed, air-dried, carefully disaggregated if necessary, and sieved at 1/2-phi intervals through a nest of three inch diameter sieves (Hoskins Scientific Ltd.). Material passing the last (230 mesh) sieve was added to the settling tube of the same sample.

Pipette aliquots were removed at times calculated according to Stokes' Law to permit the weights of material in each phi interval to be obtained.

Raw weights obtained by sieving and from the pipette analyses were combined to calculate weight percent per ½ or 1 phi interval respectively for each sample. Reproducibility of the technique was tested by sieving the same sample more than once, and by conducting complete pipette analyses on more than one subsample of the same sample. Results are presented in Tables II and III. Almost all samples contained sufficient fine material to require pipette analysis, although many did not have sufficient sand to warrant sieving. The class limits used are those of the Wentworth (1922) grade scale (see also chart in Folk, 1968, page 25).

Raw data was processed with the aid of an IBM Systems 360 model 67 computer (UBC Computing Centre). Measures of mean grain-size, standard deviation, skewness and kurtosis were derived from hand-plotted cumulative probability curves using the graphical parameters of Folk

Size θ	mm.	Weight percent 1	2	3	4	mean	Δ	%	δ	%
0.5	0.71			.05	.03		.05	100		
1	0.5	.44	.51	.62	.49	.52	.18	30	.01	1.6
1.5	0.35	21.45	20.97	21.76	20.33	21.13	1.43	6.6	.16	.74
2	0.25	44.26	45.32	44.92	45.83	45.08	1.57	3.4	.16	.35
2.5	0.177	27.34	28.72	26.63	27.01	27.42	2.09	7.3	.08	.28
3	0.125	5.78	3.99	5.40	5.71	5.22	1.79	31	.09	1.6
3.5	0.088	.57	.36	.52	.50	.48	.21	34	.02	4.0
4	0.0625	.14	.12	.11	.11	.12	.03	21	0	0

TABLE II: Reproducibility of sieve analysis. Sample 82 split into four approximately equal subsamples. Δ = greatest difference, δ = least difference between subsamples.

Size θ	mm.	Wt % 1	2	Δ	%
4	0.0625	.539	.581	.042	8
4.5	0.044	0	.581	.581	100
5	0.31	1.124	0	1.124	100
6	0.0156	1.686	1.163	.023	1.3
7	0.0078	6.181	6.395	.214	3.3
8	0.0039	12.924	15.698	2.674	17
9	0.002	26.410	20.349	6.061	23
10	0.00098	14.610	23.837	9.227	39
>10		36.525	31.395	5.130	14
$\bar{x}$		9.60	9.55	.05	.5
σ		2.38	2.25	.13	5.5

Table III part 1: Sample 350.

Size θ	mm.	Weight percent 1	2	3	Δ	%	δ	%
4	0.0625	0	1.627	1.678	1.678	100	.051	3
4.5	0.044	.683	.740	0	.740	100	.057	7.7
5	0.031	.341	.370	1.342	1.001	75	.029	2.2
6	0.0156	2.901	2.959	1.342	1.617	54	.058	2
7	0.0078	6.997	8.876	9.396	2.399	26	.520	5.5
8	0.0039	18.089	15.533	16.107	2.556	14	.574	3.2
9	0.002	17.406	16.642	17.114	.472	3	.292	1.7
10	0.00098	14.505	15.163	16.107	1.602	10	.658	4.1
>10		39.079	38.092	36.913	2.166	6	.987	2.5
$\bar{x}$		10.02	9.92	9.90	.12	1.2	.02	.2
σ		3.14	3.20	3.13	.07	2.2	.01	.31

Table III part 2: Sample 230.

TABLE III: Reproducibility of pipette analyses. Separate analyses of samples 350 and 230. Δ = greatest difference, δ = least difference between analyses. $\bar{x}$ = graphic mean grain size, σ = inclusive graphic standard deviation.

and Ward (1957).

Q-mode factor analysis was performed on the granulometric data - percent weight of sediment in each 1 phi interval - using a computer programme belonging to the Geology Department, U.B.C.

Isopleth maps were constructed using the technique described by Cullen (1966), which assumes a continuous, linear change in the values from any one station to its immediate neighbours. Due regard is taken of topographic features between stations, and sensible, although subjective, modifications to the contours can be made by eye.

3.3 DISTRIBUTION OF BEDROCK OUTCROPS

Bedrock is exposed in the main tidal channels between the islands on the west side of the Strait. The determination of the outcrops as bedrock is based largely on negative evidence: the inability to obtain grab samples from these areas despite successful triggering of the grab; long, deep score marks on the outside of the grab; the retrieval of only isolated cobbles and boulders from nearby sample sites; and the existence in these areas (Boundary, Active and Porlier Passes) of strong tidal currents that locally exceed 6 knots. Huggett (1966) presents information obtained by the U.S. Coast and Geodetic Survey from current measurements made near Boundary Pass. Here currents are commonly up to 5 knots and constant, with bottom currents generally equalling or exceeding the speeds of surface currents. In the vicinity of these tidal passes the bedrock outcrops are believed to be of Upper Cretaceous Nanaimo Group sediments.

3.4 DISTRIBUTION OF GRAVELS

The distributions of gravel and very coarse sand are considered together for two reasons: there is often a mode in the gravel to very coarse sand range separated from modes in the finer sizes by a distinct gap in the size distribution; the two size-classes are believed to be genetically related in so far as they occur either together or separately in areas where they are unrelated to present depositional mechanisms.

Generally, the gravels are restricted to the marginal areas or to the tops of the banks in the northern part of the study area. However, the appearance of gravels in Boundary Basin led to a theoretical distinction of two types of gravel deposits: those out of equilibrium with the present sedimentary regime, considered to be relict deposits; and those located in areas believed to be erosional, and hence considered to be lag concentrates. The practical distinction is not easy, in fact is rather subjective, being based on features of grain shape and surface texture, and upon topographic and sedimentologic considerations.

Relict gravels occur on upstanding features such as the ridges and in some marginal areas. The components tend to be angular to subangular (roundness scale of Powers, 1953) with only a few subrounded elements. Surface textures vary but tend to be rough, and may also be pitted by preferential removal of minerals from the pebbles. The pebbles rarely support any form of attached animal life, although sponges and sponge fragments are a common, integral part of the sediment.

The occurrence of gravels on ridges, separated by basins or by long distances from possible sources, precludes their origin as modern deposits. There is no known sedimentary process acting in the Strait of Georgia which could transport gravels to these areas. They are out of equilibrium with present conditions existing in the Strait. Their continued existence is a function of either sufficient current movement around the ridges preventing deposition of all but a small amount of mud, or a lack of, or low rates of, sedimentation as a result of insufficient sediment reaching these sites. The presence of sponges and other life forms associated with these gravels suggests a maintenance of food supply and a lack of suffocating deposits of mud (Figures 10 and 11). Sponge debris has been collected from the sediments on the flanks of some ridges indicating that currents or, perhaps at times, violent storms may be strong enough to move and redeposit this material. A lack of gravel on the bank flanks, however, suggests that the banks themselves are not presently active as local sources of sediment. Decreasing amounts of gravel, but the continued presence of very coarse sands away from the crests of McCall and Halibut Ridges, and around Ballenas Islands, implies that the ridge deposits may have been reworked during lower stands of sea level.

Lag concentrate gravels occur in the southern part of the area of study, in the vicinity of Point Roberts, Trincomali Trough and Boundary Basin. Here the gravels are associated with areas that show topographic and internal morphological features attributed to active submarine erosion (see Section 2.3). The gravel components are more commonly subrounded than angular, although a range of shapes does occur. Their surfaces are generally more pitted and abraded than those of the ridge top samples. Encrustation of the pebbles with a wide variety of life forms including mussels, brachipods, barnacles, bryozoans, and worm tubes is common.

Near Point Roberts a sample with a low concentration of very coarse sands appears to be closely related to those of the ridge top samples; however, it is considered to be the result of erosion of Pleistocene deposits similar to those on nearby Roberts Peninsula.

Gravels of the island shelf and slope are related to a relict origin. Derivation from local sources, particularly in the area south

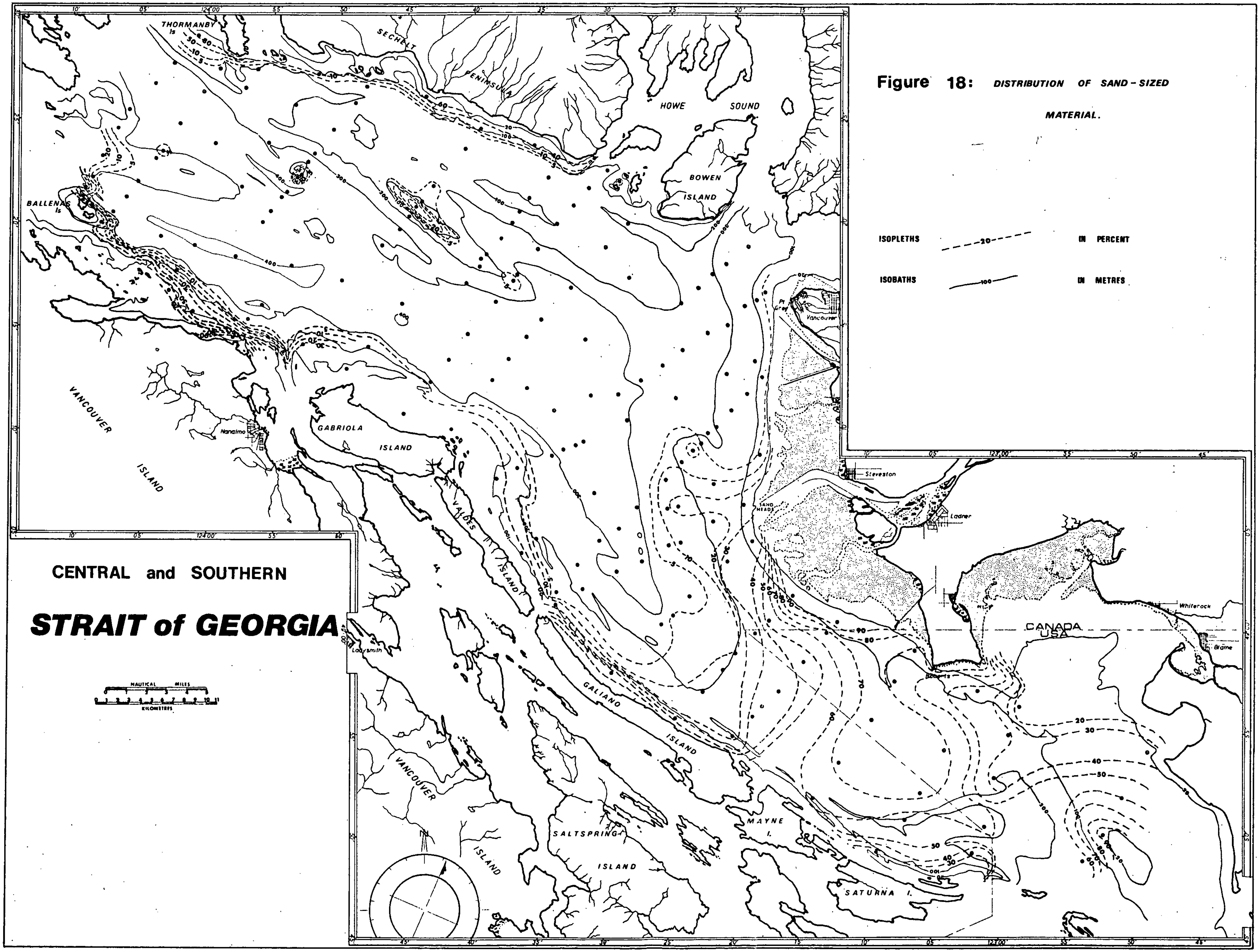


Figure 18: DISTRIBUTION OF SAND-SIZED MATERIAL.
ISOPLETHS IN PERCENT
ISOBATHS IN METRES
CENTRAL and SOUTHERN
STRAIT of GEORGIA
NAUTICAL MILES
KILOMETRES
THORMANBY Is
SECHELT PENINSULA
HOWE SOUND
BOWEN ISLAND
BALLENAS Is
VANCOUVER ISLAND
Nanaimo
GABRIOLA ISLAND
VALDES ISLAND
Ladysmith
GALIANO ISLAND
SALTSPRING ISLAND
MAYNE I.
SATURNA I.
Pt Grey
Vancouver
Steveston
SAND HEADS
Ladner
Whiterock
CANADA
USA
Blaine

of Gabriola Reefs, is a possibility, but the composition of the gravels here is not significantly different from those of the ridges or the island shelf and slope to the north.

3.5 DISTRIBUTION OF SAND

Figure 18 shows the distribution of sand in the Strait of Georgia, with isopleths constructed at 5, 10, 20, 30, etc percent. The isopleths refer to sand only. Had they been constructed on a sand-plus-gravel basis a slightly modified picture would have emerged in the vicinity of Boundary Basin. The general distribution is consistent with patterns derived by other methods. Sand content of the sediments is high in the south, decreases from the delta basinwards to the north and west, and basinwards from the margins of the Strait. Sand content is high in the Roberts Swell, Boundary Basin and Alden Bank areas in the south, along the Island Shelf and upper slope, the upper slopes of the Delta front and along the mainland slopes north of Burrard Inlet.

Proximity to source and/or the effects of current action are reflected in the distribution of sand content isopleths. No sand occurs in the tidal channels between the Gulf or San Juan Islands. High percentages of sand are encountered in Boundary Basin which, as has been indicated, is considered to be an erosional feature. High sand and gravel contents here are believed due to a washing of fine material from older Holocene sediments, and prevention of deposition of suspended sediment now by tidal currents. Sand concentrations over the broad dome of Roberts Swell, west of Point Roberts, are large. In this area tidal currents of the reversing type may exceed speeds of 30 cm/second only 41 cm. above the bottom (Pickard, 1956; Waldichuk, 1957). Washed material will tend to be carried northwest or southeast and either redeposited or even entirely removed from Georgia Strait. The sands of Roberts Swell thus represent lag concentrates or relict sediments. A similar explanation is advocated for the sand and gravel contents of the bank tops - current velocities are sufficiently strong to prevent accumulation of muds other than as a thin, superficial veneer, or trapped in the interstices between pebbles and cobbles.

Dispersal trends of sediment from the Fraser River upon entering the Strait are evident from the distribution of sand. The northwards bend of the 5% and 10% sand isopleths just west of Sand Heads suggests the immediate northward deflection of the Fraser River plume on entering the Strait, and the transport of material in this direction. Decreasing sand contents from the delta northwards, and from the margins basinwards, follow the classical pattern of higher sand concentrations closer to source areas or to land.

It has not been possible to resolve unequivocally what happens to the bed-load material of the Fraser River when it reaches the Strait of Georgia. Tiffin et al. (1971) considered that the bed-load, after initial deposition on bars and banks, was eventually redistributed on the extensive tidal flats around the river's mouth. Johnston (1921) suggested that bed-load sediment eventually made its way to the delta front, after periods of rest on bars and banks, and generally only during the freshet, where it either came under the influence of strong, persistent, northward tidal currents or was buried under finer material. Mathews and Shepard (1962) proposed that under the influence of the salt-water wedge that intrudes up the Fraser River to approximately near Steveston during the flood tide, bottom-load sediment was stopped from reaching the Strait. With the aid of south-setting ebb flow, the coarser material was believed to be moved to the south. Evidence from factor analysis presented later in this chapter tends to support this hypothesis. However, most observations (Johnston, 1921; Waldichuk, 1957; Giovando and Tabata, 1970; Tabata et al., 1971; and Tabata, 1972, oral comm.) indicate that north-setting flood tides are stronger and of longer duration than south-setting ebb-tides on the eastern side of the Strait, and that in fact there is a net northward movement of sediment by currents along the delta front, even during ebb tibes. This would tend to move the bottom-load sediments to the north along with most of the suspended material. A possible explanation for the anomalous situation of higher sand contents south of the delta may be that during the freshet seaward flow from the river is strong enough to overpower the northward moving currents even during flood tides.

If southward movement of Fraser River bed-load but northward transport of suspended-load was occurring on their reaching the Strait of Georgia, isopleths of mean grain size and of sand content should show a pattern of decreasing values more or less concentric about Sand Heads, since South Arm is the most active of the various distributary channels of the Fraser River. Examination of Figures 18, 22, and 23 indicates that the patterns displayed by these parameters are not logically consistent with southward transport of bed-load sediment, although this observation is diametrically opposed to conclusions that can be drawn from the factor analysis (see section 3.10).

Also, apart from stations 21 (on Alden Ridge), 286 (on the Island Shelf close to shore just north of Nanaimo), and 351 (close to shore on the mainland side at the northwestern end of the study area), the highest sand values of the samples investigated occur at sample sites

82 and 83, northwest of Point Roberts and south of Canoe Pass. While the areal distribution of sand contents could be considered consistent with southeastward transport of bed-load sand from Sand Heads, those of the mean and median grain sizes are not. Rather than a southeasterly decrease in grain-size, the decrease is northwestward, from 82 to 83, and the mud content of the samples increases in the same direction. Sediment samples collected from the bed of the Fraser River at Ruby Creek, 12 miles east of Agassiz, had a lower sand content and a finer mean grain-size than did 82 or 83.

The composition of the sands from samples 82 and 83 is indistinguishable from those of the Fraser River and from some of the relict Pleisotcene deposits (e.g. 354 on Halibut Ridge, and Quadra sediments at Point Grey). Since the Fraser River flows through, and derives much of its load from, extensive Pleistocene deposits, it is not surprising that Fraser River and (relict) Pleistocene sediments should be similar in composition. Samples 82 and 83 could therefore have been derived from either the Fraser River or from the erosion of Pleistocene deposits on or close to the present coast.

Derivation by erosion from the Pleistocene material of Point Roberts is precluded by the occurrence, closer to Point Roberts and in shallower water, of samples that contain less sand and of finer mean grain size.

It is suggested that these samples were collected from an area of erosion and washing of older Fraser River delta material, perhaps deposited at a time when Canoe Pass was more important as a distributary than it is now. If this hypothesis is true, material removed from these sites will be redeposited both to north and south along the delta front, and may obscure or modify the expected patterns of percent sand and of mean grain-size distributions (see also Appendix III).

3.6 DISTRIBUTION OF SILT AND CLAY SIZE MATERIAL

Fine to very fine sand, silt and clay comprise the bulk of the modern sediment accumulating in the Strait of Georgia (see Figure 19). Accumulation of sandy material along the margins away from the Fraser River delta is, as has been pointed out, attributable to local derivation and deposition. Figures 20, 21, 22, and 23 indicate the distribution of the finer sediments. As can be seen from these figures, most of the fine material is currently being deposited to the west and north of the Fraser River mouth. While some is obviously reaching bank tops and the area to the south, its contribution to the sedimentary makeup in these areas is relatively minor.

The fine fractions are mineralogically very similar over the entire area of the Strait of Georgia. The Fraser River, accounting for over 80% of the fresh-water inflow to the Strait (Waldichuk, 1957), is the main contributor of fine material, to the extent that donations from other sources are swamped and consequently indistinguishable.

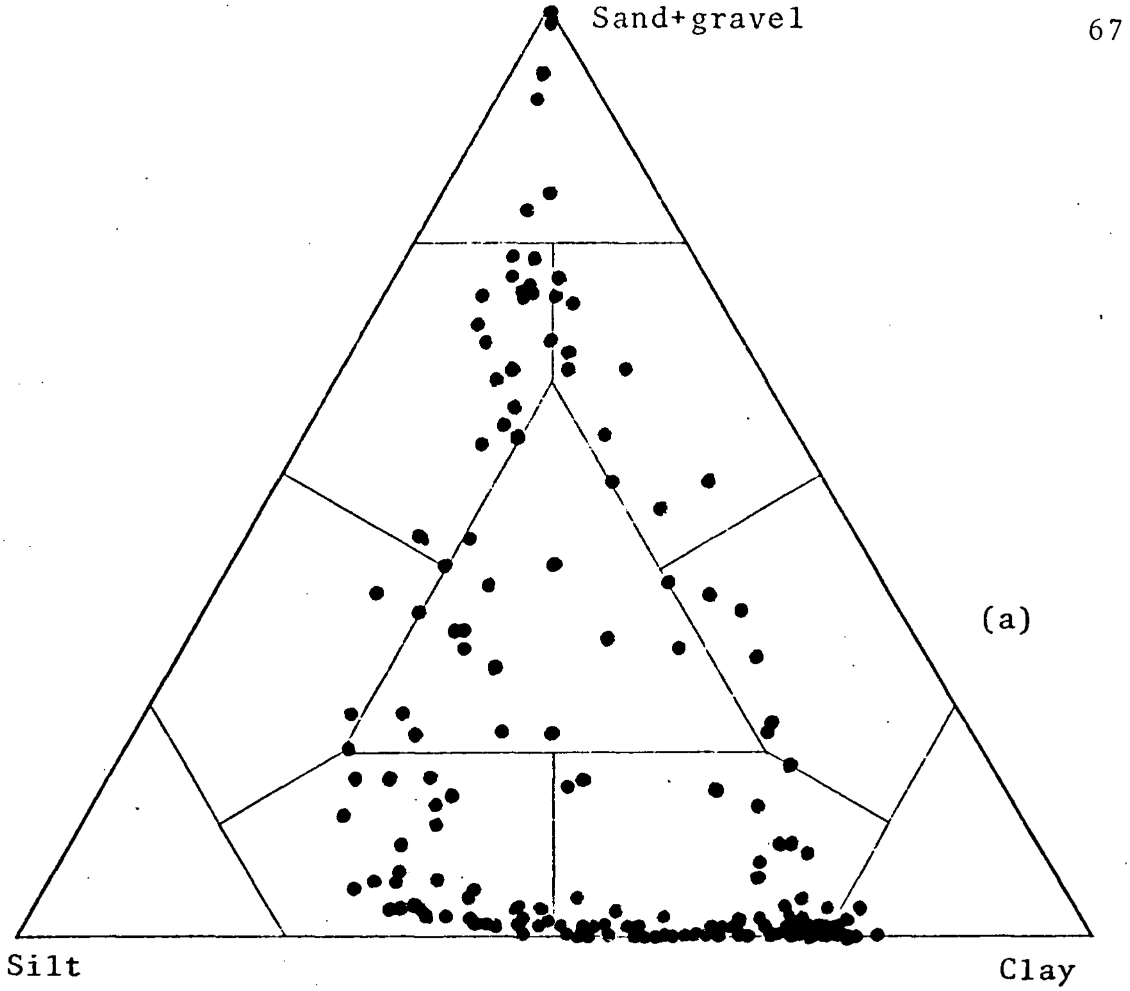
3.7 SAND-SILT-CLAY RATIOS

The technique of plotting proportions of size components on a ternary diagram provides an invaluable basis for the construction of facies maps of Recent sediment distributions. The diagram can be subdivided in any way that is considered to be meaningful, and the individual subdivisions given names and used as components on a facies map.

The choice of end-members is purely arbitrary but, like the subdivision of the diagram, they should be components that have some sedimentological meaning. For facies maps the end-members are usually size-grades. Various size intervals have been used (Wimberley, 1955) but the most common are the gravel, sand and mud, or sand, silt and clay grades.

Consideration was given to utilising a possible break in the size distributions at 6 phi (i.e. coarser-than-6 phi, 6 to 8 phi, and finer-than-8 phi) but it was considered to be a little too tenuous since: (1) it meant combining material analysed by sieving with that determined by pipetting; (2) the mineralogy of the coarse silt fractions is not significantly different from that of the fine sands; and (3) it would not significantly alter the plots of samples composed of only finer material, much of which fell into the finer-than-6 phi range. The final decision was to retain the conventional end-members sand, silt and clay. Since gravels have only restricted distribution, grouping these with sand as one end-member was not considered to detract from the interpretive value of this technique for Georgia Strait sediments.

Folk (1954) and Shepard (1954) devised useful and widely used ways of presenting sediment data on triangular diagrams (Figure 19). Sediments from Georgia Strait have been plotted on both these schemes and the resulting distribution of facies, based on subdivisions of the respective ternary diagrams, are presented in Figures 20 and 21. While Shepard's (1954) scheme is encountered more commonly in the literature it is presented here primarily for purposes of comparison with other studies. Folk's (1954) subdivision is considered to have more advantages for the construction of facies maps. It utilises a



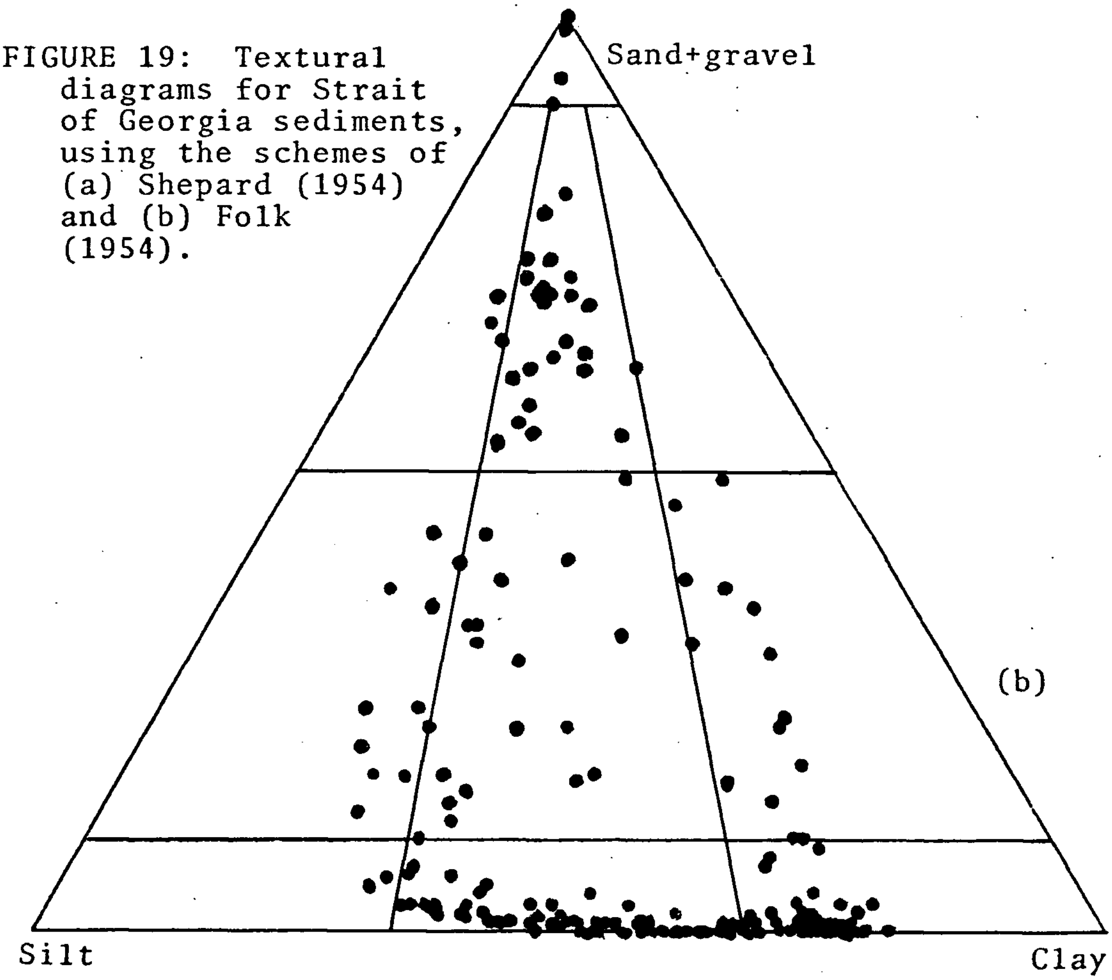


FIGURE 19: Textural diagrams for Strait of Georgia sediments, using the schemes of (a) Shepard (1954) and (b) Folk (1954).

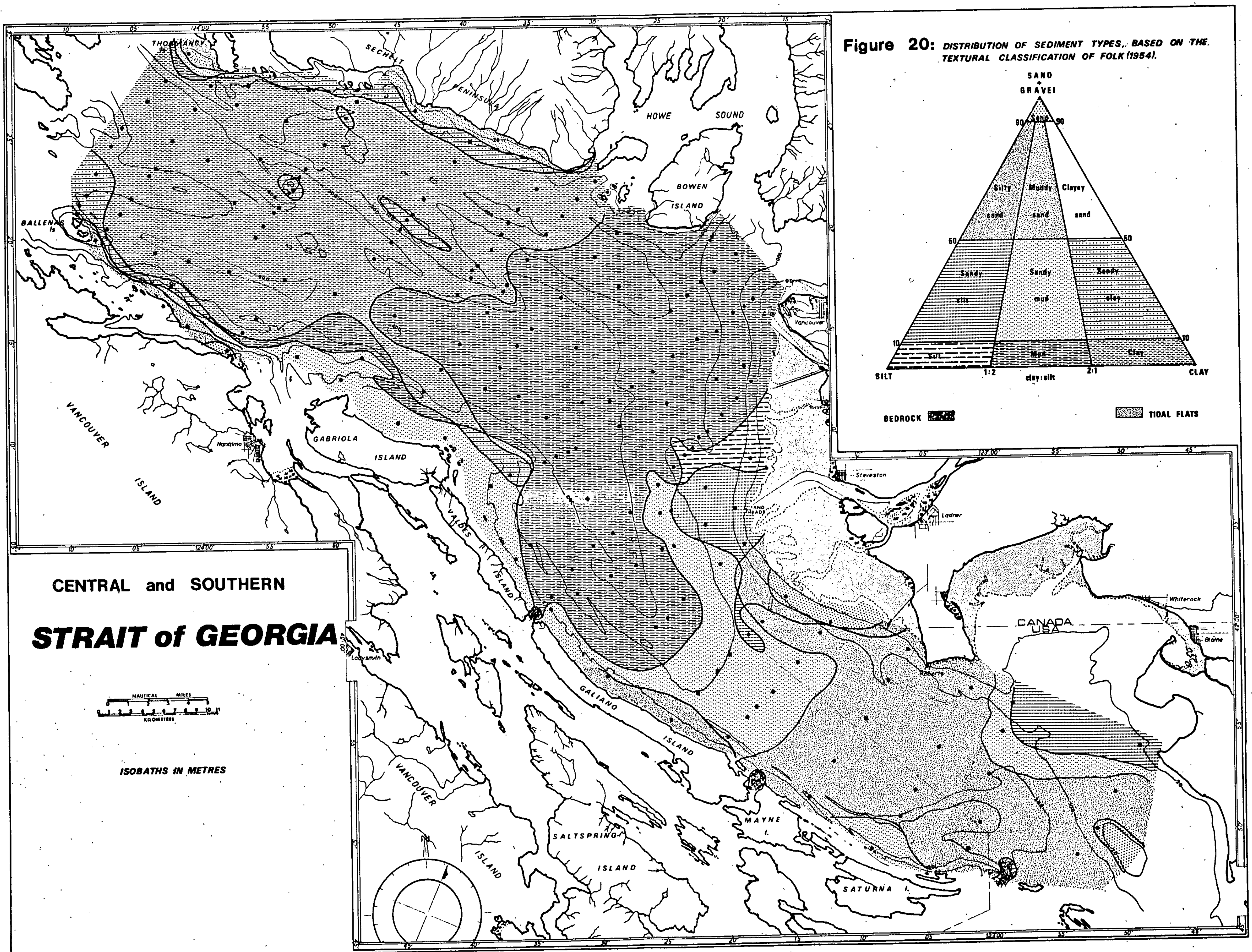


Figure 20: DISTRIBUTION OF SEDIMENT TYPES, BASED ON THE TEXTURAL CLASSIFICATION OF FOLK (1954).

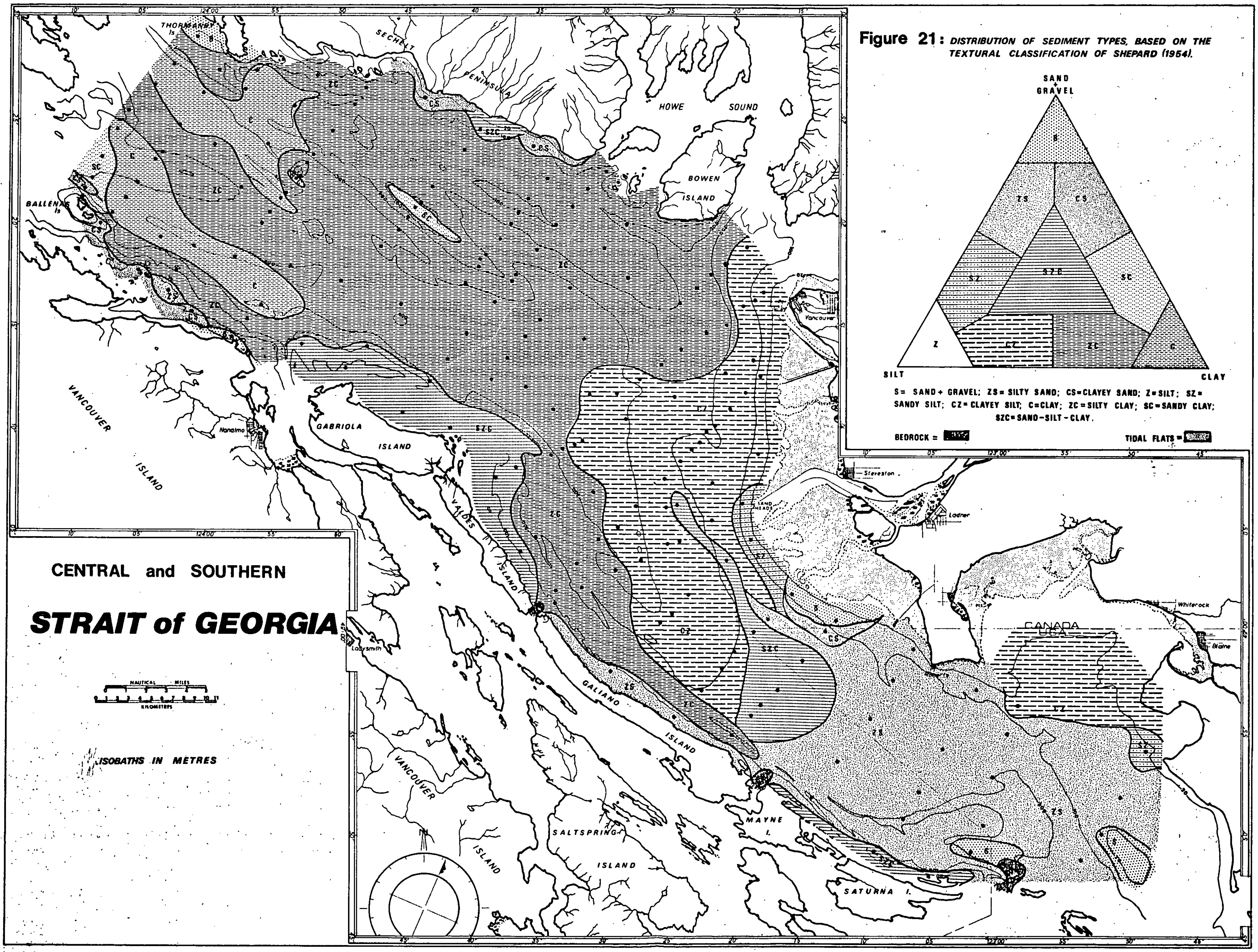


Figure 21: *DISTRIBUTION OF SEDIMENT TYPES, BASED ON THE TEXTURAL CLASSIFICATION OF SHEPARD (1954).*

sand (≥62 micron) end-member that can be taken to represent bed-load or saltation-load material and two end-members in the finer range, the suspended load. The suspended-load is divided in the proportion of clay-size to silt-size material that is present in the sample. The scheme produces what is virtually a sand:mud ratio, which can be taken as representing the amount of washing at the site of deposition. Construction of facies maps requires the drawing of only five contours (90%, 50%, and 10% sand, and 1:2 and 2:1 clay:silt ratios), the segments bounded by three of these contours thus being related directly to the subdivisions of the ternary diagram. The remainder of the discussion on the distribution of facies in the Strait will be based on Figure 20, after Folk's scheme.

Most of the sediments in the Strait of Georgia are muds and clays, containing less than 10% sand, with a scatter of samples in the sandy-mud and muddy sand fields. Very few samples fall in the sand category (>90% sand-sized material) and in fact only 15% of the samples analysed had more than 50% sand, whereas 65% contained less than 10% sand.

The occurrence of an area of anomalously sandy, and coarse, sediments on the east side of the Strait northwest of Point Roberts and southeast of Sand Heads has been discussed already. Other areas of sand deposits include: Alden Bank where wave and current action have sorted and graded older sandy sediments (?old delta sediments - Tiffin, 1969); the west side of the Strait between Nanaimo and Nanoose at locality 286, where the sands appear to be locally derived as well as in part relict; and at the far northwestern end of the study area, on the eastern coast (#351), where a similar, local derivation is suspected.

South Arm of the Fraser River is the most active distributary in supplying sediments to the delta front and to the Strait. In the vicinity of South Arm sandy silts, silts, and silty sands grade westwards and northwards into the muds and, eventually, clays that floor the largest part of the Strait. To the south, what are believed to be old delta foreset beds (Roberts Swell sediments, Tiffin, 1969) are represented by a zone of muddy sands which grades southwest and eastwards into finer sediments of Boundary Bay. Overlying the muddy sands of Roberts Swell at its northwestern edge, and extending toward the northwest is an area of sandy muds which has a broad U-shaped distribution closing toward the southeast. The arms of the U extend northwestward along the Island Shelf and Slope and along the mid and lower delta slopes. They embrace a broad, north - south trending swath of mud that has a short northwesterly extension into Ballenas Basin. To the northwest the muds grade into clays that cover the basin floors and are an integral part of the ridge-top sediments in the northwestern part of the study area.

Along the axis of the Strait, from southeast to northwest, there is a gradation from muddy sand through sandy muds to muds and finally clays. Where the delta encroaches on the Strait silty sand and sandy silts grade laterally westward through sandy mud, and northward via silts, to muds and clays. Similar gradations from sandier sediments to basin muds take place from the margins basinwards although the areal distributions are more compressed.

3.8 SIZE ANALYSES

Most size analyses, and the subsequent attempts at environmental discrimination using the data from the grain-size distribution or parameters derived from it, have been developed through the study of sands and coarser sediments. The limitations involved in the size-analysis of fine-grained sediment have been repeatedly pointed out in the literature, and many arguments have been presented against the empirical "size-analysis-to-ultimate-particles" approach for these sediments (see Gripenberg, 1934; Swift et al., 1972; among others). Because of this, few authors have attempted to do more than merely state that dominantly muddy sediments exist in various environments. Duane (1964) for example, would not analyse samples containing more than 5% sub-sieve size material.

There are two possible approaches to a study of muddy sediments. Either all arguments against analysing this type of sediment can be reviewed and considered, and their overwhelming bias against such procedures accepted. Or, disregarding all logical arguments to the contrary, samples can be subjected to conventional analytical techniques and the results studied. If, when mapped, the quantitative descriptive parameters thus derived produce geologically sensible areal distributions, with due regard to known oceanographic features of the environment of deposition, then the practical results must take precedence over the theoretical arguments. The second approach has been taken in this study. Apart from Gripenberg's (1934) study of the North Baltic Sea sediments, few people have taken this approach with fine-grained sediments.

Granulometric studies of sediments usually produce a mass of data that must be reduced for more efficient handling. Statistical treatment of sediment size data has been used extensively to accomplish this end. The statistics used, however, have relied heavily on two important assumptions: that the size-frequency distribution follows or approaches a log-normal (or normal, when using the log transform of the grain-size in millimetres) probability function; and that the size distribution is continuous. It is apparent from the literature that neither assumption is entirely valid, and this has important implications for the interpretation of cumulative probability curves of sediment size distributions.

Arguments for and against the concept of normal distribution of sediment size-frequency distributions have been proposed by, among others, Krumbein (1934, 1938), Krumbein and Pettijohn (1938), Doeglas (1946), Pettijohn (1957), Herdan (1960), Friedman (1962), Middleton (1962), Rogers and Schubert (1963), Rogers et al. (1963), and Tanner (1964).

Considerable evidence has been published that refutes the concept of continuity of the size distribution (Folk, 1966). Udden (1914) showed a shortage of 3 to 4 phi diameter grains in aeolian sands. Wentworth (1933) found two gaps in natural size distributions at -1 phi and at 8 phi, plus a minor minimum at 3.5 phi. Minima in the -1 to $-1^1/_2$ phi and 4 to $4^1/_2$ phi ranges were noted by Hough (1942), while Pettijohn (1957) records gaps at 0 to -2 phi and 3 to 5 phi. Tanner (1958, 1959), Spencer (1963) and Rogers et al. (1963) all reported minima in the size distributions of sediments in similar size ranges. Griffiths (1962, 1967), however, contends that the gaps are artificial, and are induced by a change in analytical technique. Swift et al. (1972) discuss evidence that suggests the break between 50 and 30 microns (4.5 to 5 phi), commonly considered to be analytically induced, is in fact real. Belderson (1964) used sieves over the range 230 to 18 microns (2 to 6 phi), and found that the break still occurred in the same place. He suggested that the break was caused by particles in aggregates. Sheldon (1968) recorded the same break and considered that it was formed naturally, during transportation of the sediment, not during analysis. A similar explanation is offered for the origin of the "Sawdust Sand" by Pryor and Vanwie (1971).

The existence of minima in particle size distributions led some workers to postulate either the existence of primary populations in the gravel, sand (+ coarse silt), and clay grades, or derivation of the sediment by mixing of populations that represent different sources, different ages, or different methods of transportation (Doeglas, 1946; Folk and Ward, 1957; Tanner, 1958, 1964; Spencer, 1963; Rogers and Schubert, 1963; Sengupta, 1967; Visher, 1969).

More detailed consideration is given later to the implications of zig zag or polymodal cumulative probability curves of size distributions.

An abundant literature exists on the use of certain statistical parameters derived from grain-size distribution curves to characterise sediments by their environment of deposition (for examples see: Krumbein, 1934; Krumbein and Aberdeen, 1937; Krumbein and Pettijohn, 1938; Inman, 1952; Passega, 1957; Folk and Ward, 1957; Mason and Folk, 1958; Friedman, 1962, 1967; Koldijk, 1968; Moiola and Weiser, 1968; Isphording, 1972; among many others). This use, however, has been severely criticised by Klovan (1966) and Solohub and Klovan (1970) on sound experimental grounds.

Statistical descriptors derived from the size-frequency distributions are important in facilitating communication about the nature of the sediment, and permitting comparisons to be made between and among samples. The choice of which statistical measures to use, however, is complicated by the great number available, and, especially with respect to graphical measures, there do not seem to be any good reasons for accepting any one kind over any other. Although Cadigan (1954), Davis and Erhlich (1970) and Isphording (1972) have shown that graphical measures give results that are significantly different from the method of moments for the same curves, the present author believes that the former may be the only theoretically sound way of quantifying size data for fine grained sediments.

Limitations are more or less imposed. Polymodal curves are difficult to treat adequately despite Folk's (1966, 1968) contention that inclusive graphic measures compensate for polymodality more than any other graphic solutions, and "open-ended" curves create their own problems. But as Folk (1968) points out, graphic techniques provide a quick, reasonably accurate method for approximating the measures of central tendency of the distribution (i.e. the mean and median: the average grain size), the spread of values about the centre (the standard deviation - a measure of the degree of sorting for sediments), asymmetry (skewness) or how well-defined the curve is (kurtosis).

Size analyses of Strait of Georgia sediments are complicated by the large quantity of admixed subsieve-size material. As a result, two methods of measuring grain-size may be involved: sieving, which measures a purely mechanical or physical size based on intermediate diameter or least cross-sectional area; and pipetting, which measures an hydraulic equivalent to the mechanical size. Because two separate properties are being measured, the results must be interpreted with some caution. Fortunately, many of the samples from the deeper or more northerly parts of the study area contained little (less than 5%) or no sand, so that for these samples the question of changes in technique did not arise. Instead, they were replaced by problems of effective disaggregation and dispersal of flocculated clays, and of "open-endedness" of the resulting size-frequency distributions.

The problem posed by fine-grained sediments is centred on the type of information that is required from the results. If all that is required is a purely mechanical separation of a sample into its original constituents, then the problem is much reduced. If, however, the prime reason for conducting size analysis is to obtain information about the environment of deposition, mechanical separation into component grains may well be meaningless (see Swift et al., 1972). Separation of floccules into individual grains creates a situation that never existed in the first place, and results in comparing sand grains that acted independently with clay particles that did not. Gripenberg's work suggests that clay floccules attain an optimum size in sea water; therefore, to be consistent in size measurement, comparison should be made between sand-grains and clay floccules.

Recreating conditions encountered in nature in the laboratory is virtually impossible. No knowledge may be available of the salinity of the water in the depositional area, and reproduction of the concentration of fine, terrigenous, suspended matter in the water column is impossible. Even in the Fraser River maximum concentration of suspended material rarely exceeds 1 gram per litre (Pretious, 1969), a concentration far too low for effective size analysis by pipette. Five samples from Georgia Strait were size-analysed in sea water to compare the size distributions obtained in this way with those resulting from standard procedures (washed to remove sea-salt, dispersed in CALGON). The resulting curves were quite irregular; probably as a result of the concentration required for analysis and the non-turbulent nature of the water column.

During dispersion, the ultimate effect of which is theoretically to disaggregate floccules into their component grains without reducing the size of the individual particles composing the floccules, the clay minerals, by virtue of their weakly bonded platy structure, may well be reduced in size by cleaving. Arguments have been advanced (e.g. Griffiths, 1962, 1967) that size measurements in the sub-sand range are basically measurements of degree of effectiveness of dispersion techniques, and these may only be reliable when done at the same time, by the same technique, in the same laboratory, by the same worker.

Despite all theoretical arguments, however, it is interesting to consider Figures 22 and 23, showing the distributions of median and mean values. Both show similar trends and both are explicable in a way that is sedimentologically reasonable. If the Fraser River is the main source of sediment for the Strait it would be expected that mean size would decrease to the north and west away from the delta. There is information available suggesting that net current movement in the Strait is to the north (see section 1.5.1), and if this is true then the sediments should reflect this movement. In fact, sediments probably provide the best record available of net long term current movements in any body of water.

Despite the drawbacks of flocculation effects, it is evident from Figures 25 to 30 that there is a steady fining of sediment to the north and west away from the river mouth. It can be assumed that the variations in grain size, such as the regular decrease in mean size from samples 201 to 317 along the axis of Ballenas Basin (Figure 30), are real. The variation cannot be a function of the analytical technique, since samples were not analysed in numerical order. Five pipettes analyses were done simultaneously, with slight staggering of withdrawal times, and samples were taken at random such that some from the northwest, some from the southeast, and some from the central regions were analysed either together or on successive days.

The implication is that the use of statistical analysis to characterise properly treated, consistently analysed, fine-grained sediments may be justified. However, the following limitations must be realised: only graphical methods are valid; frequency and cumulative curves may have to be subjectively extrapolated beyond the last measured size in order to span the desired range of percentile values (5 to 95); and while the dispersion and analytical procedures may be reproducible, and provide values that can be compared from sample to sample, they do not necessarily give any indication of conditions or state of the sediment as it was being deposited.

The parameters used to describe the Strait of Georgia samples are the inclusive graphic measures of Folk and Ward (1958). Phi percentile values were read directly from cumulative probability curves. In many samples the cumulated amount of sediment accounted for at the time of removal of the last pipette aliquot was less than 70%. Inclusive graphic measures require percentile values up to 95%. To obtain this value the probability curve was extrapolated beyond the last measured point by extending the curve as a straight line through and beyond the last three plotted points. If curvature was encountered in this region of the graph, extrapolation was based on an approximate "best-fit" line determined by eye through these points.

Extending the curve in this way introduces a degree of subjectivity to the results obtained - it implies that this part of the distribution is normal. As has already been discussed, and can be seen from Figures 25 to 37, this is not necessarily a valid assumption. As an approximation, however, it does permit the derivation of the desired parameters. While the median values are all unaffected, some of the graphic mean values and all of the standard deviation, skewness and kurtosis parameters may be based on values read from the extrapolated portion of the curve.

The final pipette aliquot was taken at a time equivalent to all material coarser than 0.98 micron (10 phi) effective diameter having settled below the level sampled by the pipette. This is a little larger than 0.6 micron limiting diameter for pipetting suggested by Griffiths (1967). It is believed that, from the point of view of expediency and because further decrease in particle size results in greater deviation of settling velocity from Stokes' Law, extending the pipette analysis beyond this (0.98 micron) is unwarranted.

The cumulative probability curve must have a limit at the fine end. The theoretical physical limit is the unit cell thickness of the clay minerals. They can only be reduced by cleaving to a certain thickness, and there is probably a limiting surface area related to any particular thickness also. Grim (1968) gives values for optimum minimum dimensions of well crystallised kaolinite of 0.3 microns x 0.05 microns, and of illite 0.1 microns x 0.003 microns. No values were given for smectite (montmorillonite group) or chlorites. Holeman (1965) contends that the thicknesses of clay minerals may approach single, or small multiples of, unit cell dimensions. He suspects montmorillonite is able to produce flakes of 14Å (1 unit cell) to 20Å thickness and areal dimensions 10x to 100x the thickness. Gibbs (1965) lists sizes of clay particles determined by electron microscope as: kaolinite, average 1 micron, range 0.3 to 4.0 microns; illite no average given, range 0.1 to 0.3 microns; montmorillonite average size 0.1 micron, range 0.02 to 0.2 microns.

Some idea of the lower limit of sizes present in Strait of

Georgia samples may be gleaned from the results of size separation of some samples prior to X-ray diffraction studies. Four samples were separated into 2.0 to 0.2 micron, 0.2 to 0.08 micron and finer-than-0.08 micron size fractions using a Sharples continuous-flow super-centrifuge. Very little clay-mineral material was found in the fraction finer than 0.08 microns. While this is consistent with Toombs' (1958) observations that the bottom-sediments from Bute Inlet were the result of mechanical rather than chemical size reduction, and therefore the clay sizes should be rare, it is at odds with other observations.

Montmorillonite is generally considered to be restricted to the finer clay size ranges (Grim, 1968; Holeman, 1965; Whitehouse et al., 1960; Jackson, 1956), less than 0.2 microns in diameter. Montmorillonite has been identified from the Strait of Georgia sediments, and might therefore have been expected in the fraction finer than 0.08 microns. That it does not appear in more than trace amounts may reflect one of two things. First, that in fact no clays, montmorillonite included, are finer than 0.08 microns in the Strait of Georgia sediments. If this is so, the limit to the extrapolated end of the probability curve should be somewhere between 13 and 14 phi (0.12 and 0.06 microns respectively), and commonly will be rather abrupt. The second possibility is that the relative lack of finer-than-0.08 micron grains is an artifact of the treatment process for these particular samples. While the aim of the pre-analysis treatment was to clean the samples, removing organic matter, amorphous oxides and extraneous poorly crystallised phases, the procedure may at the same time induce a greater degree of crystallinity in the clay minerals than actually existed in the untreated state. This suspicion is reinforced after comparing X-ray diffractograms obtained from untreated samples with those from samples that were treated (see next Chapter). Peaks are generally more intense, higher, sharper, and narrower at their bases, and the background much reduced for the treated specimens.

During the course of washing some samples prior to separating the sand fraction from the mud, one sample was inadvertently overlooked for a period of three to four weeks. In that time the bulk of the sediment had settled, but a transparent greenish layer, obviously denser than the overlying water, was present above the sediment. It was expected that this fluid would contain colloidal organic material, but addition of hydrogen peroxide to it produced no visible effect. Some was X-rayed as an oriented sample on a glass slide, and a regular series of 14Å reflections that fitted a sequence characteristic of chlorite, all well-ordered, sharp peaks, resulted. This would suggest that chlorite can exist, at least in unnatural conditions, in particles of extremely small size.

In a way, the anomaly of the finest size for clay minerals emphasises Griffiths' (1962, 1967) contention that size analyses of multicomponent systems are difficult to interpret. Even among clay minerals each species has its range and optimum size (Gibbs, 1965).

Median, mean, standard deviation, skewness and kurtosis were calculated for most samples, regardless of the number of modes involved on the frequency distribution. Folk (1966, 1968) contends that the wider coverage of the curve provided for by the inclusive graphic measures permits a more or less satisfactory interpretation of the curve. However, no single parameter, or combination of them, is adequate to describe polymodal curves. Dissection of multimodal curves into separate components will be discussed in the next section. Possibly the only satisfactory way of dealing with polymodal systems is merely to indicate that they occur, the grain-sizes corresponding to the modes, and what they might indicate.

In Georgia Strait multimodal curves are most commonly associated with samples containing gravels and coarse sands, and represent a combination of present-day hemi-pelagic sedimentation of muds with relict sediments, lag concentrates or locally derived sands. Finer sediments are usually unimodal, although their cumulative probability plots are often curved rather than straight (see Figures 25 to 37).

Examination of Appendix I, which lists the statistical parameters for each sample, shows that most Georgia Strait samples are very poorly sorted. Apart from two samples taken from the delta front between Sand Heads and Point Roberts (samples 82 and 83), which are well sorted, the sorting ranges from poor to extremely poor. Poor sorting values in Strait of Georgia bottom sediments are the result of one of two things: in areas of sandy or gravelly sediments the sorting is naturally poor by virtue of admixed hemi-pelagic mud; and in the deeper basins, or areas characterised by muddy sediments, the sorting is more likely a function of dispersal and disaggregation methods in the laboratory prior to analysis. Gripenberg's (1934) research suggests that, in nature, finer sediments may actually be better sorted as a result of flocculation of clay minerals. A similar situation is argued by Rolfe (1957), who suggests that median diameters of clay-rich systems may shift ten-fold from a dispersed to a flocculated situation.

Most of the Georgia Strait sediments are strongly fine skewed to near symmetrical. The fine skewness reflects the mixing of hemi-pelagic muds with sands and gravels. Nearly symmetrical curves may occur in sandy or muddy sediments. While there is a general trend from strongly fine-skewed through fine-skewed to nearly symmetrical curves from southeast to northwest along the axis of the Strait, skewness is not considered to be of environmental significance. Instead it reflects only the general change from coarse, sandy, relict sediments to fine, totally hemi-pelagic clays in the northwest that has already been shown to take place in the Strait.

Kurtosis values calculated from the Strait of Georgia samples range from 0.33 to 5.18, that is, from very platykurtic to extremely leptokurtic (Folk and Ward, 1957), with the majority in the mesokurtic range. Southeast of the Fraser Delta values are predominantly in the leptokurtic and very leptokurtic range, as is one sample from near the river mouth at Sand Heads and some of the marginal samples at the northwestern end of the study area. Platykurtic values are scattered sporadically, and with no apparent pattern, throughout the length of the Strait.

Mapping the distributions of values for inclusive graphic standard deviation, graphic skewness and graphic kurtosis, using the verbal limits applied by Folk and Ward (1957), resulted in irregular, more or less random patterns. General, but vaguely defined, trends could be established for skewness and kurtosis, but not for standard deviation. It is stressed that, because of the limitations discussed earlier, little emphasis should be placed on values obtained after subjective extrapolation of the cumulative probability curves well beyond the last measured points. Values obtained for the median and mean, however, do show patterns that have some sedimentological meaning.

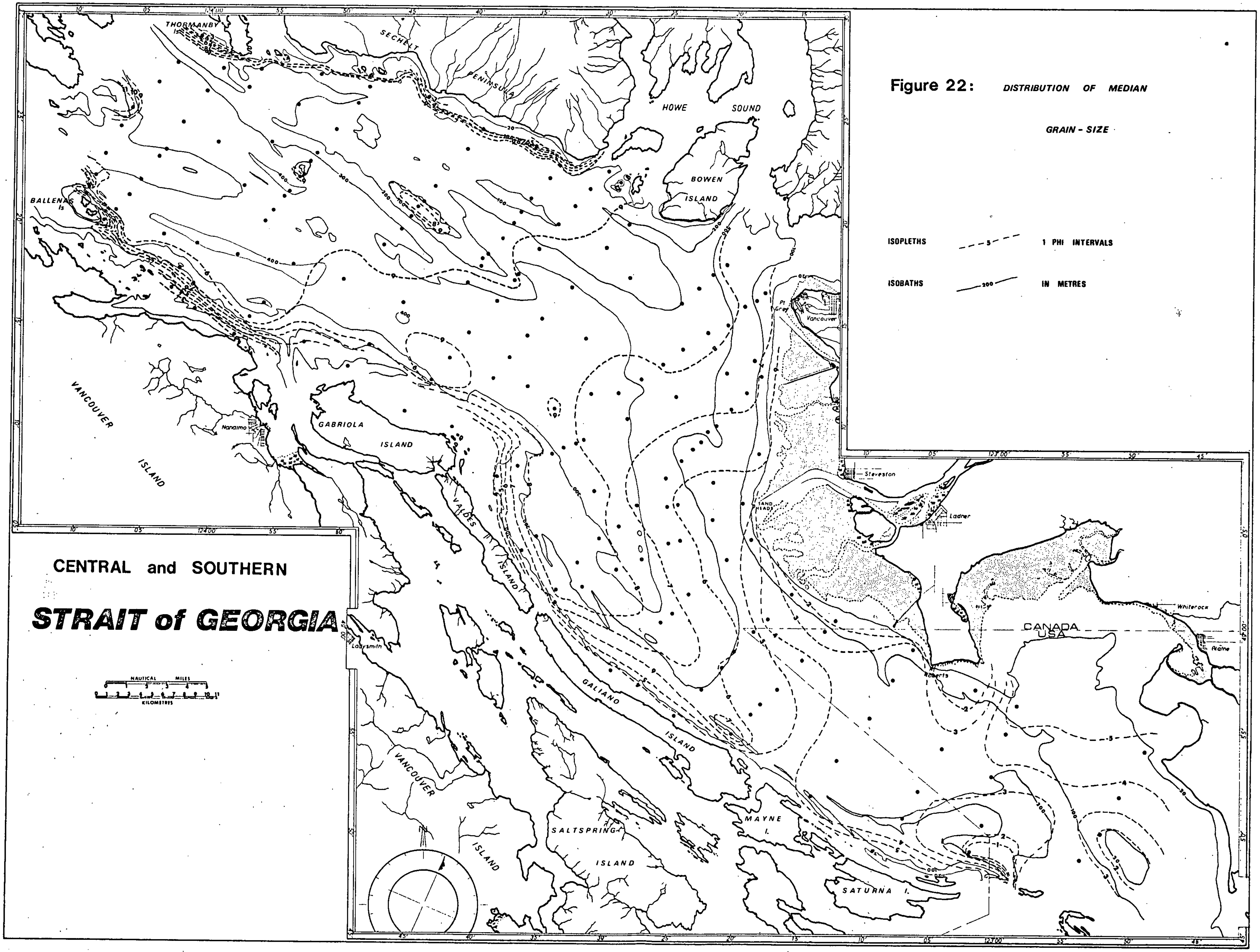


Figure 22: DISTRIBUTION OF MEDIAN GRAIN-SIZE
ISOPLETHS 1 PHI INTERVALS
ISOBATHS IN METRES
CENTRAL and SOUTHERN
STRAIT of GEORGIA
NAUTICAL MILES
KILOMETRES
THORMANBY Is
SECHELT PENINSULA
HOWE SOUND
BOWEN ISLAND
BALLENAS Is
VANCOUVER ISLAND
Nanaimo
GABRIOLA ISLAND
VALDES ISLAND
Ladysmith
GALIANO ISLAND
SALTSPRING ISLAND
MAYNE I.
SATURNA I.
Pt Grey
Vancouver
Steveston
SAND HEADS
Ladner
Whiterock
CANADA
USA
Blaine
Pt Roberts

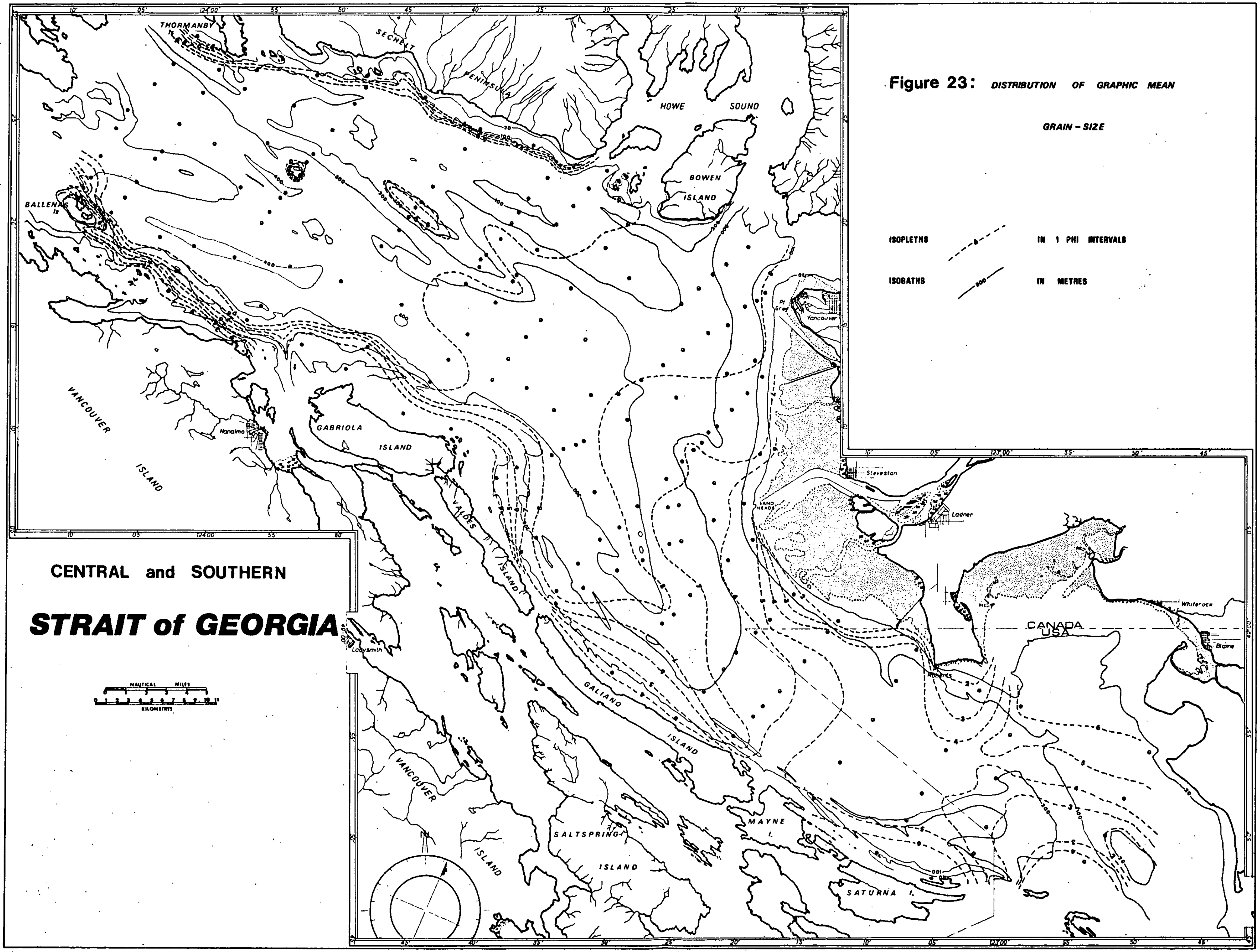


Figure 23: DISTRIBUTION OF GRAPHIC MEAN GRAIN-SIZE

Areal distributions of the median and graphic mean size are shown in Figures 22 and 23. Since both are so similar and because they are approximations of the same thing, they will be discussed together, referred to loosely as mean grain size or mean size. Mean size decreases radially, outward from Sand Heads. Along the line of samples that comprise Figure 30, extending from Sand Heads northwestwards along the axis of Ballenas Basin to Ballenas Islands, the median and mean grain-sizes decrease continuously, as they do across the Strait from Sand Heads to at least the foot of the Island Slope. The anomalous region of coarse, extremely well-sorted sand to the southeast of Sand Heads has been discussed above, but it is interesting to note that from sample #82, mean size decreases both to northwest and southeast along the delta front, and to the southwest across the Strait. South and southeast of Sand Heads the influence of strong, reversing tidal currents, which have bottom current velocities up to 30cm./sec. (Pickard, 1956; Waldichuk, 1957) is reflected by the unusual distribution of isopleths and the region not only of coarser mean size, but also of a high percentage of sand. Mean size increases southwestward of Roberts Swell, giving way to gravels and finally to bedrock on the floor of Boundary Pass. Eastwards the fine silty sediments of Boundary Bay overlie the coarser, sandier Roberts Swell sediments. The Boundary Bay sediments probably result from deposition of material derived by erosion of Pleistocene deposits of Point Roberts, and from masses of silty water from the Fraser River that make their way southeastward under unusual conditions of surface flow, are blown into Boundary Bay, and cannot escape. The fast-flowing currents over Roberts Swell may carry washed material either out of the system via Boundary Pass, or northwestward and into deeper water on the northwest side of Roberts Swell.

The narrowness of the band of isopleths along the mainland and island shelves and slopes opposite and north of the delta region suggests that material locally derived in these areas is deposited locally, and does not influence the main pattern of sedimentation in the Strait. The relict Pleistocene sediments of the ridges likewise do not affect the general picture very much, if at all.

The main pattern of sedimentation can be seen from the distribution of mean sizes. Assuming size decreases continuously in the direction of transport, bulges in the general line of the isopleths should indicate the path of maximum sediment transport. On both Figures 22 and 23 a bulge is evident on the near-source isopleths, indicating westerly/northwesterly transport for the main mass of sediment. A similar trend is indicated on Figure 20.

Along the axis of the Strait there is a general decrease of mean grain size from the southeast to northwest. The trend is modified by a reentrant of finer sediments on the west side of the Strait directed toward the southeast. The finer sediments may represent the remnants of an older situation, when the delta was somewhat further away than at present: the shape of the reentrant is a result of the growth of the modern delta. In the northwestern sector of the study area a northwesterly bulge in the 9 phi isopleth may indicate more rapid sedimentation into and in the head of Ballenas Basin rather than to the north.

The relationship of the trends displayed by changes in mean grain size to suspected current patterns and their value in helping portray net current movements will be discussed later.

It has been established that, although the precision involved with pipette analysis of fine sediment may not be excellent, the results that were obtained produced reasonably logical patterns when mapped.

Descriptive parameters of the size distribution can be obtained graphically, but care must be exercised when interpreting the results obtained after extensive extrapolation of the fine end of the cumulative curve.

3.9 CUMULATIVE PROBABILITY CURVES

Cumulative curves of sediment analyses plotted on probability paper with an arithmetic scale (e.g. CODEX #3127; DIETZGEN #340-PS90; C.C & S G-23) are presented in Figures 25 to 37. Distributions following a normal Gaussian probability function plot as straight lines on this paper because of the expanded scale in the "tail" regions of the curve (Otto, 1939). Reading percentile values for graphic statistics is facilitated (see also arguments in Folk, 1968), as are comparisons between and among various samples.

Probability plots of many sediments however are not straight lines (Tanner, 1958, 1964; Doeglas, 1946; Spencer, 1963; this study), suggesting that most sediment size populations do not follow a normal distribution. Departures from a straight line have been variously explained as being the result of: transporting mechanisms (Doeglas, 1946); truncating, censoring or filtering of a single population, or mixing different populations (Tanner, 1958, 1964); simple mixing of populations (Folk and Ward, 1957; Curray, 1960; Spencer, 1963; Sengupta, 1967); and skewness of a single population (Herdan, 1960). Fluctuations in current strength, fluctuating current directions, changes in rate and quantity of sediment supplied, and mixing of sediments of more than one source, mode of transport or age, whether naturally or artificially, all contribute to asymmetry of distribution curves and associated bending of probability plots.

Harding (1949) and Cassie (1950, 1954, 1963) discussed the use of probability curves in biological research, and described how they might be dissected into component parts on the basis that the straight sections between inflections were due to the influence on the curve of one, single component. Their assumption was that the components have distributions (plots) that follow a normal probability function. Harris (1958), Spencer (1963), Tanner (1964) and Sengupta (1967) used the assumption of normality in the size distribution of sediments to dissect non-linear cumulative probability curves from sediments or sedimentary rocks from various localities.

The dissection of a polymodal curve may be feasible and practical from a mathematical point of view but is it from a geological one? Since skewed (or asymmetrical) distributions seem to be the rule rather than the exception in nature (that is, the size-frequency distribution curves of natural sediments are generally not normal) the basically artificial process of separating polymodal curves of sediments into normally distributed components must be held to question. It may be an unjustified exercise.

Figure 24 shows the positions of the samples which were used to construct Figures 25 to 37. Figures 25 and 33 to 37 are composite figures of probability curves without regard to position in the Strait, with sample 317 included in Figures 33 to 37 for comparison. Certain features are apparent upon inspection of these figures: (1) sediments from areas containing gravels are definitely polymodal and the resulting curves quite irregular; (2) of the finer samples, most have probability plots that are continuously curving and do not show definite inflexion points; (3) as the sediments become coarser, the plots become more obviously bimodal or even polymodal; and (4) along the axis of the

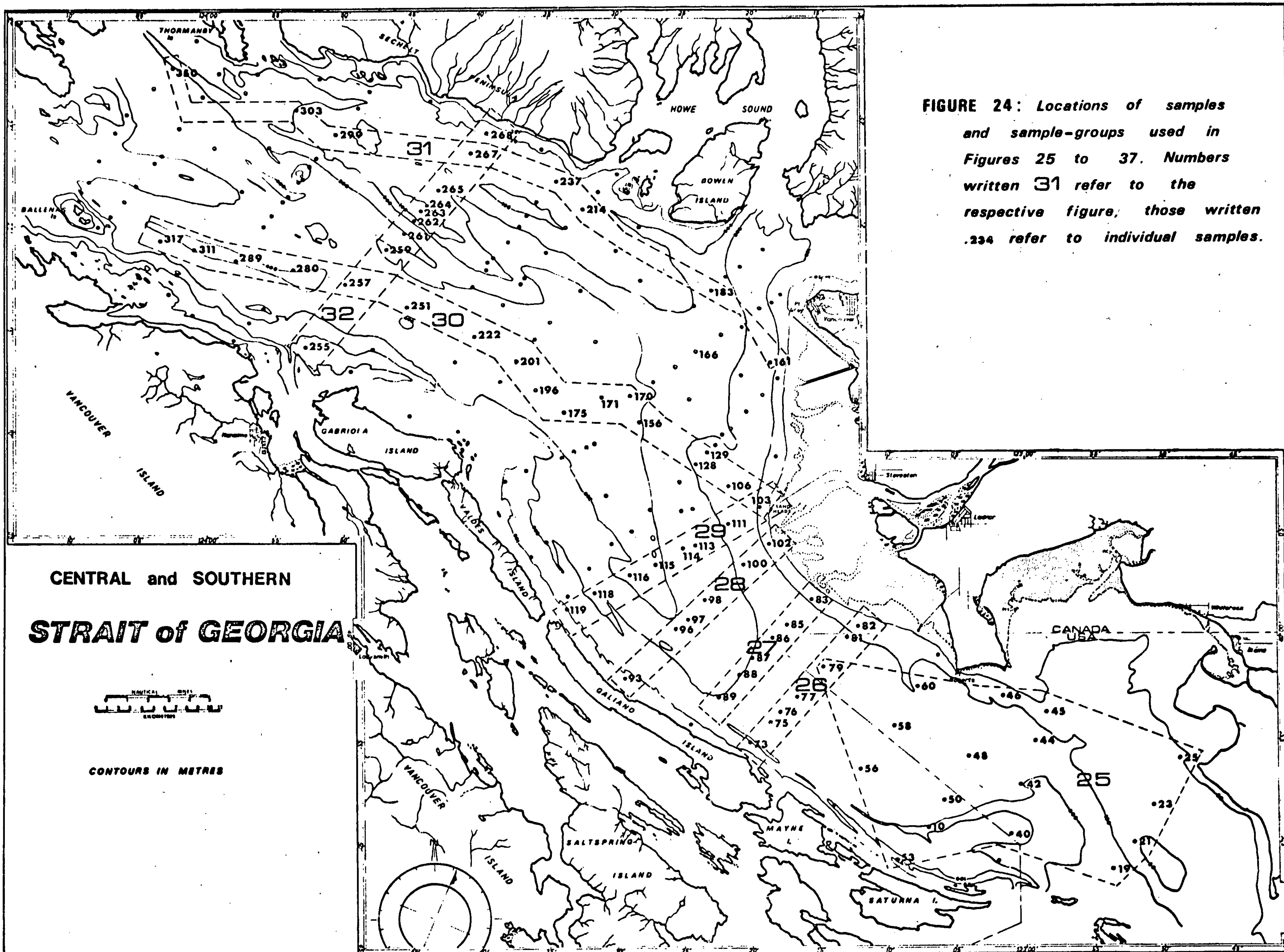


FIGURE 24: *Locations of samples and sample-groups used in Figures 25 to 37. Numbers written* 31 *refer to the respective figure, those written .234 refer to individual samples.*

On the following seven pages are figures composed of cumulative probability curves constructed from grain-size frequency data.

Figures 25 to 32 show cumulative probability curves for groups of samples arranged along or across the Strait of Georgia. Figure 24 shows the locations of these sample groups.

Figures 33 to 37 are composite diagrams of cumulative probability curves from all analysed samples. Sample 317 has been included for comparison.

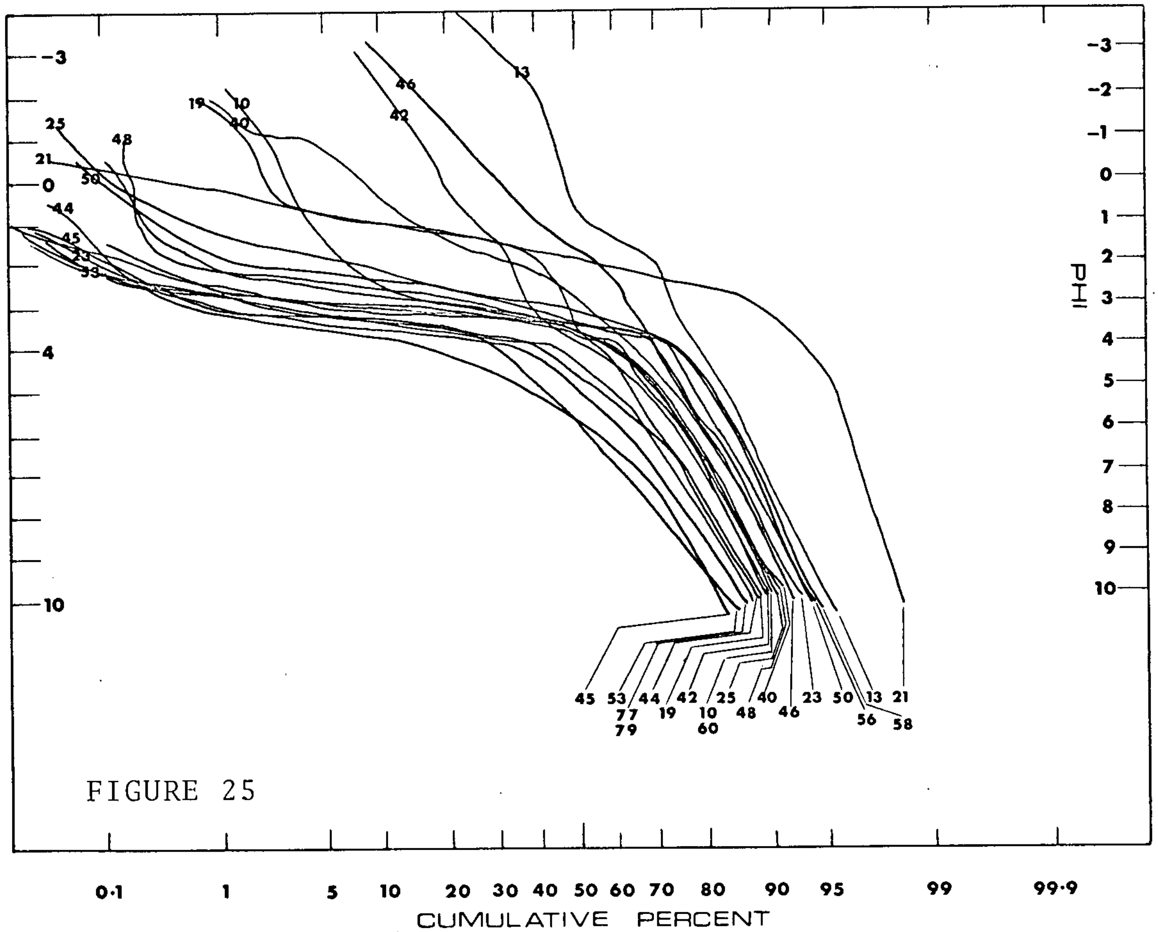


FIGURE 25

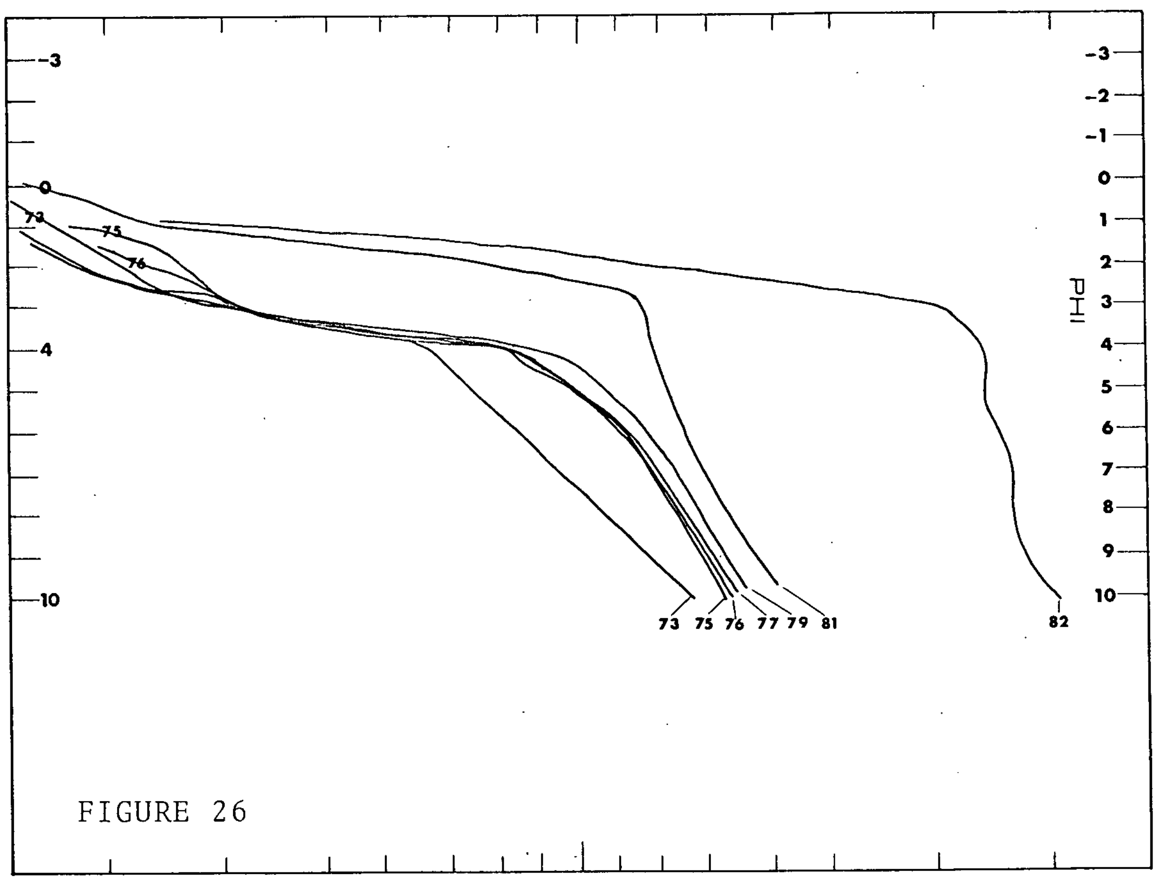


FIGURE 26

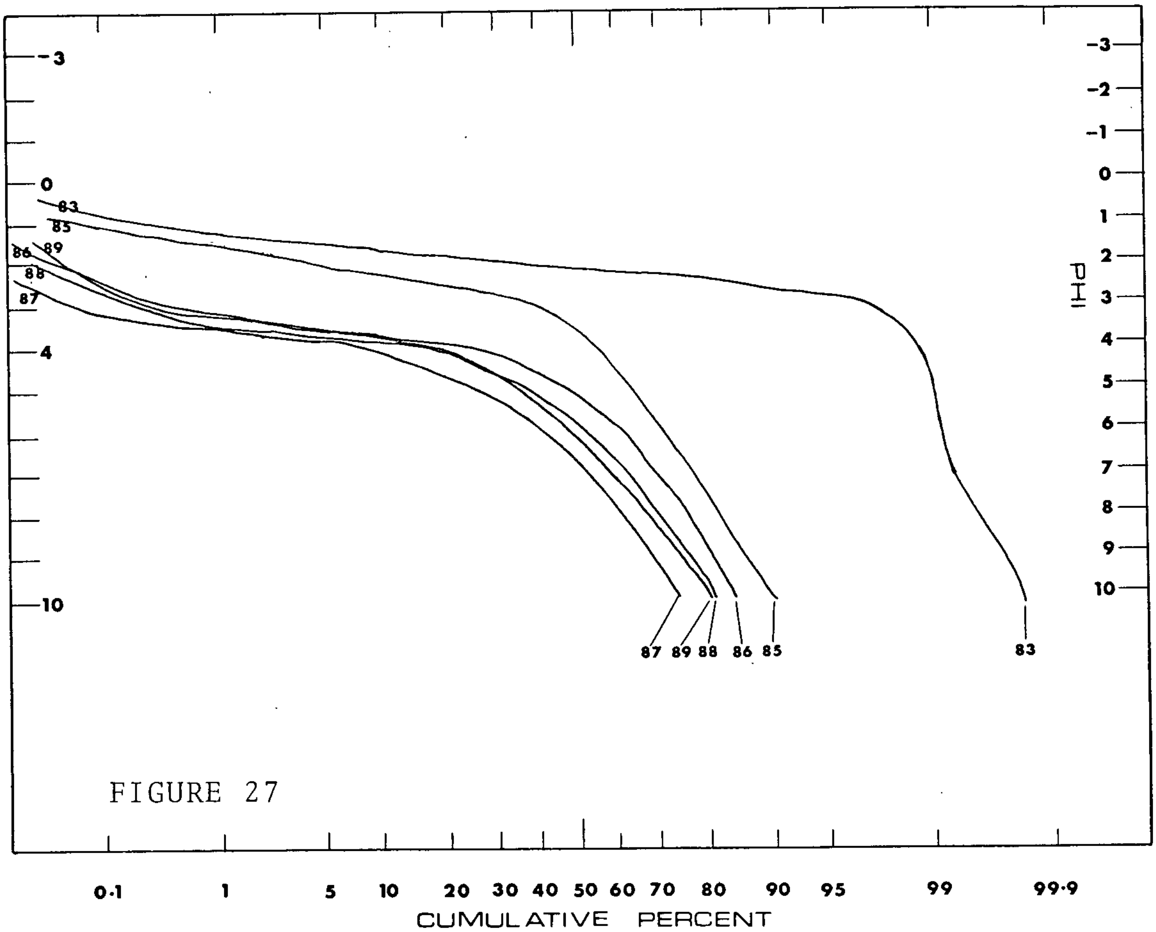


FIGURE 27

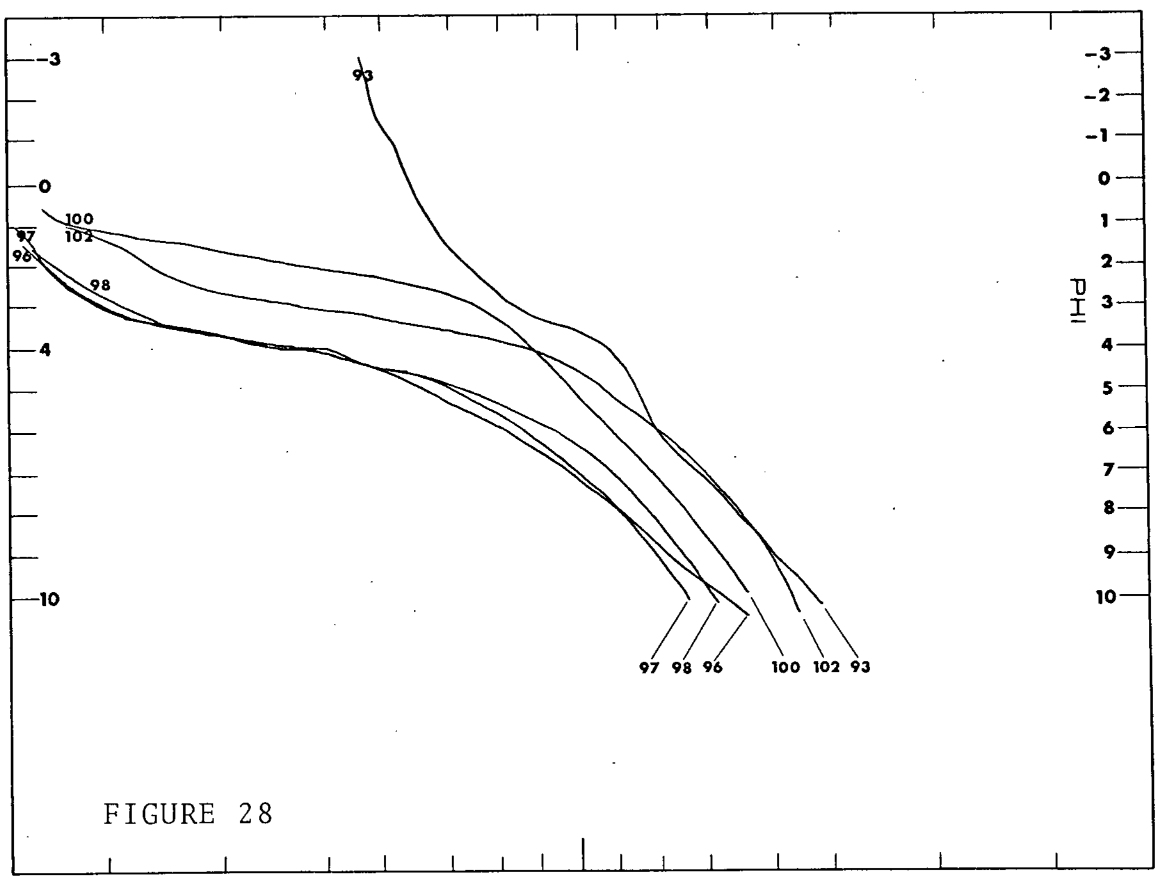


FIGURE 28

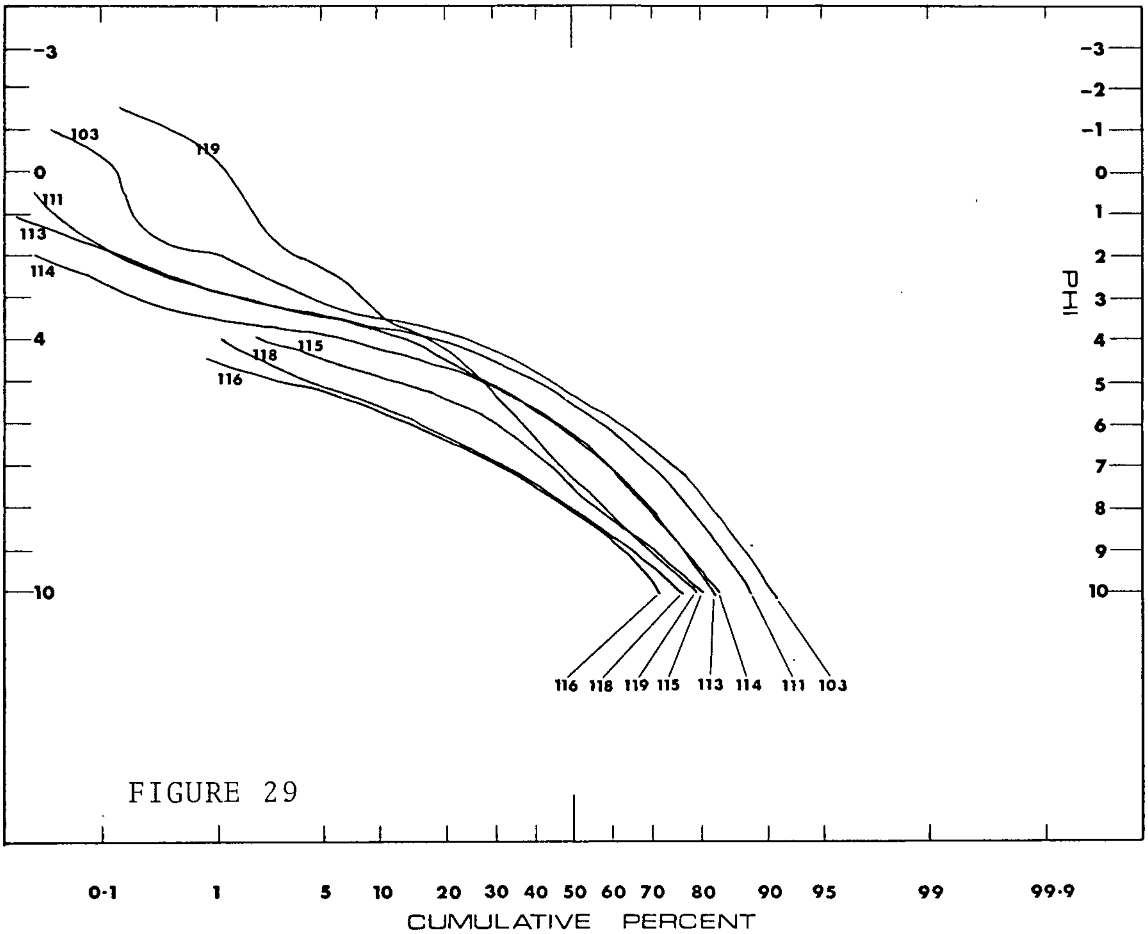


FIGURE 29

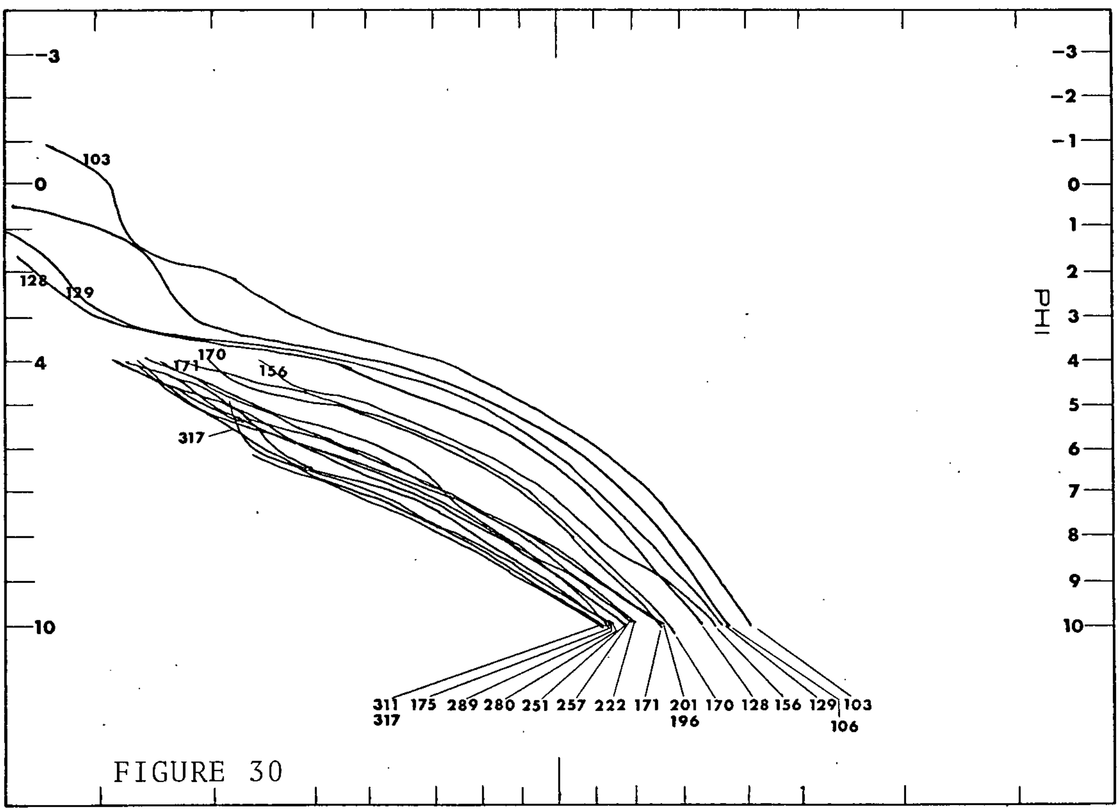


FIGURE 30

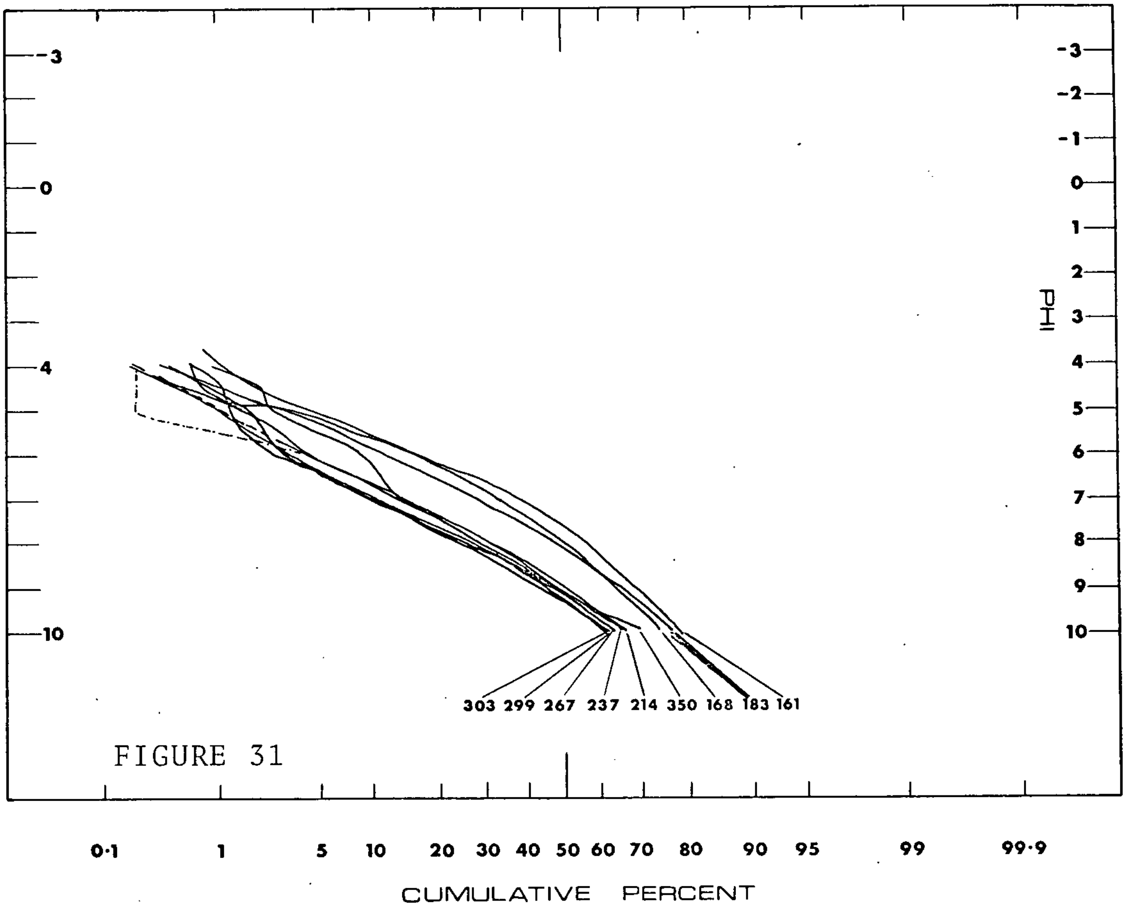


FIGURE 31

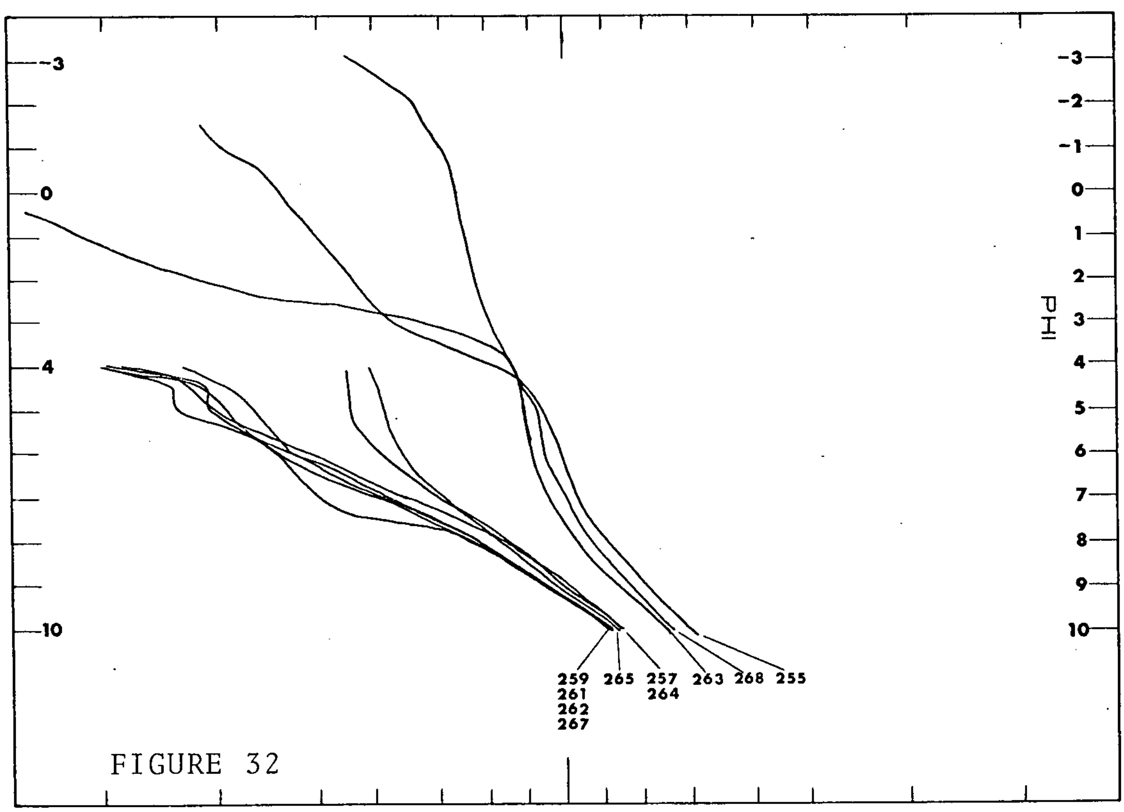


FIGURE 32

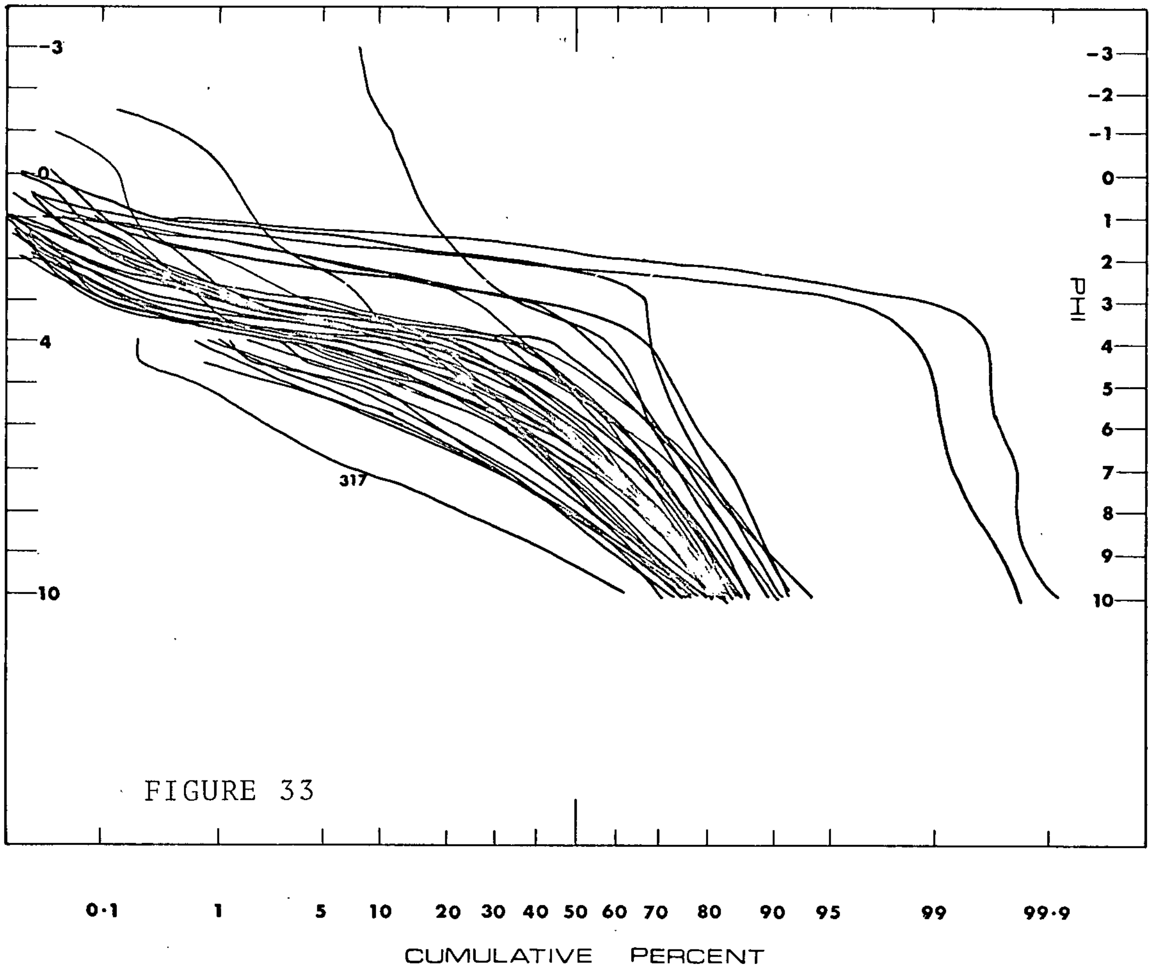


FIGURE 33

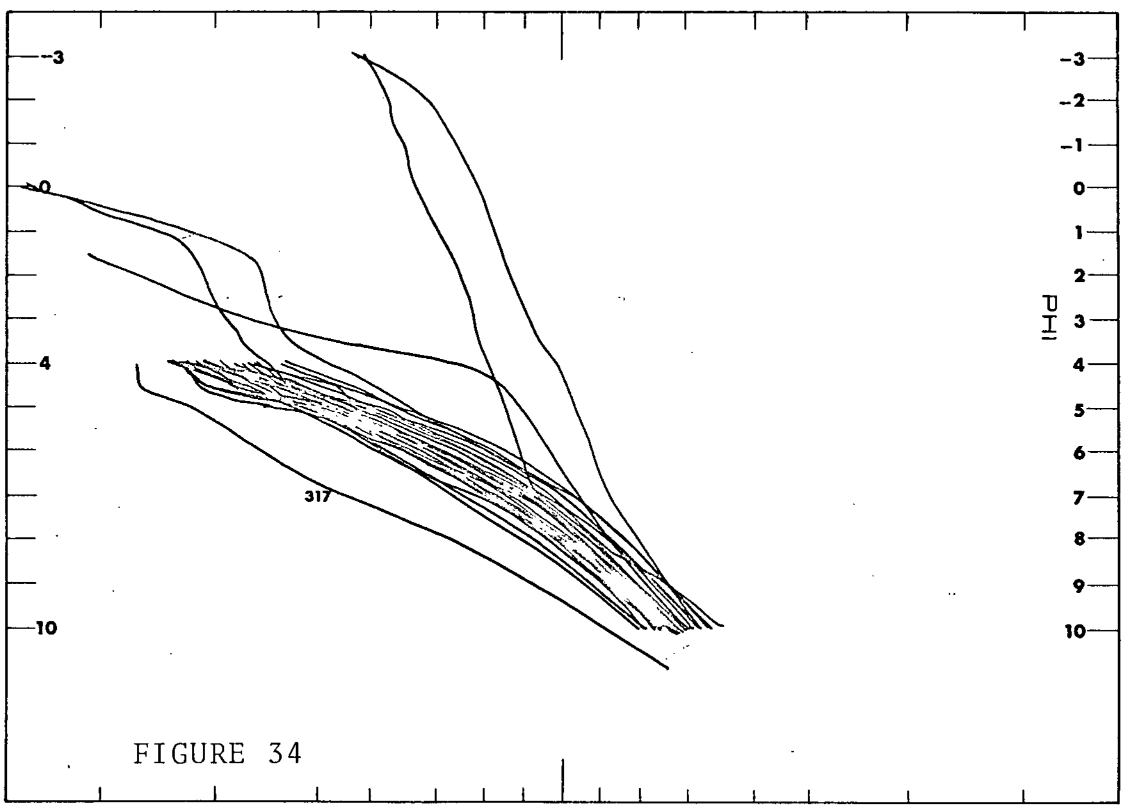


FIGURE 34

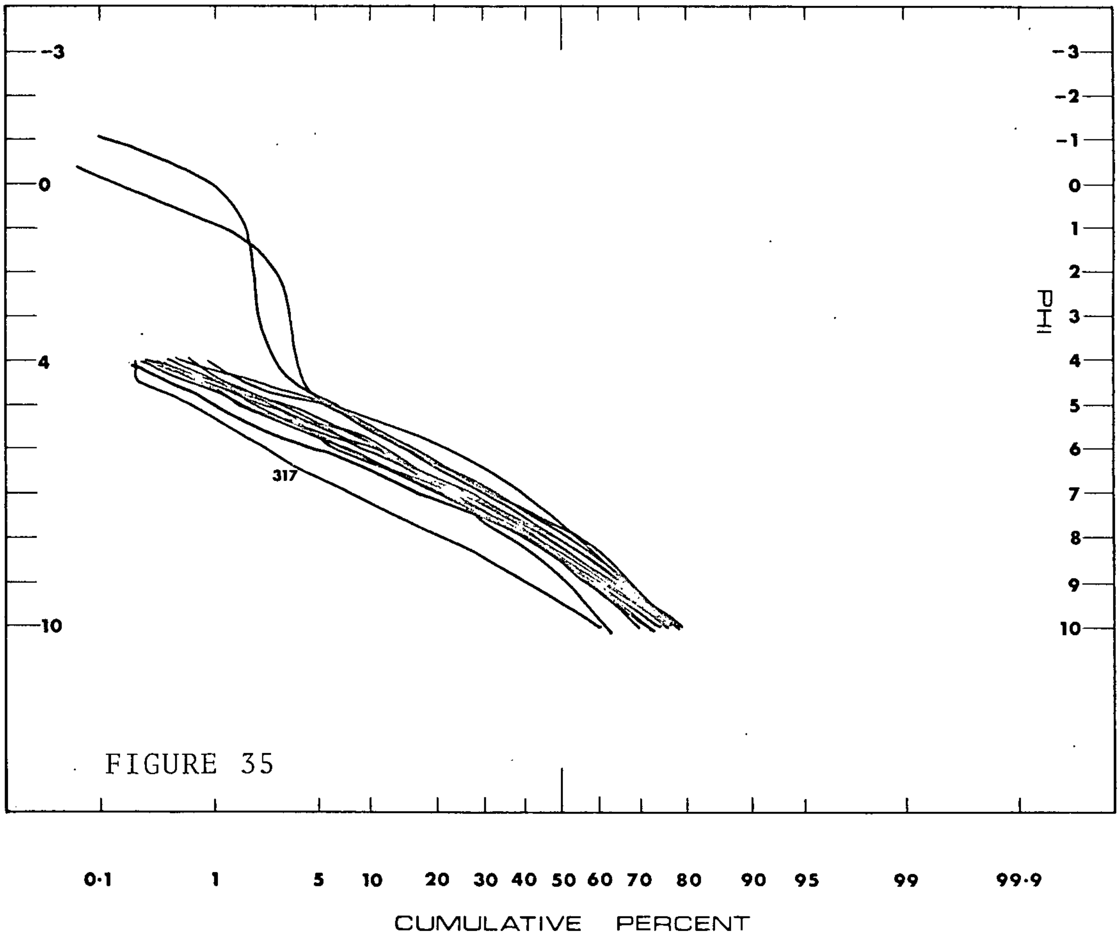


FIGURE 35

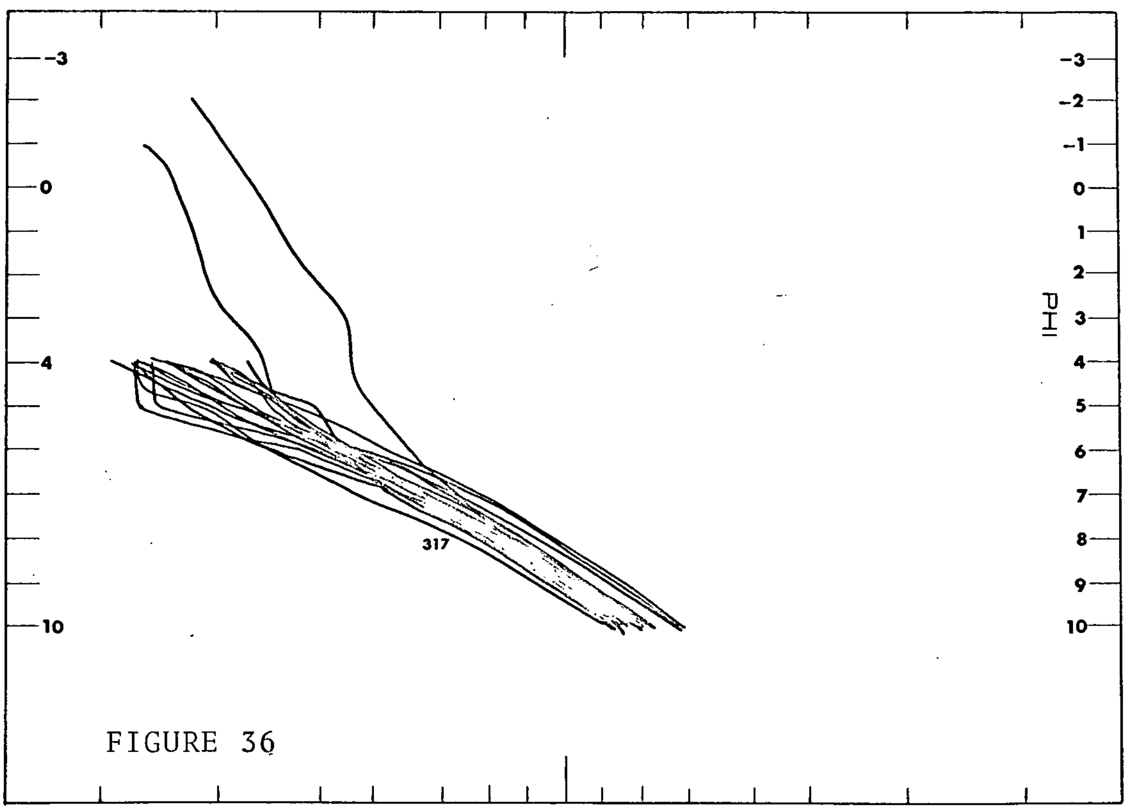
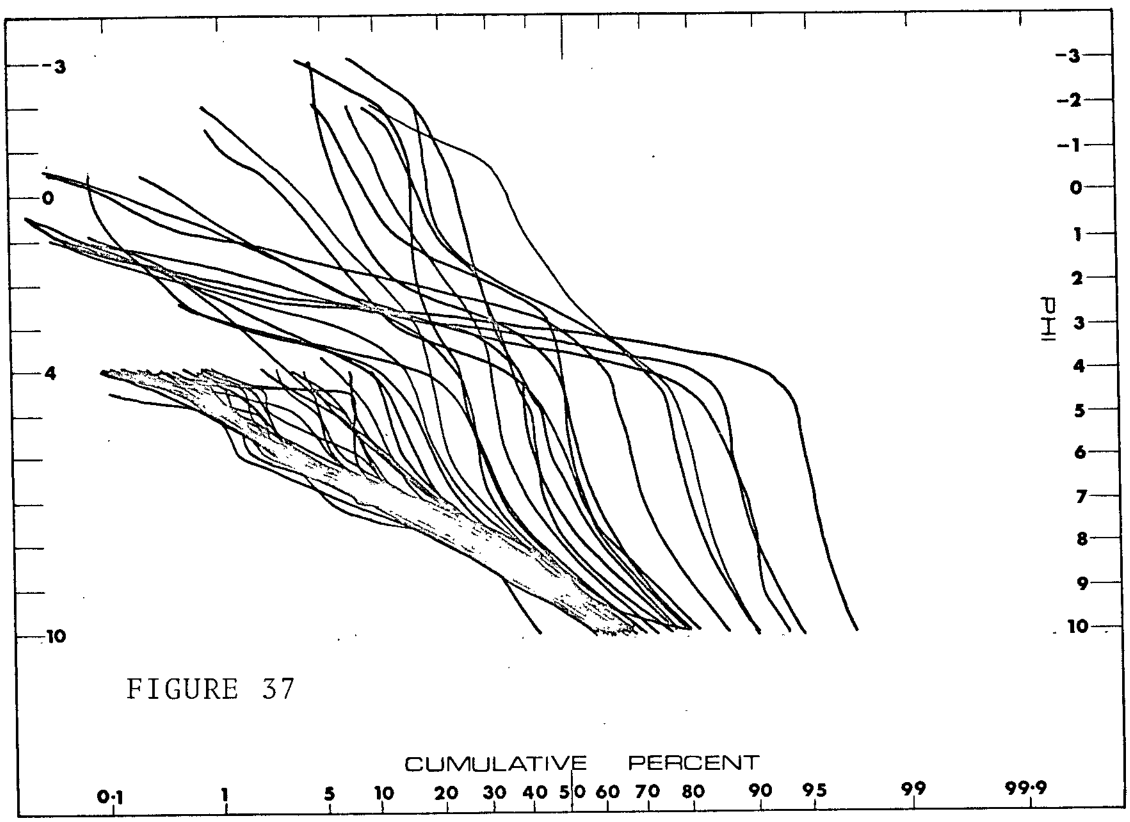


FIGURE 36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99·9

FIGURE 37

Strait (i.e. along Ballenas Basin, Figure 30) from Sand Heads in the southeast to the northwestern margin of the study area, and across the axis of the Strait from the delta to the Gulf Islands, progressively finer sediments occur away from the delta. In the southeastern portion of the area, in the vicinity of Roberts Swell and Boundary Basin, the sediments are often coarse and their probability plots quite irregular. Across the axis of the Strait in the northwest (Figure 32) the change from polymodal gravelly muds to muds and back to gravelly muds reflects the change from marginal and bank top deposits to basin sediments.

Curves of fine sediments are often bent, which renders their interpretation subjective. It may be possible to approximate them by a best-fit straight line, but these cases are few. It is difficult, on a continuous curve, to construct two or more straight lines whose resultant will take the bend into account, and the resultant of these lines is often as far off the actual curve as the plotted points deviate from a single best-fit straight line. The lack of inflexion points also makes the interpretation of the amount of mixing of populations difficult or impossible. Geologically, however, it presents a potentially interesting situation when the bent curve is entirely in the fine (suspended?) sediment range. Consideration can be given to the possibility of two types of material in the suspended load that might behave differently in the depositional environment. One, the coarser portion, comprises discrete particles that do not tend to flocculate, that are sub-equant in shape, and are composed predominantly of quartz and feldspar grains. The other, finer, portion is composed of platy minerals that tend to behave differently hydraulically, and to flocculate, particularly if the clay mineral suite is well represented. Figures 42 and 41 show tracings of X-ray diffractograms of selected samples (the same in both figures) of the 2 to 5 micron and the 5 to 20 micron size fractions. There seems to be an increase, even more marked in the size fractions finer than 2 microns (Figures 44 to 49), of clay or platy minerals that might suggest a mineralogical explanation for the shape of the cumulative probability curve.

Interpretation of the flexed regions of probability curves as caused by truncation (Tanner, 1964) of coarser material was suggested by the smoothness of the curvature and the lack of definite inflexion points. Arguing against this explanation is the fact that the deviation from a straight-line projection toward the coarser from the finer end of the curve is often not continuous and may even reverse.

In Figure 30 a progressive decrease in the deviation from the straight-line projection of the fine end of the curve is evident, the curve becoming almost straight for samples 317, 311 and 289. The percentage of clay-size material in the samples increases in the same direction as the decrease in deviation (away from the delta and Fraser River mouth). Perhaps this may provide more evidence in favour of a mineralogical explanation of the curvature. Closer to the mouth of the Fraser the region of the greatest flexing of the curve becomes coarser, shifting to 6 to 7 phi from 7 to 8 phi, and the deviation of the coarser end of the curve increases. Total amount of curvature of the graph increases closer to the river mouth. This could be interpreted as follows: for the finest sediments, the total sediment most closely resembles the finer material, the "coarse suspended load" being much reduced; closer to the source the influence of the coarser suspended material, or the increasing coarseness of the sample, is greater and the effect on the curve consequently more pronounced.

Sediments that are maladjusted to the present sedimentational environment (factors of source and transport) but which may be adjusting to the oceanographic one (that is, the tidal currents, etc.) often possess a probability curve that is marked by a coarser segment joined by a region of low or zero increase in cumulative percentage (often between 1.5 and 3.0 phi) to a typically bent finer section. In some instances a minimum appears at or close to 4.0 phi, but as this is the region of change from sieve to pipette techniques, the possibility that it is analytically induced cannot be ignored. The shapes of these curves are believed to be caused by the mixing of relict or lag sands or gravels with modern suspended material. The hiatus indicated by a low increase in percentage of material is probably the result of modification (e.g. by washing) of the sand or older deposit during changing levels of the sea.

Individual features of interest displayed by Figures 25 to 37 include:

1. Figure 25 is constructed from samples at the southeast end of the study area. It shows the effects of mixing fine material representing modern accumulation of muddy sediment, and/or redistribution of older, winnowed fines, with relict sands and gravels. The irregularity and multicomponent nature of some of these curves is marked.

2. Figures 26 and 27 are from samples arranged in lines across the Strait from Canoe Pass to Galiano Island. Samples 81 and 82, 83 and 85 are coarser than the rest, which tend to have the sandy portions of their curves in the region of 3-4 phi. Samples 82, in particular, and 83, are the coarsest of the suite, are the best sorted, and have minimal amounts of admixed fines. The remaining samples have very similar curves, suggesting similar conditions of deposition.

Explaining the curves of 82 and 83 as the result of erosion and winnowing of fines leads to the suggestion that the limits of this erosion were once more extensive (basinwards) but have since narrowed to the zone between 81 and 82 and the shore, and between 85 and 83 and the shore. Addition of fine material now may be indicated by the higher percentage of fines in 81 and 85 relative to 82 and 83.

3. Superimposing Figure 28 over Figure 27 indicates that, while sample 81 is not too different in content of fines or coarseness of sandy material from sample 100, there is a grouping of samples from further offshore (96, 97, 98) that are extremely similar to each other and are only slightly finer in the sand fraction from the group in Figure 27. Sample 93 reflects the addition of gravels at the coarse end of the distribution.

4. Figure 29 portrays cumulative probability curves of samples collected along a line between Sand Heads and Porlier Pass. Samples close to either end of the line (119, 103) show irregular variation in the coarser end of the distribution. Samples 111 to 114 have distributions very similar to those of 86 to 89 (Figure 27) while 115, 116, and 118 show the influence of large amounts of fine material. The bent curves displayed by 115 to 118 are fairly typical of those for fine material from samples relatively close to the river mouth.

5. A line of samples extending from near Sand Heads northwestward nearly to Ballenas Islands (Figure 30), and aligned along the axis of Ballenas Basin, shows a gradual increase in fineness of the sediment to the northwest away from the delta. It is a classical example of decrease in grain size away from the source and is associated with an increase in clay content that is both gradual and continuous. Samples from near the

top of the delta such as 129 have similar curves as 86 to 89 of Figure 27. Curves of samples 132 and 156 to 171 are similar to those of 115 to 118 (Figure 29). Samples 196 to 317 form a package of curves representing the finest material in the Basin. The curves of samples 289, 311 and 317, at the northwestern extremity of the basin, become increasingly linear although their cumulated totals are only slightly greater than 60% at the time of the last size measurement.

6. The line of samples shown in Figure 31 is situated along the northern side of the Strait, in the deeper water between McCall Ridge and the mainland coast. A similar separation of curves into two groups separated by a distinct gap occurs here also. Curves for samples 161, 166 and 183 comprise the coarse group. Although finer than the coarse group from Figure 30, they are distinctly separated from the rest of the curves in this figure. While some of the remaining samples have curves that are decidedly irregular at the coarser end, they are similar overall to the finer part of the second group of Figure 30.

The reason for the grouping is not clear. It may be fortuitous, or it may be a reflection of the clockwise current pattern that is suspected to exist in the central Strait (Tabata et al., 1971). It could also be explained by a mineralogic change. The curves of the finer group tend to be straighter than those of the coarser group. As suggested above this could be explained by the existence of a "coarse" and a "fine" suspended load (an "equant-grain" load and a "platy" load) so that the change from the bent to the straighter curves might indicate a limit to the region of maximum deposition of "coarser" suspended load material. However, when all curves are compared by overlaying Figures 25, and 33 to 37 no such gaps are obvious; the changes are essentially continuously gradational from the finer to the coarser samples.

As a pictorial method of presenting the results of granulometric analysis, the cumulative probability curve is excellent. The mixing of populations of differing size characteristics, whether of different sources, ages or methods of transport, is often evident. Polymodality is generally clearly expressed by changes in slope or irregularities of the curve. The dissection of such curves into their fundamental components, however, relies on the assumption that the components have distributions that are normal (or log-normal). This assumption is not necessarily true, and dissection into components consequently not justified.

Vishner (1969) advocates the more extensive use of cumulative probability plots in presenting granulometric data. He suggests that with continued presentation of data in this form it may eventually be possible to distinguish environments by distinctive shapes of probability plots. The present writer supports these suggestions, and would extend them further to suggest more detailed investigation of the possibility that cumulative probability curves are sensitive enough to show different components in the suspended load.

3.10 FACTOR ANALYSIS

Granulometric analysis provides the basis for the calculation, or graphical derivation, of statistical descriptors of the grain-size distribution. Careful interpretation and analysis of the descriptors can be a valuable tool in communicating information about a sediment, or for elucidating the nature of the appropriate sedimentary processes. However, it has been adequately shown, both by the inconsistent results achieved by many workers (c.f. Moiola and Wieser, 1968, and Friedman, 1967), and by the comparative study of Solohub and Klovan (1970), that use of size parameters derived from grain-size distributions to distinguish between environments of deposition has not been particularly successful. It has proved of limited value for modern environments, and of no value whatever for ancient ones since previous knowledge of the environment is required.

Solohub and Klovan (1970) subjected the same size data derived from samples from Lake Winnipeg to various treatments proposed in the literature, using only those samples that were predominantly sandy since the techniques to be evaluated were developed through the study of sands. They concluded that, for the most part, unless a priori knowledge of the environment was available, distinctions of different environments were practically impossible by these techniques (C-M plots: Passega (1957); Inclusive Graphic Measures: Mason & Folk (1958); moment parameters: Friedman (1961); discriminant functions: Sahu (1964)).

Klovan (1966) and Solohub and Klovan (1970) argued that there was no good reason for using any one type of derived parameter in perference to any other, and pointed out that it was futile to use relatively simple bivariate analysis to explain or describe what is in reality a complex multivariate (multidimensional: see Folk and Ward, 1957) situation. Sediments lend themselves to analysis by multivariate techniques, and utilising the weight percent of material in each size interval will make use of all the information that is usually available to statistical analysis.

Like statistical techniques, factor analysis manipulates empirical data by reducing the complexity of the original data matrix. It attempts to create a minimum number of new variables (factors) that are linear combinations of the original ones such that the new variables account for as much of the original variance as possible. For example, Klovan (1966), in a study of the application of factor analysis in sedimentology using Krumbein and Aberdeen's (1938) Barataria Bay data, found that 97% of the variance between 69 sample vectors based on 10 components (variables) could be accounted for by only 3 factors.

A mathematical description of factor analysis is outside the scope of this report. Excellent, detailed accounts of the theory can be found in Harman (1960) and Catell (1952, 1965a,b). Discussion of the theory and practical geological applications of factor analysis are available in Imbire and Purdy (1962), Imbrie and Van Andel (1964), Klovan (1966, 1968), McManus, Kelley and Creager (1969), Solohub and Klovan (1970).

Factor analysis may be carried out by two distinct but related procedures: R-mode and Q-mode. The R-mode procedure focuses attention on n variables, and calculates results following the inspection of an n x n matrix of variables; i.e., it compares variables on the basis of all samples. This method often leads to trivial or, in the case of size data, meaningless geological results. The Q-mode procedure inspects the relationships between N samples on the basis of all (n) variables; i.e., attention is focussed on N samples and results follow the inspection of an N x N matrix of relationships between all pairs of samples. The Q-mode procedure was used for the Strait of Georgia sediments.

For the Georgia Strait sediments the data matrix used for factor analysis was the weight percent in each size class of 1 phi interval (Appendix II(a)). The half-phi intervals used for sieving were grouped into whole phi values so that the entire grain-size spectrum was represented by the amount of sediment contained in equal-size class intervals. Since it uses size data for the input matrix, results of the factor analysis are subject to the same practical and theoretical limitations and restrictions as have been mentioned earlier. One hundred and eighty-two samples were treated, using 15 size-classes as variables.

The factor analysis programme used belongs to the Geology Department, U.B.C. (Dr A.J. Sinclair); the computer was the IBM systems 360 model 67 in use at the Computing Centre, U.B.C. The programme calculates the minimum number of factors required to account for 95% of the variance of the original data. It then proceeds with each successive iteration to drop one of the factors and recalculate and print the varimax factor matrix and varimax factor score matrix. Factor loadings are stored on file, and can be used to construct plots of factor distributions using the Calcomp plotter.

The minimum number of factors necessary to account for 95% of the variance in the Strait of Georgia samples is eight, which, considering the nature of the input data, is far too large a number of factors to consider. A four-factor model was eventually chosen, which accounted for 88% of the total variance (Factor I: 38.5%; Factor II: 28.5%; Factor III: 16.8%; Factor IV: 6.8%). It is not as easy to handle as the three-factor models of Klovan (1966) and Solohub and Klovan (1970). A three-factor model for the Georgia Strait samples was also inspected however, although Factors I and II are the same as in the four-factor model, the varimax factor score matrix was not easily interpreted.

The varimax factor score matrix (Appendix IIc) reveals that Factor I is accounted for by variables representing the 9, 10 and >10 phi size classes; Factor II by 6 to 8 phi classes inclusive, and Factor III by 4 to 6 phi classes inclusive. Factor IV was best accounted for by variables representing the -3 to 1 phi classes inclusive. The factor

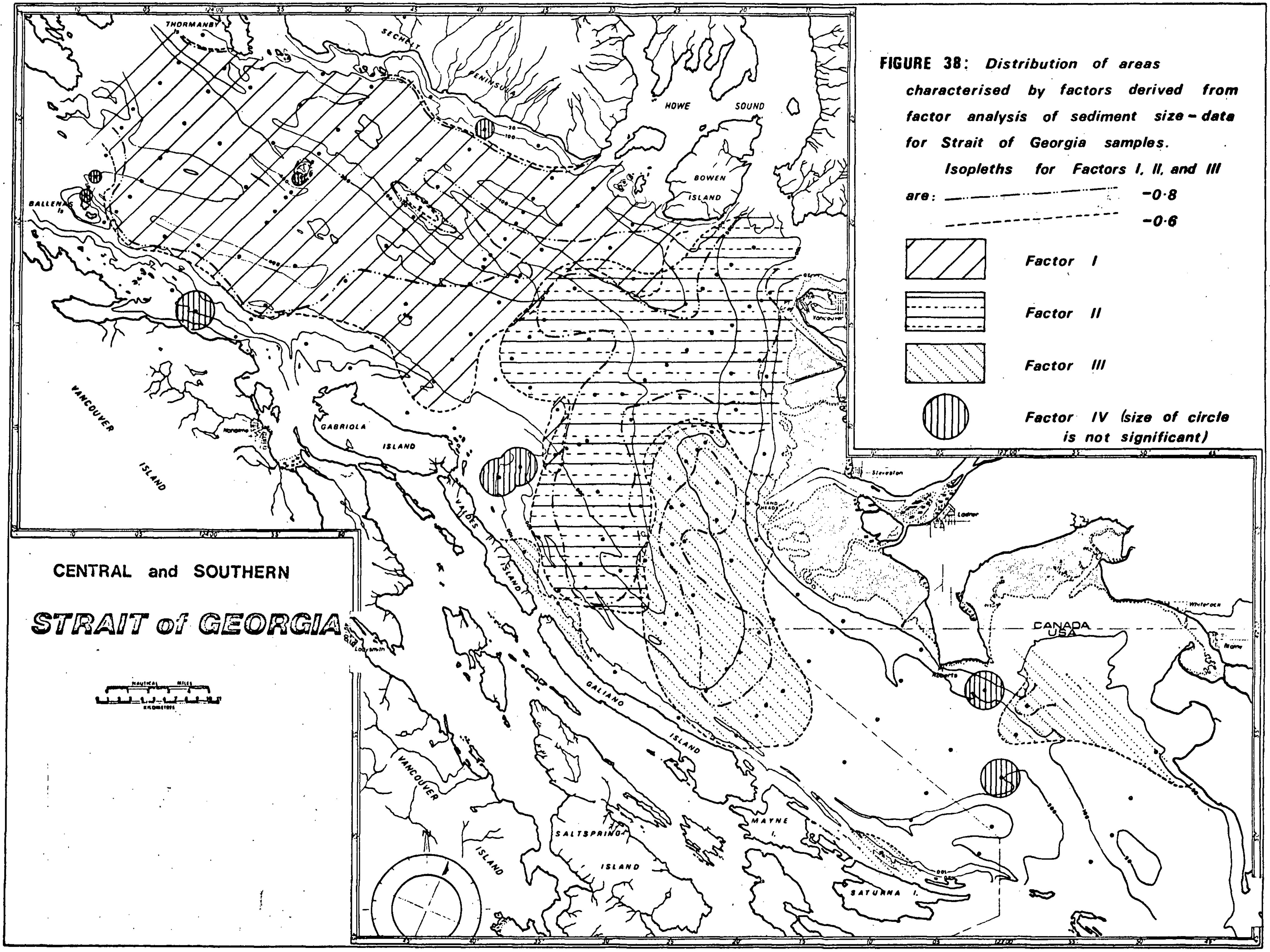


FIGURE 38: *Distribution of areas characterised by factors derived from factor analysis of sediment size-data for Strait of Georgia samples.*

score matrix also reveals that large negative values for factor loadings in the varimax factor matrix (Appendix IIb) are the descriptors for Factors I through III, and high positive loadings characterise Factor IV.

A map of the distribution of loading values for the various factors is presented as Figure 38. Limits to the boundaries of the areas best described by Factors I through III were arbitrarily chosen at a factor loading value of -0.6: within the areas shown to be represented by these factors the values are more negative than -0.6. Factor IV has been indicated where the loading value was greater than 0.6.

With due regard to the problems involved in analysing fine-grained sediments, and the consequent reservations that must be held about the precision of the results, certain features of the factor distribution are worth noting, and some conclusions can be drawn.

1. The factors represent certain size grades, and may be taken to indicate (represent) some function of the depositional process(es) (as opposed to certain environments - see Solohub and Klovan, 1970).

2. The size groups represented are:

   I - clays (<2.0 microns)

   II - medium to very fine silts (15.6< 2 microns)

   III - coarse silt (62 < 15.6 microns)

3. The pattern depicted on Figure 38 is basically identical to that of Figure 20, based on the sand (+gravel):silt:clay ratios.

4. The boundary between Factors I and II, and II and III are located in positions that account for the gaps between bundles of cumulative probability curves of similar shape and slope (Figures 26, 27, 29, 30

and 31) i.e. the separate bundles are associated with different factors.

5. Since the main source of sediment for the Strait of Georgia is the Fraser River, the three factors should be related to this situation. In favour of this idea is the fact that none of the factors, except Factor III locally on the Vancouver Island side of the Strait, is related to the marginal areas.

6. The factors can be interpreted in terms of the sediment contributed by the Fraser River.

a) Factor III represents bed load and some coarse suspended load.

b) Factor II represents the coarse fraction of the suspended load.

c) Factor I is the fine portion of the suspended load.

It has already been suggested, and some evidence exists in support of this suggestion, that the distribution of fine-grained sediment is to some extent mineralogically controlled.

7. Factor I, representing mainly material that is finer than about 2.0 microns, represents the clay minerals and particles that tend to flocculate. They are platy rather than blocky, and even in the flocculated state tend to settle somewhat slower than blocky grains of the same diameter.

8. Although clay-mineral matter is still admixed, Factor II represents the coarse suspended fraction composed of blocky, free-settling grains The region of Factor II coincides with that of the muds in Figure 20, which is believed to be the zone of heaviest deposition of suspended sediment beyond the delta front.

9. Most of the sediment supplied by the Fraser River to the Strait of Georgia is contributed during the freshet. At that time the muddy, brackish, sediment-laden water leaves the river at Sand Heads as a

narrow jet with a velocity at the surface of up to 5 knots (Giovando and Tabata, 1970) and may extend all the way across the Strait to northern Galiano Island. Current data (see map, Figure 9) suggest that the surface waters turn north from the jet and become part of a clockwise rotation of surface water in the central Strait.

10. The clockwise rotation is reflected by the distribution of Factor II.

11. The northward transport of clays (Factor I) is effected by spin-off of surface water toward the north out of the eddy, and by the general northward flow of deeper water along the east side of the Strait north of Burrard Inlet.

12. Factor III has been interpreted as bottom-, and some suspended-, load from the Fraser River. The distribution pattern of this factor is of considerable interest. Mathews and Shepard (1962) suggested that bottom-load sediment from the Fraser entered the Strait of Georgia only during the ebb tide, having been stopped during flood tide conditions by the intrusion of a wedge of higher salinity water along the channel bottom. During ebb tide flow the salt wedge moves out of the channel permitting the release of bottom-load sediment to the delta front. Current velocities are increased during the ebb, and especially during the freshet, since river flow and tidal outflow are in the same direction.

Ebb tide in Georgia Strait near the river mouth sets to the south, as indicated by some of the drifter studies (Giovando and Tabata, 1970) and the shape of the isohalines (Waldichuk, 1957). Movement of bed-load sediment southwards might occur on an ebb tide.

A continuous, perennial, northward flow seems to exist along the delta front close to the river mouth (Johnston, 1921; Giovando and Tabata, 1970; Tabata <u>et al</u>., 1971). This northward current should have some effect on the suspended and bottom-load sediments, and is manifest by the northward bulge in Factor II north of Sand Heads. Once beyond the western margin of the narrow northward-flowing zone (Tabata et al., 1971) the bottom load may come under the influence of the strong tidal currents on the east side of the Strait near Point Roberts.

The southward movement of bottom-load sediment, shown as a southeasterly bend in the distribution of Factor III, provides an explanation for the filling of the northern end of Trincomali Trough that Tiffin (1969) describes.

13. That Factor III should appear in Boundary Bay may be a function of erosion and deposition of Pleistocene sediment from Point Roberts and other places around the bay.

14. Factor IV, representing the coarser material, has only a sporadic distribution.

15. The lack of factor representation of most sediments from marginal areas and those from Roberts Swell may reflect the (partially) relict nature of these sediments.

It is evident that factor analysis provides another useful analytical tool with which sediments, or the data derived from them, can be manipulated and compared. Interpretation of factor analysis must still be made with care, but when done in conjunction with other techniques and procedures it can yield information that may either corroborate interpretations made by other methods, or it may suggest patterns that might indicate the next procedure to attempt in order to decipher the sedimentary processes involved.

3.11 WATER CONTENT

Water contents of sediments used for textural analyses were determined from the weight loss upon drying to constant weight at 120°C.

There is a general trend, except toward the south and southeast, of increase in water content away from the Fraser River mouth. This observation is in general agreement with Mathews and Shepard (1962) who relate it to changes in packing of particles. It follows the same general trend as those of the median and mean grain-size changes and clay content. Water contents are highest - up to 72% - where clay content is high, at the northwest end of Ballenas Basin and in Malaspina Basin. This trend is very similar to the observations of Inderbitzen and Simpson (1971), from studies of sediments along a gullied section of the upper San Diego Trough off Del Mar, California, that water content is related to grain-size, and is related to depth or to topography only to the extent that grain-size is. In the Strait of Georgia the water content is related to, if not controlled by, the clay content.

Lowest values are associated with sandy well-sorted sediments (82, 83, 21). The sandy sediments of Roberts Swell have relatively low water contents.

3.12 SEDIMENT COLOURS

Colours of sediments were determined by comparison with the G.S.A. Rock Colour Chart. Despite the apparent potential for objective determination of sample colours by different workers it was intriguing to note that personal bias in the interpretation of colours could still occur. This was manifested by different watches selecting slightly different values to describe the most commonly occurring colour. Changing light conditions inside the ship's laboratory and sea conditions outside, coupled with a tendency for marine sampling to become more than a little boring, must have contributed to the variation in colour coding.

Wet sediments, immediately upon retrieval but, in the case of large grab samples usually after subsampling, were compared with the rock colour chart and their colours noted. In the laboratory the colours of dry sediment were noted after separation into gravel, sand and mud components.

Composition determines colour in sediments to a large degree. Gravels tend to be multi-hued, the colour depending on the source, degree of alteration, and subsequent encrustation by iron or manganese oxides or encrusting animals. Sands likewise show a close relationship between colour and mineralogy, and the colour changes associated with different grain sizes reflect the commonly observed feature of grain-size control of mineralogy. Very coarse and coarse sands tend to be multi-hued, but fine sands, through loss of the multicomponent grains (especially rock fragments of igneous origin), tend towards a more monotonous colour. Quartz and feldspar are generally the two most common constituents of the sands, tending to make the colour an overall light greyish. Admixtures of varying proportions of ferromagnesian minerals, and fragments of dark, fine-grained rocks may modify the colour toward darker values.

Muds tend to be greenish grey (10Y4/2) to olive grey (5Y 3/2) or dark greenish grey (5GY 4/1). Greyish olive green (5GY 3/2) is also a common colour. Since muds are a prominent part of almost all samples, the majority of the wet sediments are dark and greenish or greyish olive hued. On drying, the muds change to light grey (N7) or light olive grey (5Y 6/1).

No systematic patterns were evident in the colour determinations. Some variability occurred in the southern part of the area, but this was probably the result of the presence of sandier material with the consequent heterogeneity of colours.

During the course of treatment of samples prior to determination of mineralogy by X-ray diffraction, several chemical procedures aimed at selectively removing certain amorphous constituents were employed. These include: oxidation of organic material with 30 percent hydrogen peroxide; removal of organic material and non-crystalline iron, aluminum, manganese and silica with acidic ammonium oxalate; removal of amorphous oxides of iron, aluminum and manganese with sodium dithionite-citrate-bicarbonate. Table IV shows the colour changes that occurred after the various treatments.

TABLE IV - COLOUR CHANGES IN SEDIMENTS INDUCED BY SELECTIVE REMOVAL OF CONSTITUENTS

SAMPLE	ORIGINAL COLOUR	ACID AMMONIUM OXALATE	H_2O_2	SODIUM DITHIONITE-CITRATE-BICARBONATE
53	10Y4/2	5Y4/3*	5Y4/2**	N4-N3***
145	10Y4/2	"	"	"
280	5GY4/1	"	"	"

*, **, *** refer to colours of the Munsell Colour Chart, and are approximately equivalent, on the G.S.A. Rock Colour Chart, to 5Y4/4, 5Y4/1 and N3-N4 respectively.

The most pronounced colour change occurred after treatment with sodium-dithionite-citrate-bicarbonate, indicating that amorphous oxides and hydroxides of iron and manganese are the prime causes of the dark colours of the muds. Exposure to the atmosphere of many of the muddy samples from the deep basins (i.e. 280 from Ballenas Basin and 295 from Malaspina Basin) resulted in a reddish brown colour developing at the surface and extending inwards, probably indicating oxidation of ferrous iron.

Greenish to brownish green colloidal organic material contributes to the colour of the very muddy sediments. This material is almost impossible to sediment using even a high-speed centrifuge (indicating that it may not be particulate but due to organic pigments), but can often be removed effectively by adding 30 percent hydrogen peroxide to the sample.

Limonitic stains were noted on some rock fragments, and on some grains of coarse sand. Iron staining of coarse sand is apparent in the Pleistocene sediments of Point Grey, suggesting that the stained grains in the Georgia Strait sediments may be either inherited by erosion of the Pleistocene, or may have developed their stains in situ.

3.13 DISCUSSION: SEDIMENTATION RATES AND SEDIMENT DISPERSAL

Calculation of sedimentation rates in various parts of the Strait of Georgia from the information derived from sediment studies has not been possible. The longest core collected was only 3 metres, which, on the basis of rates of sedimentation calculated by other workers (see below) does not represent more than 200 to 900 years. No material was found in the cores that could have been used for C^{14} dating, and the cores were, in the most part, monotonous homogeneous mud. Some mottling due to burrowing organisms was evident in one or two cores, while rare isolated, displaced single valves of pelecypods and small twigs were encountered.

Fortunately, information from other sources is available, especially for sedimentation rates on the delta front (see also Appendix III). From core samples taken from the subaqueous part of the delta front Johnston (1921) suggested that annual increments may vary from a few inches to several feet. Off the main mouth of the river he suggested an average rate of deposition of 20 feet per year, with the variation ranging from a few inches to as much as 50 feet annually. Core samples from depths between 50 and 100 fathoms apparently showed no evidence of seasonal or annual layering, but rather were believed to be an expression of massive bedding. The sedimentation rate was postulated as 1 foot or more annually.

The lack of layering in the cores noted by Johnston was substantiated from the cores collected for this study. No layering was found in any of the cores studied that were taken off the delta front or in Ballenas Basin. This contrasts sharply with the cores studied by Fleischer (1972) from the Santa Barbara Basin, California, where layering that is believed to be related to flood discharge of the Santa Clara River is conspicuous. Fleischer identified the origin of the layers on the basis of colour as well as mineralogy, the colour differences being related to differences in carbonate content between the normal marine muds and the river sediments. In the Strait of Georgia carbonate contents in the marine sediments are low and the colours of both river and marine sediments are similar.

Johnston (1921) and Mathews and Shepard (1962) calculated rates of delta growth based on comparisons of depth soundings taken several years apart over the same areas. Comparisons of depth soundings made in 1859 with those made in 1919 (Johnston, 1921, p.43-44) led Johnston to believe an annual advance of the active part of the delta of 27 feet per year. Mathews and Shepard (1962) compared charts composed in 1929 by the Canadian Hydrographic Service with a chart made in 1959 by the Public Works Department. From these they constructed hypsographic curves permitting an estimation of the annual average increment to the delta over the 30 year interval. They arrived at a figure of 28 feet per year at the 300 foot contour, although the annual advance at shallower depths was somewhat less. Vertical increments were in the order of 1 foot per year (Mathews and Shepard, 1962, Figure 7, p.1423).

Cockbain (1963a) constructed an isopach map of sediment thicknesses based on echosounding profiles in the Central Strait of Georgia, between the lower slopes of the delta front and Texada and Lasqueti Islands. Isopachytes were drawn at 0, 50 and 100 feet of thickness of Recent sediments. Cockbain concluded that the elevated areas, the banks and ridges, were not covered by modern sediment, although the valleys between the ridges may contain over 100 feet of modern muds. The deep basins contain thick sequences of Recent sediments, with isopachytes compressed along the basin margins suggesting both steep basin sides and a thick accumulation of sediment. The deposits in Ballenas Basin show at least three sub-bottom reflecting horizons paralleling the surface and dipping gently from southeast to northwest. They can be followed across the basin and extend most of its length. Malaspina Basin did not show the same development of sub-bottom reflectors; the shallowest reflector occurs at 150 feet, while in Ballenas Basin the shallowest reflector found occurs at 50 feet. These observations were confirmed by Tiffin (1969), who also found that whereas the reflectors in Ballenas Basin dip and thin toward the northwest, those of Malaspina Basin dip and thin toward the southeast.

Cockbain (1963b) also suggested that relative rates of sedimentation could be obtained from a consideration of the total number of foraminifers present in any unit volume of surface sediment. Where sedimentation rates were high, the number of foraminifers would be diluted, and where rates were low their numbers would be correspondingly relatively higher. Low numbers of foraminifers in the Strait of Georgia thus suggested high sedimentation rates. Only brief mention was given to the possibility of other factors, such as productivity and death rates, causing variations in abundance of foraminifers.

Thicknesses of Quaternary sediments and rates of accumulation of Holocene sediments were calculated from sparker profiles by Mathews, Murray and McMillan (1966). In the northern central part of the Strait, the accumulation rate is given as 18 feet per thousand years (0.55 cm./yr), assuming the end of the Pleistocene to be 10,000 years B.P. In the vicinity of the Fraser River Delta, the accumulation rate was calculated at 90 feet per thousand years (2.7 cm./yr). Unfortunately, the actual places in the Strait from which these rates were calculated were not indicated.

An extremely high average rate of sediment accumulation in Ballenas Basin was calculated by Tiffin (1969) as 2 cm./yr. This figure is based on the assumption that sedimentation commenced some 10,000 years ago. Tiffin implies that this rate is rather high this far from the delta, but quotes Holtedahl (1965) as finding an accumulation rate of 1 cm./yr in a Norwegian fjord that did not have a large river to supply the sediment. However, if an empirical compaction correction is applied to the maximum thicknesses of sediment in Ballenas and Malaspina Basins (260 and 230 metres respectively), the corresponding thicknesses of loose sediment would be in the order of 300+ metres, which, for a 10,000 year period of accumulation, increases the rate of deposition in the deep basins to over 3 cm./year.

Accumulation rates for sediments from areas close to the Strait have also been established. Kellerhals and Murray (1969) proposed an average rate of vertical growth of the tidal flat at Boundary Bay of 0.42 mm./yr, for the last 4,351 years. In Saanich Inlet on the southeastern end of Vancouver Island a sedimentation rate of 12 to 18 feet per thousand years (0.36 to 0.55 cm./yr) based on C^{14} dates is estimated by Mathews, Murray and McMillan (1966). This particular area is of considerable interest because the sediment accumulating is biogenic rather than terrigenous.

The results of the present study tend to substantiate the conclusions reached in the studies cited above. In the southeastern part of the area, in the region of Roberts Swell, Boundary Basin, Alden Bank and the eastern end of Trincomali Trough, sedimentation rates are either extremely low or negative. The bathymetric form of Boundary Basin and the Eastern end of Trincomali Trough suggest active erosion, as does evidence from seismic profiles (Tiffin, 1969), and the presence of gravels and very coarse sands in these areas that are believed to be lag concentrates tends to support this contention. Dredge hauls from the flanks of Trincomali Trough (by Dr J.W. Murray, Geology Dept, U.B.C.: dredge haul #10, July 26, 1968: 48^{o} 51.5'N 123^{o} 02.7'W) retrieved highly irregular carbonate cemented concretions that contained shell and sand debris, and were extensively bored. These concretions resemble some of those described in Garrison _et al_. (1969), which were collected from an area of low sediment accumulation and vigorous wave and tidal current action in distributary channels and from shallow-water marine localities close to the Fraser River Delta front.

The abundant epi- and in-faunal elements of the Roberts Swell sediments, as well as the generally sandy nature of these deposits, also suggests slow, if any, accumulation of fine sediment. In fact, the shape of Roberts Swell, and the high current velocities near the bottom (over 30 cm./sec.; Pickard, 1956) suggests that the sediments of Roberts Swell may be being washed and the sands concentrated. Some of the washed material may be redistributed to the northwest where currents are less strong, and some to the south where they are removed from the area by the intense current action through Boundary Pass, probably to accumulate in Juan de Fuca Strait or in more sheltered waters around the Gulf and San Juan Islands.

Within Boundary Pass itself, and the other tidal passes among the Gulf Islands (Active Pass, Porlier Pass) the effects of tidal scour appear to be sufficient to prevent deposition of any material and to actually expose bedrock.

Suspended material derived from the Fraser River, and sediment eroded from the Pleistocene cliffs around Point Roberts, that is carried into Boundary Bay tends to be retained and deposited there. Southwesterly winds blowing into the Bay keep the sediment-laden water trapped.

The region of the Fraser River Delta, especially in the upper parts reached in this survey, presents evidence of both active, heavy sedimentation in the vicinity and to the north of Sand Heads, and possible erosion southeast of Sand Heads (see also Appendix III). The anomaly of the coarse sands at sample locations 82 and 83 has already been discussed. Because of the high current velocities recorded from Roberts Swell close by, the possibility of tidal scour and washing of older delta deposits in this area cannot be discounted. Johnston (1921) could find no evidence of measurable advance of the delta front more than three miles south of the present Sand Heads light despite an active growth seawards of 28 feet per year north of here.

The existence of coarse sands and gravels, in areas where they could not possibly be transported under the present sedimentary regime, and of other features to be discussed below, indicates that the bank tops and flanks are areas of little sediment accumulation. The sedimentological evidence also suggests, albeit tentatively, that sedimentation rates are higher to a shallower depth on McCall Ridge than on Halibut Ridge, and are low in even the deeper parts of ridges in the northwest (e.g. Sangster Ridge) and in the area between the northwestern end of McCall Ridge and the mainland.

The evidence upon which these suggestions are based includes: the existence of manganese nodules; abundant faecal pellets; the distribution of sands and gravels; the occurrences of large numbers of diatoms; the existence of agglutinated mud lumps and some glauconite "pellets."

Discoidal concretions of earthy ferromanganese material usually about a pebbel nucleus, and poorly developed crusts or stains that give positive tests for manganese have been found locally in the Strait. Discoical concretions were collected from locality 341, on the side of the col connecting the northwestern end of Sangster Ridge with the rise that emerges as the Ballenas Islands, and from the southern side of Sangster Ridge (dredge haul collected in 1968 by Dr J.W. Murray, U.B.C. Geology Department, from position 49° 21.8'N, 124° 02.0'W). These nodules will be described in greater detail later. Low rates of sedimentation are conducive to their growth and development (Degens, 1965, p.89).

Limonitic and manganiferous stains or thin irregular accretions are present on cobbles and pebbles in other areas of the Strait, notably in the south, in the Trincomali Trough - Boundary Basin area which has already been discussed as an area of low or negative sediment accumulation. Stains and small crusts of iron and manganese compounds are present on pebbles from locality 172, at Gabriola Reefs on the Island Shelf, and on some pebbles from ridge top samples (e.g. 354, 242).

Faecal pellets have been found in some ridge-top and island shelf and slope samples. Their uniform size, shape and colour suggests the same, but unknown, organism was responsible. They occur mainly in the 0.3 to 0.5 mm. size range, are ellipsoidal in shape with smooth surfaces, and tend to be a light yellowish grey, which may indicate removal of organic pigments by the organism responsible. While not a conclusive indicator of slow sedimentation, the occurrence of these in areas where other evidence points to slow sediment accumulation suggests that the habitat of the organism responsible was one where sedimentation rates are low. No similar pellets were discovered from muddy sediments collected from areas at similar depth but where sedimentation rates are believed to be higher.

The occurrence of sands and gravels on bank tops and flanks in positions that the present sedimentary processes active in the Strait could not place them, and the lack of sufficient fine material deposited from suspension under the present regime to bury them beyond the reach of the grab sampler, has already been discussed. The occurrence with these unburied coarse deposits of sedentary bottom-dwelling organisms such as sponges is interpreted as strong evidence in favour of relatively slow rates of sedimentation in these areas. Some of the larger sponge fragments have iron and manganese compounds accumulating within their skeletal framework and staining their surfaces.

These specimens seem to have been lying in the sediment for some time, and may have smaller vase sponges growing from them.

In at least one locality, 242 (see Figure 2), diatoms provide a conspicuous and prominent part of the sediment. The frustules were identified by Dr F.J.R. Taylor, Institute of Oceanography, U.B.C., as Coscinnodiscus centralis which is found in great abundance in Howe Sound. They were found in smaller quantities at other localities and are interpreted as indicating sufficient current activity to maintain a good supply of nutrients that would support an abundant diatom fauna. Other ecological factors would no doubt be important, but the relative cleanness of the gravels, abundance of sponge debris and presence of a few, abraded foraminifer tests suggests a low sedimentation rate and at least some current activity.

Associatied commonly with faecal pellets, but also from some shelf and ridge samples that did not contain pellets are irregularly shaped, pale greenish, agglutinated lumps of mud. These lumps are similar in shape to some of those illustrated by Murray and Mackintosh (1968) from Queen Charlotte Sound. They are not associated with foraminifer tests, and their size is not consistent. Although their origin as a function of sample preparation cannot be discounted, other possibilities exist. They may have a similar origin to the particles that make up the Eocene Sawdust Sand from Tennessee (Pryor and Vanwie, 1971) which were believed to be self-accreted aggregates that grew in an area where they were agitated by water movements. They may also represent a form of glauconite. The irregular cracked surface is probably a result of gel shrinkage. Their mineralogical composition is similar to that of the accompanying muds. Further consideration on the origin of the mud lumps will be given in Chapter 4.

In a core from sample site 300 darker green lumps of quite irregular shape, plus smaller, more evenly sized though irregularly shaped pellets, are associated with a large number of faecal pellets. A relationship is not suspected because of the wide range in size and shape of the lumps. They occur in greater quantity near the top of the core, decreasing in abundance with increasing depth until they disappear at about 80 cm. X-ray diffraction studies indicate they are composed of a mixed-layer clay mineral that conforms to a variety of glauconite containing a high percentage of expandable layers (probably Burst's (1958a, 1958b) type 3 glauconite (Hower, 1961)).

Conditions conducive to the development of glauconite include (Cloud, 1955; Degens, 1965): an environment with a negative oxidation potential; available potassium and iron; source and presence of three-layer clays; slow sedimentation; near normal salinity; high organic content of the sediments. All these conditions, except high organic content, are met in Georgia Strait. Hower (1961), considering Burst's (1958a, b) models of glauconitisation and the relationship between glauconite structure and the lithologic type of the enclosing sediment, believes that the process of glauconitisation reflects the sedimentation rate, being carried closer to completion in an environment where sediment accumulation is slow or negative. The glauconites from core 300 are poorly ordered, contain a large amount of expandable material and occur in muddy sediments. Their existence permits only speculation about the sedimentation rates; it is probably not as high as in the adjacent basins where the dark green lumps have not been found in the cores or grab samples. The area in which core 300 is located does not appear to have a thick sediment cover (Cockbain, 1963a; Tiffin, 1969, plates V, VI).

In summary, in the southeastern portion of the study area, sedimentation rates are low or negative with active erosion in Boundary Basin and the tidal passes between islands, but north and northwest of a line between Galiano Island and Sand Heads sedimentation rates range from high or very high on or near the delta, especially to the north of Sand Heads, decreasing to the northwest but still high in the deeper basins, to low on the Island Shelf, Mainland Slope, and on the tops and upper flanks of the ridges within the Strait.

Sedimentologically, the Strait can be considered as consisting of three basically different regions: the area to the south and south-east of Sand Heads, an area of erosion; the Fraser Delta, the region of heaviest sedimentation; and the northwestern region, an area of lower rates of sedimentation where clays are accumulating.

The area of the Fraser Delta includes the delta front foreset beds and the muds that are transitional to prodelta clays of the basins in the northwest. Foreset bed sediments forming the present delta now extend across the Strait to the Gulf Island slope, where they lap up and onto Pleistocene sediments. The sediments also overly the north end ōfd Roberts Swell, but do not cover this feature.

Dispersal of sediment to the north and northwest over the delta area has been discussed in sections on mean grain size, sand content, sand:silt:clay ratios, and factor analysis. Sediment dispersal will be determined (influenced) first by the circulation of surface waters (section 1.5.1). Subsequently, as sediment settles from suspension, it will come under the influence of deeper currents. Suspended material might then be expected to show the effects of net surface-water circulation patterns. Clays and clay-sized particles that stay in suspension for a considerable length of time would be expected to be influenced by both surface and deep water circulation. Movement of muddy, silt-laden water northwards, and sometimes southeastwards, along the delta front is clearly displayed on air photographs (e.g. Figures 12, 13) and by direct observation from a high vantage point such as on Point Grey or from the slopes of the mountains on the north shore of Burrard Inlet.

Persistent seaward movement of surface water from the Fraser River occurs during the freshet (June, July). This is the time of maximum sediment influx to the Strait. Bottom sediment is deposited on the delta front, on the upper and middle slopes, to be redistributed by either the strong, predominantly northward, tidal currents active along the delta front, or northwesterly winter storms, or be covered by finer sediments. It contributes to the continual outward growth of the delta. Suspended sediment is carried out with the jet of surface water, and may reach the opposite side of the Strait. Once in the Strait there is a general tendency for the surface water to veer north, whether close to the delta front or near the opposite side. This will bring the surface water and its suspended sediment load under the influence of the clockwise rotation or eddy that is suspected to exist in the central Strait of Georgia (Tabata et al., 1971). The water then follows a sweeping curve to the right, that takes it eventually into Burrard Inlet, passing over the southeastern extension of McCall Ridge. This covers the area considered to be the region of major mud deposition (coarse suspended load from cumulative probability curves, or Factor II from the factor analysis: see Figure 38) which extends due west from the river mouth in a broad inverted L-shaped swath north then east into Burrard Inlet.

Current movements along the east side of the Strait north of Burrard Inlet are not well known but appear to be northwesterly directed at speeds in the order of 0.1 to 0.4 knots at the surface. About the currents at depth nothing is known, but their existence and persistence are suggested by the lack of a thick muddy Recent sediment cover on Halibut or McCall Ridges even though the adjacent Sechelt Basin has a thick accumulation (60+ metres: Tiffin, 1969) of modern muds. The currents may be of sufficient strength to prevent deposition of sediment on the banks.

The northwestern portion of the study area, referred to above as the region of slower accumulation or modern sediment, has an intriguing anomaly associated with it. The deep basins, Ballenas in particular, have thick accumulation of sediment but the flanking basin sides and adjacent elevated areas have only thin veneers, or may even be devoid, of modern sediments. Sediments in this region are very fine-grained, generally clay minerals and other minerals of clay-size.

Two special problems are associated with the sediments in the northwestern region:

1. How does the finest sediment get to the north? That it does is evident from the mean grain size (mean and median), sand:silt:clay ratios, and from the factor analysis. Along Ballenas Basin, from southeast to northwest, the mean grain size decrease is continuous.

2. Why are the ridge tops and flanks, even the ridges in deeper water in the northwest, relatively free of modern sediment while the adjacent basins have 4 to 6 times or more the thickness of Recent sediments?

In the laboratory, during size and mineralogical analysis, two situations were observed which bear on these problems: (1) a considerable amount of the washed samples (to remove sea salt) tended to remain in suspension for very long periods of time, and the possibility exists that without the addition of electrolytes the material would never settle; (2) in sea water, or with the addition of calcium chloride, a sample rapidly flocculated. This latter observation, and the studies of Gripenberg (1934), of Whitehouse et al. (1960) and Hahn and Stumm (1970), indicate the importance of flocculation in the setting of the fine-grained material.

Floccule formation in the natural environment may not be simple. Dr L.M. Lavkulich (Dept of Soil Science, U.B.C.) suggests that in a system of relatively low concentration such as this one is supposed to be, the floccules may form and break up continuously. It is possible, therefore, that some size fractionation may be achieved in suspension. Under the physical conditions of wind or wave generated turbulence, formation and disaggregation of floccules may be occurring during dispersal of the suspended sediment, and size fractionation accomplished in this manner. On dropping below the level of more intense turbulence, and into water of higher salinity, the floccules may remain formed and settle under gavity while at the same time being transported by the slower, northerly directed, deeper water currents.

A model or mechanism for sedimentation in the northwestern region must account for the differences in sediment thickness over the banks and in the basins. Recent sediment thicknesses in Ballenas Basin, while varying with bedrock topography, are a maximum of 260 metres and an average of 200 metres. Within the sediment pile numerous parallel reflecting horizons occur, generally thinning to the northwest and dipping in the same direction at very slight angles (Tiffin, 1969). The internal reflectors may be more obvious nearer the delta, and may disappear before reaching the far northwestern end of the basin. The source of the sediment, as determined by thinning of internal reflecting horizons (Tiffin, 1969), is the Fraser River. Sediment must reach the northwestern end of the area by one or both of two mechanisms: settling of material held in suspension; and by traction or turbid currents along the bottom.

Settling of suspended material should theoretically result in an even blanket of sediment over everything, the thickness of the blanket depending on the distance from the river mouth. It would be expected therefore that in the deeper areas, presumably out of the influence of even moderate currents, such as the low saddle connecting the northwest and southeast segments of Sangster Ridge, the thickness of the sediment mantle should be uniform from "ridge" top to adjacent basin. In fact, the basin sediments are 4 to 6 times thicker than those on the adjacent saddle (Tiffin, 1969). Other ridges and many of the basin walls and ridge sides are devoid of significant modern sediment cover. Very often the flat basin floor meets the adjacent ridge flank abruptly. There is no evidence on the floor of the basins adjacent to the sidewalls that would suggest removal of material by sliding or slumping.

Although there are no current measurements at depth in the northern section of the Strait, currents of sufficient strength to keep the ridge tops and flanks sediment-free must exist. However they cannot be uniform throughout the Strait, as some deep areas in the Strait have slower sedimentation rates than others at the same or shallower depths.

Probably the most important information permitting elucidation of sedimentational mechanisms is provided by the seismic records. The presence of reflectors that change from strong to weak away from the delta front and thin in the same direction, but which appear to be contained within the sidewalls of the basin, all point to the probability that turbidity currents are an important mechanism in distributing sediments along Ballenas Basin.

Cores taken from and along Ballenas Basin, however, do not give any evidence of the existence of turbidity currents (graded bedding, laminations, ripple-drift laminae, clear basal demarkation of the flow: Kuenen, 1957). Some mottling of the cores that was probably due to the activity of burrowing organisms, and some poor but decipherable photographs of the bottom taken from station 280 that show tracks and burrows, suggest that bioturbation may have disturbed any bedding features. Also, if a turbidity current was initiated in fine-grained, moderately sorted sediment and deposition occurred in an area of similarly fine-grained, moderately sorted sediment, there might not necessarily be any visible evidence for the existence of turbidity flow deposits. It must also be realised that if the sedimentation rate in Ballenas Basin is indeed 2 cm./year, then the longest core obtained (3 metres) records history only as far back as 1820 AD. At a rate of 0.55 cm./year (Mathews, Murray and McMillan, 1966) the recorded time would extend only as far as 1372 AD. Even allowing 1.5 metres compaction, the maximum time represented would still be only 900 years. Tiffin et al. (1971) suggest that the formation of the hillocks at the base of the delta west of Sand Heads was due to a sliding of material from higher on the delta front, and they estimate this to have occurred only

200 years ago. This sliding should have triggered at least one turbidity current, but no evidence of any was found. Either the expected turbidity flow did not occur or, assuming the estimated age given by Tiffin et al. (1971) is not too low, the sedimentation rate is indeed high enough to prevent a record being obtained with the apparatus used. In the seismic records resolution is not particularly good in the upper 12 to 18 metres, making it difficult to determine whether or not turbidity flow has occurred in the time interval represented by this thickness. The evidence for the existence of turbidity currents in Georgia Strait is not unequivocal, but the mechanism does provide an explanation for the apparent anomaly of the differences between ridge-top and basin sediment thicknesses.

Low sedimentation rates have been suggested for the ridges, particularly the deep ones at the northwest end of the study area (Sangster Ridge, Ballenas Island Ridge), and the shallower region between northwest McCall Ridge and the mainland. Some clay is mixed with the sands and gravels of the ridges and its mineralogy is the same as that from the Fraser River, but the fact that manganese nodules can grow on the deeper ridges, and coarser sediments have not yet been buried beyond the reach of the grab sampler, suggests that the amount of clay accumulating in these areas is relatively small.

Either little hemipelagic sediment reaches the northwestern end of the study area, an unlikely situation given currents with measured strengths of up to 0.75 knots to 312^{o} at 90 metres depth (Station F11, Tabata et al., 1970) in the central Strait, or bottom currents are sufficiently strong to prevent significant accumulation of mud on bank tops. The different depths at which coarse sediment still exists exposed on the bottom suggests that current strengths and movements are not uniform throughout the Strait. The present writer believes that currents provide the means of preventing permanent sedimentation on the ridges. The thick sediment accumulations in Ballenas and Malaspina Basins are the result of deposition of hemipelagic muds introduced to the Strait by the Fraser River. As will be shown in the following chapter, the sediments from both basins are practically identical in composition (with due regard to grain-size effects on mineralogy) to sediments on the delta and from the Fraser River. Texturally, the surficial sediments from Ballenas and Malaspina Basins are identical.

CHAPTER 4

MINERALOGY

4.1 INTRODUCTION

Information on the composition of potential sources for the Strait of Georgia sediments is scarce. A generalised account of the composition of the sand fraction to be expected from the Cascade Mountains, the Coast Mountains and from Vancouver Island is given by Mathews, Murray and McMillan (1966). Their findings are summarised here:

Composition of sand-fractions from:

(i) Coast Mountains - granitic detritus important; quartz 20% to 50%; plagioclase 15% to 40%; potash felspar 10% to 20%; amphibole (hornblende) ±5%; plus biotite, epidote, garnet, magnetite, fragments of metamorphic and volcanic rocks, basaltic hornblende and volcanic rock fragments.

(ii) Cascade Mountains - quartz 15% to 25%; felspar 15% to 45% (plagioclase and potash felspar in about equal proportions); chert and quartzite 25% to 50%; plus chlorite, garnet, micas, sphene and staurolite.

(iii) Vancouver Island - high proportion of lithic grains and metavolcanic material.

(iv) Fraser River sands seem most closely related to the Cascade Suite; the dark colour of the sands being due to dark grains of chert. Muscovite is conspicuous although present in small quantities, and is supplied to the Strait only by the Fraser and perhaps the Nooksack Rivers.

Unfortunately, no information was provided describing the locations of the samples from which this information was taken, and no mention was made whether the descriptions apply to total sand fraction or only a portion of it. No information is available on the mineral composition of Pleistocene deposits either around the margins of the Strait, or those through which the Fraser River flows and from which it derives much of its load.

A mineralogical study of the silt- and clay-sized components from alluvial sediments of the Fraser River was undertaken by Mackintosh and Gardner (1966). They described a progressive increase in phyllosilicate mineral content with decreasing grain-size. Silt fractions were essentially similar to fine and very fine sand-size material, consisting of a preponderance of quartz, felspar and chlorite, with lesser amounts of amphiboles and pyroxenes. The clay fractions contained montmorillonoid and chlorite minerals plus lesser amounts of micas, mixed-layer montmorillonoid-chlorite, quartz and felspar.

In the present study, mineralogical analysis of the sub-sand-size fractions has been stressed. Less emphasis has been placed on the gravel and sand fractions because of the relatively smaller amounts and restricted distributions of the coarser sediments.

Bands or patches of sediments with distinctive, unique mineralogic compositions or associations have been used successfully in some areas for determining sediment dispersal patterns (e.g. Van Andel, 1964; Imbrie and Van Andel, 1964; Ross, 1970). The application and success of this technique relies on the presence of more than one source of sediment supply, the separate sources being located in areas of different bedrock lithologies. Such a situation does not exist in the Strait of Georgia. Easily eroded local sources around the margins of the Strait are glacially derived Pleistocene deposits. The Fraser River, which supplies most of the sediment to the Strait also derives much of its load from Pleistocene deposits. The result is a generally uniform composition for the sediments throughout the Strait. Consequently sediment composition is of little help in elucidating dispersal patterns in this area, but instead points to the dominance of one heterogeneous source for Strait of Georgia sediments. This source is primarily Pleistocene deposits either by local erosion or via the Fraser River. Around the margins of the Strait, local sources other than Pleistocene deposits may be apparent; volumetrically they are of little importance.

All samples containing gravels and very coarse sands were examined, and hand-specimen identifications of coarse constituents were verified by thin section study of selected pebble lithologies. Sand fractions of gravelly and non-gravelly samples were examined qualitatively with a binocular microscope. Fifteen samples chosen from various parts of the Strait were size-separated into eight fractions by wet-sieving through 10, 18, 35, 45, 60, 120, 230, and 325 mesh sieves, and the material caught on each sieve was examined separately. Thin-sections of grain-mounts and stained grain-mounts were made from the 60 to 120 mesh (fine sand) fractions of these samples. Staining to distinguish potash and plagioclase felspars and quartz was performed on light fractions separated from the total 60-120 mesh fraction by centrifuging in bromoform. The light minerals were mounted on glass slides using DOMTAR Lap Cement as the mounting-medium (c.f. Gross and Moran, 1970). Felspars were stained with sodium cobaltinitrate solution (Chayes, 1952) following an eight-minute etch in hydrofluoric acid vapour (time schedule and procedure according to Gross and Moran, 1970). Point-counts were made of quartz, plagioclase and potash felspar using a binocular microscope. Results are presented in Table V as the ratio of quartz-plagioclase-potash felspar.

Nine samples from the Strait of Georgia and three from the Fraser River at Ruby Creek, 12 miles east of Agassiz, B.C., referred to as the Group A samples, were subjected to detailed physical and chemical treatment and analysis for sub-sand-size mineralogy, cation exchange capacities, content of exchangeable bases and possible diagenetic effects. The essentially uniform composition of the sediments throughout the Strait of Georgia was established with these samples. Mineralogical analysis by X-ray diffraction was conducted on 53 to 20, 20 to 5, 5 to 2, 2 to 0.2 and finer-than-0.2 micron size fractions of the Group A samples.

Another fifty-seven samples, Group B, were separated into coarse to medium silt, and clay (less than 2.0 microns) size-fractions and subjected to X-ray diffraction analysis without any treatment other than washing to remove soluble sea salts. These samples were used for semi-quantitative clay-mineral analysis after the method of Johns, Grim and Bradley (1954). They confirmed the uniformity of the sub-sand-size mineralogy found from the Group A samples.

One of the more important features of the mineralogy is the distribution of sand-size flakes of muscovite. Mathews and Shepard (1962) and Mathews, Murray and McMillan (1966) contend that muscovite is contributed to the Strait of Georgia only by the Fraser and perhaps by the Nooksack Rivers. Examination of the sand-size fractions from various Strait of Georgia sediments, paying particular attention to the presence or absence of obvious even if quantitatively unimportant muscovite, revealed this contention to be erroneous. With the exception of some samples from close to shore on the western side of the Strait at the northwestern end of the study area, which did not appear to contain muscovite (e.g. 286, 337, 341), this mineral has been found in the sand fractions of almost all other samples studied, particularly those from ridge crests (e.g. 354, 263), on the western side of the Strait, and from the region opposite and south of the delta. Sample 351 for example contains a considerable quantity of muscovite and other micaceous minerals similar to those of the Fraser River. This sample site is at the extreme northwestern end of the study area on the eastern side of the Strait. Muscovite is present, but not abundant, in samples located between site 351 and the Fraser Delta suggesting that suspended-load transport of sand-sized muscovite from the Fraser River along the eastern margin of the Strait of Georgia cannot be occurring. Bottom topography between the delta and sample locality 351 is very irregular, and is cut by the axis of Queen Charlotte Trench, which suggests that bottom transport of muscovite from the delta area is unlikely. Since muscovite is present, sometimes in moderate quantities, in sediments on ridge crests within the Strait, both as discrete grains and as a constituent of granitic rock fragments, Pleistocene deposits as well as the Fraser River are likely to provide a source for muscovite.

4.2 GRAVELS

Gravel is used here as a general term for all material coarser than 2mm. effective sieve diameter. Most gravels are associated with sand and mud, except in the tidal channels and passes, and were separated from the remainder of the sediment by wet-sieving. Individual gravel components - pebbles and cobbles - range from angular to rounded although the majority are subangular to subrounded. Their surface textures may be smooth or quite irregular and pitted. They may possess flattened but rarely striated faces, and numerous broken pebbles with rounded edges were found. Pebbles and cobbles collected from Boundary Basin and the southern parts of the Island slope, and less commonly those from ridge crests, may support a varied fauna of encrusting organisms, including long, convolute, sandy worm tubes, barnacles, corals, sponges and occasionally pelecypods such as Mytilus. Ferromanganese stains are common, and accretionary manganese nodules around pebble nuclei were found at two localities at the northwest end of the study area.

The composition of the gravel constituents is similar to that in Pleistocene deposits in nearby land outcrops. Lithologies include: fresh and altered diorites and granodiorites, the most common rock type (ranging from coarsely crystalline with varying proportions of hornblende, and plagioclase and quartz, to finely crystalline and often epidotised); amphibolites; volcanic and low-grade metamorphic rocks; sandstones and argillites. Red volcanic rock fragments are not common in this size fraction but are conspicuous in the fine gravel, very coarse sand and coarse sand size ranges. The variety of lithologies is not as great as that of the gravels on the Point Grey beaches, which may be a function of the sampling procedure rather than the actual conditions. Many of the pebbles and cobbles have a more weathered appearance than the beach material with iron or iron and manganese stains, pitted or rough surfaces, and a superficial greenish discolouration especially evident on some granodiorites and diorites that is not common on beach boulders. The difference can be attributed to subaqueous weathering.

Origin of the gravels as either relict Pleistocene or lag-concentrate has been considered earlier. The Fraser River is not transporting gravels as bed-load to near Sand Heads at present, even during the freshet. Their distribution in the Strait is such that, except perhaps for local marginal accumulation, glaciers, fluvio-glacial streams or floating ice afford the most likely explanations as means of transport. The composition is heterogeneous and reflects the geology of the surrounding areas (see Figure 3).

4.3 SANDS

Quartz and felspar dominate and, with lithic fragments and green and brown hornblende, provide the bulk of the sand-size mineralogy. Micas, including muscovite, biotite and chlorite, and pink garnet are conspicuous if not always quantitatively important constituents of the sand mineralogy of almost all samples. Magnetite is present in most samples although never in abundance. Epidote and rare grains of sphene and spinel are also persistent trace components.

In an excellent discussion introducing the results of mineralogic studies of Recent sediments from Barkley Sound, Carter (1970) pointed out that meaningful comparisons of sand-size mineralogy can only be obtained from study of total sand mineralogy among samples with similar size ranges and, presumably, means and standard deviations. He also suggested that mineralogic studies of single size-fractions can be misleading because of the dependency of mineral composition on grain size. Carter's research produced reliable evidence in support of his contentions. The idea of size control of mineralogy has also been discussed by Davies (1972).

Examination of eight size-fractions separated from several Strait of Georgia samples, one sample from the Fraser River and one from Pleistocene sediments near the base of the cliffs at Point Grey, indicated that size control of mineral composition is an important factor influencing these sediments also. Coarser size fractions contain quartz, felspar and hornblende as dominant individual mineral species but the bulk of the samples consist of a variety of lithic fragments. Granodiorites, quartz diorites and diorites are the dominant lithic constituents in the coarser sizes, but their coarse crystallinity results in their loss by reduction to individual minerals in finer size grades. Red grains of volcanic rock are conspicuous and are apparent in most sandy sediments from the east and central parts of the Strait. They seem to be rarer or even absent from sandy sediments on the Vancouver Island side. Dark, fine-grained lithic fragments are apparent in all sands, but decrease in prominence in finer sizes as a result of both their breakdown and the relative increase in quantities of quartz, felspar and hornblende. Fragments of metamorphic rocks are more conspicuous from samples close to the western margin, but are present over the entire Strait. Finer size fractions are dominated by quartz and felspar, with subordinate but prominent amounts of red and green hornblende and dark, fine-grained lithic fragments. Garnet, micas and other minerals may be conspicuous but are of much less importance volumetrically.

Minor differences in the mineralogy can be detected, mainly in samples from the western side of the Strait at the northwestern end of the study area and close to shore. Further from shore either the differences no longer exist or the sediments are chiefly muds. The principal departures from the usual composition include lesser quantities of mica, especially muscovite (none at all in 337, 341, 342), or less variety of mineralogy (286). Sample 315, close to sample 286, does have a sand composition similar to most others, however, which may be interpreted as further support for the contention that the mineral composition, and muscovite, may be derived from Pleistocene deposits as well as from the Fraser River, while sources marginal to the Strait are local and of minor importance. This suggestion is consistent with the compositions of samples such as 263 and 354 from ridge tops within the Strait, 21 from Alden Bank, 58 from Roberts Swell,

SAMPLE	Q :	P :	K	Q:F	%H
8	3.08	3.62	1.0	.68	16
21	3.42	3.67	1.0	.74	10
40	4.09	4.00	1.0	.81	11
58	2.73	2.93	1.0	.70	2
82	3.14	3.07	1.0	.77	10
93	2.16	1.89	1.0	.74	8
103	5.71	7.57	1.0	.67	7
172	1.57	2.14	1.0	.50	9
238	9.00	9.80	1.0	.83	8
242	2.53	3.13	1.0	.61	9
286	3.43	2.71	1.0	.92	5
351	3.54	3.15	1.0	.85	3
354	3.21	2.93	1.0	.83	5
QUADRA	4.63	6.88	1.0	.58	13
FR3U	2.53	2.41	1.0	.74	5
AV.	3.65	3.99	1.0	.73	
* 1				3.00	
* 3				6.29	
* 4				1.65	
* 8	NO INFORMATION			4.00	
* 9	GIVEN			2.43	
*11				8.00	
*12				6.14	
*AV.				3.64	

TABLE V: RATIOS OF QUARTZ(Q) : PLAGIOCLASE(P) : POTASH FELSPAR(K), AND QUARTZ(Q) : FELSPAR (F) FOR 60 TO 120 MESH LIGHT FRACTIONS OF SELECTED GEORGIA STRAIT SAMPLES. %H IS THE PERCENTAGE OF HEAVY MINERALS IN THIS FRACTION. * REFERS TO INFORMATION FROM TABLE I, P.36, GARRISON ET AL (1969): DISCREPANCY BETWEEN THESE AND THE GEORGIA STRAIT VALUES IS DUE TO THE INCLUSION OF QUARTZITE AND CHERT GRAINS WITH QUARTZ IN THE FORMER'S ANALYSES.

103 and 106 from the delta front, and FR3U from the Fraser River, which are all very similar, differing only in proportions of components.

That any differences in the mineralogy of sands in the Strait are of minor importance is suggested by determination of quartz:felspar, and quartz:plagioclase:potash felspar ratios for the light mineral fractions of the 60 to 120 mesh size ranges for several samples scattered throughout the Strait. The results (Table V) did not indicate any trends in variation among samples and in fact the variation among samples was similar to that found by Garrison et al. (1969) among compositions of early diagenetic concretions collected from distributary channels of the Fraser River.

A propos of an earlier consideration, that of comparing mineralogy of samples within similar size ranges, the Georgia Strait sediments do not lend themselves to this kind of treatment. Few sandy samples are well-sorted. Only three samples are entirely sand with little or no mud; all others have sufficient quantities of sub-sand-size material to render them poorly sorted. A large number of the samples that do contain sand have this fraction in the fine to very fine sand range as a coarse tail to a dominantly silt and clay size distribution. Compared to the silts and clays, sands are volumetrically of much less importance.

4.4 SUB-SAND-SIZE MINERALOGY

As mentioned in the introduction, X-ray diffraction analysis of the sub-sand-size mineralogy was conducted on two groups of samples that had undergone quite different chemical and physical pre-analysis treatments. The reasons for this division are:

i. a crude experiment designed to show what detectable diagenetic effects might occur when the sediments passed from a fresh-water to marine environment was carried out on Group A samples. Sediments from the Strait that had obviously been in the marine environment some time were included to compare with the Fraser River material. A few samples were chosen to be representative, covering as wide an area as possible of the Strait. These samples were subjected to detailed X-ray analysis and selected chemical techniques.

ii. Johns, Grim and Bradley (1954) developed a widely used, semi-quantitative technique for clay-mineral analysis. Samples to be analysed by this technique should not be chemically treated in any way, except for removal by washing of soluble sea salts. The 57 samples from Group B were chosen for the purpose of semi-quantitative analysis.

iii. Two schools of thought exist concerning the preparation of clay-rich sediments (or clays) for X-ray analysis (Bradley, 1964). The first school employs chemical and physical treatments which attempt to remove organic matter and amorphous, poorly crystalline or badly deteriorated phases, thus attempting to high-grade the residue or to regrade it to a relatively constant composition (Jackson, 1956, 1964; used in many soil science laboratories). The second group believes that the natural assemblage should be examined untreated, following the argument that the previous technique tends to create a clay-mineral condition (of orderliness or crystallinity) that did not exist in the natural state. The second approach studies the mineralogy as it really is and may, for example, lead to the identification of greater quantities of mixed-layer clays. It can also be argued, in favour of the second alternative, that clays in the marine environment are not usually associated with as much organic matter or amorphous material as are clays in soils, and because mixed-layer phases may be the most stable form in the marine environment (Berry and Johns, 1966), a technique that requires no more involved pre-analysis treatments than soluble salt removal may be quite satisfactory for marine clays.

Some conclusions to this problem can be reached having used both techniques on samples from the same, relatively small area. Comparing Figures 44 to 49 with Figures 50 to 53 indicates that the two approaches give quite different results. X-ray peaks are better developed, sharper, and narrower at their bases in Group A samples. For Group B samples the background is greater, and mixed-layer clays, with a fairly high percentage of expandable layers, are more apparent.

Considerable difficulty was encountered in identifying and clearly separating kaolinite and chlorite. As has been well established in literature on clay mineralogy, chlorites have even-numbered orders of basal spacings that coincide with the standard basal spacings of kaolinite. The usual method of distinguishing the two minerals has been to X-ray an air-dried sample, heat the sample to 550°C to 600°C for some period of time (there is no general agreement on the time period required, although Carroll (1970) believes one hour to be adequate), X-ray again and compare the two diffractograms. Theoretically the kaolinite structure should have collapsed while the chlorite (001) peak should have increased in sharpness if not in intensity; higher order chlorite peaks are thermally unstable (Grim, 1968; Carroll, 1970). Grim and Johns (1954) and Johns, Grim and Bradley (1954), on the other hand, have found that this method does not always give the desired results. After much experimentation Johns, Grim and Bradley (1954) concluded that any changes in the 7Å and 3.5Å peaks (chlorite (002) -

kaolinite (001) and chlorite (004) - kaolinite (002) peaks respectively) found after heating for 45 minutes at 450°C, then air-quenching, can be attributed to chlorite if the two minerals are suspected to be present, and if the degree of crystallinity of the chlorite is not particularly good. Johns and Grim (1958) were unable to identify with certainty small amounts of kaolinite in the presence of chlorite by heat treatment.

The technique of heat treatment to distinguish between kaolinite and chlorite is not a satisfactorily unambiguous technique. Use of this method led to the somewhat anomalous situation of having sediments derived from the Coast Mountains and interior of British Columbia, from rocks that are rich in chlorite, apparently having abundant kaolinite but only minor amounts of chlorite.

To identify kaolinite in the presence of chlorite Andrew et al. (1960) presented a method based on the formation of intersaltation complexes. Basically this technique depends on the formation of a 14Å kaolinite-potassium acetate complex followed by replacement of the acetate ion by a nitrate ion from ammonium nitrate. This results in a kaolinite-potassium nitrate complex with a first-order basal spacing of 11.6Å, which does not coincide with any other spacing of common clay minerals. The method is laborious, requiring closely controlled humidity conditions and, as pointed out by Biscaye (1965, p.1284), dry-grinding with potassium acetate can be detrimental to the crystallinity of Recent clays. This method was attempted on some Georgia Strait samples (e.g. Figure 49) with inconclusive results.

Brindley (1961) and Vivaldi and Gallego (1961a) suggested heating in acid solutions clay-mineral mixtures in which chlorite and kaolinite were believed to occur. Brindley proposed hydrochloric acid; Vivaldi and Gallego refluxed a sample for 30 minutes in 20% sulphuric acid. The solubility of chlorites in acids has been summarised by Grim (1968, p.435-439). Some limitations to this method were pointed out by Brindley (1961) who suggests that the chlorite composition, particle size, acid concentration, time and temperature may all be important in acid solubility. Vivaldi and Gallego (1961a) indicate that some chlorites are acid-insoluble, and some kaolinites specifically those members of the kaolin group containing iron, may be dissolved under acid conditions.

Simmering the (Group B) Strait of Georgia samples at about 95°C for two hours in 1N HCl seemed to offer some solution to the problem of distinguishing kaolinite in the presence of chlorite. The chlorite 14Å peak was greatly diminished and the 4.7Å peak lost entirely. The 7Å peak (chlorite (002)/kaolinite (001)), while always remaining, was very much reduced from its former intensity, especially when compared to the illite (mica) 10Å peak. The 3.53Å peak (chlorite (004)) was generally lost and a small peak remained at 3.58Å (kaolinite (002)). While not absolute in its ability to quantitatively separate the two minerals, the warm HCl treatment is adequate enough to permit their qualitative identification. This method indicated the more logical situation for the Strait of Georgia samples: that most of the 7Å peak was chloritic in origin rather than kaolinitic. At the same time it effectively precluded the semiquantitative analysis of samples treated and analysed in this way. Duplicating orientations, thicknesses, segregation, and crystallite size distribution becomes a very real problem when making slides for X-ray diffraction studies, and this problem is enhanced after chemical treatments. Because of these difficulties, measurement of peak areas on samples X-rayed after different treatments, even relating them to the same internal standard, often is not satisfactory.

Simple slow-scanning of the regions of the (001) kaolinite - (002) chlorite (7Å) and (002) kaolinite - (004) chlorite (3.5Å) peaks was advocated by Biscaye (1964) as a definitive method of identifying kaolinite in the presence of chlorite. At slow scan-speeds of $1^{\circ}2\Theta$/min. or less the differences between the locations of these peaks should be resolved: the kaolinite (001) occurs at 7.16Å ($12.3^{\circ}2\Theta$) for Cu $K\alpha$ radiation, while the chlorite (002) occurs at 7.08Å ($12.5^{\circ}2\Theta$); kaolinite (002) is situated at 3.58Å ($24.87^{\circ}2\Theta$) and chlorite (004) at 3.54Å ($25.1^{\circ}2\Theta$). At the faster scan speed of $2^{\circ}2\Theta$/min. these couplets are usually unresolved. An indication of the presence of small quantities of kaolinite in some Group A samples is seen as an inflection on the lower angle side of the 7Å ($12.5^{\circ}2\Theta$) and 3.5Å ($25^{\circ}2\Theta$) chlorite peaks (Figures 44 to 49).

For convenience and relative efficiency when dealing with large numbers of samples the techniques of either warm 1N HCl treatment or slowly scanning the region of the 7Å and 3.5Å peaks offer a reasonable way of determining the presence or absence of kaolinite in the presence of chlorite. The latter technique can be used for semiquantitative studies (Biscaye, 1964, 1965). Vivaldi and Gallego (1961b) maintain that the acid treatment is also useful for distinguishing swelling chlorite from montmorillonite. Naidu _et al_. (1971) chose to use all 3 techniques: heat treatment at $600^{\circ}C$ for 1 hour; treatment in 2N HCl for 1 hour at $80^{\circ}C$; and slow scan-speed over critical regions.

4.4.1 ANALYTICAL METHODS

Differences in the X-ray diffractogram traces between Group A and Group B samples (compare Figures 44 to 49 with Figures 50 to 53) can be directly correlated with the pre-analysis treatments the two groups of samples underwent.

Group A samples were subjected to a sequence of chemical treatments designed to upgrade the constituents to a common level of crystallinity, and to remove amorphous or poorly crystalline phases that tend to produce large background values. The technique is slightly modified from that of Kittrick and Hope (1963). Samples were kept wet after collection by being placed in plastic bags within closed containers. The following technique was used:

1. Place approximately 20 grams dry weight equivalent of sample in a 250 ml. centrifuge bottle.

2. Add about 100 to 150 ml. distilled water, then shake, using a wrist-action or tray shaker, 2 hours, then centrifuge; decant and discard supernatant.

3. Repeat step 2 unless or until the supernatant does not give a positive test for chloride on addition of a drop of silver nitrate solution.

4. Wash the sample through a 230, 275 or 325 mesh sieve with 100 ml. sodium acetate (NaOAc) solution (82gm. $NaOAc \cdot 3H_2O$, 27ml. glacial acetic acid, adjust to pH 5.0, make to 1 litre).

5. Shake 5 mins; heat at 80°C in water bath; centrifuge and discard supernatant.

6. Wash with 50 ml. NaOAc (wash = shake, centrifuge, decant).

7. Add 20 ml. water to residue, shake 3 mins.; add 1 ml. 30% H_2O_2, stir; when frothing ceases add more H_2O_2 in 1-2 ml. aliquots; heat in water bath at 75-80°C to facilitate oxidation of organic matter and to eventually clear the solution of H_2O_2.

8. Add 10-15 ml. saturated NaCl, fill bottle 2/3 full of water; stir, centrifuge, decant.

9. Add 100 ml. citrate buffer (dissolve 188 grams sodium citrate dihydrate, 31 grams $NaHCO_3$, and 175 grams NaCl in water, adjust to pH 7.3 with citric acid or NaOH and make to 2.5 litres with water); shake 5 minutes; heat to 75-80°C in water bath; add 4 grams sodium dithionite slowly, stir slowly then vigorously; heat 15 minutes, cool, centrifuge, decant.

10. Wash with 50 ml. citrate buffer.

11. Add water to 10 cm. mark on bottle; shake 5 minutes; centrifuge at a convenient speed and time for the 0.2 micron particles to settle 9 cm. Jackson (1956) gives tables and nomographs of centrifuge speeds and times.

12. Decant, and repeat step 11 on the residue. Supernatant holds particles less than 0.2 micron in diameter.

13. Add water to 10 cm. mark on bottle; shake 5 minutes; centrifuge at a convenient speed and time for the 2.0 micron particles to settle 9 cm. Decant the 2-0.2 micron fraction. Repeat.

14. Repeat step 13, with adjustment to centrifuge speed and time,

to separate the 5-2 micron fractions.

15. Obtain the 53-20 and 20-5 fractions by sedimentation.

The citrate-bicarbonate-dithionite treatment removes iron oxides in particular, and other amorphous and crystalline oxides and hydroxides (McKeague et al., 1971). It can also separate an intergradient 10Å and 14Å mineral into its 10Å and 14Å phases (Jackson, 1964).

For four of the Group A samples this procedure was slightly modified by separating the clay fraction into 2 to 0.2 micron, 0.2 to 0.08 micron and finer-than-0.08 micron size fractions using a Sharples continuous-flow super-centrifuge.

Samples were mounted for X-ray diffraction analysis by the "dropper-on-glass-slide" technique which, while apparently resulting in some segregation errors (Gibbs, 1965), produces excellent preferentially oriented samples. Preferential orientation results in accentuated basal (for phyllosilicates) reflections and increases the sensitivity, permitting detection of small amounts of even poorly crystalline material.

To facilitate glycolation, enhance basal spacings, and to provide a means of distinguishing especially the 14Å minerals, finer-than-2 micron size fractions of Group A samples were homoionically saturated with magnesium and potassium. Homoionic saturation ensures that hydration will be more or less uniform within all crystals of a species, since different cations retain different amounts of water of hydration. Magnesium permits (as does calcium) relatively uniform interlayer adsorption of water by expandable-layer clays. Potassium specifically restricts interlayer adsorption of water by vermiculite while leaving chlorite phases expanded.

The magnesium saturation procedure involves acidifying a sample aliquot with two to three drops of 0.1N HCl to prevent precipitation of $Mg(OH)_2$ and consequent possible formation of 14Å chlorite-like minerals from montmorillonites (Jackson, 1956). 10 to 20 ml. 1N $Mg(OAc)_2$ (magnesium acetate) is added to the suspension, which is mixed thoroughly in a vortex mixer, shaken for three minutes, centrifuged and the supernatant poured off. The $Mg(OAc)_2$ wash procedure is repeated a total of three times. Two washings (10 to 20 ml. solution added, mixed thoroughly, shaken, centrifuged and decanted) with 1N $MgCl_2$ follows, then two washings with distilled water and two with either ethanol or methanol. After the last washing about 2 ml. of water is added and a slurry is made from which slides for X-raying can be prepared.

The potassium-saturation procedure is basically the same as that for magnesium, except that no acidification is necessary, and only 1N KCl is required. Samples are washed three times with 1N KCl, and excess salt is removed by washing twice with distilled water and twice with alcohol.

Glycerol solvation, or glycolation, of magnesium-saturated samples results in the expansion of montmorillonite group clays to 18Å; magnesium-saturation facilitates this expansion. Either ethylene glycol or a 10% glycerol solution may be used. The technique employed is basically that of Jackson (1956). A few mls of 10% glycerol is added to the residue left after the last alcohol wash. A slurry is prepared and sufficient material transferred to a slide by eye-dropper to make an oriented sample. Samples are not permitted to dry out completely or the expanded phase may collapse (Hoffman and Brindley, 1961), and if necessary they can be stored in a dessicator in a glycerol atmosphere.

Potassium-saturated slides were X-rayed after air-drying, and heating to 300°C and 550°C for one and a half to two hours. Magnesium-saturated slides were X-rayed after air-drying and after glycolation. All Group A samples were X-rayed in a Philips X-ray unit utilising nickel filtered, copper $K\alpha$ radiation generated at 40 Kv and 20mA and passed through 1°, 0.1", and 1° slits. Scan speed was 1° 2Θ/minute; time constant 3 seconds; counts full scale 300. Chart speed, regulated to suit the scan speed and type of chart paper used, was 31.54"/hour.

Pre-analysis treatment of Group B samples was considerably less sophisticated. It involved washing three times with distilled water to remove soluble sea-salts, sieving through a 230 mesh sieve to separate sand from the silts and clays, and size fractionation by settling to separate the silts from the clays at 2.0 microns. To distinguish the expandable-layer clay component (montmorillonite), glycolation was performed on the same slide that had been X-rayed after air-drying. Glycolation was achieved by heating a dessicator containing the slides plus ethylene glycol in an oven for 1½ hours at 60°C (Brunton, 1955), then keeping the slides in the glycol atmosphere until they were X-rayed, usually the next day. While this technique is directly opposed to that of Jackson (1956), and even though magnesium saturation was not attempted, it was successful in so far as a peak at about 18Å, clearly separated from the 14Å peak, was evident (see Figures 50 to 53). The reason for this success with marine clays as opposed to soil clays may be related to the findings of Carroll and Starkey (1960) that magnesium ions from sea-water move into exchange positions on clays in preference to sodium or calcium ions. Hence marine clays are probably sufficiently naturally magnesium-saturated that glycol expansion is facilitated.

A discussion on the problems of distinguishing kaolinite in the presence of chlorite has been presented elsewhere in this chapter. Only the technique of warming the sample with 1N HCl for two hours was used with the Group B samples. While the method may not be amenable to quantitative interpretations, it did show that chlorite is present in greater quantities than kaolinite, and confirmed the conclusions reached after studying the Group A samples.

X-ray diffractograms were obtained from powder mounts of the coarse silt fraction from Group B samples. Group A samples were separated into 53-20, 20-5, and 5-2 micron fractions. X-ray diffractograms were made of each of these fractions on oriented specimens mounted on slides (Figures 40, 41 and 42) and, for the 53-20 micron fraction, on powder mounts also.

4.4.2 MINERAL IDENTIFICATION CRITERIA

The same criteria for identification of minerals was used for both Group A and Group B samples. The terms employed refer to clay mineral groups identifiable by X-ray diffraction and not to individual species. Identification of individual species requires somewhat simpler mixtures, detailed chemical analysis and, usually, X-ray powder photographs (e.g. Brindley and Gillery, 1956; Warshaw and Roy, 1961), and is beyond the scope of this study.

The clay-mineral groups are identified by their characteristic X-ray diffraction maximum related to their specific basal spacings. Clay-minerals with similar basal spacings can be distinguished by their unique reactions to different physical or chemical treatments. The following criteria were used in this study:

Illite: A basal (001) reflecting series of 10Å (8.9° 2Θ), 5Å (17.8° 2Θ) and 3.3Å (26.8° 2Θ) that is not affected by glycolation is attributed to illite. The term illite is used as originally defined by Grim, Bray and Bradley (1937, p.816) as "...a general term for the clay mineral constituent of argillaceous sediments belonging to the mica group...." Peaks at 10Å, 5Å and 3.3Å are generally sharp, narrow and very well defined in both the 2 to 0.2 micron Group A samples and in the Group B clays. In fact, the mineral responsible is more than likely a well-crystallised, finely ground mica. Much micaceous material - muscovite, biotite and leached varieties of both - is evident in the sand fractions of the Georgia Strait and Fraser River sediments. "Mica" and "illite" are therefore synonymous and have been used arbitrarily for the same reflections in the silt- and clay-sized fractions respectively.

Kaolinite and chlorite: The problem of the identification of kaolinite in the presence of chlorite has been discussed elsewhere. For Group A samples slow scanning speeds revealed small amounts of kaolinite by shoulders on the low angle sides of the 7Å and 3.5Å peaks. Warm acid treatment of Group B samples similarly suggested a small quantity of kaolinite. Mackintosh and Gardner (1966) record only small amounts of kaolinite from alluvial sediments of the Fraser River.

Chlorite has diffraction maxima at 14Å, 7Å, 4.7Å and 3.5Å. Persistence, and intensification, of the 14Å peak after heat treatment to 550°C of potassium-saturated samples, despite thermal instability of the 7Å, 4.7Å and 3.5Å peaks, provides a sound basis for the identification of chlorite (Grim, 1968; Carroll, 1970).

Because of the problems presented for quantitative studies by the chlorite-kaolinite separation using acid treatments, the 7Å peak area was attributed to both chlorite and kaolinite for the purposes of constructing Figure 54. A similar procedure was employed by Knebel et al. (1968).

Montmorillonite: Material which expanded its (001) spacing from 14Å to about 18Å following glycol solvation was assigned to the montmorillonite group. For the Group A samples this expansion was usually complete, and the expanded peak quite distinct. Glycolated clay-fractions of Group B samples did not expand as much, commonly only to 16Å or 17Å, and only occasionally to 17.5Å. MacEwan (1961) records this lesser expansion with ethylene glycol as being universal for all montmorillonite. The low angle side of the expanded peak (Group B) was invariably very irregular consisting of many small, sharp peaklets. Between the 14Å chlorite and 17Å expanded montmorillonite peaks one or more peaklets occurred either as distinctive features or as bumps on the side of the expanded peak (see Figures 50 to 53).

Vermiculite: The apparent absence of vermiculite from Group A and Group B samples is interesting. The micaceous components of the sand fractions consist of: a colourless, clear or translucent, fresh, angular mica that is identified as muscovite; a black or very dark coloured mica identified as biotite; a soft, rounded, greenish micaceous mineral that is probably chlorite; a pale, bronze-coloured mica that can occasionally be seen developing from biotite and is consequently believed to be a leached variety of this mineral; and a gold coloured, generally very friable, curled, exfoliating mica of unknown origin. This last mica is very common in the Fraser River samples and from the sand fraction of sample 351, but rarer in other samples. The abundance of fresh and weathered micas, particularly biotite, might be expected to provide loci for the development of vermiculite (Barshad, 1948; Keller, 1964).

Magnesium-saturated vermiculite has an (001) diffraction maximum at about 14Å, coincident with the (001) diffraction maxima of both chlorite and montmorillonite. Heat treatment (at 500^{o}C) will eventually collapse the vermiculite to 10Å (Carroll, 1970; Walker, 1961) while chlorite remains at 14Å. Montmorillonite undergoes a similar lattice collapse on heating. Solvation with polar organic liquids will expend the montmorillonite lattice to 18Å, but not vermiculite which, along with chlorite, remains at 14Å. Consequently, in the presence of both chlorite and montmorillonite, positive identification of vermiculite becomes very difficult if not impossible. It is quite possible that vermiculite does occur, but its identification is prevented by a masking effect due to chlorite and montmorillonite.

That vermiculite is probably present, at least in the sand and silt fractions, was indicated by the results of rapidly heating some of the ragged, gold-coloured micaceous minerals from sample 351 in a Bunsen flame. Some of these micas underwent rapid, relatively large, expansion in a direction normal to the cleavage (perpendicular to the c axis), a feature that is characteristic of vermiculite (Berry and Mason, 1959; p.510). Barshad (1948), in a discussion on the relationships between vermiculite and biotite, showed that sodium-saturated vermiculite has a basal spacing of 12.56Å. As will be discussed later the X-ray diffractograms of the silt fractions from Group A samples showed a peak at 12.4Å. Since the Group A samples were extensively treated with sodium salts it is possible that the 12.4Å peak represents sodium-saturated vermiculite. Although not always so obvious the 12.4Å peak was also observed in 53-20 micron fraction powder mounts of Group A silts. It is not seen in Group B silts. As will be discussed in the section on mixed-layer phases, its obvious appearance in oriented slides but not in powder mounts suggests that this peak is due to a phyllosilicate, and its presence in Group A but not Group B powder mount diffractograms may be strongly in favour of its interpretation as due to a sodium-saturated vermiculite. A discussion of other possible sources of the 12.4Å peak is given later.

Mixed-layer minerals: The incomplete expansion, in Group B samples, of the montmorillonite peak and the relatively reduced size of the chlorite 14Å peak compared to that of Group A samples suggests that the montmorillonite forms an expandable and dominant component of a chlorite-montmorillonoid mixed-layer clay. Mackintosh and Gardner (1966) record the presence of a mixed-layer montmorillonoid-chlorite clay mineral from Fraser River alluvial sediments, but do not illustrate or describe it further. The asymmetry of the 14Å peak of air-dried, unglycolated Group B clay fractions suggests the possibility of a 10Å-14Å mixed-layer series, but if so the 14Å component must be mostly montmorillonite and predominant.

Mixed-layer phases were not identified from any Group A clay fractions. However, the silt fractions (Figures 40, 41 and 42) showed

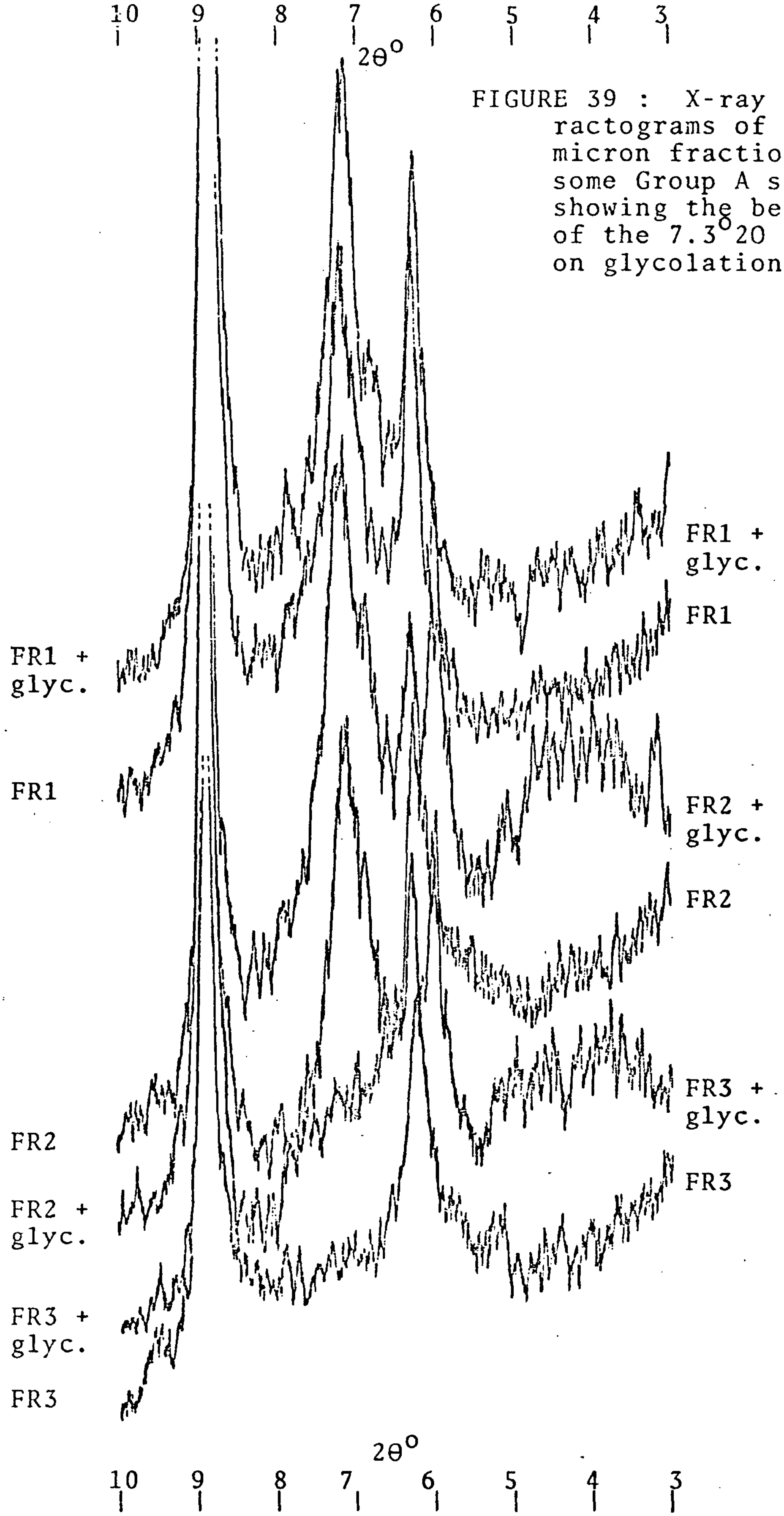


FIGURE 39 : X-ray diffractograms of 2 - 5 micron fraction of some Group A samples showing the behaviour of the 7.3°2θ peak on glycolation.

a sharp peak at 12.4Å which may be interpreted as either due to a sodium-saturated vermiculite (see above) or as the expression of a mixed-layer phase. That this peak is generated by a phyllosilicate is suggested by comparing Group B silt fractions and Group A 53-20 micron fractions X-rayed as powder mounts (the 12.4Å peak was absent) with the Group A silts X-rayed as oriented slides to accentuate phyllosilicate reflections (where the 12.4Å peak is obvious). It is a sharply-defined peak, best developed in the finer silts and becoming less obvious in the coarser fractions, and more prominent in the Fraser River samples than in the Georgia Strait ones. Sample 102 (Group A) from close to the river mouth at Sand Heads has the best developed example of this peak from the Georgia Strait samples. Figure 39 shows the effects of glycolation on this peak: a 14Å peak is evident in all unglycolated analyses and in some of the glycolated ones; after glycolation the 12.4Å peak may not move at all, may shift to 14Å, or may migrate to a slightly higher spacing at 14.7Å. The peak has been identified from Group A silt fractions only, and has no expression in the clay-sized material. Possible interpretations are:

1. It is the expression of sodium-saturated vermiculite (and therefore evidence of the presence of vermiculite) as discussed above.

2. It is a relatively large mineral of random mixed-layer type that is broken into its constituent phases below a certain size limit. Arguing against this is the fact that it occurs in Group A silts, which have been subjected to citrate-dithionite treatment along with the associated clays, and this process is sufficiently intense to separate intergradient or mixed-layer clays into their different components (Jackson, 1964).

3. The peak maximum occurs between 10Å and 14Å suggesting a regular 10Å–14Å mixed-layer structure. Its limited expansion following glycolations suggests a mica-vermiculite interlayer mineral, in which the vermiculite is developing from, or in, the weathered mica. The prominence of this peak in samples from the Fraser River and the occurrence in these samples of the golden, highly weathered, mica flakes suggests some relationship between the two.

4. The sharpness of the peak and its at least partly expandable properties could be interpreted as due to a 12.5Å montmorillonite (sodium-saturated montmorillonite with only one water layer). Counting against this is the poor expansion of the peak on glycolation and the occurrence of this peak in coarse silt fractions whereas montmorillonite is generally only found in the fine clay sizes (Jackson, 1956; 1964).

5. Figure 6, p.84, from Jonas and Brown (1959) indicates that possible combinations of 10Å (illite) and 15.4Å (montmorillonite) or 10Å (illite) and 14Å (chlorite) minerals also exist to explain this peak. The 14Å chlorite peak did not shift following glycolation, and nowhere else was there any hint of the existence of a "swelling chlorite" (Grim and Johns, 1954). It is unlikely that the mixture is of any of these combinations.

The interpretation favoured here is that the 12.4Å peak is caused by the presence of small amounts of vermiculite. Preferred orientation accentuates the reflections from even small quantities of phyllosilicates. The identification is based on the limited expansion of this peak after glycerol solvation, and its presence in sodium-saturated samples only.

Varying quantities of non-clay minerals were present in all samples. In the finer-than-2 microns size-fraction quartz and felspar are common; amphibole is generally rarer. In the silts amphibole is more conspicuous, and is particularly evident on diffractograms of powder mounts. Quartz and felspar also increase in abundance in the silt fractions, at the expense of the clay minerals.

Quartz: Peaks at 4.26Å and 3.33Å (the latter coincident with the (003) reflection from mica) identify quartz. In an oriented sample with accentuated reflections from layer silicates the 4.26Å peak becomes diagnostic for the presence of quartz.

Felspar: Stained grain-mounts of the sand-sized fractions indicate the presence of both potash and plagioclase felspar; the former in only small amounts. Felspar peaks were identified in the X-ray diffractograms, but no attempt was made to separate the two types by X-ray methods.

Amphibole: A peak with a maximum at 8.4Å-8.5Å was used to identify amphibole (Jackson, 1956, 1964).

4.4.3 DISCUSSION OF SUB-SAND-SIZE MINERALOGY

Comparing Figures 40 to 43 with Figures 44 to 49 suggests a significant difference between silt- and clay-fraction mineralogy for the same samples, although among all samples a marked similarity in the mineral suites is evident. Non-phyllosilicate minerals increase in abundance relative to phyllosilicates from the fine to the coarse silt fractions. The coarse silt and fine sand fractions are essentially identical, consisting primarily of quartz, felspar and amphibole, with small but conspicuous amounts of micas and garnet. Clay fractions contain chlorite, montmorillonite and mica as dominant minerals, with lesser amounts of kaolinite, quartz, felspar and sometimes amphibole. Finer clay fractions show a greater amount of montmorillonite, which is a function of the more common fine size of this mineral (Jackson, 1956, 1964).

4.4.3.1

Silt fraction: Figures 40, 41 and 42 are tracings of X-ray diffractograms for oriented samples of 53-20, 20-5 and 5-2 micron fractions respectively for Group A samples. Figure 43 shows tracings of X-ray patterns from random powder mounts of Group B samples. The latter show the same mineral suite occurring throughout the Strait of Georgia which, apart from minor differences in proportions of components among samples and differences related to the method of sample preparation for X-raying, is basically identical to that of the Group A samples. The main differences in the results suggest quartz and felspar are much more abundant in the powder mounts than in the preferred orientation slides. This observation is consistent with conclusions reached following visual inspection of the fine and very fine sand grades where chlorite and mica are much less obvious. Amphibole is present in much less quantity than quartz or felspar, but is usually in excess of the micaceous minerals. The apparent anomaly in the relative orientation of micaceous minerals accentuating reflections and resulting in peak intensities that are out of proportion to the minerals' true abundance.

Group A silt fractions show a higher layer-silicate content for Fraser River samples than for those from Georgia Strait. Amphibole

FIGURE 40 : X-ray diffractogram tracings for the 20 - 53 micron size fraction of Group A samples.

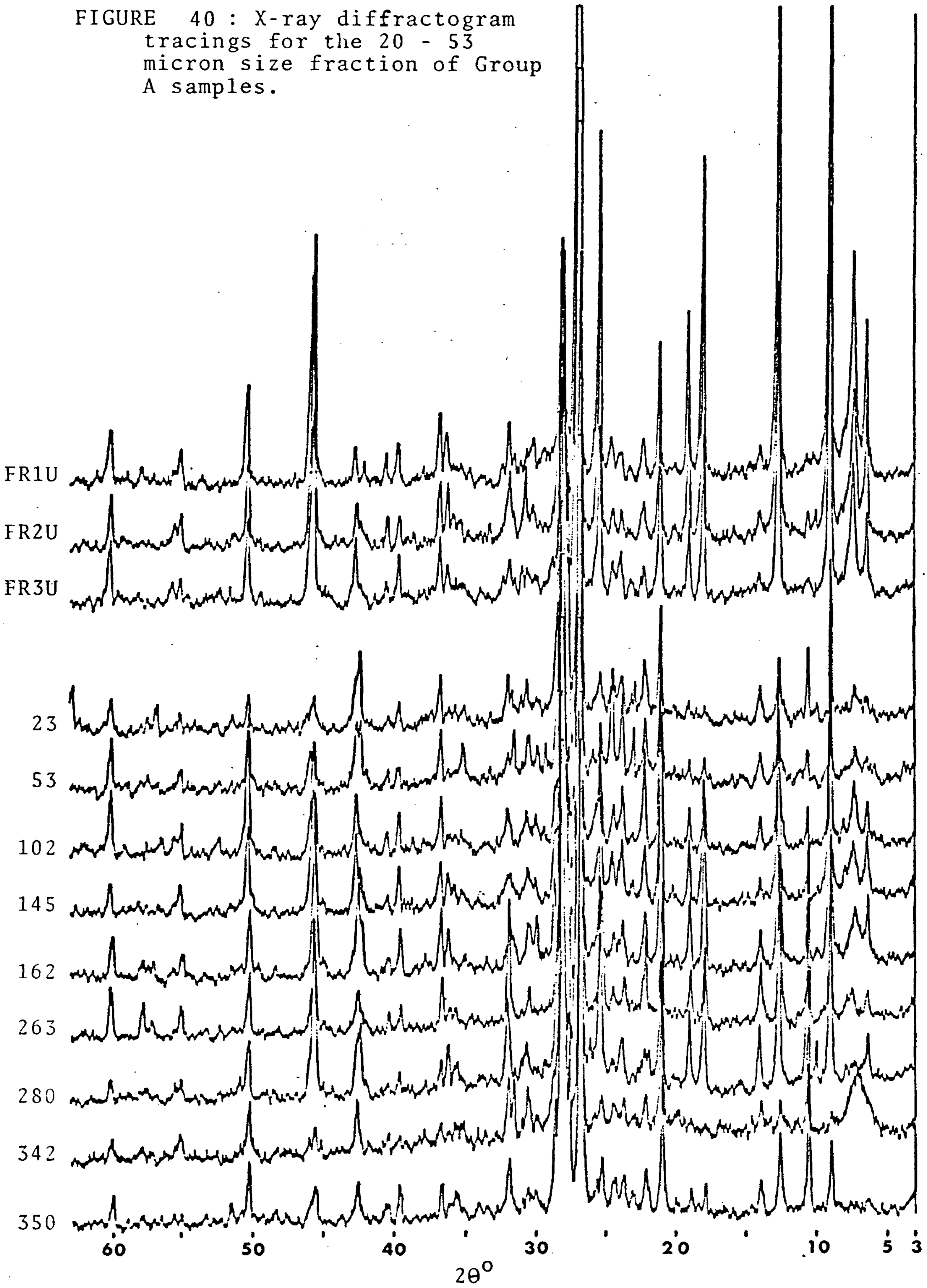


FIGURE 41: X-ray diffractogram tracings for the 5 - 20 micron size fraction of Group A samples.

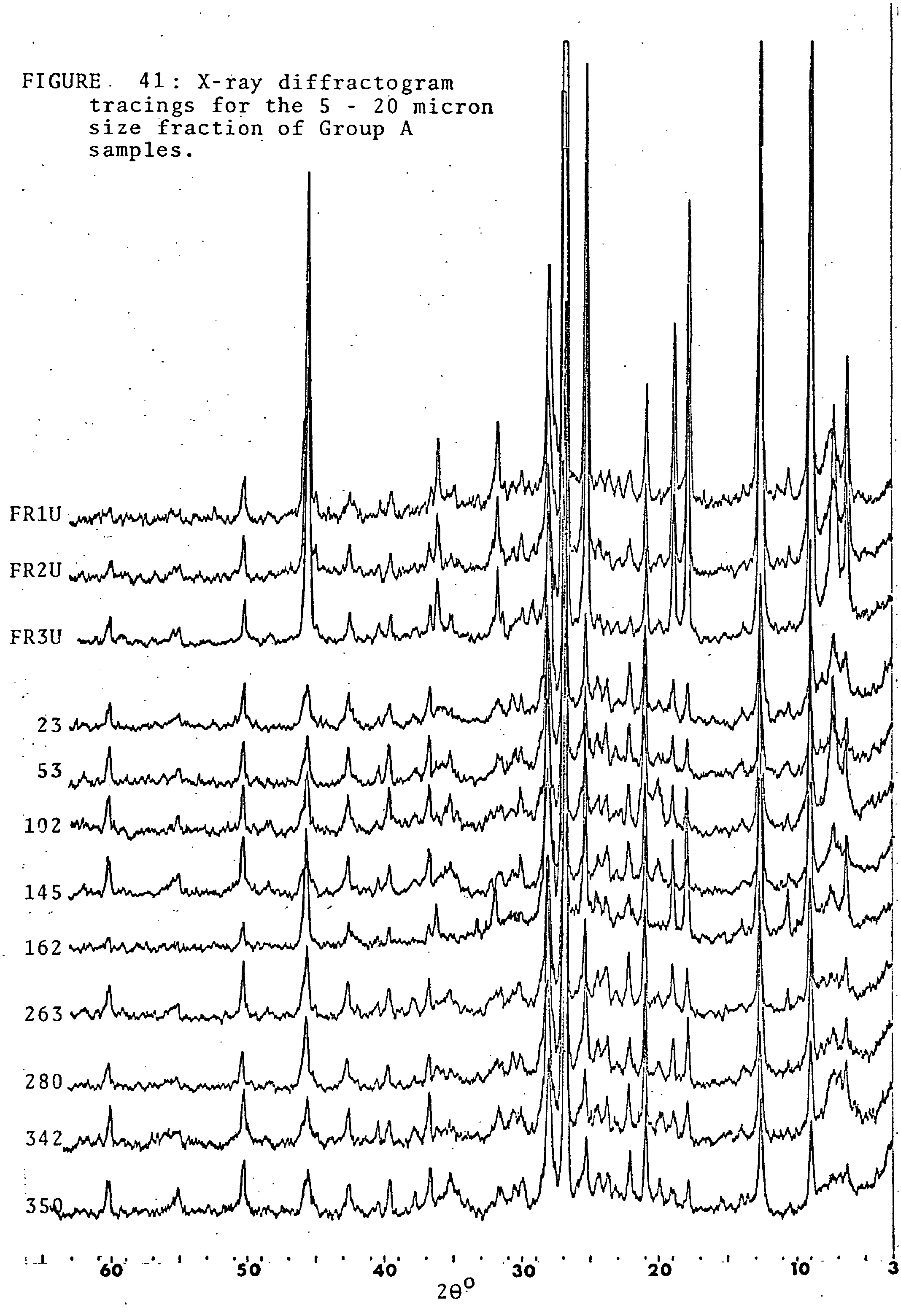
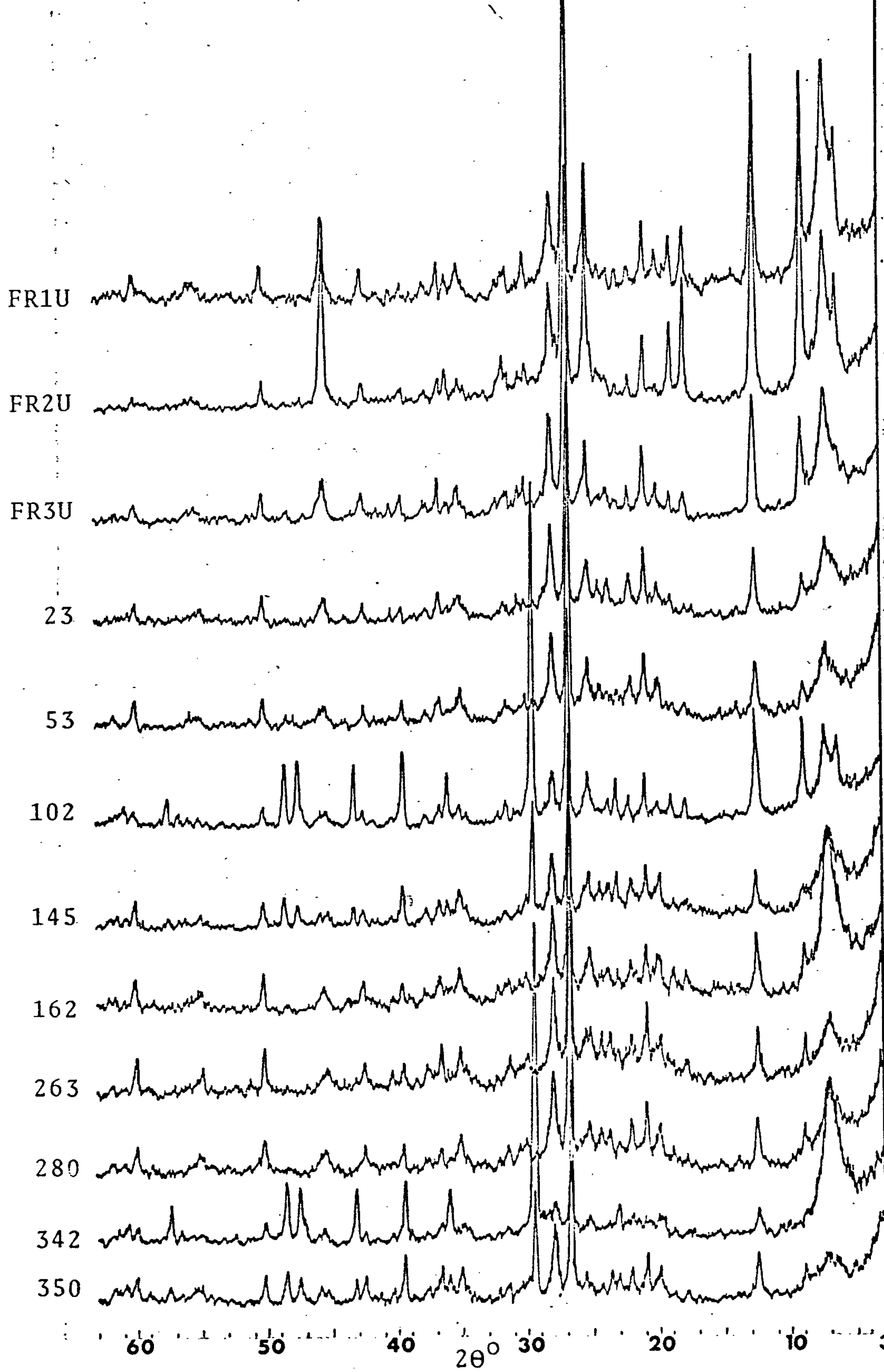


FIGURE 42 : X-ray diffractogram tracings for the 2 - 5 micron size fraction of Group A samples.



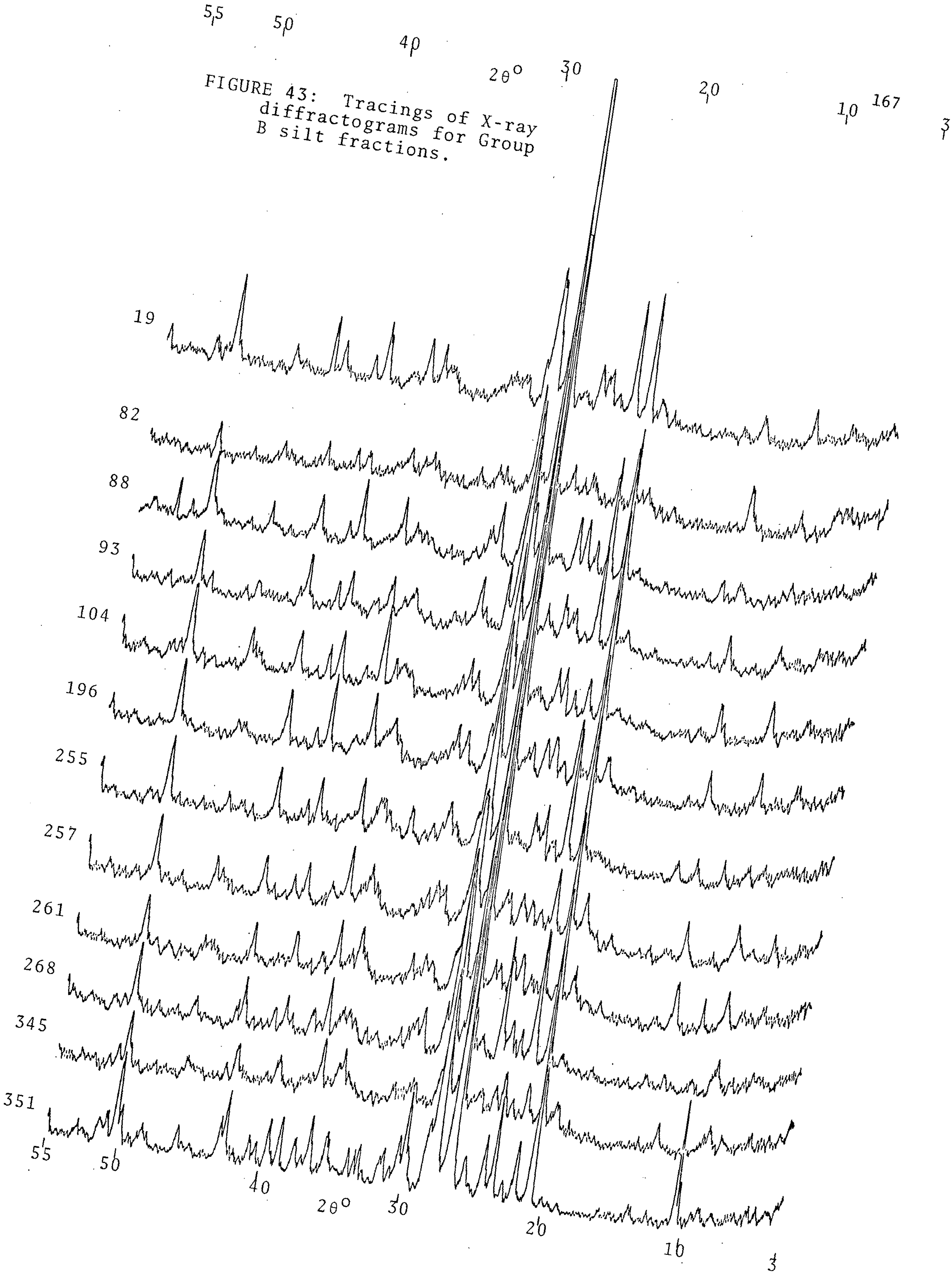


FIGURE 43: Tracings of X-ray diffractograms for Group B silt fractions.

contents however are higher in the Strait samples, especially in the coarse silt fraction. The enhanced 8.4Å peak for amphiboles in an oriented slide is believed by Biscaye (1965) to be a result of preferred orientation on (110) cleavage surfaces, the 8.4Å spacing being related to the (110) series.

53-20 micron fraction (Figure 40): mica, quartz, chlorite and felspar peaks, plus a well-developed 12.4Å peak are present in the Fraser River samples. Georgia Strait specimens display the same peaks but with better developed amphibole and a less obvious 12.4Å peak.

20-5 micron fraction (Figure 41): the same mineral suite exists as above except that amphibole is much less obvious than in the 53-20 micron fraction. Layer silicates are still more obvious in the Fraser River than in the Georgia Strait samples.

5-2 micron fraction (Figure 42): a greater change in the mineralogy than between the previous fractions is apparent. The non-phyllosilicate content has decreased, while the phyllosilicate fraction has become more prominent. The 12.4Å peak is much more pronounced (relative to the 14Å peak), especially for the Fraser River samples. Calcite of unknown origin occurs in some Georgia Strait samples (342, where it is prominent; 102, 145 and 350). Theoretically the pre-analysis treatment should have removed most if not all the calcite, and calcite values calculated from the amount of carbonate-carbon present in the samples is low (0.42-2.96% $CaCO_3$; see Table XI).

As will be described below there is an even greater mineralogic change in the clay-sized fractions than between the silt fractions. Somewhere within the 2 to 5 micron range there is a change from a suite of minerals dominated by blocky grains of quartz and felspar to a suite dominated by platy, micaceous (fine-grained mica and clays) minerals. Mineralogical changes between size fractions and differences among samples is a function of the source mineralogy which may be accentuated by, or impose modifications or restrictions on, the mode of transport of the minerals to the depositional sites.

4.4.3.2

Clay fraction - Group A: Subsequent to the pre-analysis treatments described above, Group A clay fractions were separated into 2-0.2 micron and finer-than-0.2 micron fractions by centrifugation. For five of the samples the fractionation was carried further using a Sharples continuous-flow super-centrifuge to separate the 0.2 to 0.08 and finer-than -0.08 micron fractions. Each fraction of all samples was subjected to magnesium-saturation, glycerol solvation, potassium-saturation, and heating, at least 5 X-ray diffractograms being obtained for each sample fraction. In some 2 to 0.2 micron fractions extra diffractograms were obtained following intersaltation with ammonium salts, and/or after HCl treatment, in order to substantiate the chlorite/kaolinite distinction.

Components of the coarse clay (2 to 0.2 micron fraction) are chlorite, montmorillonite, illite (mica), quartz and felspar. All samples are basically extremely similar in development of peaks and in mineralogy. Small differences are apparent, such as the appearance in some but not all samples of the 8.4Å amphibole peak. Intensities of some of the phyllosilicate peaks vary from sample to sample, but there is no systematic change in the ratios of mica to montmorillonite (Table VI).

No.	Mica:Montmorillonite (x:1)	No.	Mica:Montmorillonite (x:1)
FR1U	1.91	162	1.09
23	0.92	263	1.79
53	0.97	280	1.97
102	1.41	342	1.36
145	1.39	350	1.50

Table VI: Ratio of mica to montmorillonite (as x:1) on the 10Å and 18Å peaks of magnesium-saturated, glycerol-solvated samples using the technique of Johns, Grim and Bradley (1954): peak area = peak height x peak width at 1/2 peak height; area of mica peak x4.

Montmorillonite (generally dominant) and chlorite are the main minerals in the fine clay fraction (<0.2 microns), occurring in all samples although more obvious in some than in others (e.g. 280, 342). Quartz and felspar peaks are rare or absent, and clay mineral peaks dominate but are generally broader and not as sharp as those of the coarse clay fractions.

Calcite peaks were identified from all samples. The peaks are all well developed, sharp, and clear, with a sequence practically identical to that of calcite. The origin of the calcite is not known. Treatment procedure includes an acid stage which is meant to rid the sample of calcite and other carbonates, and calcium chloride was not added to flocculate the sample.

The mineralogy of the 0.2 to 0.08 micron fraction is the same as that in the 2 to 0.2 micron fractions, being mostly the clay minerals montmorillonite (dominant), chlorite and illite, with very minor amounts of quartz and felspar. The peaks are usually more ragged and less sharp than those of the 2.0 to 0.2 micron fractions; even the

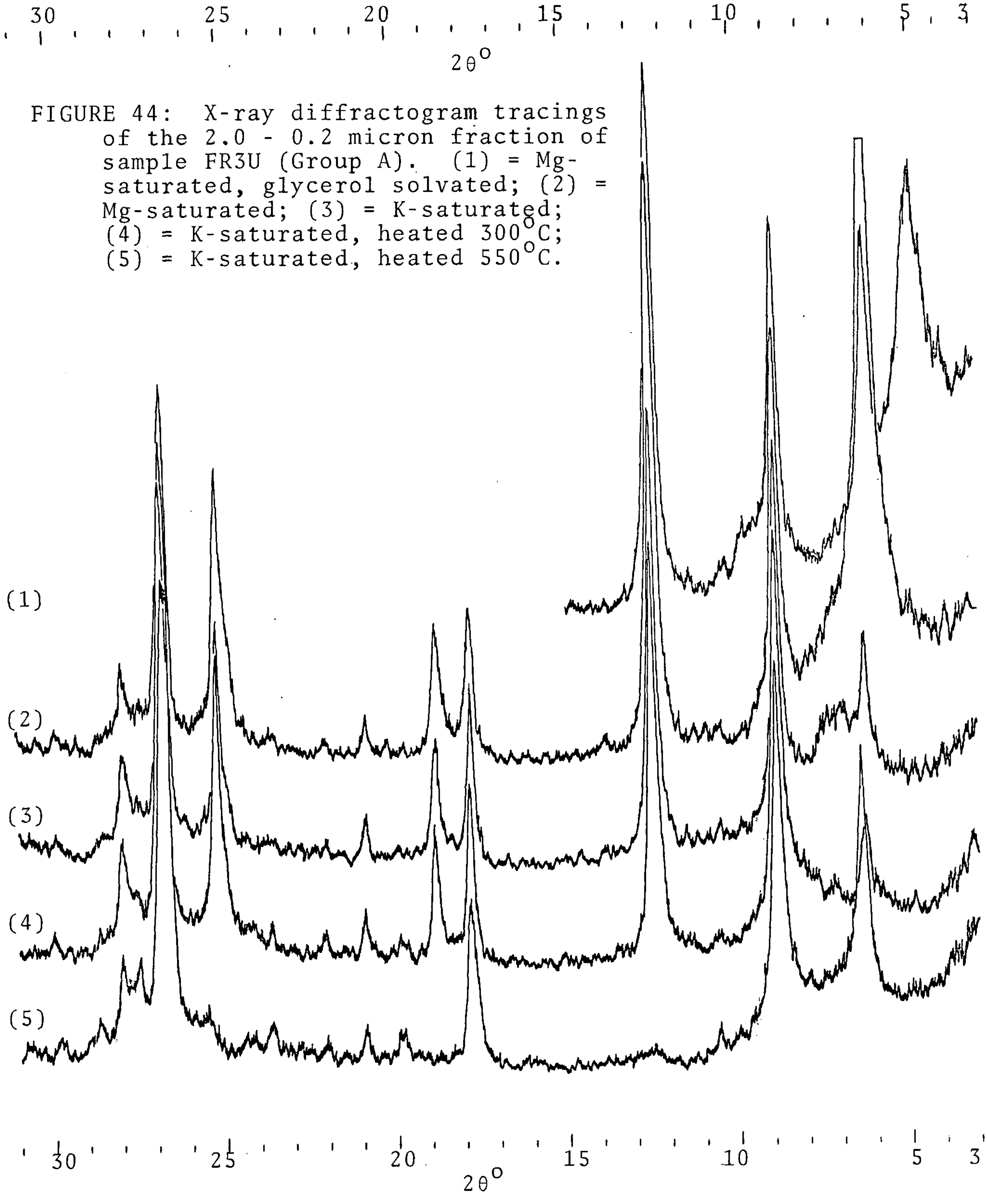


FIGURE 44: X-ray diffractogram tracings of the 2.0 - 0.2 micron fraction of sample FR3U (Group A). (1) = Mg-saturated, glycerol solvated; (2) = Mg-saturated; (3) = K-saturated; (4) = K-saturated, heated 300°C; (5) = K-saturated, heated 550°C.

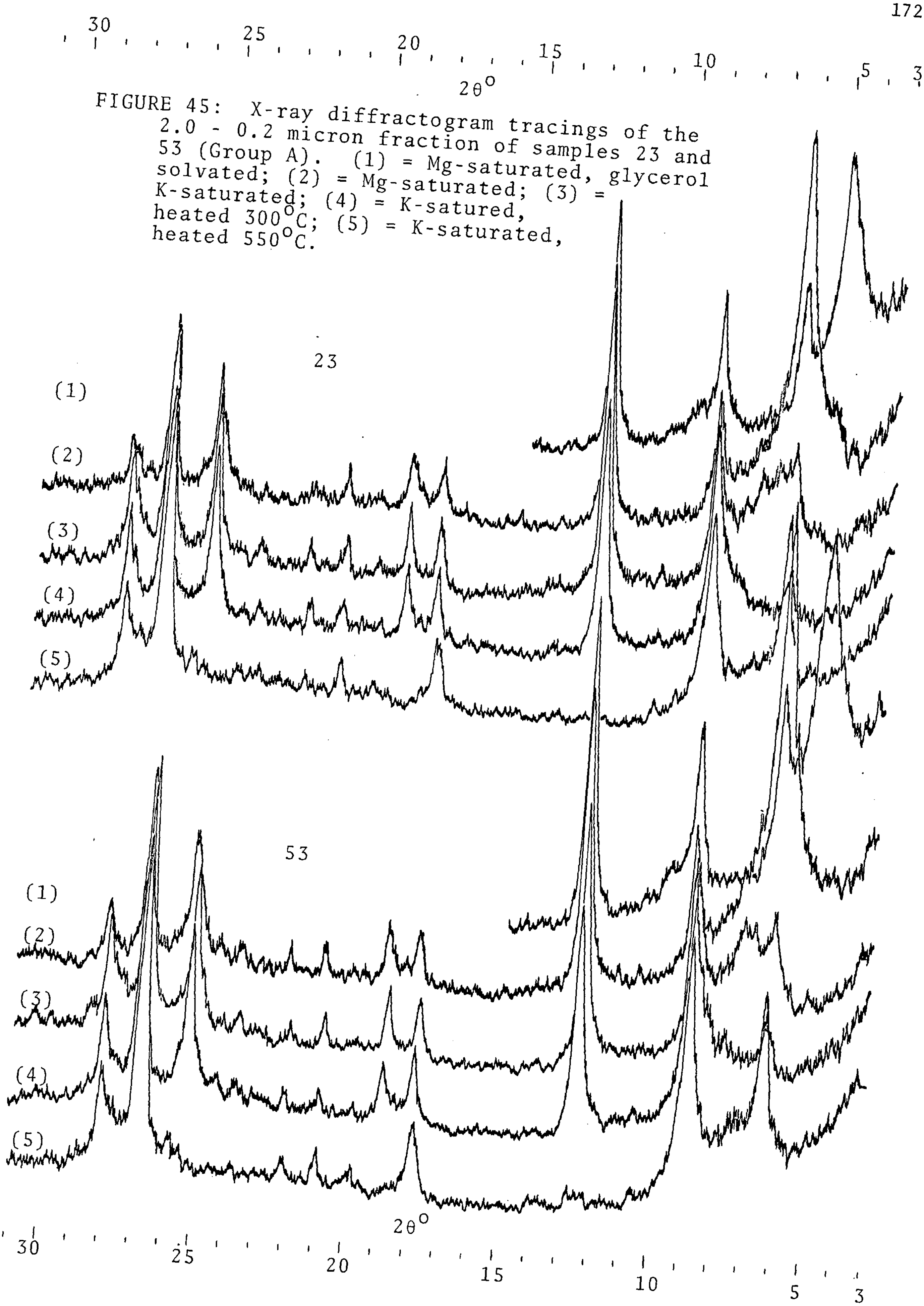


FIGURE 45: X-ray diffractogram tracings of the 2.0 - 0.2 micron fraction of samples 23 and 53 (Group A). (1) = Mg-saturated, glycerol solvated; (2) = Mg-saturated; (3) = K-saturated; (4) = K-satured, heated 300°C; (5) = K-saturated, heated 550°C.

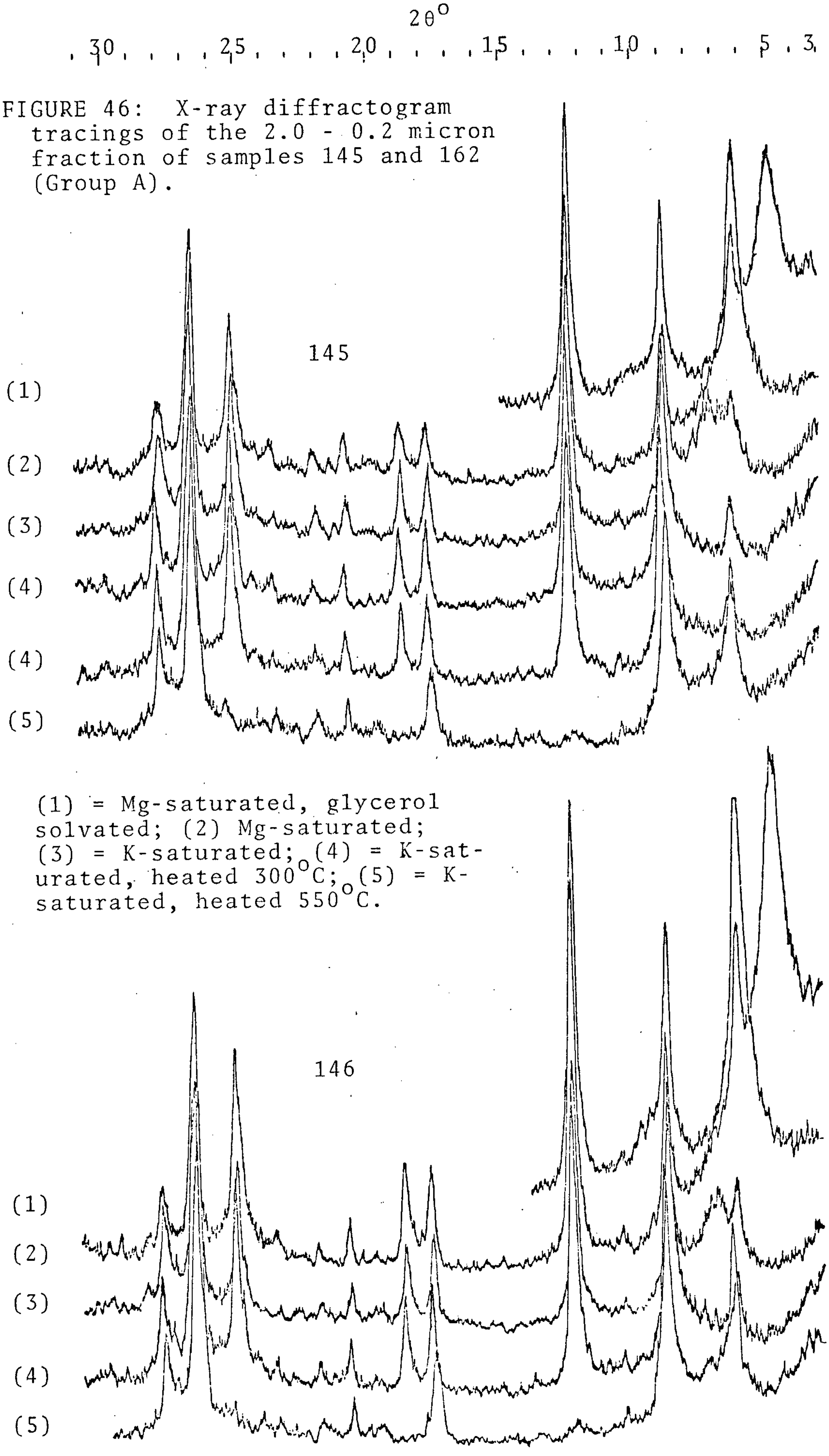


FIGURE 46: X-ray diffractogram tracings of the 2.0 - 0.2 micron fraction of samples 145 and 162 (Group A).

(1) = Mg-saturated, glycerol solvated; (2) Mg-saturated; (3) = K-saturated; (4) = K-saturated, heated 300°C; (5) = K-saturated, heated 550°C.

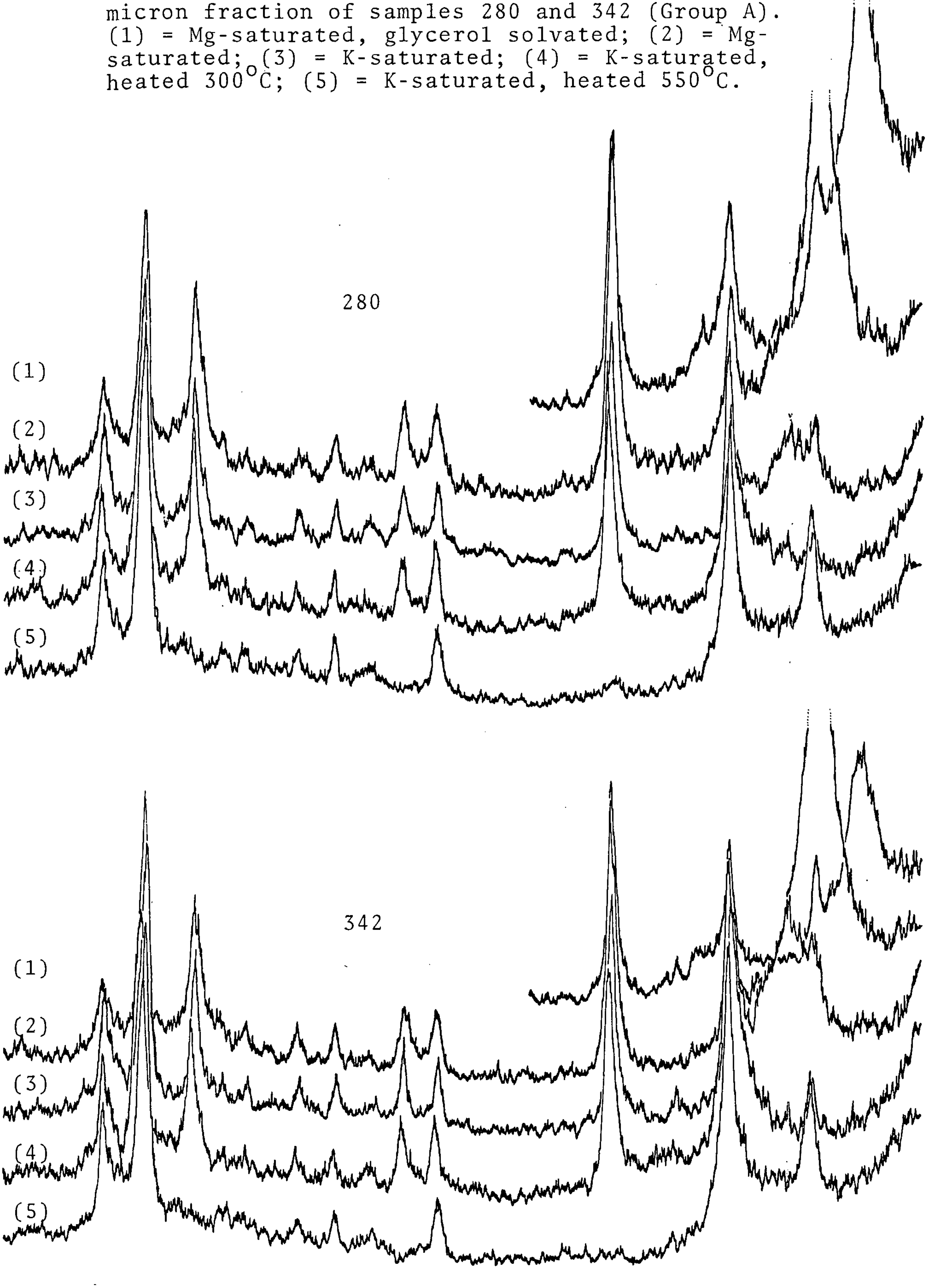


FIGURE 47: X-ray diffractogram tracings of the 2.0 - 0.2 micron fraction of samples 280 and 342 (Group A). (1) = Mg-saturated, glycerol solvated; (2) = Mg-saturated; (3) = K-saturated; (4) = K-saturated, heated 300°C; (5) = K-saturated, heated 550°C.

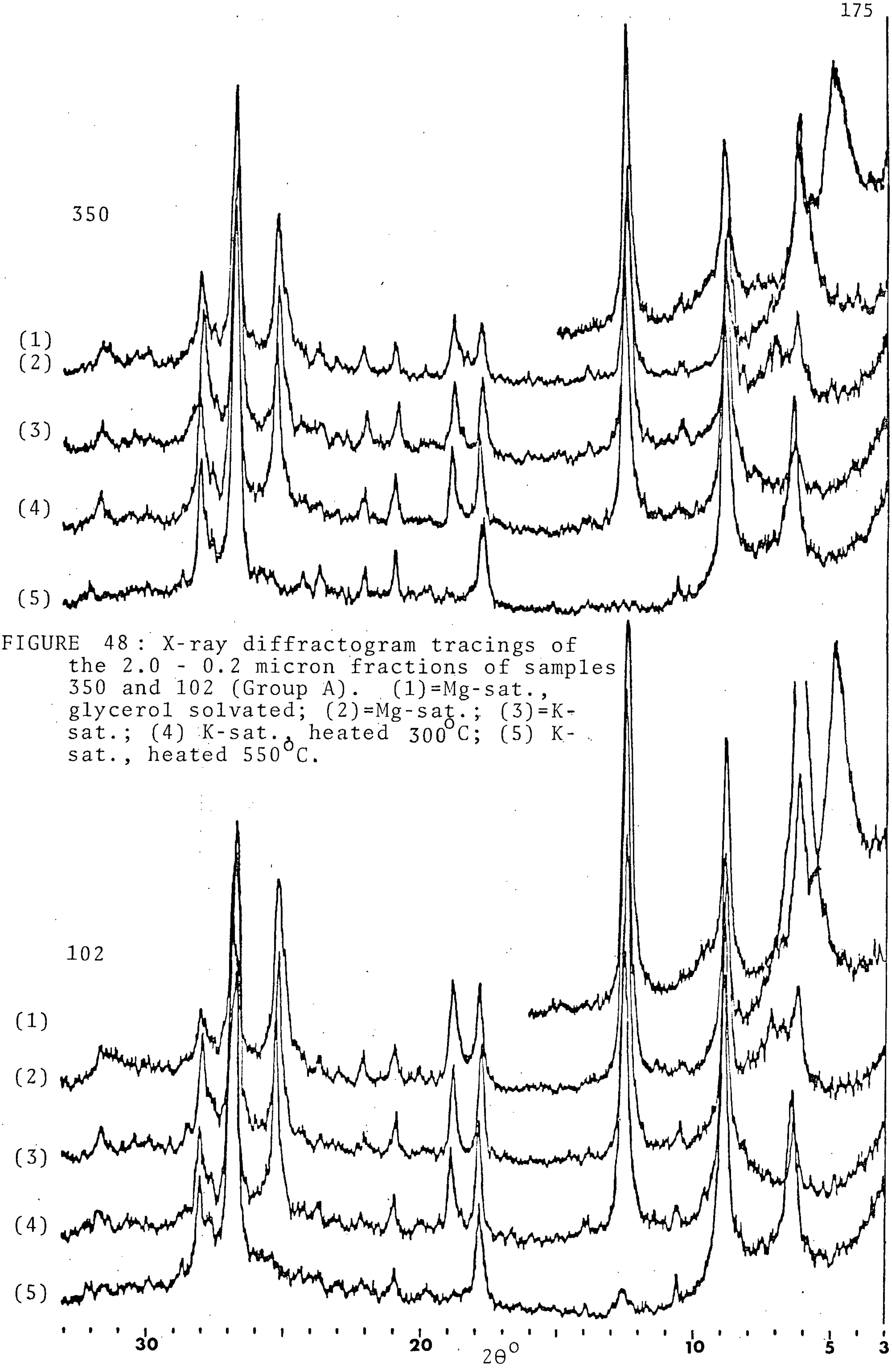


FIGURE 48 : X-ray diffractogram tracings of the 2.0 - 0.2 micron fractions of samples 350 and 102 (Group A). (1)=Mg-sat., glycerol solvated; (2)=Mg-sat.; (3)=K-sat.; (4) K-sat., heated 300°C; (5) K-sat., heated 550°C.

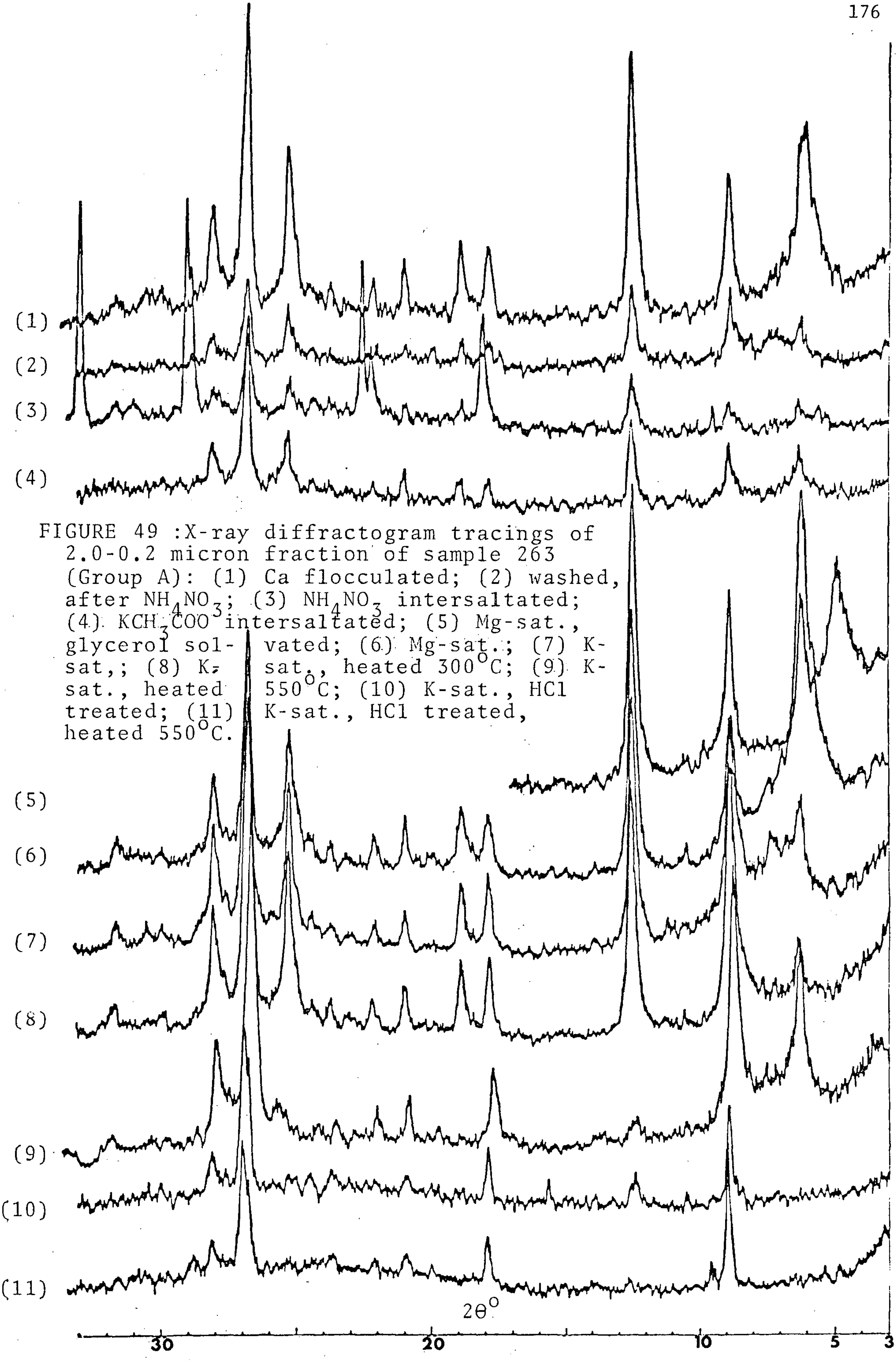


FIGURE 49 :X-ray diffractogram tracings of 2.0-0.2 micron fraction of sample 263 (Group A): (1) Ca flocculated; (2) washed, after NH_4NO_3; (3) NH_4NO_3 intersaltated; (4) KCH_3COO intersaltated; (5) Mg-sat., glycerol sol- vated; (6) Mg-sat.; (7) K-sat,; (8) K- sat., heated 300°C; (9) K-sat., heated 550°C; (10) K-sat., HCl treated; (11) K-sat., HCl treated, heated 550°C.

illite peak is less sharply defined than in the coarser sizes. Peaks are distinctive for the various separate mineral groups, but there is a hint of a 10Å–14Å interlayer mineral given by the asymmetry of the 10Å peak, and the grassiness of the diffractogram between the 10Å and 14Å peaks for the magnesium-saturated fraction from sample 350.

Montmorillonite was the only clay mineral detected in the fraction finer-than-0.08 microns, but with the exception of sample FR1U its peaks were usually very poorly defined. They were often displayed as only low bumps in the region of 14Å that showed a diffuse expansion to 18Å following glycerol solvation. Calcite peaks appear in all samples and are well developed. However, the solid material was flocculated with calcium chloride prior to X-raying which suggests at least a possible source for the calcite.

Group B: X-ray diffractograms of the finer-than-2.0 micron fraction of Group B samples are not as clean and distinctive as those of the Group A clays. The peaks are generally not as sharp, usually broader at their bases, and often more ragged in appearance than those of the Group A clays. A mixed-layer clay consisting of 10Å and 14Å expandable material is present in small quantities. Montmorillonite, chlorite, illite, minor kaolinite, quartz and felspar are the basic mineral constituents. Amphibole, in small amounts, is present in some samples (e.g. 351).

The essential similarity in the mineralogy among samples that had been established by the Group A material is evident among the Group B samples also. Such a similarity throughout the area of the Strait among samples containing this variety of basic clay-mineral types is

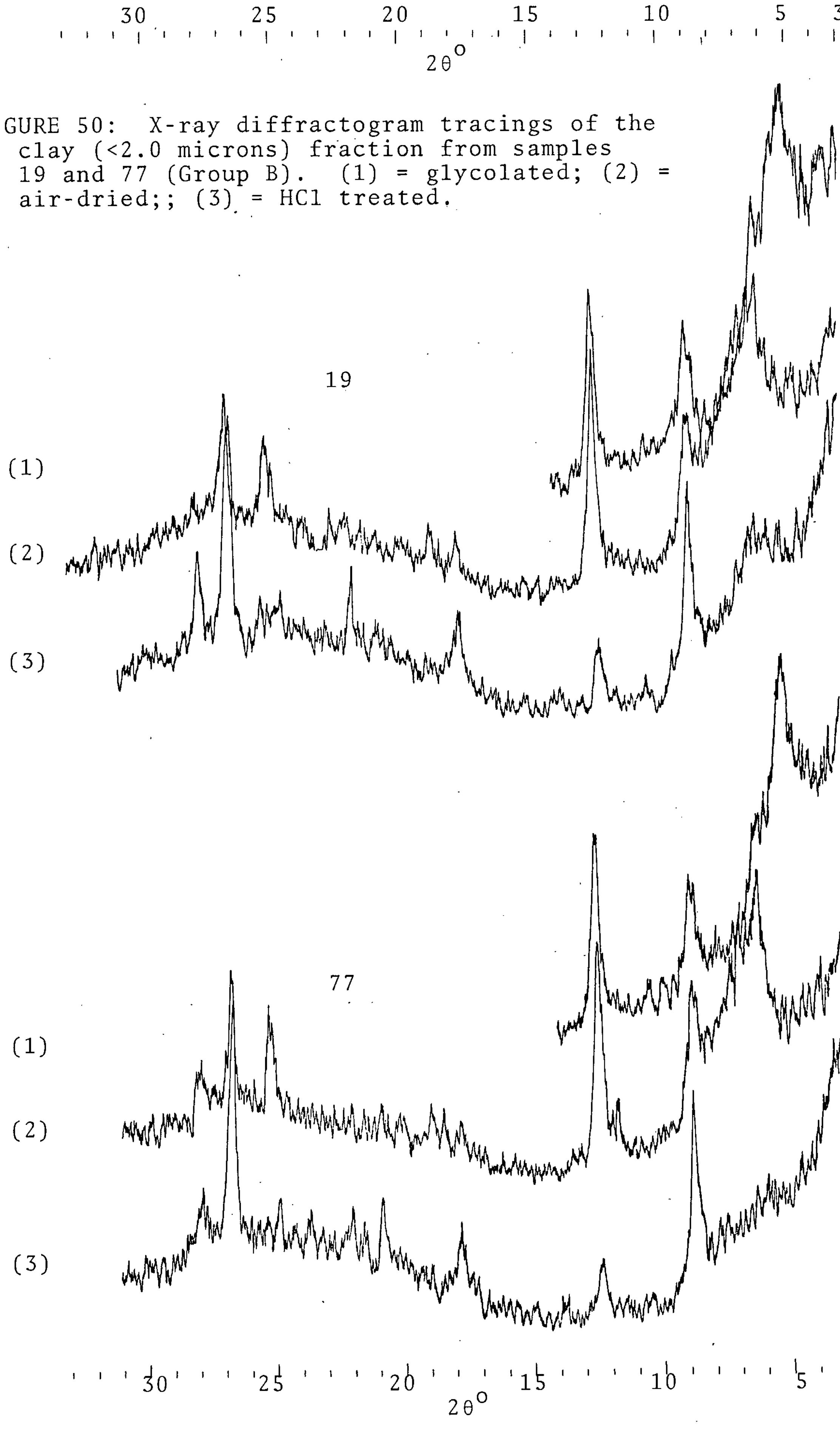


FIGURE 50: X-ray diffractogram tracings of the clay (<2.0 microns) fraction from samples 19 and 77 (Group B). (1) = glycolated; (2) = air-dried;; (3) = HCl treated.

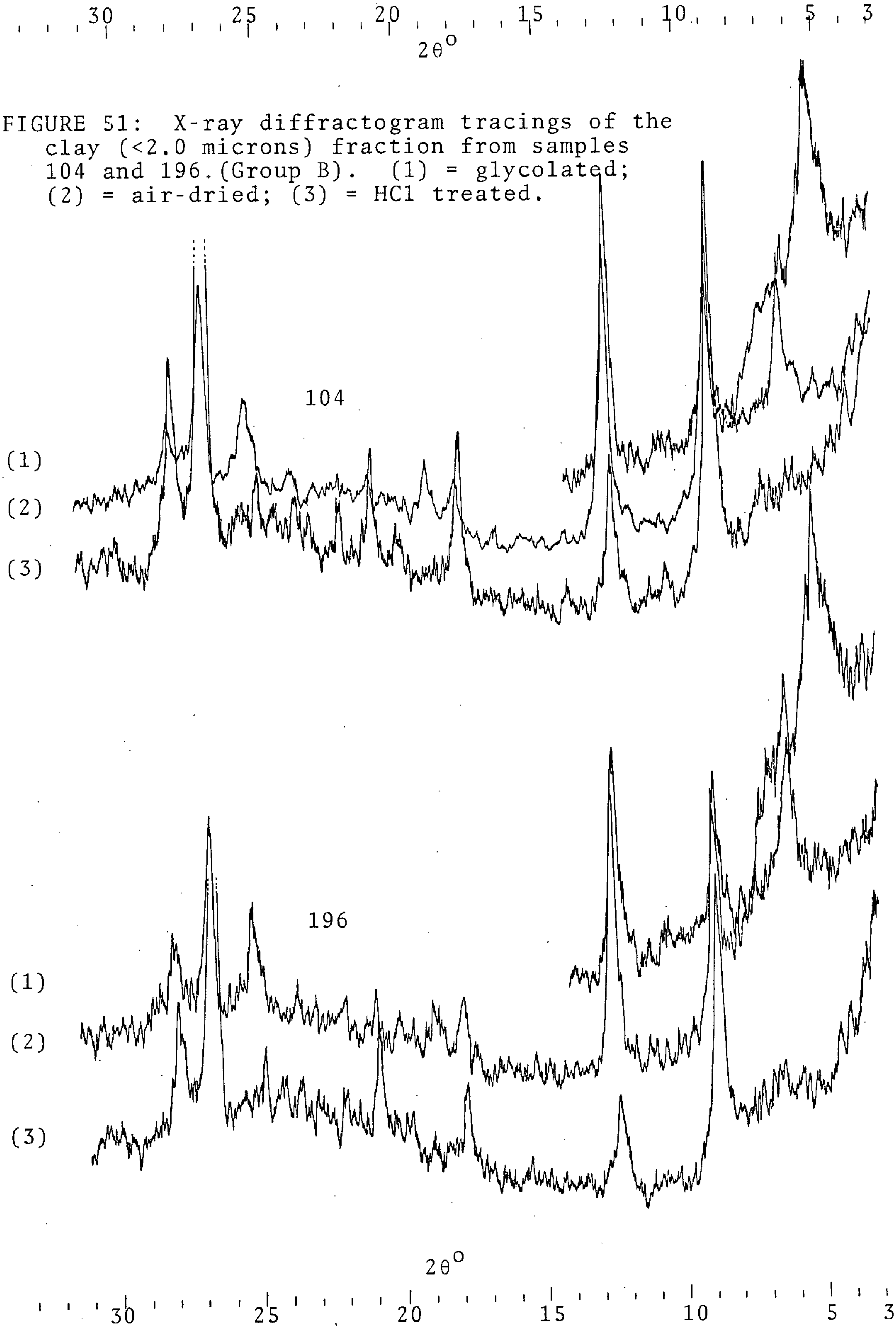


FIGURE 51: X-ray diffractogram tracings of the clay (<2.0 microns) fraction from samples 104 and 196. (Group B). (1) = glycolated; (2) = air-dried; (3) = HCl treated.

FIGURE 52: X-ray diffractogram tracings of the clay (<2.0 microns) fraction from samples 257 and 268 (Group B). (1) = glycolated; (2) = air-dried; (3) = HCl treated.

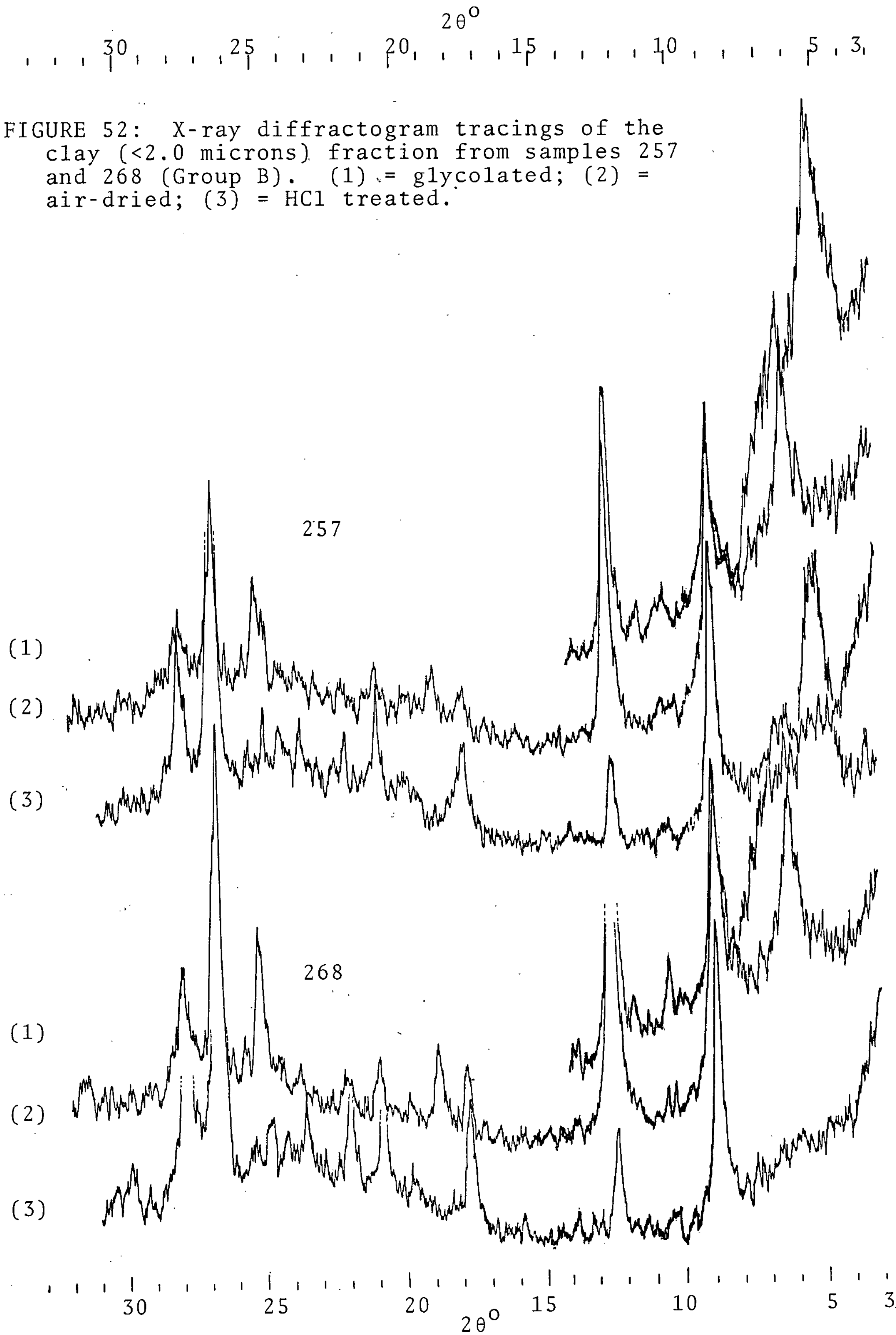
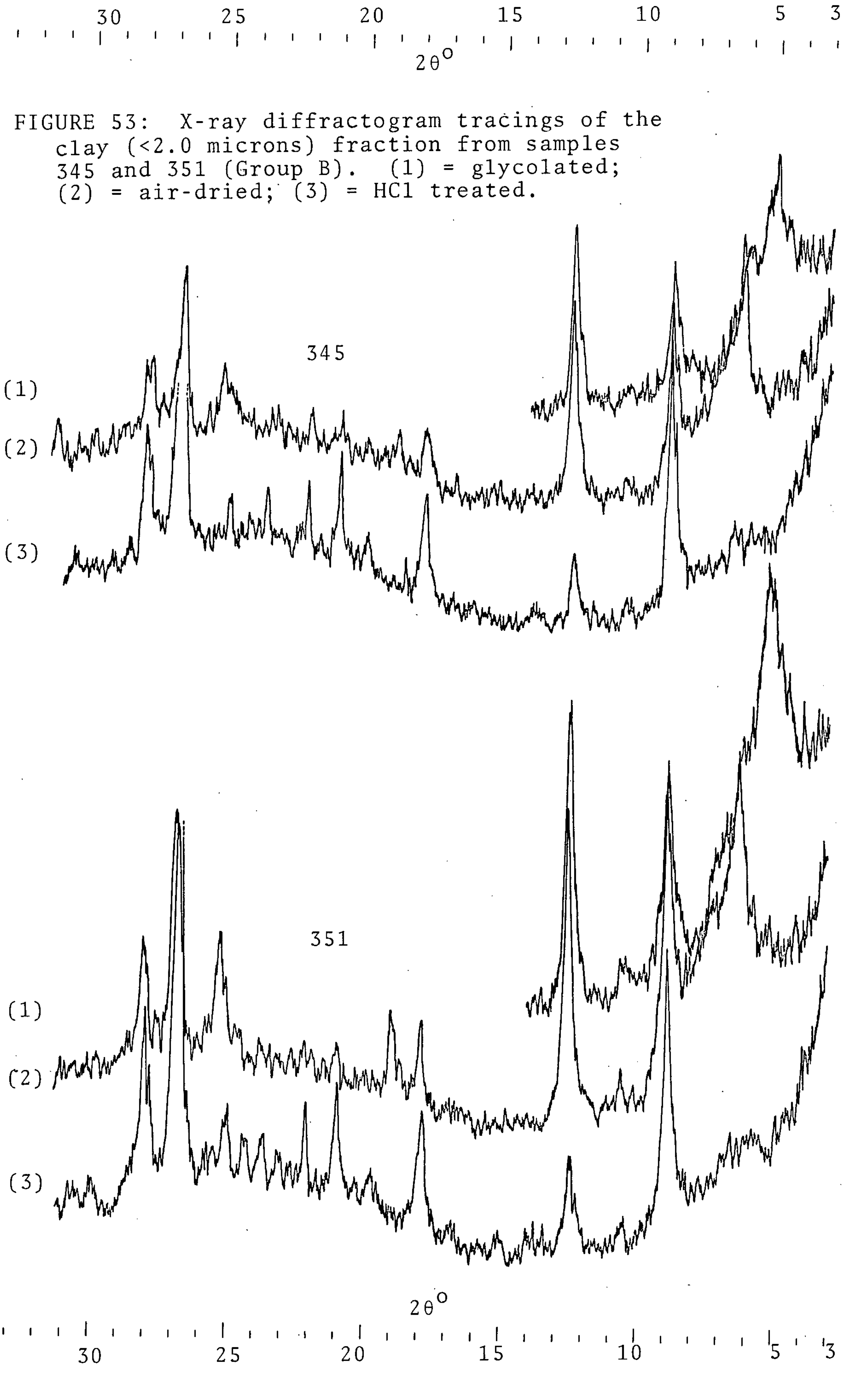


FIGURE 53: X-ray diffractogram tracings of the clay (<2.0 microns) fraction from samples 345 and 351 (Group B). (1) = glycolated; (2) = air-dried; (3) = HCl treated.



not consistent with the experimental and practical findings of Sherman (1953), Whitehouse et al. (1960), Griffin (1962), Meade (1964) and Hahn and Stumm (1970). An explanation for this situation may be provided by the geographic and oceanographic conditions of the Strait of Georgia.

The close similarity between the Fraser River and Georgia Strait sediments in the silt and clay sizes, as well as the enormous amount of sediment that the Fraser River supplies to its delta and to the Strait each year (700 x 10^6 cubic feet annually: Mathews and Shepard, 1962; also Pretious, 1969, 1972) suggests that the primary source of the Georgia Strait fine-fraction sediments is the Fraser River. The mineralogy is primarily of detritial terrigeneous origin reflecting the composition of sediment source of the Fraser River, which is largely the more easily eroded, semi- or un-consolidated Pleistocene deposits upstream of the Fraser Canyon (Pretious, 1972). The area of the Strait is relatively small, and is semi-enclosed with a virtually closed circulation of at least the surface waters (see Chapter 1). Sediment is introduced by the Fraser in large quantity over the two to three month long spring and summer freshet. Compared to the Gulf of Mexico for example (e.g., Pisnak and Murray, 1960; Griffin, 1962) neither the time, the distance from source, nor the area of basin is sufficient to permit a clay-mineralogic segregation or fractionation.

Under laboratory conditions it is very difficult to recreate such an important environmental condition as turbulence. Regardless of flocculation tendencies – either rate or ultimate optimum size attained – of different clay minerals, turbulent transport will profoundly influence the distribution and dispersal of clay minerals. Early-flocculating clay minerals will be buoyed-up under conditions of turbulence, and if this turbulence is severe enough the floccules may not last for any length of time, but instead will be continuously forming and disaggregating.

4.4.4 SEMI-QUANTITATIVE STUDIES

Numerous quantitative or semi-quantitative methods, of varying degrees of sophistication, for estimating clay mineral proportions in sediments or soils have been proposed in the literature. Pierce and Siegel (1969) summarise and compare a few of these, and point out the inconsistent results that can be obtained from the same X-ray diffractograms when analysed by the different techniques. They also indicate that while there is confusion because of the lack of a standard method for quantification of clay-mineral studies, those methods that are in use are usually internally consistent within themselves, and each is as well-founded as any other for quantitative studies.

The method chosen here was that of Johns, Grim and Bradley (1954), which was modified slightly by using the weighting factors advocated by Biscaye (1965) to make direct comparison of peak areas more feasible. The weighting factors are: 1 x the area of the 17Å glycolated peak for montmorillonite; 4 x the 10Å peak in the glycolated sample; and 2 x the 7Å peak in the glycolated sample. Biscaye's (1965) discrimination of chlorite from kaolinite was not made because of the poor resolution of the chlorite/kaolinite couplets at 7Å and 3.5Å. The technique was applied only to Group B samples, which were chosen to cover the entire Strait with a sufficient number of samples to produce a useful

NO.	M.	4XI.	2X (C+K)	M	I	C+K	DSH KM	% CLAY
	CORRECTED PEAK AREAS			CONTENT AS PERCENT				
19	1053	940	600	41	36	23	42.5	20
25	820	800	624	37	36	28	40.6	19
42	552	864	480	29	46	25	32.2	17
46	902	696	552	42	32	26	25.5	13
54	780	576	560	41	30	29	26.6	17
58	684	492	488	41	30	29	21.4	10
62	610	800	426	33	44	23	19.8	13
73	738	720	608	36	35	29	20.6	44
77	720	688	600	36	34	30	16.6	25
86	770	672	608	38	33	30	11.6	24
88	656	864	546	32	42	26	14.8	30
92	890	996	904	32	36	32	20.2	9
93	1372	1740	928	34	43	23	20.0	17
98	828	588	492	43	31	26	10.0	33
104	1012	864	642	40	34	25	4.0	29
111	924	1088	558	36	42	23	4.6	23
115	1079	1104	856	36	36	28	11.6	46
121	900	1680	672	28	52	21	20.0	55
124	832	900	816	33	35	32	15.0	50
126	873	880	594	37	38	25	11.2	34
128	1020	976	534	41	39	21	7.8	32
133	639	800	600	31	39	29	8.5	37
148	2392	1344	888	52	29	19	23.8	31
152	938	780	450	43	36	21	18.4	54
161	910	832	438	41	38	21	12.6	46
167	1056	672	474	48	31	21	15.2	51
170	1296	928	552	47	33	20	16.2	44
184	896	1240	736	31	43	26	20.5	50
186	1404	948	774	45	30	25	22.4	45
190	1152	848	704	41	31	25	23.0	60
196	1443	1180	664	44	36	20	23.5	58
212	1032	864	656	41	34	25	32.0	72
215	1040	1500	760	32	46	23	30.6	71
220	1155	1040	704	40	36	24	29.5	65
222	756	768	492	37	38	24	30.4	62
227	168	688	488	12	52	36	33.2	
255	720	700	426	39	38	23	43.4	39
257	1722	1440	760	44	37	19	41.2	67
261	984	720	632	42	31	27	40.5	71
265	1260	1008	812	41	33	26	40.5	67
268	1440	2064	1016	32	46	22	41.5	42
299	1236	1008	658	43	35	23	50.2	73
302	748	744	396	40	39	21	55.0	67
309	1521	1328	606	44	38	17	54.2	74
311	528	1008	426	27	52	22	55.4	76
315	150	768	544	11	53	37	56.0	10
329	980	1460	688	31	47	22	61.5	75
330	704	672	498	38	36	27	61.6	74

332	1164	1292	784	36	40	24	62.0	77
335	665	1056	602	29	45	26	62.8	77
337	616	1140	680	25	47	28	63.5	18
345	560	864	420	31	47	23	66.0	78
351	1326	1216	690	41	38	21	65.8	10

TABLE VII: CORRECTED PEAK AREAS AND CONTENT OF THE THREE MAIN CLAY-MINERAL GROUPS MONTMORILLONITE (M), ILLITE (I), AND CHLORITE+KAOLINITE (SEE TEXT: C+K), FOR THE FINER-THAN-2.0 MICRON SIZE-FRACTION OF GROUP B SAMPLES. DHS=DISTANCE FROM SAND HEADS IN KILOMETRES. %CLAY REFERS TO CLAY CONTENT OF TOTAL SAMPLE.

or meaningful picture. Oriented slides of the finer-than-2.0 micron fraction were X-rayed after air-drying and following glycolation. This treatment served to separate the montmorillonite (expandable fraction) from the chlorite (14Å non-expanding clays), and to permit their comparison with 10Å illite; all measurements were made on the diffractograms from the glycolated samples.

The problems encountered with the distinction and consequent quantitative separation of small amounts of kaolinite in the presence of chlorite have been discussed earlier. It was eventually decided to call the 7Å peak "chlorite plus kaolinite" rather than to separate the two, and to use this peak, weighted accordingly, relative to the 10Å illite. While Johns, Grim and Bradley (1954) advocate comparing the 3.5Å chlorite+kaolinite peak with the 3.3Å illite, the coincidence of a quartz peak in this position restricts the usefulness of the illite 3.3Å peak for comparative purposes. Analysis of Group A samples and warm HCl treatment of Group B samples, as well as the findings of Mackintosh and Gardner (1966), indicate that kaolinite is present in only small amounts and therefore the 7Å peak is largely chlorite.

Results of the semiquantitative study are presented in Table VII, which lists weighted peak areas and percentages of montmorillonite (M), illite (I), and chlorite+kaolinite (C+K). The weighted peak area of illite was assigned a value of 1 and the other peak areas, appropriately weighted, were referred as a ratio to illite. From the ratios the percentage contribution of each mineral was calculated assuming they accounted for 100% of the mineralogy; a reasonable assumption for the finer-than-2 microns size-fraction. A small error due to the presence of quartz and felspar, as well as possible vermiculite, will result but has been neglected.

Results of the semiquantitative analysis have been plotted on two figures (54 and 55) to determine whether any preferential flocculation of certain clay minerals had occurred. The studies alluded to elsewhere (including Whitehouse et al., 1960; Griffin, 1962; Hahn and Stumm, 1970) predict early, rapid flocculation of kaolinite, chlorite and illite in even low salinity water, with the formation of large floccules. Montmorillonite tends to remain dispersed for longer, being transported further, finally flocculating only in water of higher salinity and into samller-sized floccules. Researchers in the Gulf of Mexico have recognized clay mineral provinces, delineated by the predominance of certain clay types, that can be explained by the preferential flocculation of the various minerals (e.g. Pisnak and Murray, 1960; Griffin, 1962). It is quite apparent from Figures 54 and 55 that this situation does not exist in the Strait of Georgia. The spread of the sample points in Figure 54 can be almost covered by a circle representing an estimated error of measurement of 18%, and even an error of only 10% can account for the variation among many samples. If preferential flocculation had occurred, the ratio of montmorillonite to either illite or to chlorite+kaolinite would be expected to increase with distance from the source (Sand Heads). Figure 55 displays no such relationship; in fact the regression line is almost horizontal suggesting no correlation at all. As has been pointed out above this situation can be explained by the rapid influx over a short time interval of large volumes of sediment into a semi-enclosed area with an almost closed circulation pattern of intensively mixed water. The area is too small and the mixing too thorough to permit the development of clay mineral zones by preferential

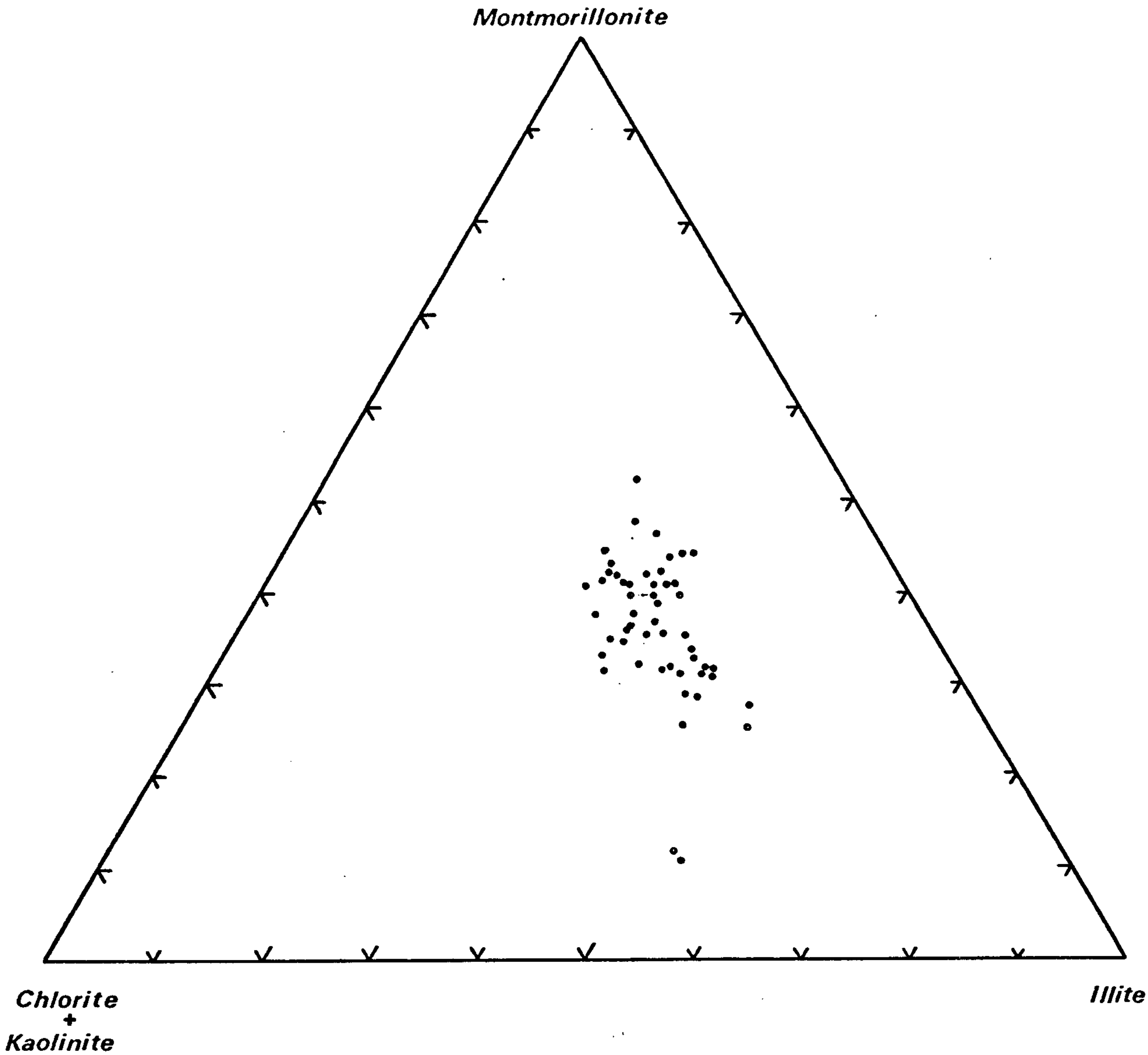


FIGURE 54: *Ternary plot of clay mineral ratios for Group B Strait of Georgia sediments.*

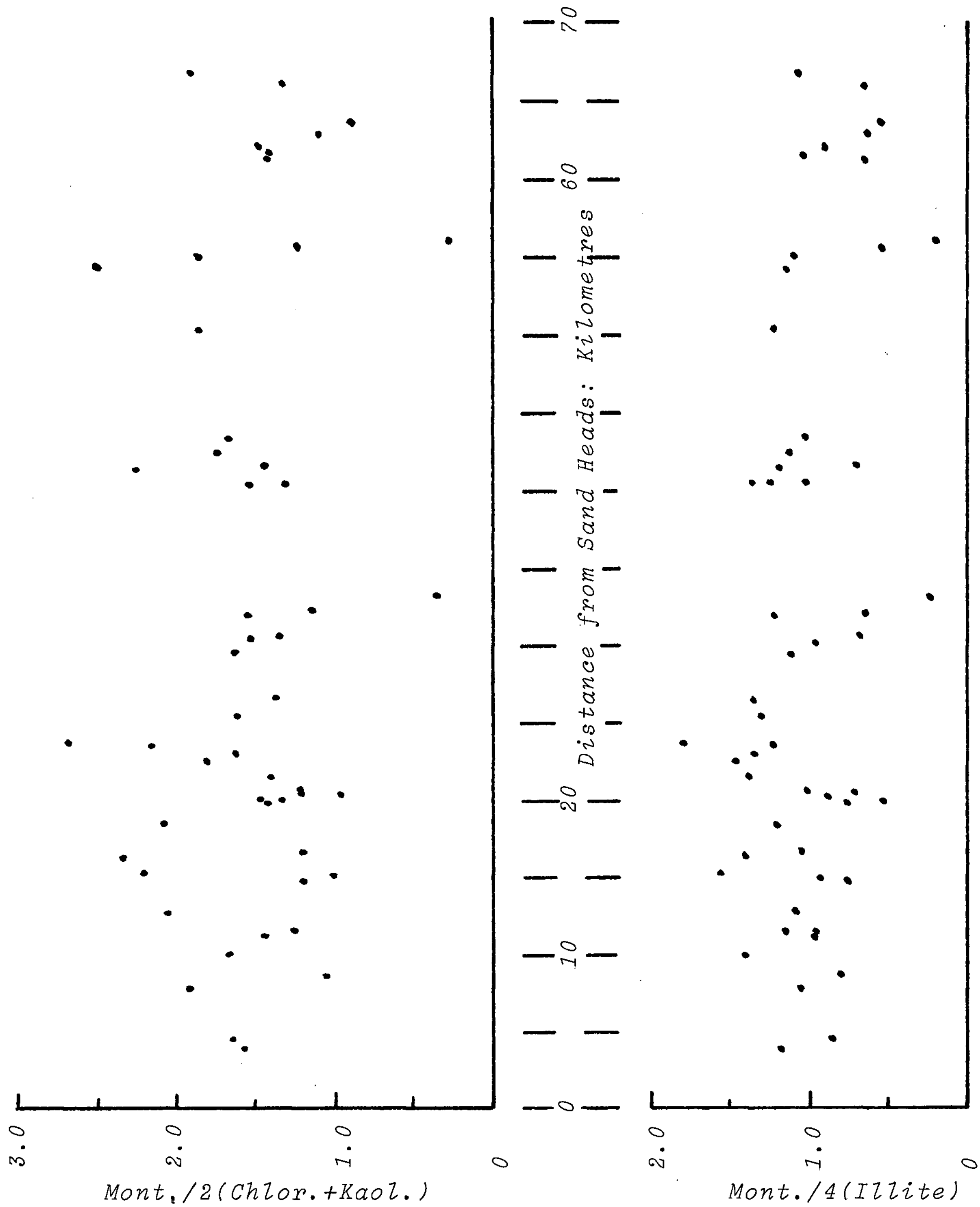


FIGURE 55: Bivariate plots of the ratio of montmorillonite to chlorite+kaolinite and to illite (appropriately weighted peak-area ratios) against distance from Sand Heads.

flocculation.

4.4.5 CHEMISTRY

To determine the effect on Fraser River sediments on their passing from fresh- to salt-water environments, three sediment samples were collected from the Fraser River near the mouth of Ruby Creek, 12 miles east of Agassiz, B.C., well upstream of possible contamination by salt-water. These samples did not include very coarse sands and gravels. Subsamples were split from the Fraser River samples, and two from each were placed in Georgia Strait sea-water (from 200 metres depth, U.B.C. Biological Oceanography Station No. 1: salinity 31.01%. oxygen 3.44 ml./l.; October, 1970) for 95 days. One of each of the subsample pairs was agitated and aerated daily while the other was left undisturbed for the duration of the experiment. pH and Eh were monitored over the 95 day period (Figures 56 and 57).

pH was measured on the water near the sediment-water interface using a Portomatic model 175 pH meter. Over the duration of the experiment, the non-aerated sub-samples generally maintained a slightly higher pH than the aerated ones. There was an initial rise in the pH from 7.0 to nearly 8.0, followed by a decrease to about 7.4. The pH maintained this value for nearly 70 days then rose to values near 7.5 for the aerated samples and near 8.0 for the non-aerated. They remained reasonably constant then until the experiment was terminated on the 95th day (Figure 56). Figure 57 shows the highly irregular results obtained from the Eh measurements. Little emphasis should be placed on the redox values; the experiment maintained positive values indicating generally oxidising conditions throughout the time involved. In the Strait, however, the

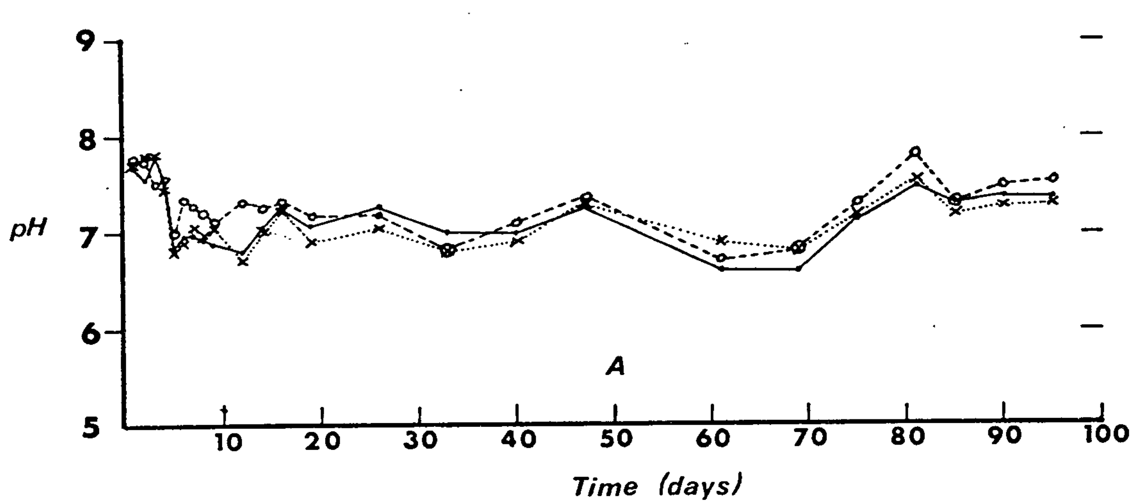
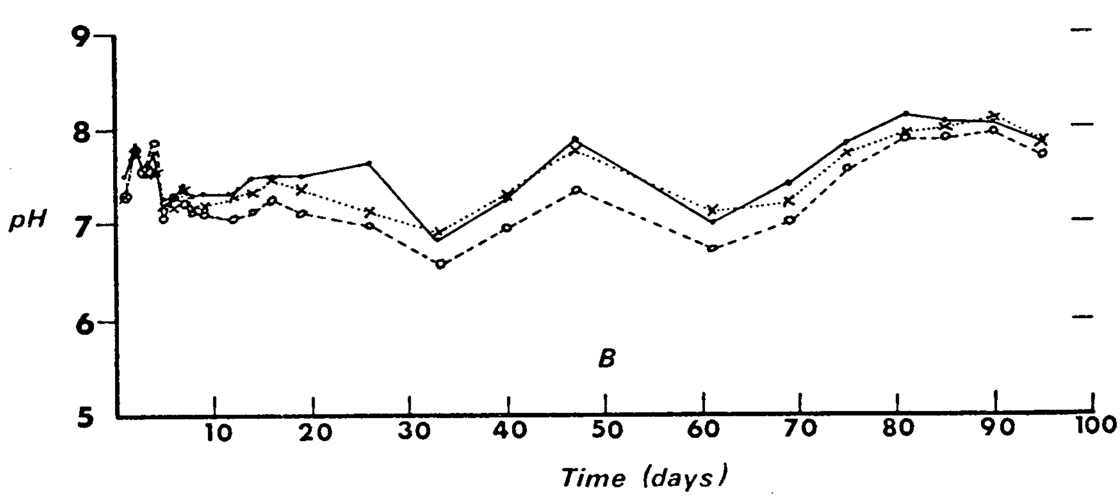


FIGURE 56: Change in pH with time for non-aerated (A) and aerated (B) Fraser River samples in sea water. •——• = FR1,1A; ×·······× = FR2,2A; o----o FR3,3A. See text for explanation of sample numbers.



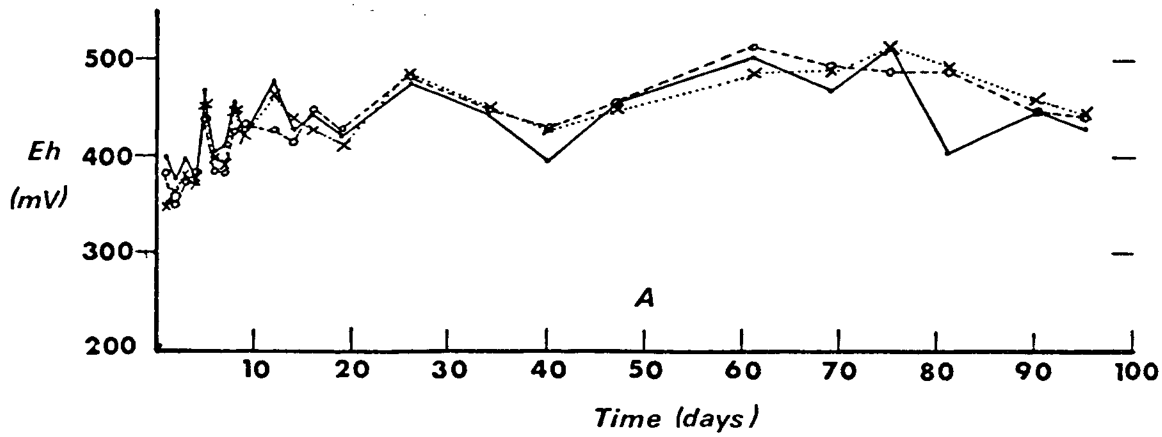
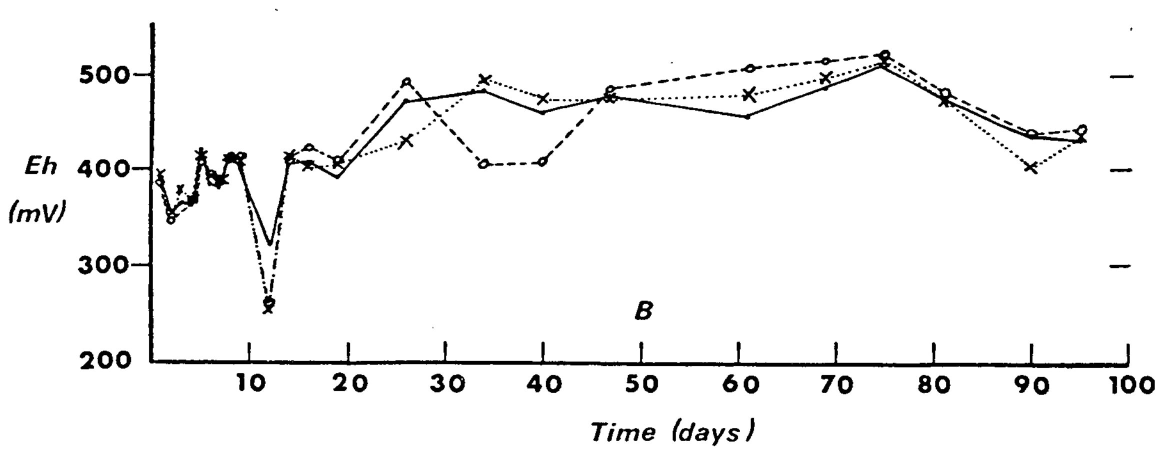


FIGURE 57: Change in Eh with time for non-aerated (A) and aerated (B) Fraser River samples in sea water. •——• = FR 1,1A; x·······x = FR2,2A; o------o = FR3,3A. See text for explanation of sample numbers.



sea-bottom conditions are believed to be more generally reducing at least in the deep basins. Samples 280 and 350 for example were retrieved as olive greenish muds. After relatively short exposure to the atmosphere a red-brown surface, that moved inward as an ever-thickening layer, developed. It is believed that the laboratory experiment was not an adequate reproduction of the true environment, and no conclusion could be obtained from it.

At the end of the experiment all subsamples as well as untreated Fraser River material and nine samples from various locations in the Strait of Georgia (Group A samples) were analysed for total cation exchange capacities and amounts of exchangeable bases. Acid ammonium oxalate extractions of amorphous, inorganic, oxides and hydroxides of iron, manganese, aluminum and silica were also obtained from these samples. Techniques employed were standard methods of soil analysis used in the Department of Soil Science, U.B.C. Results are presented in Tables VIII and IX. Samples prefixed FR are those from the Fraser River: FR1, 2 and 3 were those left undisturbed in sea-water; FR1A, 2A and 3A were the subsamples in sea-water that were aerated daily; FR1U, 2U and 3U refer to the raw samples from the Fraser not subjected to sea-water treatment.

Ion exchange capacity and other chemical measurements were conducted on whole samples of the sediments, not on the clay fractions only. It has been pointed out by Carroll (1959) that clays are not the only minerals with the capacity for base exchange. Measuring these parameters in multicomponent systems, such as these samples are, results in average values from the sediment that are integrated sums of values from the individual components. It is not possible to use base-exchange capacity to identify clay-mineral groups under these circumstances. The value of the measurements lies more in their implications for environmental studies. It is the sediment's capacity to adsorb and perhaps fix introduced ions that is being measured, not simply that of the clay fraction which would be higher and could consequently lead to erroneous assumptions of how much material might be safely introduced to the system. The data presented here (Table VIII) gives an indication of the potential that Georgia Strait and Fraser River sediments have for adsorbing and "fixing" metal ions.

4.4.5.1 ANALYTICAL METHODS

1. Exchangeable cations and total exchange capacities:

a. Weigh 10gm. (dry weight equivalent) into 100 ml. centrifuge tubes.

b. Add 40 ml. ammonium acetate solution, stopper, shake 5 min., let stand overnight, and shake again 5 min.

c. Prepare Buchner funnels - Whatman #2 filter papers plus a layer of "Celite" = and place above collecting jars.

d. Transfer contents of centrifuge tube to funnels with suction applied. Rinse tubes and stoppers with ammonium acetate (NH_4OAc) solution from wash-bottle.

e. Wash sample with 4 successive 40 ml. portions of NH_4OAc, with aspiration between each wash.

f. Transfer the leachate to 250 ml. volumetric flask, rinse bottle with NH_4OAc, make volumetric to mark with NH_4OAc. Mix well. Save 70 to 80 ml. in a plastic bottle for analysis of Na, Ca, K and Mg. (exchange cations). 1 ml. toluene may be placed in each plastic bottle if samples are to be stored.

g. Replace funnels containing NH_4^+-saturated samples on suction bottles and wash with 3 successive 40 ml. portions of isopropanol, with aspiration between each washing. Discard washings. Rinse bottles 3 times with distilled water.

h. Leach sample with 4 successive 50 ml. portions of 1N KCl. Transfer leachate to 250 ml. volumetric and make to mark with distilled water. This extract is used to determine total exchange capacities.

i. Total exchange capacity is determined by micro-Kjeldahl determination of NH_4^+.

j. Concentration of exchangeable bases is determined by atomic absorption (using a Perkin-Elmer model 303 atomic absorption spectrophotometer).

k. Note: samples rich in montmorillonite may undergo a change similar to syneresis, resulting in the sediment cake partially dehydrating and cracking. The cracks permit easy flow of solution resulting in values for the total exchange capacities that are too low. One way of combatting this may be to mix the sample with "Celite" or filter pulp (after the normal "Celite" layer has been constructed).

2. Acid ammonium oxalate extraction of amorphous, inorganic, iron, manganese, aluminum, and silica:

a. Place 1.00 gm. (dry weight) of sample finer than 100 mesh in 100 ml. tubes.

b. Add 40 ml. oxalate solution (700 ml. 0.2M ammonium oxalate plus 535 ml. 0.2M oxalic acid, adjusted to pH 3) and stopper the tubes tightly.

c. Place the tubes horizontally in a box and shake for four hours (extraction must be done in the dark).

d. Centrifuge and analyse the supernatant by atomic absorption spectrophotometry.

4.4.5.2 DISCUSSION

Exhaustive studies, and/or discussions, are available concerning the changes wrought on clay-mineral suites subsequent to passage from fresh- to salt-water environments or as a consequence of laboratory treatment of clay minerals with sea-water (e.g. Grim and Johns, 1954; Powers, 1957; Johns and Grim, 1958; Carroll, 1959, 1964; Carroll and Starkey, 1960; Pisnak and Murray, 1960; Whitehouse et al., 1960; Griffin, 1962; Grim and Loughnan, 1962; Berry and Johns, 1966; Keller, 1970; Naidu et al., 1971; Morton, 1972). Despite this abundant literature there is still controversy over whether the clay-mineral suite in the marine environment is a result of marine diagenesis or an expression of the composition of the source area. Arguments for and against these ideas are presented in the works cited.

Detailed and comprehensive accounts of ion-exchange phenomena and processes are available in the literature (see for example and for reference Carroll, 1959; Carroll and Starkey, 1960; and Gillot, 1968). Only the results obtained in this study will be discussed here.

Carroll (1959, 1964) and Carroll and Starkey (1960) suggest that base exchange, also referred to as ion-exchange (which does not restrict the process to metal or hydrogen cations) or cation exchange, occurs as a prelude to diagenesis when clays are moved from fresh- to salt-waters. They also showed that Mg^{++} ions tend to move into exchange positions in preference to either Na^{+} or Ca^{++} despite the far greater concentrations of the former in sea-water, and the apparently greater bonding energy of the latter.

SAMPLE NO.	CA	MG	NA	K	ION-EXCHANGE CAPACITY	%CLAY
FR1	10.94	3.75	2.20	0.69	8.36	
FR1A	11.56	3.97	2.67	0.56	8.24	
FR2	11.25	4.66	2.53	0.66	10.96	
FR2A	10.63	3.63	2.67	0.53	7.89	
FR3	8.13	3.22	1.69	0.53	6.96	
FR3A	8.75	3.19	2.39	0.56	7.77	
FR1U	13.44	1.63	0.15	0.27	6.73	10.2
FR2U	13.44	1.75	0.26	0.28	8.29	12.3
FR3U	10.94	1.31	0.22	0.32	6.90	9.2
GS23	15.00	8.22	3.19	2.81	16.79	14.7
GS53	8.75	12.28	2.48	3.75	40.89	30.5
GS102	9.69	7.91	1.99	1.84	14.76	15.2
GS145	5.94	12.25	2.63	3.41	30.00	56.6
GS162	5.94	11.63	6.34	3.41	30.68	35.7
GS263	5.63	15.94	5.25	5.03	29.38	46.7
GS280	10.94	33.13	5.25	7.63	39.51	72.1
GS342	7.50	23.38	8.25	9.50	34.28	58.6
GS350	10.63	33.88	6.11	7.72	31.37	75.6
*MURR.1	13.83	2.02	0.79	0.53	23.45	
*JACK.6	7.64	5.99	0.42	0.48	20.92	
*LEHM.1	3.68	1.72	0.005	0.42	7.42	
*HAN.1	8.00	11.62	0.13	0.66	27.89	

TABLE VIII: EXCHANGEABLE CATIONS AND ION-EXCHANGE CAPACITIES, FRASER RIVER, GEORGIA STRAIT, AND GLACIOMARINE UPLAND SOILS (* AFTER AHMAD, 1955; MURRAYVILLE, JACKMAN ROAD, LEHMAN ROAD, AND THE HANEY CLAY PIT). VALUES ARE RECORDED AS MILLIEQUIVALENTS PER 100 GRAMS OF DRY SAMPLE (MEQ/100GM).

While the content of exchange Ca^{++} does not show any consistent differences between the untreated or treated Fraser River or Georgia Strait samples, the contents of Mg^{++}, Na^{+} and K^{+} do (Table VIII). These cations are all taken up by the sediments after contact with sea-water. Of them the change in the Mg^{++} content is by far the greatest, substantiating the experimental findings of Carroll and Starkey (1960. The Na^{+} increase is reasonably obvious but K^{+} does not seem to be taken up by the sediment after only a short time in sea-water. Samples from Georgia Strait have exchangeable base concentrations that seem to be related to the distance the sample is from Sand Heads which, if all sediment is considered to be derived from the Fraser River, implies a longer transport time during which the sediment is in reactive contact with sea-water. Total exchange capacity is also related to the clay content of the sample. Samples close to Sand Heads (102) have values, especially for Na^{+} and K^{+}, that are little different from the values obtained from sea-water treated subsamples from the Fraser River. Georgia Strait samples 280, 342 and 350, the furthest away of all from Sand Heads, had the highest values for all exchangeable base concentrations. Significantly, the values for total exchange capacities have a practically identical distribution.

Contents of inorganic, amorphous oxides and hydroxides removed by oxalate extraction show an only slightly different picture (Table IX). In none of the cases (Fe, Mn, Al, Si) did the untreated Fraser River samples differ significantly from the treated ones. Iron values are fairly uniform throughout the entire set of samples. Aluminum, manganese and silica show increasing concentrations for samples taken at increasing distances from Sand Heads and with high contents of clay-size material.

SAMPLE NO.	%IRON	%ALUMINUM	MANGANESE PPM	SILICA PPM
FR1	.564	.1312	208.0	2440.0
FR1A	.536	.1400	246.0	2720.0
FR2	.640	.1744	272.0	2720.0
FR2A	.552	.1620	228.0	3200.0
FR3	.528	.1168	150.0	2400.0
FR3A	.498	.1232	148.0	2520.0
FR1U	.580	.1424	226.4	2320.0
FR2U	.634	.1520	225.6	2400.0
FR3U	.600	.1208	176.0	2440.0
GS23	.364	.1328	28.0	2240.0
GS53	.328	.2480	34.0	3360.0
GS102	.620	.1696	91.2	4000.0
GS145	.554	.3520	132.8	5440.0
GS162	.646	.2840	88.0	5120.0
GS263	.268	.3280	47.2	3400.0
GS280	.552	.3540	3408.0	5520.0
GS342	.408	.3568	335.2	4500.0
GS350	.468	.4080	798.4	5360.0

TABLE IX: CONCENTRATICNS OF AMORPHOUS INORGANIC OXIDES EXTRACTABLE WITH ACID AMMONIUM OXALATE.

The manganese values show this particularly clearly. Sample 280 has a marked anomaly in its concentration of manganese, the value being nearly an order of magnitude greater than for the next highest concentration, while the clay content is about the same, and distance from Sand Heads slightly less. Table X did not indicate any significant correlations between the concentration of manganese and the clay content, or any other of the variables considered. The control of the concentration of manganese is not known.

The results obtained from the determinations of exchangeable base contents, total exchange capacities, and acid ammonium oxalate extractions were submitted to correlation analysis using the Small Triangular Regression Package (STRIP) computer programme from the U.B.C. Computing Centre library. The data was submitted in three ways: (1) using only the samples from the Fraser River; too few observations were included for significant correlations to be obtained; (2) all the Georgia Strait plus the three subsamples from the Fraser River that had not been subjected to sea-water treatment; (3) all 18 samples (Table X). Values for the correlation coefficient ("r") indicating significance at the 1% and 5% levels are included in Table X.

From Table X, it seems reasonable to suggest that the amount of clay in a sample exerts the most control on exchange capacities and concentration of some exchange ions or oxalate-extractable elements. The very high correlation between clay content and oxalate extracted aluminum at the 1% level in all cases suggests a basic relationship between the two, but it is not understood. Carroll and Starkey (1960) found that Al_2O_3 (as well as SiO_2 and Fe_2O_3) was dissolved from clay minerals, probably by its removal from the octahedral layer. Al_2O_3

VARIABLE	%CLAY	MEDIAN SIZE	IRON	ALUMINUM	MANGANESE	SILICA	CALCIUM	MAGNESIUM	SODIUM	POTASSIUM	EXCH. CAP.
%CLAY	1.0000										
MEDIAN SIZE	0.9815	1.0000									
IRON	-0.3316	-0.2567	1.0000								
ALUMINUM	0.9777	0.9870	-0.3333	1.0000							
MANGANESE	0.5450	0.4983	0.0983	0.4140	1.0000						
SILICA	0.0139	0.0015	0.0201	-0.0325	0.0423	1.0000					
CALCIUM	-0.4209	-0.5165	0.2146	-0.5209	0.1278	-0.3015	1.0000				
MAGNESIUM	0.9496	0.8962	-0.3537	0.8952	0.6495	0.0213	-0.2564	1.0000			
SODIUM	0.7645	0.7703	-0.3949	0.7841	0.2968	0.0074	-0.4855	0.7885	1.0000		
POTASSIUM	0.9237	0.8921	-0.4783	0.8966	0.4839	-0.0066	-0.3504	0.9433	0.8696	1.0000	
EXCH. CAP.	0.8674	0.8525	-0.4772	0.8832	0.4080	-0.0448	-0.4891	0.8272	0.7279	0.8633	1.0000
% ORGANIC C.	0.9006	0.9004	-0.3156	0.8960	0.3291	-0.0091	-0.3571	0.8444	0.7850	0.9080	0.7430

TABLE X : Correlations between twelve variables determined from eighteen samples: nine from Georgia Strait and nine from the Fraser River (see explanation in text). To be significant at the 5% and 1% levels, 'r' must be greater than 0.792 and 0.842 respectively.

is insoluble at the pH of sea-water, and the process was believed to be possibly due to a complexing reaction with organic material. If the Al_2O_3 hydrolysed, it could become available for the formation of gibbsite-like material that could combine with montmorillonite or vermiculite clay minerals to form either a chlorite or a mixed-layer montmorillonite-chlorite mineral.

Zeolites have not been recognised in the X-ray diffractograms. These minerals have high exchange capacities similar to those of the clay minerals (Carroll, 1959). Other minerals can also take part in exchange reactions, particularly if present as small grains. The cation exchange capacities of the sediments considered here, however, must be largely determined by the clay mineral content, and is an averaged value of the exchange capacities of the various clay mineral species present. Carroll (1959) records the ranges of cation exchange capacities for various clay mineral groups, the range being a function of differences in structure, size and chemical composition of the members of the groups. The recorded ranges are (in milliequivalents of base exchangeable per 100 grams of dry sediment): kaolinite 3 - 15; montmorillonite 70-- 100; illite 10 - 40; vermiculite 100 - 150; glauconite 11 - 20.

The preferential uptake of Mg^{++} by clay minerals, whether in exchange positions or substituting for Al^{+++} in octohedral positions, is recorded by numerous workers (e.g. Carroll, 1959, 1964; Carroll and Starkey, 1960). Mackintosh and Gardner (1966) consider this process to be occurring in sediments from the sea (Georgia Strait), and the high correlation between clay content and exchange Mg^{++} recorded here, as well as the obvious marked increase in Mg^{++} content from untreated (FR1U etc.) to treated (FR1 1A etc.) Fraser River and Georgia Strait samples seen on Table VIII substantiates this hypothesis.

The correlation between clay content and % organic carbon is discussed in the next chapter. It is a commonly observed and anticipated relationship (see references quoted, and Hahn and Stumm, 1970).

The interpretation of studies of ion exchange capacities and exchangeable or extractable ion contents is neither easy nor, in the case of marine sediments, satisfactory because of the uncontrollable changes to chemical equilibria that can occur. Any addition of water will alter the chemical equilibrium of populations of exchange cations. It is also believed (Carroll, 1959) that values obtained for calcium may not reflect the true exchange calcium contents as this ion tends to be preferentially adsorbed onto other cations. Carroll and Starkey (1960) emphasise the complicated nature of exchange reactions, pointing out that the different bonding energies of the common exchange cations Ca^{++}, Mg^{++}, Na^{++}, and K^{+}, the effect of cations already held in exchange positions, the variations in charge of the exchange positions, the ionic activity and the buffer mechanism of sea-water all contribute to this complexity. The bonding energies, or order of replaceability, has been found to be: $Li < Na < K < Rb < Cs$ and $Mg < Ca < Sr < Ba$ (Carroll and Starkey, 1960). Of the usually encountered cations, the order is $Na < K < Mg < Ca$. However occasionally the order can be $Ca < Mg$ (Carroll and Starkey, 1960), and Mg^{++} ions move into exchange positions in preference to Na^{+} or Ca^{++}. That Mg^{++} will be preferentially adsorbed over Na^{+}, which is present in sea-water in far greater concentrations, is due to the preferential uptake of divalent over monovalent cations by clays. The preferential uptake of Mg^{++} over Ca^{++} when the latter has the higher bonding energy is explained by Carroll and Starkey (1960) as a function of greater availability of Mg^{++} ions in sea-water.

4.4.6 FINE-SEDIMENT TEXTURES

Textural studies were made of four separate materials of the clay-size fractions using a Cambridge Stereoscan Scanning Electron Microscope (SEM). The features studied included freeze-dried clay from sample 280 (it was hoped that freeze-drying would remove adsorbed and occluded water leaving the clay structure in much the same state as when it had settled), faecal pellets, mud lumps and glauconite grains. The last three were examined in an attempt to determine whether the self-aggregation process to form mud lumps or floccules, as advocated by Pryor and Vanwie (1971), could be recognised. Pryor and Vanwie (1971) suggested a differential flocculation mechanism of suspended clay material with the formation of floccule aggregates in an agitating, turbulent environment to explain the origin of the aggregate grains in the Eocene "Sawdust Sand" of Tennessee. The transportation and sedimentation of silts and clays as floccules has been described and discussed by, among many others, Gripenberg (1934), Sherman (1953), Lambe (1960), Rosenqvist (1958, 1959, 1962), Whitehouse et al. (1960), Belderson (1964), Meade (1964), Hahn and Stumm (1970), Pryor and Vanwie (1971), Biddle & Miles (1972).

The clay-mineral suite in the Strait of Georgia is transported in and sedimented from a weak salt solution. Floccules are expected and the anticipated fabric of the floccules would be close to a perpendicular, card-house-type array (Lambe, 1960) or the edge-edge and edge-face types of Pryor and Vanwie (1971) (Figure 58). The freeze-dried sample was expected to give some idea of the nature of the original floccules, Explanation of Figure 58.

(a), (b), (c) and (d) are from Pryor and Vanwie (1971): (a) = face-face (FF); (b) = edge-edge (EE); (c) = edge-face (EF); (d) = edge-edge, face-face, edge-face, and grains. (c) is the basic Goldschmidt - Lambe concept of the cardhouse structure. (c) and (d) appear to be the particle arrangements displayed in Figure 62 (a - k).

(e), (f) and (g) are from Meade (1964), after Lambe (1960). (e) = edge-face floccules from salt-free water; (f) = face-face floccules from salt solution; (g) = preferentially oriented, or Lambe's (1960) dispersed system.

(h), (i) and (j) are from Rosenqvist (1962), showing in an idealised way the Goldschmidt - Lambe cardhouse structure. (h) = undisturbed, salt-water deposit; (i) = undisturbed, fresh-water deposit; (j) = remoulded structure.

Lambe (1960) theorised that particles settling from a dispersed system resulted in a parallel arrangement of plates with consequent efficient packing. When particles are flocculated in, and settle from, suspension, the floccules are closer to a perpendicular array, with more plates parellel if the suspension is non-salty (non-electrolyte), but mostly perpendicular if salt-flocculated.

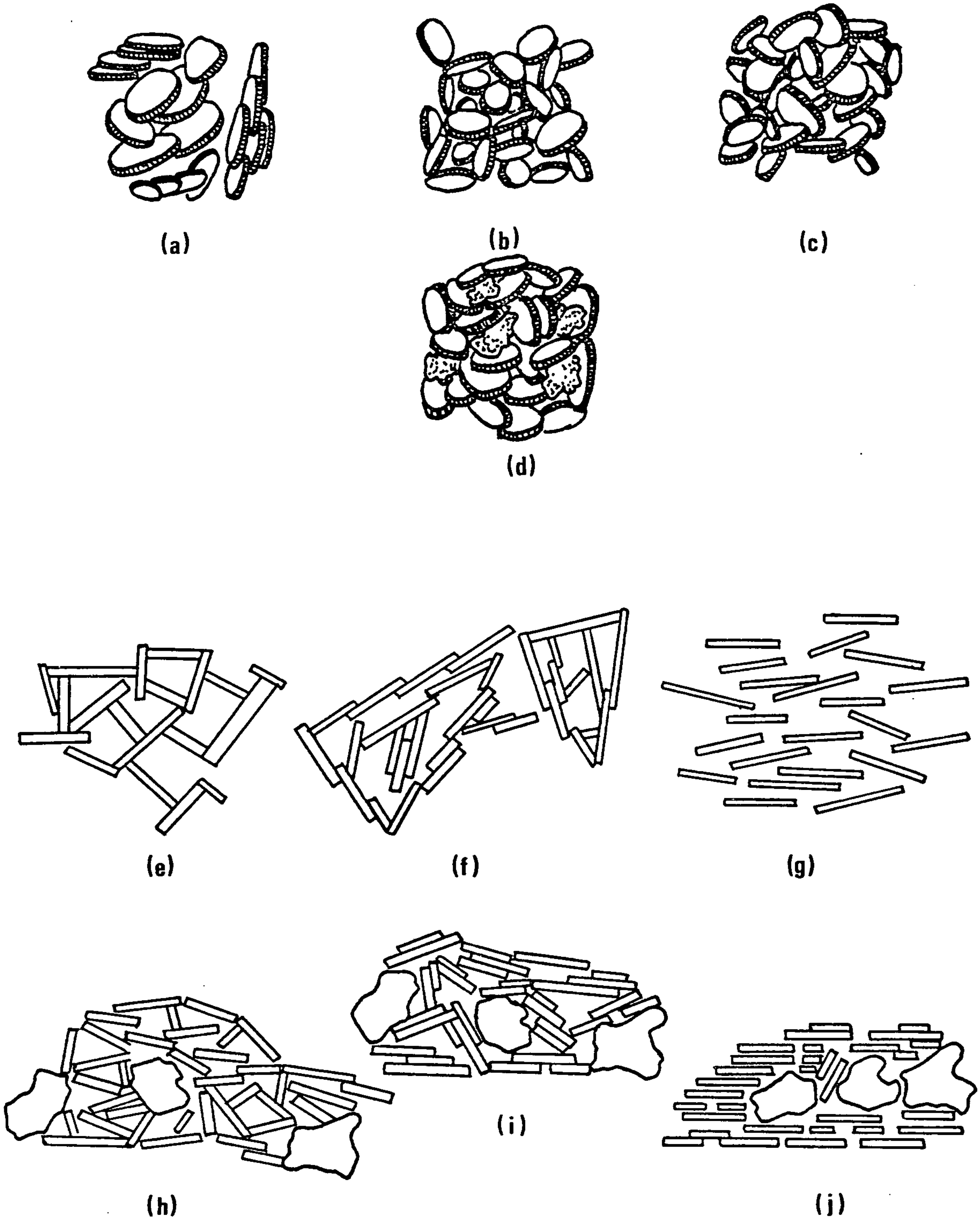


FIGURE 58: *Various concepts of the arrangements of clay particles in sediments and floccules. Explanation on opposite page.*

assuming that the structure was still preserved. Partial or complete destruction of floccule structure was anticipated in the faecal pellets. The mud lumps and the glauconite grains, however, although not believed to represent the same thing and coming from quite different environments, were believed to have been at least potentially ideal for testing Pryor and Vanwie's (1971) concept of aggregated floccules. The freeze-dried clay and the faecal pellets were chosen as "control" features against which the fabric of the lumps and the glauconite could be compared.

Treatment of the samples prior to SEM study was very simple. It involved only air-drying the pellets, lumps and glauconite, and cementing these (as whole and broken grains) plus some of the freeze-dried mud to separate specimen stubs with Silver Dag. The samples were coated with gold to render them conducting. The air-dried material gave few problems during examination, but the freeze-dried mud seemed to change volume slightly under electron bombardment, developing minute cracks in the gold coating which resulted in the formation of discharge lines across photographs.

Sample 280 is a largely clay-sized (72% clay; median diameter 9.2 phi) sediment with a fairly high water content (67%) that was originally a drab olive-greenish colour. After freeze-drying a fine, pale reddish brown, fluffy, loose powder remained. Some coarse silt-sized grains could be detected by rubbing the powder between the fingers. These grains may have been carried even as far as site 280 as an integral part of a clay-mineral floccule (Biddle & Miles, 1972).

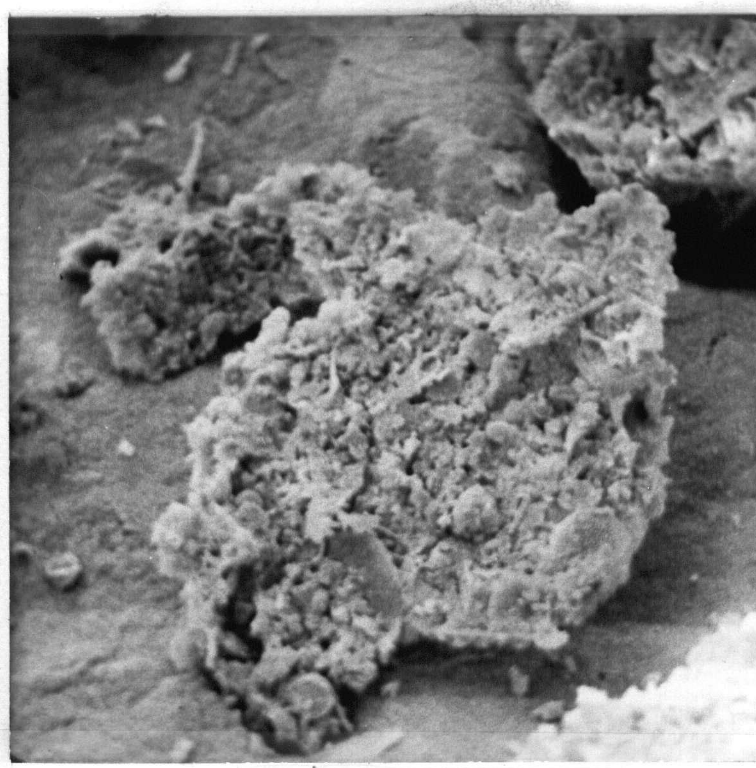
Features referred to as pellets are ellipsoidal, generally fairly smooth-surfaced aggregates that are a uniform drab grey colour in all samples, and are most common in the 32 to 60 mesh range. The pellets viewed with the SEM were from locality 150, but are not restricted to this site. They were common in samples from bank or ridge tops and where poorly sorted gravelly or coarse sandy muds were collected.

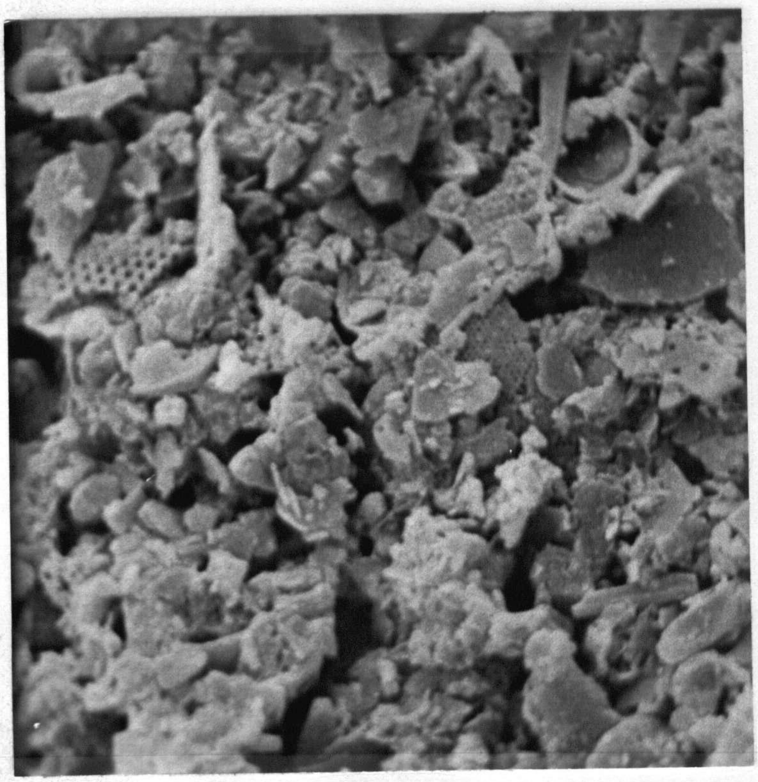
The mud lumps are an enigma. They are irregular shaped, often spheroidal, pale greenish lumps with, when dry, a cracked, almost botryoidal, surface. They have been found in many of the sandy mud samples, particularly those containing very coarse sands and gravels. They were not found in the size-analysed samples, presumably because the dispersion treatment destroyed them if they were present. The problem they pose is one of origin. Three possibilities exist, none of which can practically be discounted: (1) they could develop slowly in the container of stored sediment during slow drying out of the sample, their shape and surface features then reflecting shrinkage on water-loss; (2) they could be produced artificially as a function of washing (using a wrist action shaker, which agitates by oscillating the sample through a small arc) and wet-sieving to separate the sands from muds; (3) their origin could be natural, by aggradation of mud on the bottom in a slightly turbulent, current-affected, environment. In size they are irregular and variable, being present in most sand grades. Like the glauconite, they are not floccules, since the size of floccules tends to be smaller (20-50 microns) and limited (Gripenberg, 1934; Lambe, 1960; Belderson, 1964). It is possible too that these lumps are not only formed by the third alternative but also represent a low-order form of glauconite (Burst, 1958a, b). Compositionally they are not significantly different from the usual clay mineralogy. It must be emphasised, however, that an artificial origin as a function of size separation by sieving cannot be disregarded.

The glauconite grains pose no such problems. They were found in a core (300C), in greater concentration near the top, taken from an area where sedimentation is relatively low (see above, Chapter 3). Their shape is generally quite irregular but rounded, ranging from ellipsoidal to spheroidal. Size is variable, generally in the coarse to very coarse sand grade, and much larger than the faecal pellets. Their colour is similar to those described by Van Andel (1964), pale-greenish inside a dark green, almost black, thin outer skin. When wet they are a more uniform dark green. Mineralogically they have a high content of montmorillonite. These grains are therefore glauconite in the morphological sense (Burst, 1958; Degens, 1965), not the mineralogical. Reviews of the nature, mineralogy, geochemistry and formation of glauconite are available in Could (1965), Burst (1957a, b), Hower (1961) and Degens (1965). It is sufficient to point out that most of the conditions favouring the syndepositional formation of glauconite are met in this environment. A relatively slow rate of sedimentation is suspected; 2:1 layer clays are present; the environment is marine, and reducing; organic material is available but not abundant. Although not measured in this sample, iron and potassium are available in other sediments in the Strait.

Clay fabrics of the freeze-dried sample are illustrated in Figure 59 (a - d). The illite (mica) and organic constituents (diatom mainly) are quite distinctive; other components are not identifiable. The size of components ranges from silt through clay, and the coarser particles exert a modifying influence on the floccule and packing structure. The fabric of this sediment is not obvious but seems to be a

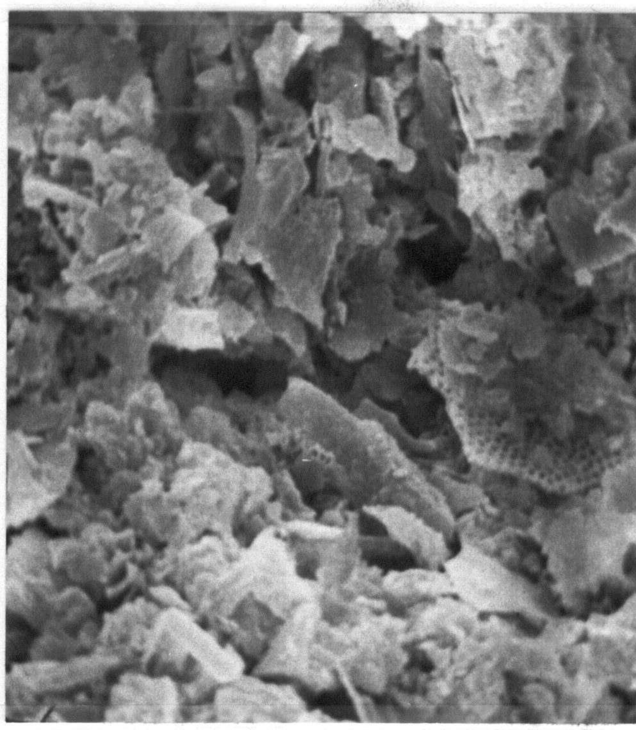
(a)
X580



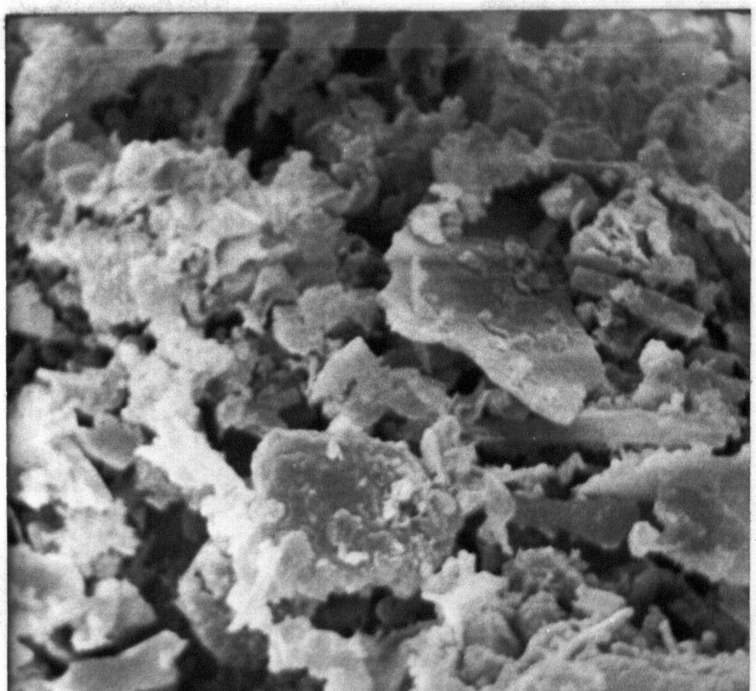


(b)
X2350

FIGURE 59: Scanning Electron Microphotographs of textures from freeze-dried mud. Sample 70-1-280.



(c)
X2400

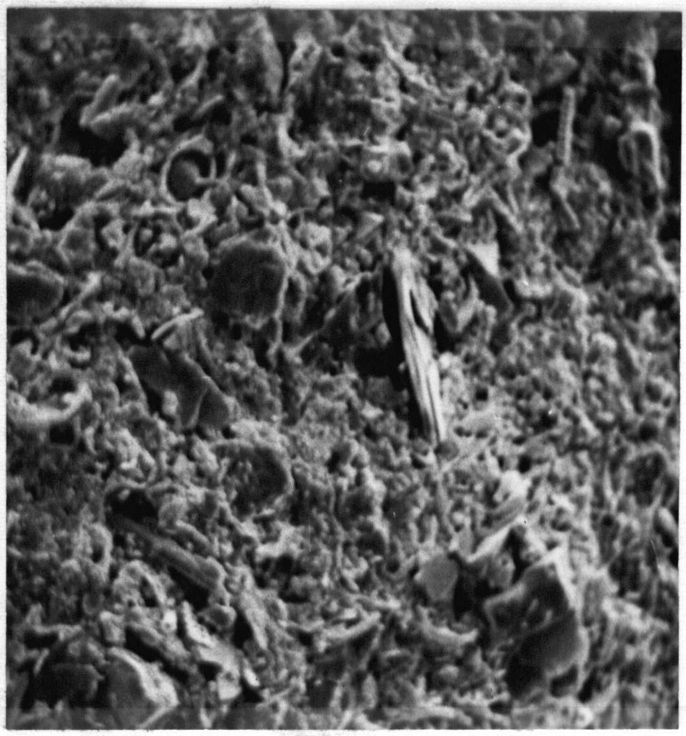


(d)
X2200

Figure 59 ..... continued.

(a)

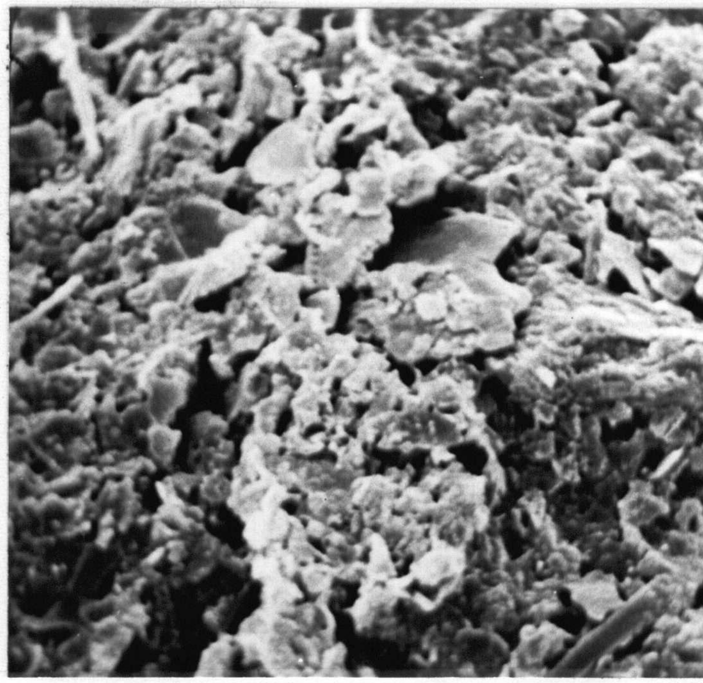
X1050



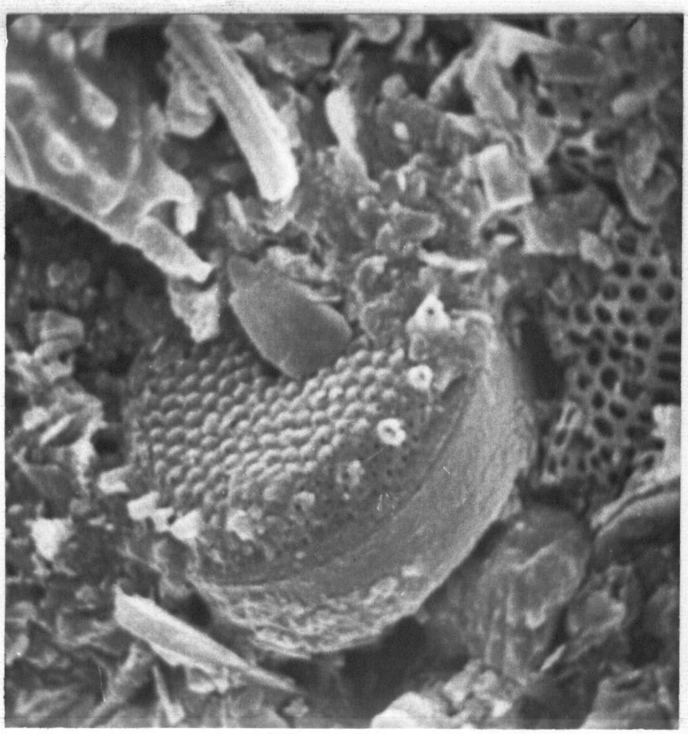
(b)

X5300: enlargement of central portion of (a).

FIGURE 60: Scanning Electron Microphotographs of textures from faecal pellets. Sample 70-1-150.



(c)
X1750



(d)
X2000

Figure 60 ..... continued.

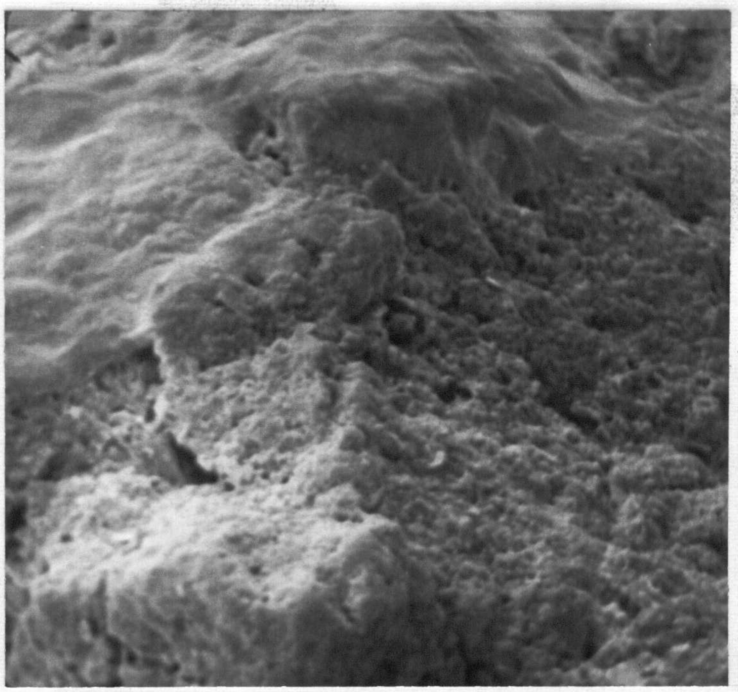
mixture of edge-edge, edge-face, face-face and grains, modified toward a remolded structure (Figure 58).

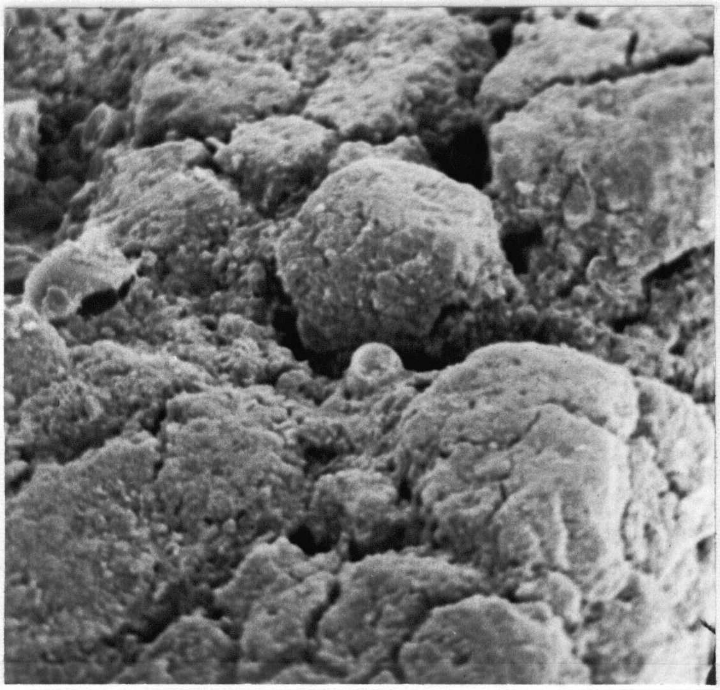
Packing of grains and fabric in faecal pellets from sample 150 are revealed in Figure 60 (a – d). Organic debris and what appear to be micaceous mineral fragments are conspicuous but the packing fabric is not clear. Because of the origin of faecal pellets no fabric was expected to be preserved.

Surface features and some internal structure of the enigmatic mud lumps are shown in Figure 61 (a – g). Figure 61 (a) and (b) show two variations of surface texture, the smooth and botryoidal types respectively. Figures 61 (c) through (g) portray internal features of the mud lumps. Figures 61 (c) and (d), while resolving the plate-like habit of the mineral grains, do not reveal obvious fabric. If anything, the fabric of 61(c) is of the face to face type. Figures 61 (e) through (g) however represent progressive enlargements of a zone of what appears to be clay floccules with very obvious and spectacular fabric. The open, card-house structure of Lambe (1958) and Rosenqvist (1958, 1962) is clearly shown. Although the thickness of the gold coating has rendered Figure 61 (c) a little fuzzy at high magnification, an open, edge-edge and edge-face arrangement of particles is evident. Although only a relatively small area within a mud lump, this type of structure is suggestive of an agglutinated or aggregated floccule origin, which would support the idea of formation of the mud lumps.

An aggregated floccule origin, in which the floccules have an open, perpendicular array structure (Lambe, 1958), is even more evident in the electron photomicrographs of the glauconite grains (Figure 62, a – m). Edge-edge, edge-face and face-face arrangements are

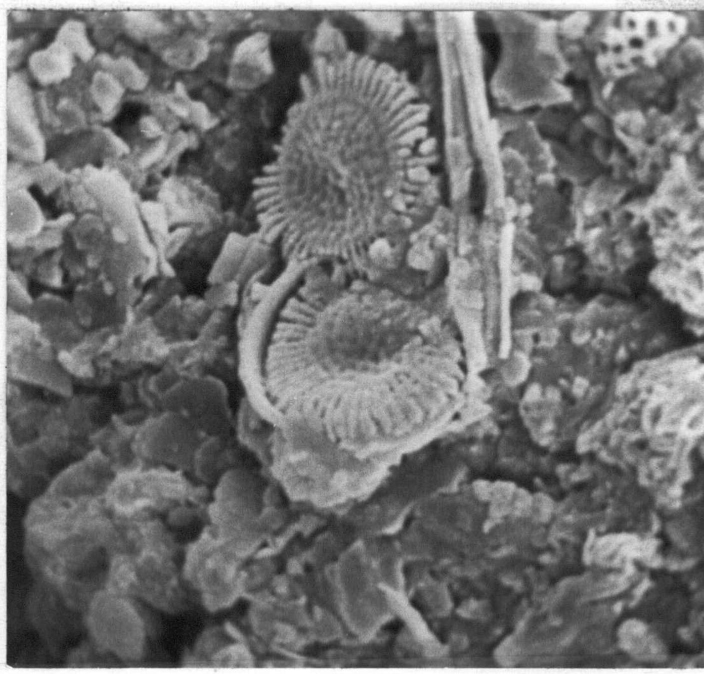
(a)
X500



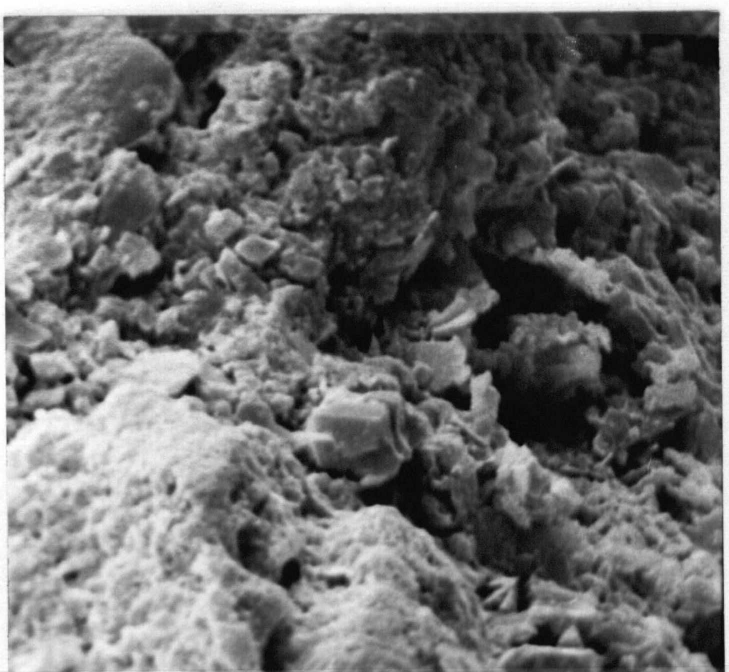


(b)
X500

FIGURE 61: Scanning Electron Microphotographs of textures from agglutinated mud lumps. Sample 70-1-150.

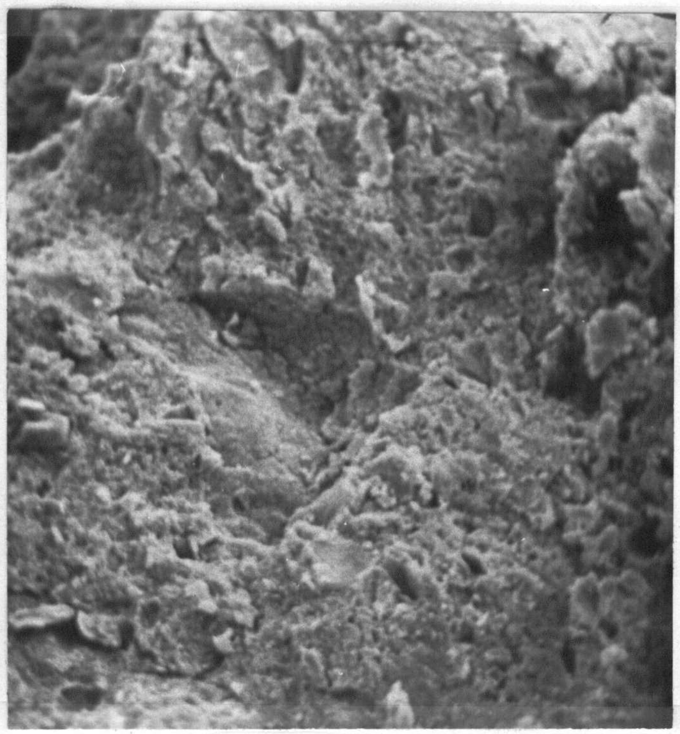


(c)
X5000

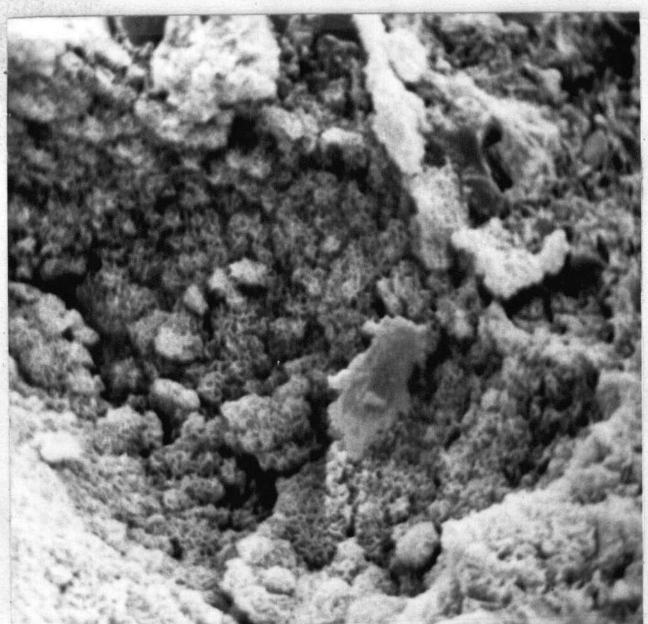


(d)
X2000

Figure 61 ..... continued.

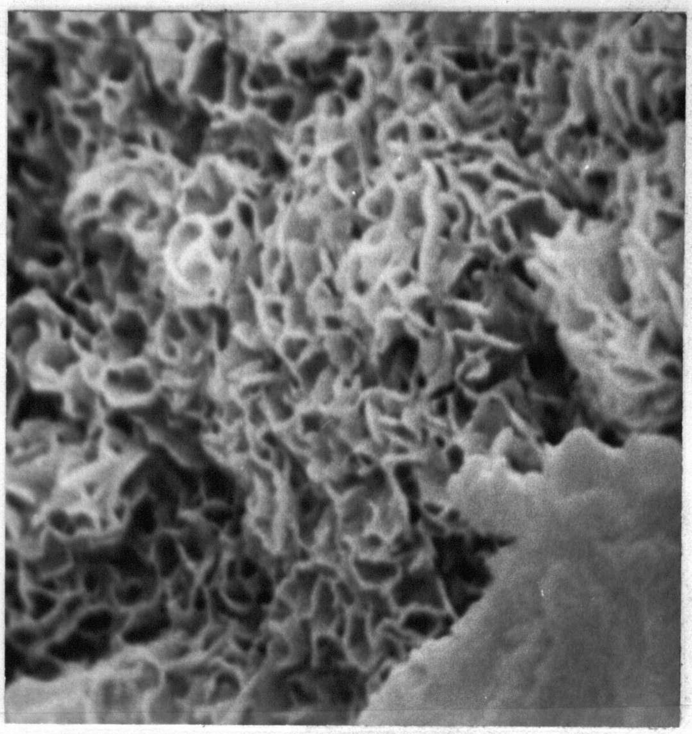


(e)
X500



(f)
X2000: enlargement of central portion of (e).

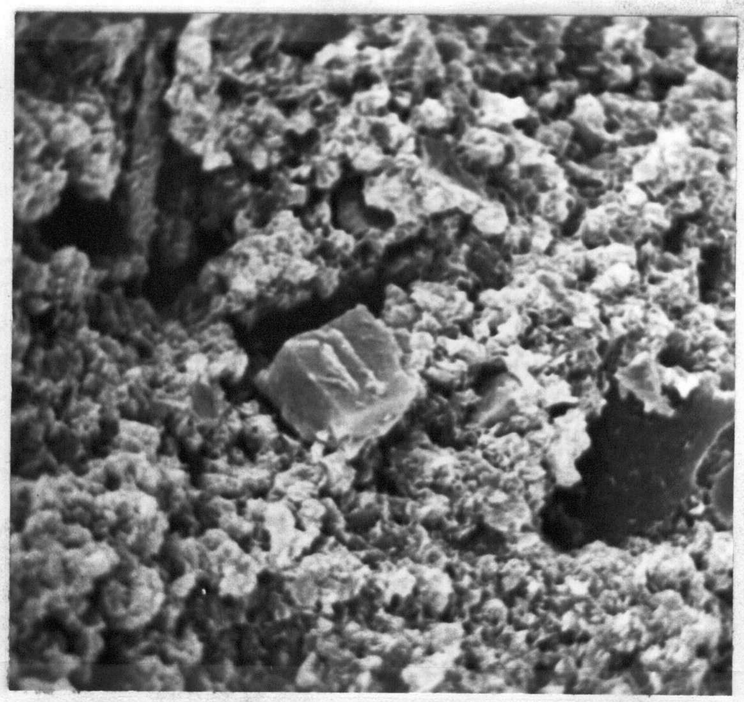
Figure 61 ..... continued.



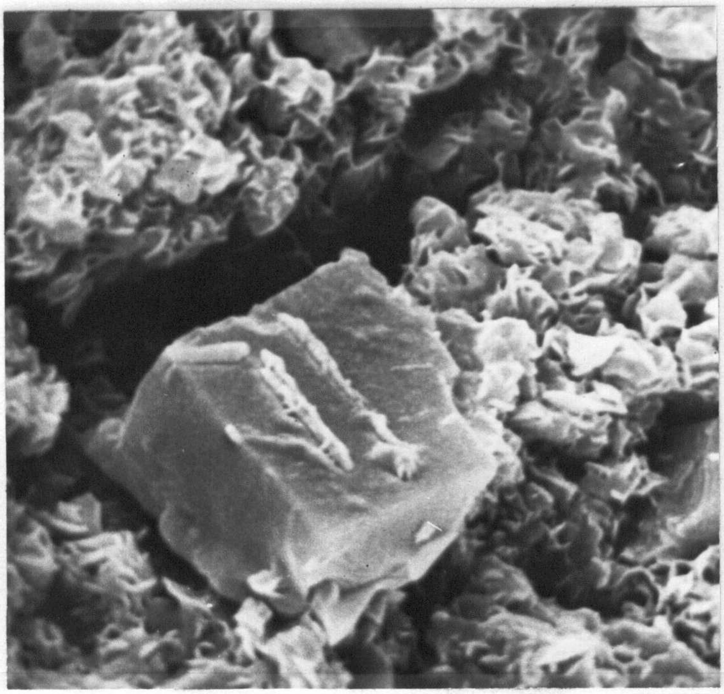
(g) X10,000

Enlargement of central portion of (f).

Figure 61 ..... continued.

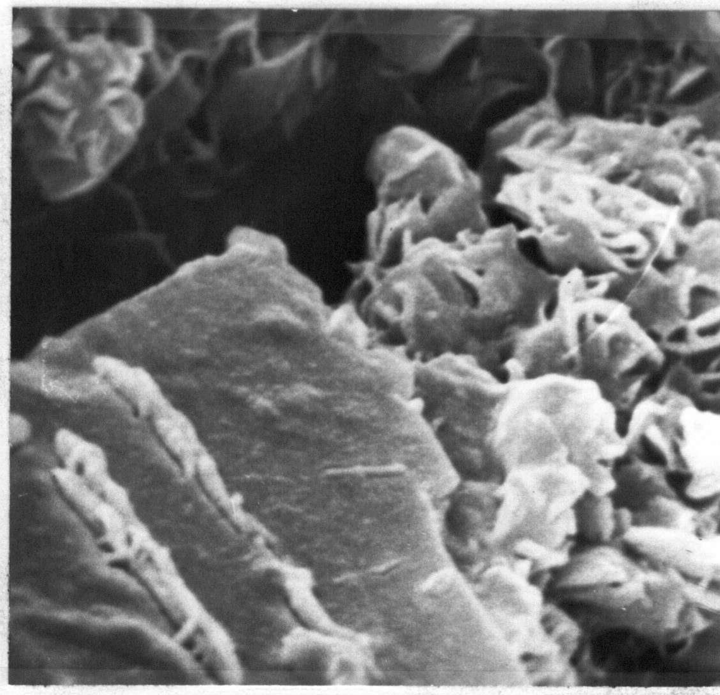


(a)
X2000

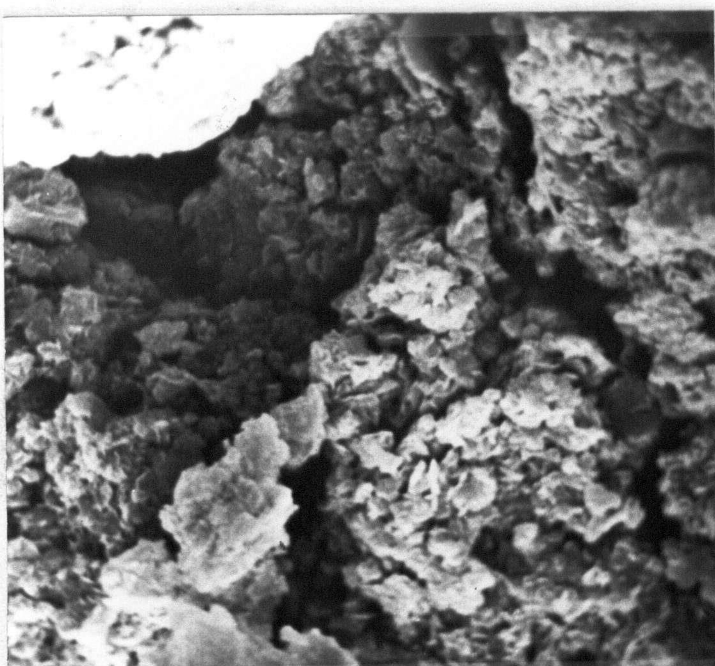


(b)
X5000: enlargement of central portion of (a).

FIGURE 62: Scanning Electron Microphotographs of textures from glauconite pellets. Sample 70-1-300C.



(c)
X10,000
Enlargement of central portion of (b).



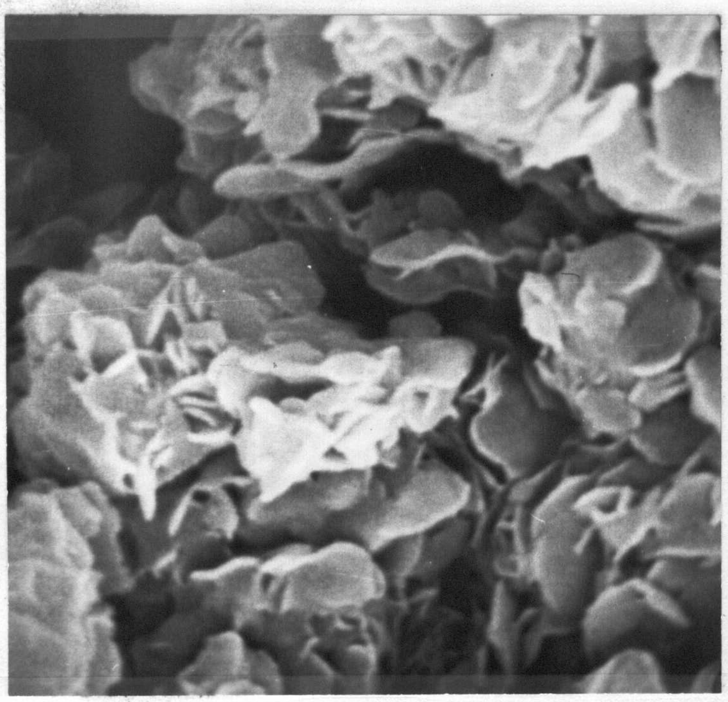
(d)
X2280

Figure 62 ..... continued.

(e)

X5400

Enlargement of central portion of (d).

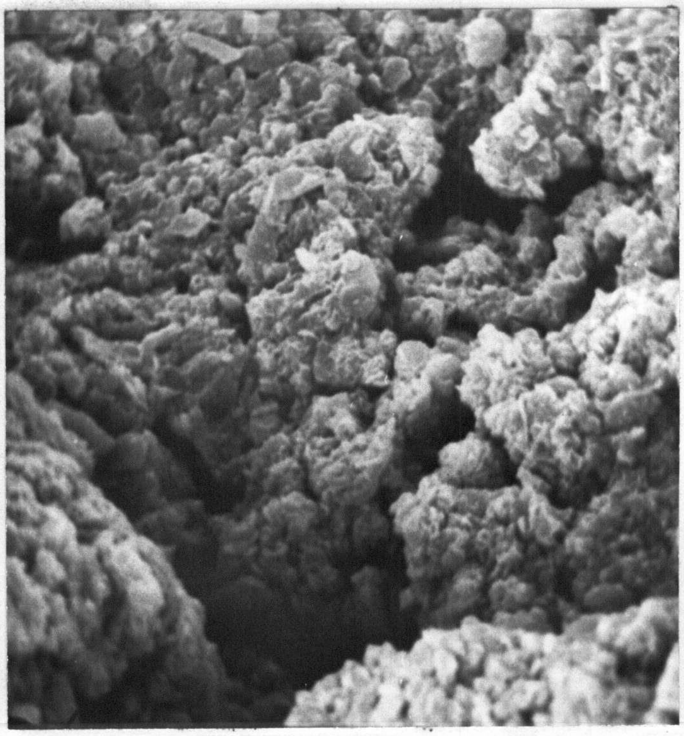


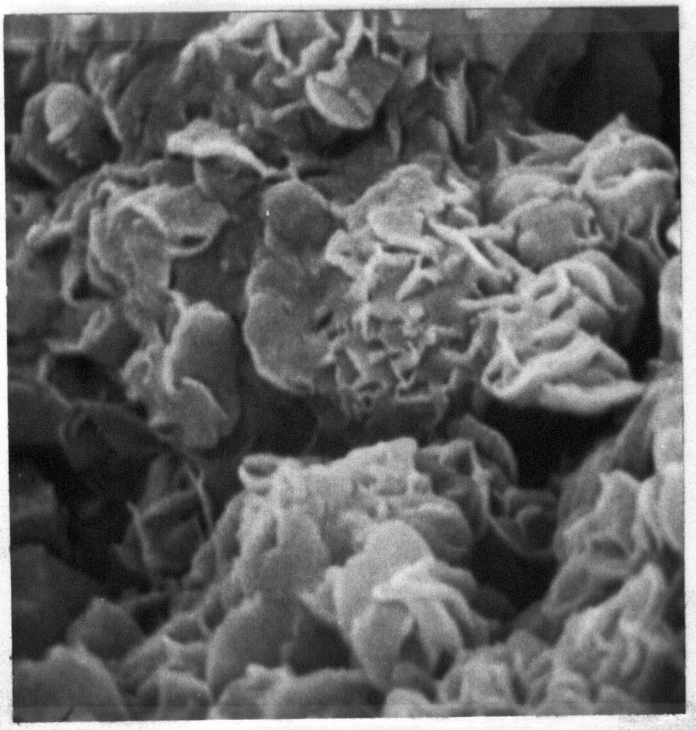
(f)

X10,800: enlargement of central portion of (e).

Figure 62 ..... continued.

(g)
X2300

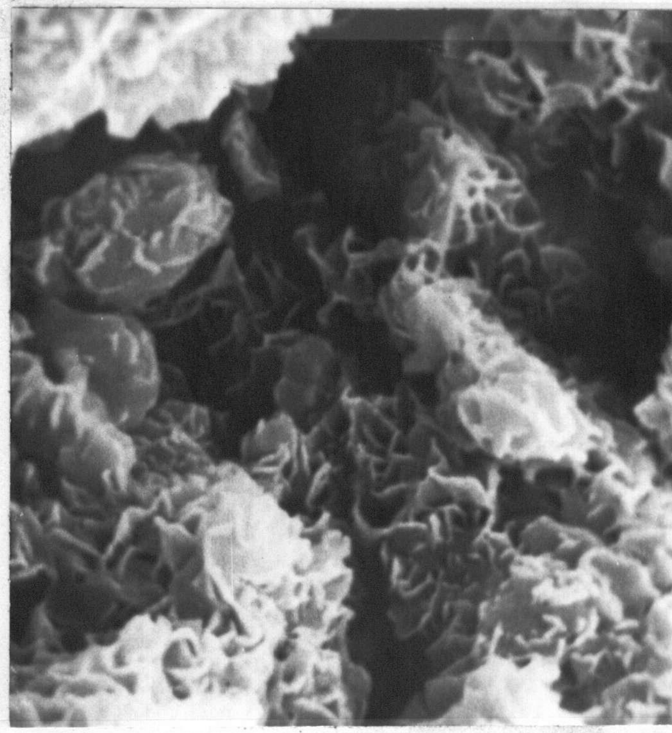




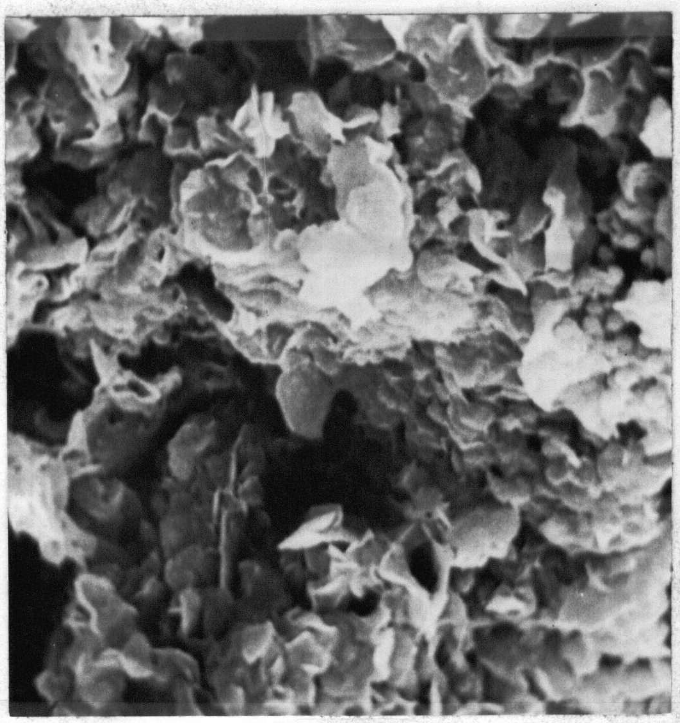
(h)
X10,600

Enlargement of central portion of (g).

Figure 62 ..... continued.

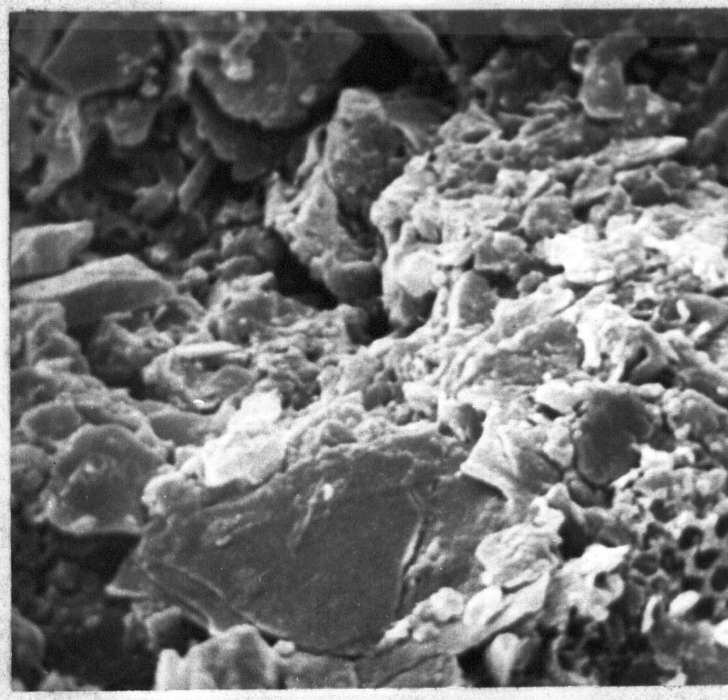


(i)
X9,200



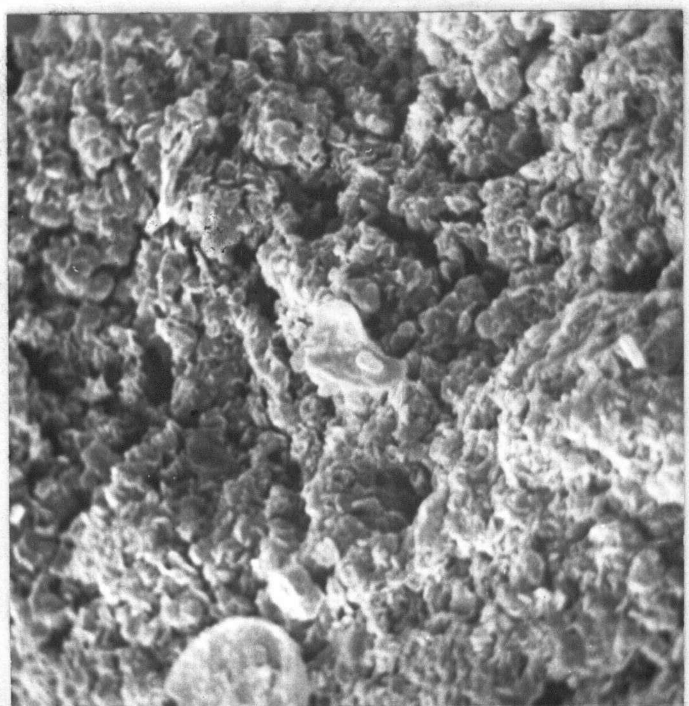
(j)
X5000

Figure 62 ..... continued.



(k)

X5000



(1)
X2180

Figure 62 ..... continued.

apparent. The face-face arrangement (Figure 62 (f), (j) and (k)) seems to have developed by remolding or slight compaction of an originally predominantly edge-edge, and/or edge-face structure.

Fabrics portrayed by the mud lumps and glauconite confirm the "corner plane-cardhouse" (or Goldschmidt-Lambe) theory of mineral arrangement in flocculated clays (Rosenqvist, 1958; Lambe, 1960; Meade, 1964). That no distinctive fabric could be recognised in the faecal pellets was to be expected, and at least supports an argument against a faecal origin of the mud lumps and glauconite grains. The apparent absence of open fabric in the freeze-dried clay was disappointing. It may be a reflection of the sample preparation, or even the sampling process. Freeze-drying samples collected with a grab or corer that produces less sample compression and disturbance than a LaFond-Dietz or Phleger respectively might reveal or preserve original floccule structures. That the fabric structures, which appear fairly delicate, should be preserved in the lumps and glauconite grains is believed to result from the eventual protection of the inner portions of these grains from further disruption. The outer surfaces are always smoother and do not show fabric structure. Slow sedimentation and perhaps relatively gentle agitation may be the explanation for the better preservation of the open structures in glauconite grains compared to those of the mud lumps.

4.5 SUMMARY AND CONCLUSIONS

The Fraser River is the primary source for the Recent sediments in the Strait of Georgia. This river has an immense watershed involving a wide variety of rock types. In its lower reaches (south of Quesnel) much of its course is through soft, easily eroded, glacial drift and till. A large part of its load is derived from this material.

Within the Strait, local sources of sediment include Pleistocene deposits such as Point Grey and Point Roberts, and the upstanding ridges within the Strait, also largely of Pleistocene glacial and interglacial material (Tiffin, 1969). Marginal areas of the Strait north and west of the Fraser Delta are of only minor, local importance. No coarse sediment reaches the study area from Vancouver Island.

This situation imposes a monotonous similarity on the sediment composition within the Strait of Georgia, a feature particularly evident from the mineralogy of the silt and clay size grades.

Most of the sand-size material separated from the samples collected occurred in the fine-sand grade. Its composition is dominated by quartz, felspar and ferromanganesian minerals (mostly amphiboles). Mica is conspicuous in most samples although not necessarily abundant. The distribution of muscovite is greater than has been known, and the probability of its origin from more sources than just the Fraser River has been established. This reduces its value as a source indicator. Pink garnet is conspicuous, although present in small quantities, in all samples.

The mineralogy of the sub-sand-size fractions is remarkably consistent. Minor quantitative differences are indicated by variation in X-ray diffraction peak intensities, but the same mineralogy is recorded throughout the Strait. Coarse and medium silt fractions are basically similar to the fine and very fine sands. In the fine silt fraction phyllosilicate minerals become more prominent, eventually dominating the mineralogy in the clay fractions. Mica, montmorillonite, and chlorite are the main clay mineral types. Some kaolinite is suspected as well as, in untreated samples, mixed-layer clays.

Differential flocculation and segregation of clay-mineral species in the marine environment of the Strait does not occur.

Alteration of the clay suite on passing from fresh water to the marine environment is minor, and is revealed as an increase in content of exchangeable cations, particularly magnesium. A significant correlation exists between the content of clay-sized material in a sediment and its exchange capacity, exchange cations, and contents of some oxides and hydroxides. Similarity of Fraser River and Georgia Strait samples implies that the mineralogy in the Strait reflects the source composition and is not a function of marine diagenesis.

Examination of mud fabrics with the scanning electron microscope indicates that flocculation is an important process in clay sedimentation, with the formation of open, card-house type or perpendicular array structures.

CHAPTER 5

GEOCHEMISTRY

5.1 INTRODUCTION

A brief and mainly descriptive account is given of the distribution and content of carbon, of organic and carbonate origin, in the sediments of Georgia Strait. Nodular ferromanganese accretions collected from two sampling sites in the Strait are described.

5.2 CARBON

5.2.1 TECHNIQUES

The carbon contents of one hundred and forty-two Strait of Georgia and three Fraser River sediment samples were measured in duplicate with a LECO model 572-100 Carbon Determinator (Laboratory Equipment Corporation, St. Josephs, Michigan). Samples were oven-dried at low temperature (less than 100^0C), crushed in a porcelain mortar to pass a 35 mesh sieve, and subsampled by quartering. Total carbon content was determined from one subsample, and organic carbon was determined on another subsample following treatment with 5% HCl to dissolve carbonates (Frankenberg and Giles, 1970). The difference between the two results gave a measure of the carbonate carbon content.

The LECO Carbon Determinator measures carbon contents gasometrically, after oxidising a sample in a stream of oxygen, with iron and tin accelerators, in a high temperature induction furnace. Carbon contents of small samples (usual sample weight is 1.0 or 0.5 gm.) can be analysed with high precision. Van Andel (1964) quotes a reproducibility of 0.02% carbon. A reproducibility of ± 0.1% between duplicates of

SAMPLE NO.	TOTAL CARBON%	ORGANIC CARBON%	X1.72=% ORGANIC MATTER	CARBONATE CARBON %	X8.33=% CARBONATE AS CACO3
10	1.38	0.53	0.91	0.85	7.09
13	1.08	0.60	1.03	0.48	4.02
19	1.42	0.58	1.00	0.84	6.96
21	0.34	0.19	0.33	0.15	1.21
23	0.87	0.60	1.03	0.27	2.22
25	0.98	0.67	1.15	0.31	2.53
40	1.16	0.71	1.22	0.45	3.68
42	1.77	0.73	1.26	1.04	8.61
44	1.11	0.90	1.55	0.21	1.77
45	1.52	0.91	1.57	0.61	5.11
46	2.30	0.55	0.95	1.75	14.51
48	0.86	0.46	0.79	0.40	3.34
50	0.91	0.35	0.60	0.56	4.65
53	1.18	0.84	1.44	0.34	2.83
54	0.69	0.56	0.96	0.13	1.08
56	0.57	0.42	0.72	0.15	1.21
58	0.66	0.47	0.81	0.19	1.57
60	0.75	0.54	0.93	0.21	1.74
62	0.76	0.52	0.89	0.24	2.03
73	1.26	0.87	1.50	0.39	3.23
75	1.05	0.75	1.29	0.30	2.49
76	1.08	0.78	1.34	0.30	2.49
77	1.06	0.64	1.10	0.42	3.51
79	0.94	0.67	1.15	0.27	2.25
81	0.71	0.45	0.77	0.26	2.12
82	0.09	0.07	0.12	0.02	0.16
83	0.18	0.18	0.31	0.00	0.00
85	0.78	0.52	0.89	0.26	1.34
86	1.07	0.55	0.95	0.52	4.33
87	1.54	0.99	1.70	0.55	4.55
88	1.27	0.72	1.24	0.45	4.58
89	1.20	0.77	1.32	0.43	3.58
92	0.57	0.55	0.95	0.02	0.17
93	0.69	0.51	0.88	0.11	0.92
96	1.51	0.93	1.60	0.58	4.84
97	1.47	1.04	1.79	0.43	3.53
98	1.55	1.02	1.75	0.53	4.37
100	1.25	0.76	1.31	0.49	4.02
102	0.84	0.48	0.83	0.36	2.96
103	1.04	0.56	0.96	0.48	3.99
104	1.18	0.66	1.14	0.52	4.38
106	1.16	0.65	1.12	0.51	4.26
108	1.56	1.01	1.74	0.55	4.59
109	1.46	1.00	1.72	0.46	3.84

111	1.08	0.72	1.24	0.34	3.06
113	1.46	1.07	1.84	0.39	3.26
114	1.42	1.01	1.74	0.41	3.46
115	1.54	1.48	2.55	0.06	0.50
116	1.37	1.10	1.89	0.27	2.25
121	1.37	1.19	2.05	0.18	1.50
124	1.18	1.14	1.96	0.04	0.33
125	1.55	1.30	2.24	0.25	2.08
126	1.40	1.21	2.08	0.19	1.58
128	1.15	1.01	1.74	0.14	1.17
129	1.20	0.91	1.57	0.29	2.42
133	1.45	1.13	1.94	0.32	2.67
141	1.49	1.33	2.29	0.16	1.33
145	1.35	1.30	2.24	0.05	0.42
147	1.22	1.21	2.08	0.01	0.08
148	1.08	0.99	1.70	0.09	0.75
149	1.18	0.98	1.69	0.20	1.67
152	1.44	1.34	2.30	0.10	0.83
153	1.56	1.36	2.34	0.20	1.67
160	1.46	1.24	2.13	0.22	1.83
161	1.22	1.06	1.82	0.16	1.33
162	1.02	0.87	1.50	0.15	1.25
163	1.05	1.01	1.74	0.04	0.33
167	1.34	1.31	2.25	0.03	0.25
168	1.63	1.30	2.24	0.33	2.75
170	1.37	1.31	2.25	0.06	0.50
171	1.54	1.29	2.22	0.25	2.08
183	1.45	1.27	2.18	0.18	1.50
184	1.38	1.25	2.15	0.13	1.08
186	1.30	1.15	1.98	0.15	1.25
190	1.27	1.20	2.06	0.07	0.58
193	1.54	1.45	2.49	0.09	0.75
196	1.57	1.30	2.24	0.27	2.25
197	0.98	0.95	1.63	0.03	0.25
200	1.64	1.47	2.53	0.17	1.42
202	1.70	1.46	2.51	0.34	2.83
204	1.48	1.43	2.46	0.05	0.42
209	1.30	1.13	1.94	0.17	1.42
212	1.49	1.30	2.24	0.10	0.83
213	1.52	1.41	2.43	0.11	0.92
214	1.53	1.45	2.49	0.08	0.67
215	1.24	1.03	1.77	0.21	1.75
219	1.27	0.98	1.69	0.29	2.42
220	0.95	0.89	1.53	0.06	0.50
221	1.55	1.21	2.08	0.34	2.83
222	1.47	1.40	2.41	0.07	0.58
223	1.65	1.54	2.65	0.11	0.92
225	1.70	1.74	2.99	0.04	0.33
227	0.52	0.48	0.83	0.04	0.33
229	1.09	0.96	1.65	0.13	1.08
230	1.06		NO	DATA	
231	1.54	1.41	2.43	0.13	1.08
232	1.48	1.36	2.34	0.12	1.00
234	1.06	0.85	1.46	0.21	1.75

236	1.28	1.06	1.82	0.22	1.83
238	0.78	0.61	1.05	0.17	1.42
251	1.63	1.44	2.48	0.19	1.58
253	1.08	1.01	1.74	0.07	0.58
254	1.80	1.53	2.63	0.27	3.08
255	1.43	1.40	2.41	0.03	0.25
257	1.57	1.49	2.56	0.08	0.67
259	1.63	1.58	2.72	0.05	0.42
261	1.61	1.49	2.56	0.12	1.00
262	1.46	1.43	2.46	0.03	0.25
263	0.90	0.88	1.51	0.02	0.17
264	1.31	1.18	2.03	0.13	1.08
265	0.99	0.93	1.60	0.06	0.50
267	1.47	1.43	2.46	0.04	0.33
268	1.16	1.04	1.79	0.12	1.00
269	1.50	0.89	1.53	0.61	5.08
280	1.79	1.46	2.51	0.33	2.70
282	2.00	1.97	3.39	0.03	0.25
284	1.80	1.78	3.06	0.02	0.17
286	0.58	0.58	1.00	0.00	0.00
287	1.76	1.42	2.44	0.34	2.83
289	1.73	1.65	2.84	0.08	0.67
291	1.45	1.28	2.20	0.17	1.42
293	1.72	1.61	2.77	0.11	0.92
295	0.85	0.62	1.06	0.23	1.92
297	1.50	1.44	2.48	0.06	0.50
299	1.22	0.99	1.70	0.23	2.17
301	1.47	1.21	2.08	0.26	2.17
302	1.41	1.27	2.18	0.14	1.17
303	1.64	1.54	2.65	0.10	0.83
305	1.80	1.74	2.99	0.06	0.50
309	1.44	1.42	2.44	0.02	0.17
311	1.88	1.80	3.10	0.08	0.67
313	1.48	1.22	2.10	0.26	2.17
315	0.90	0.84	1.44	0.06	0.50
317	2.00	1.88	3.23	0.12	1.00
321	1.99	1.75	3.01	0.24	2.00
326	1.45	1.34	2.30	0.11	0.92
328	1.31	1.23	2.12	0.08	0.67
329	1.85	1.84	3.16	0.01	0.08
330	1.86	1.48	2.55	0.38	3.17
331	1.29	1.00	1.72	0.29	2.42
332	1.43	1.14	1.96	0.29	2.42
335	1.82	1.47	2.53	0.35	2.92
336	1.84	1.40	2.41	0.44	3.67
337	1.03	0.88	1.51	0.15	1.25
340	1.44	1.31	2.25	0.13	1.08
341	1.13	1.04	1.79	0.09	0.75
342	1.36	1.14	1.96	0.12	1.00
345	2.10	1.92	3.30	0.18	1.50
347	1.56	1.47	2.53	0.09	0.75
349	2.01	1.81	3.11	0.20	1.67
350	1.78	1.73	2.98	0.05	0.42
351	0.43	0.35	0.60	0.08	0.67

FR1U	0.86	0.59	1.01	0.27	2.25
FR2U	0.93	0.62	1.07	0.31	2.58
FR3U	0.71	0.50	0.86	0.20	1.75
*280	1.79	1.46	2.51	0.33	2.70
*280A	1.53	1.19	2.05	0.34	2.78
*280B	1.57	1.19	2.05	0.38	3.17
*280C	1.56	1.23	2.12	0.33	2.67
*280D	1.51	1.19	2.05	0.32	2.67
'280	1.79	1.12	1.93	0.67	5.54
'280A	1.53	0.87	1.50	0.66	5.46
'280B	1.57	0.66	1.14	0.91	7.59
'280C	1.56	0.63	1.08	0.93	7.75
'280D	1.51		NO	DATA	

	PERCENT ORGANIC CARBON	
	AVERAGE	RANGE
GULF OF CALIFORNIA		
SLOPE	3.60	0.8-7.4
BASINS	2.55	0.4-4.0
GULF OF PARIA	0.71	0.1-1.4
MISSISSIPPI DELTA	0.61	0.1-1.3
ARANSAS BAY, TEXAS	1.26	0.61-1.7
SAN ANTONIO BAY, TEXAS	0.82	0.3-2.7
CALIFORNIA OFFSHORE BASINS	4.32	
GULF OF MEXICO SHELF	0.36	
SLOPE	0.82	
SIGSBEE DEEP	0.47	
ABIDJAN LAGOON, WEST AFRICA	6.43	4.5-12.8
ARCACHON BASIN, FRANCE	2.07	0.3-5.2
BALTIC SEA	2.55	2.3-4.8
BENGAL SHELF	0.77	0.2-1.6
PERU-CHILE TRENCH		
BASIN	0.67	0.1-0.9
SLOPE	1.92	0.3-9.6

FROM VAN ANDEL (1964, TABLE X, P.259).

TABLE XI: CARBON CONTENTS OF GEORGIA STRAIT AND FRASER RIVER SAMPLES. SUBSAMPLES OF #280 WERE ANALYSED AFTER TREATMENTS WITH HCL (MARKED *) TO REMOVE CARBONATE, AND HYDROGEN PEROXIDE (MARKED ') TO REMOVE ORGANIC MATTER.

samples was regarded as acceptable for this study, and in fact most duplicates gave results that agreed within ±0.05%. High precision overlooks the fact that the subsample analysed weighs only 0.5 gm., which is assumed to be representative of a grab-bucket-full of sediment that itself is supposedly representative of a large area of sea-floor. Averages of the duplicate values are presented in Table XI, which also includes some average values for Recent marine sediments for comparison (from Van Andel, 1964, Table X, p.259).

One sample, number 280, was divided into five subsamples each of which was further split into three. Total carbon content was measured on one of the three from each subsample, the other two being treated with either hydrogen peroxide (to oxidise organic matter) or 5% HCl (to dissolve carbonate). Results are included in Table XI. More consistent results are obtained with the HCl treatment than with peroxide; the latter does not appear to be as efficient at oxidising organic matter as HCl is at removing carbonates.

5.2.2 DISCUSSION

The organic carbon content of the Georgia Strait sediments averages 1.08% (corresponding to an organic matter content of 1.86%: organic matter = 1.72x % organic carbon Kemp and Lewis, 1968; see also Trask, 1939; Emery, 1960), with values ranging between 0.07% and 1.97% (0.12% to 3.39% organic matter). These values are very low compared to those from the sediments in the basins off the California coast (Emery, 1960), and low even when compared to the carbon content of Baltic Sea sediments (Van Andel, 1964, Table X, p.259). Average values of organic carbon from the Mississippi Delta are lower than those from

Georgia Strait (Van Andel, ibid.), which may reflect a relationship between sedimentation rate and carbon content such as that discussed by Emery (1960). Too high a rate of deposition of terrigenous material dilutes the organic content, while sedimentation rates that are too low generally permit oxidation and consequent loss of organic matter before it can be protected by burial.

Carbonate carbon averages 0.23% (a calcite equivalent of 1.92% assuming all the carbonate is present as calcite: calcite % = 8.33 x % carbonate carbon), varying between 0% and 1.75% (0% to 14.51% calcite). Coarse carbonate debris, either whole or coarse sand-size fragments of skeletal material, was not included in this analysis. The average carbonate content, expressed as calcite, for the Fraser River samples is 2.19%, while the average value for organic carbon (organic matter) is 0.57 (0.98)%.

The distribution of carbonate-carbon values in the Strait of Georgia does not show a regular pattern. Generally, there is a concentration of the highest values southeast of a line between Point Roberts and the southeastern end of Mayne Island. This coincides fairly closely with the sandier, relict sediments of Roberts Swell and Boundary Basin, where a fairly abundant fauna including molluscs, echinoids, bryozoans and solitary corals occurs. Intermediate values (0.25 to 0.75%) also occur in this area, and in a broad band north, southwest and south of Sand Heads. Isolated groups of samples with intermediate values occur throughout the northwestern portion of the Strait. A belt of low values (0.1 to 0.25%) separates the Roberts Swell and Fraser Delta areas, and low values occur over most of the rest of the Strait northwest of the delta. Very low contents of carbonate-carbon (less than 0.1%) are

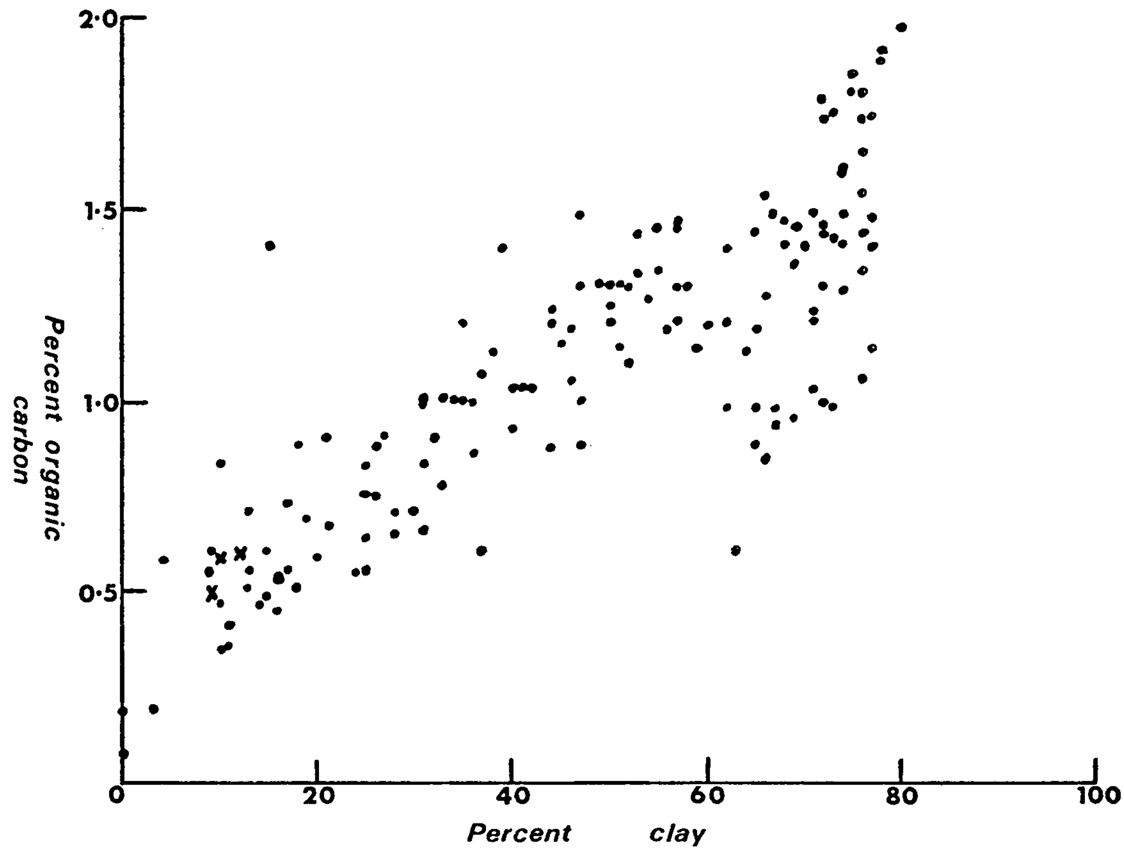


FIGURE 63: *Relationship between organic carbon and clay content for Strait of Georgia and Fraser River (x) sediments.*

scattered throughout the Strait northwest of Point Roberts.

Very low values for organic carbon (less than 0.5%) occupy a broad, hour-glass shaped zone that trends south-southeast from Sand Heads but does not reach Boundary Basin. Low values (0.5 to 1.0%) occur along the delta front from Sand Heads to Point Grey, south of a line between Sand Heads and Porlier Pass, in isolated patches around the margins of the Strait, and in local areas associated with ridge tops. Intermediate concentrations of organic carbon (1.0 to 1.5%) occur throughout most of the Strait northwest of Sand Heads except for isolated areas with high organic carbon contents (greater than 1.5%) that are associated with the clay-rich sediments of the deep basins, Ballenas and Malaspina.

Reference has already been made to the results of a correlation and regression analysis conducted on Group A samples in which % clay and % organic carbon were included as variables. In the three cases described (also Table X) the correlation between organic carbon and clay content is high. When all analysed samples (N=146) are included in a correlation matrix and regression analysis the correlation is 0.788, which is significant at the 1% level (see also Figure 63). A similarly high, positive correlation between organic carbon and clay contents has been noted by many workers (e.g. Van Andel, 1964; Thomas, 1969; Kemp, 1969, 1971; Thomas et al., 1972) which suggests that the organic matter is either fine-grained or, more likely, is adsorbed as non-particulate, molecular material onto the clay minerals (Hahn and Stumm, 1970).

5.3 MANGANESE NODULES

To date, manganese nodules have been recorded from only one other locality in British Columbia's coastal waters (Grill et al., 1968a, b).

Manganese nodules are of value in the present thesis in so far as their existence implies certain restrictions on chemical and physical conditions for localised areas in the Strait. Of primary importance is the implication of low sedimentation rates required for nodule growth and preservation. It is not proposed to attempt either a review of published information on sea-floor manganese nodules (see for further refernces Mero, 1964; Bonatti and Nayudu, 1965; Chester, 1965; Degens, 1965) or any sophisticated chemical interpretations (see Bender, Ku and Broecker, 1966; Elderfield, 1972). Manganese crusts and stains on pebbles and in sponge skeletons have been referred to and described in earlier sections; only the nodules will be discussed here.

5.3.1 LOCALITIES

Two sites are known where well-developed nodules occur. One of these was a dredge haul collected in July, 1968, from the CSS VECTOR by Dr J.W. Murray, Geology Department, U.B.C. The dredge site was located at latitude 49°21.8'N, longitude 124°02.0'W, on the southwest side of Sangster Ridge in approximately 300 metres of water. From other evidence in the dredge haul, and from seismic studies, this ridge has been interpreted as of Pleistocene age and morainal origin (Tiffin, 1969). The second locality, 70-1-341, is at 49°21.7'N, 124°09.1'W, at 326 metres depth on the eastern side of the low col connecting Sangster Ridge to the Ballenas Islands. Samples from this locality were collected with a Peterson grab sampler. In neither case is the area over which the nodules occur fully known, but samples without nodules were collected nearby suggesting the areas of nodule occurrence are small.

5.3.2 MORPHOLOGY

Sample material from Sangster Ridge includes one large, discoidal nodule, one pebble completely encircled by a narrow, raised band of accretionary ferromanganese material, two nodule fragments, and a small patch of ferromanganese material on a quartz-diorite cobble. The specimens from locality 341 include one broken and four entire nodules still with pebble nuclei, seven separate fragments of concavo-convex discoidal rims without nuclei but showing the imprint of the pebble, and some sponge skeletons containing a brown, earthy material that gave a positive test for manganese when fused with sodium carbonate (Berry and Mason, 1959, p.266).

Nodules from both localities are discoidal, and always have a pebble as their nucleus. Their shape is usually concavo-convex, and the occurrence of corals, sponge bases, bryozoa and rare worm tubes on the convex sides suggest that they probably rested on the bottom with this surface uppermost. In all specimens except one the pebble was still visible in the centre even when the discoidal rim had grown 0.3 to 0.5 cm. above the pebble surface. One nodule showed only a shallow depression in the upper surface above the pebble. The largest nodule from the Sangster Ridge dredge haul and some fragments from locality 341 possessed a second, less well-developed, bench on top of the main nodular mass (Figure 64 a).

Internally, the nodules are concentrically laminated, with thin laminae which are closely spaced parallel to the upper and lower surfaces, but wider and thicker around the curved rim of the disc. A thin limonitic skin is often developed on the lower surface.

(A)

(B)

FIGURE 64: Manganese nodules collected from (A) Sangster Ridge, and (B) sample site 70-1-341.

The largest nodule, from Sangster Ridge, while not truly circular in outline, has a maximum diameter of 13.5 cm. It is 2.5 cm. thick from the lower surface of the main nodule mass to the top of the upper bench. Radial width of manganese accumulation around the pebble nucleus averages about 3 cm., with a maximum of 4.5 cm. Fragments of discoidal nodules from site 341, still bearing the imprint of the pebble nucleus, range between 3 and 5.5 cm. in width from pebble imprint to nodule rim.

Surface textures range from almost smooth, particularly on undersurfaces, to local small areas that are finely botryoidal. The latter texture covered the entire upper surface of two nodules from site 341.

5.3.3 CHEMICAL ANALYSES

Four samples were sent to Mr S. Holland, Mineralogical Branch, Department of Mines and Petroleum Resources, Victoria, B.C., for semi-quantitative spectrochemical analysis for several elements and assays of manganese, iron, cobalt and nickel. Results are given in Table XII, which also includes the analysis of a manganese nodule from Jervis Inlet collected by Dr J.W. Murray, Geology Department, U.B.C., and analysed in the same laboratory. The analyses represent average compositions over the width of nodules from which the samples were taken. The samples were:

A: three fragments representing a wedge broken off the large Sangster Ridge nodule. It extends from nucleus to outer margin;

B: two nodule fragments from Sangster Ridge;

C: large fragment of a nodule from locality 341;

D: large fragment of a nodule from locality 341, similar

EL.	A	B	C	D	JERVIS
Si	>10	>10	>5	>5	
Al	0.3-3	1-9	0.23-2.1	0.17-1.5	1-9
Mg	0.5-4.5	1-9	0.42-3.75	0.3-3	0.25-2.25
Ca	0.07-0.6	0.22-1.95	0.03-0.3	0.017-0.15	0.45-4.05
P	0.02-0.18	0.027-0.24	N.D.	N.D.	
Fe	2.2-19.5	2.17-19.5	0.7-6	0.5-4.5	4-36
Pb	0.05-0.45	0.03-0.3	0.017-0.15	0.003-0.03	<0.1
Cu	0.013-0.12	0.007-0.06	0.003-0.03	0.0017-0.015	
Zn	0.003-0.03	0.0013-0.012	0.0003-0.003	0.0003-0.003	-
Mn	>10	>10	>10	>10	>5
Ag	TRACE	TRACE	TRACE	N.D.	N.D.
V	0.005-0.045	0.005-0.045	0.004-0.036	0.0017-0.015	0.007-0.06
Ti	0.017-0.15	0.05-0.45	0.01-0.09	0.005-0.045	0.017-0.15
Ni	0.005-0.045	0.003-0.03	0.003-0.03	0.0027-0.024	0.007-0.06
Co	0.01-0.09	0.012-0.105	0.003-0.03	0.0023-0.021	0.003-0.03
Na	>2	>2	>2	>2	>2
K	0.42-3.75	0.42-3.75	0.3-3	0.3-3	0.45-4.05
Sr	0.007-0.06	0.02-0.18	0.007-0.06	0.007-0.06	0.017-0.15
Cr	0.003-0.03	0.003-0.03	0.003-0.03	0.003-0.03	
Ba	0.027-0.24	0.07-0.6	0.023-0.21	0.017-0.15	0.07-0.6
Mo	0.003-0.03	0.002-0.018	0.003-0.03	0.0017-0.015	0.013-0.12
			ASSAYS		
Mn	22.78	21.31	32.75	31.97	28.65
Fe	9.25	9.50	3.41	3.00	
Co	0.035	0.041	0.011	0.010	0.01
Ni	0.03	0.021	0.019	0.018	0.02
Mn/Fe	2.46	2.24	9.60	10.66	
					0.04
					0.02
		TRACE QUANTITIES OF:			
	SB, AS, GA, ZR, B.	SB, AS, GA, ZR, B.	GA, ZR, B.	GA, ZR, B.	CU, ZR, CR.

TABLE XII SEMI-QUANTITATIVE SPECTROCHEMICAL ANALYSES AND ASSAYS OF GEORGIA STRAIT (A, B, C, AND D: SEE TEXT) AND JERVIS INLET MANGANESE NODULES. ANALYSES BY MINERALOGICAL LABORATORY, DEPT OF MINES AND PETROLEUM RESOURCES, VICTORIA, B.C.

to but not part of the same nodule as C.

5.3.4 DISCUSSION

Detailed chemical analyses of manganese nodules from Jervis Inlet have been presented by Grill et al. (1966a, b). X-ray diffraction data suggested that the dominant manganese mineral in these nodules was todorokite, which is also believed to be the dominant mineral in the Strait of Georgia nodules. Identification in the latter instance is based on relatively poor quality X-ray diffractograms, with no chemical compositional data to substantiate it. In physical appearance the discoidal nodules from Jervis Inlet are quite similar to those from the Strait of Georgia.

Both the Jervis Inlet and Georgia Strait nodules have relatively high manganese and low iron contents which relates them to Mero's B regions that occur close to the North and South American coasts. Mero (1964) believes the nodules in these regions may have formed relatively rapidly, at least when compared to the rates of formation of deep-sea nodules. From the location of the Jervis Inlet nodules on a submarine ridge that was believed to have been formed during the Sumas Stade of the Fraser River Glaciation, Grill et al. (1968b) concluded that they could be no older than 12,000 years. If this maximum age is accepted for the Strait of Georgia nodules also, the minimum accumulation rate for the large Sangster Ridge nodule would be 0.004 mm./year, considerably greater than some rates quoted by Mero (1964, p.154) for deep-sea nodules of 1 mm./1000 years or 1 mm./100,000 years.

For nodules to still exist on or close to the sea-bottom, or at least within easy reach of a small grab-sampler, sedimentation rates must be low. Manganese does occur in considerable concentrations in the sediments from some places in the Strait without the presence of nodules (see Table IX: sample 280 has an oxalate-extractable manganese content of 3,408 ppm.). Sedimentation rates calculated for Ballenas Basin, where sample 280 is located, range from 0.55 to 2 cm./year (see section 3.13). Ballenas Basin is also believed to be a reducing environment which tends to prevent the precipitation of manganese as insoluble oxides in nodular accretions.

CHAPTER 6

SUMMARY AND CONCLUSIONS

1. The modern sediments in the Strait of Georgia have the Fraser River as their principal source. Sediment carried by the Fraser is medium to fine sand size and finer, and the bulk of it is added during the spring and summer freshet.

2. Strait of Georgia sediments are of two kinds: those related to the modern delta and to modern sedimentation, which are fine to very fine sands, silts, and clays; and those that are related to older deltaic or to Pleistocene glacial and interglacial deposition, which are mostly coarser, more poorly sorted, sands and angular gravels.

3. Despite the problems inherent in the granulometric analysis of fine-grained sediments, the results make some sense sedimentologically. Isopleths of mean and median grain-size indicate that sediments become finer to the west and northwest away from the delta, northwestwards along the axis of the Strait, and, in a more compressed way, basinwards from the margins. Distribution of the sand-content isopleths reflects both the predominance of sub-sand-size sediment in the Strait as well as the concentration of sandy material in the area to the southeast of the delta where erosion is believed to be active. Textural facies maps present much the same picture.

The U-shaped bend in the isopleths and boundaries of the various parameters between Galiano Island and the delta could be the result of any one or a combination of the following:

a) An older delta grew from the southeast along the axis of the Strait, extending its bottomset beds northwestwards into Ballenas Basin. The old foreset beds now form the feature called Roberts Swell. A change in the sedimentation pattern resulting from diversion of the Fraser to its present course resulted in the delta growing into the Strait from the side, with its bottomset then foreset beds overlapping the old delta as it advanced. This modified the pattern of the parameters measured.

b) The pattern is related to present delta sedimentation and is due to a southward movement of bed load on the ebb tide (after Mathews and Shepard, 1962).

c) It is the result of redeposition of material winnowed from Roberts Swell and transported northward into deeper water (after Tiffin, 1969). Tiffin suspects that this mechanism is more plausible than the preceding one to explain the high concentration of sand south of the Fraser River mouth and over the northwestern edge of Roberts Swell.

In all cases the western limb of the U is explained by a local or relict source of coarser sediment on the western side of the Strait. It seems quite likely that all three mechanisms are intermixed, and the U-shape of the feature is a composite expression of this.

4. Bed load sediment (the coarser of the fine sands) is deposited on the delta front and subsequently moved northwards under the influence of the continuous longshore currents. During the freshet some sediment may, especially on an ebb tide, be moved basinwards of this influence and be deposited to the south of Sand Heads. The suspended load, on

being carried into the Strait, comes under the influence of tidal and more persistent currents. It is moved northwards along with the surface-water circulation, becoming enmeshed in a clockwise eddy of the surface water in the Strait. Deeper water, however, tends to be more constantly north-flowing. The suspended sediment must also come under the electrolytic influence of the salt water, causing flocculation of clay minerals.

5. Main depositional areas for the sediments are: a) the delta, west and north of Sand Heads. Sediments deposited here are redistributed by longshore currents. b) lower delta slopes and the eastern ends of the northern basins, especially Ballenas Basin, where Recent sediment thicknesses are in excess of 180 metres at a distance of 50 km from the Fraser River. The eastern end of Sechelt basin also has a thick sediment fill.

Recent sediments cover the eastern ends of the ridges along the mainland coast north of Burrard Inlet, but further to the northwest they thin rapidly to become only localised concentrations, with Pleistocene sands and gravels still exposed on the ridge crests. Ridge flanks often have little thickness of Recent sediment cover, and it is possible that currents are of sufficient strength to keep them sediment-free. Current velocities are poorly known for the Strait north of the delta, especially at depth. On the Vancouver Island shelf and slope, Recent sediments are thin, except where confined in local pockets behind small ridges on the slope.

6. South of Sand Heads is an area of coarser sands and gravels

suggesting a zone of erosion or winnowing of an older sedimentary feature that may have been an old delta of the Fraser. The high tidal current velocities even near the bottom in this area may be, and have been, sweeping sand from and across Roberts Swell to the northwest, to be deposited in deeper water south of Sand Heads, or to the southeast or east into Boundary Basin to be removed from the Strait through Boundary Pass.

7. Only relatively small quantities of sediment are derived locally around the margins of the Strait. Sands and gravels occur around the eastern and western margins of the Strait, the coarse fraction of the sediment being derived either locally or from Pleistocene deposition. There is little basinward movement of this material. Some mud, presumably related to the modern sedimentary regime, is admixed with the coarser detritus. It is impossible to decipher the origin of the silt- and clay-size fractions on mineralogical grounds since the mineral composition of these fractions is practically uniform over the entire Strait.

8. The ridges in the northwest, on the eastern side of the Strait, are composed of gravels plus mud. They do not appear to be supplying sediment locally except for sponge fragments. These ridges are composed of Pleistocene sediments, probably modified by reworking during lower stands of sea-level, now remaining as relict deposits. They are the sites of little, if any, accumulation of modern muddy sediment.

9. The deep basins are the sites of very thick accumulations of very

fine-grained sediments. Two depositional processes seem to be active over the basins: a) settling of fine sediment, mainly clays, from suspension; and b) some form of mass transport of sediment down the basin axes. The form this last process takes is not known for certain, however the seismic and echo-sounding profiles of Tiffin (1969) and Cockbain (1963a) respectively, showed sub-bottom reflectors whose characteristics of fading reflecting intensities, and thinning, could be explained by invoking turbidity currents as the mechanism. Sedimentation rates in these areas are very high, and the cores taken represent only a relatively very short interval of the total sedimentary history. Existence of turbidity currents active only recently cannot be discounted, and it is possible that the turbidity currents were composed of material that was already fairly well-sorted, and of similar mean grain-size to the sediment in the area in which they came to rest. If so, visible textured expression of the turbidite would not exist.

10. Inspection of cumulative probability curves of sediment size-frequency data led to a possible explanation of their non-linear shape in the sub-sand-size region. The silt-size material is composed of grains of quartz and felspar, with some amphiboles and rare garnets, and subordinate amounts of phyllosilicates. The clay-size fractions are dominated by phyllosilicates (montmorillonite, illite, chlorite, minor mixed-layer phases and kaolinite), although quartz and felspar are still present. Equant grains and platy minerals react differently in a fluid medium but, if small enough, even equant grains will be affected by electrical forces as a result of a greater number of broken bonds per unit volume than in the coarser sizes (see also Carroll, 1959).

When the mean size is larger (in the silt range) the curve often has a pronounced bend, while finer (clay-size) samples tend to approach a straight line. This can be interpreted as a result of the coarse sediments containing a greater amount of suspended material that act and settle as independent grains. The finer samples have less of this material, and more of the total mineralogy is platy. Hence not only the shape of the cumulative probability curves but also the change from Factor I to Factor II and at least part of the sediment distribution can all be explained mineralogically.

11. Recent current studies in the Strait of Georgia have suggested the existence in the upper 50 metres of the Strait of a clockwise eddy whose extent and development have not yet been established. This eddy seems to have expression in the sediments as the region of mud which corresponds to the zone of heaviest pro-delta sedimentation. Clays are distributed to the northwest by slower moving, deeper currents. That not much sediment, even clay, is settling on ridges in the far northwest of the area is indicated by unburied, relict, Pleistocene gravels, and manganese nodules, on Sangster Ridge and on the low saddle connecting Sangster Ridge to the platform from which Ballenas Islands rise. The existence in these areas of currents of sufficient strength to keep the ridges swept clear of settling sediment is believed to be responsible for this situation.

12. Direct measurement of currents in any body of water is influenced by short-term effects and variations that may mask net current movements. Variability of current movements in the Strait of Georgia on a short-term basis, reflecting changes in wind speed and direction, tidal effects,

river discharge, etc. are all evident in the studies of Huggett (1966) and Giovando and Tabata (1970). Study of sediment distribution and dispersal patterns reveals the consequences of long-term, net effects of current movements and sediment transport.

13. The distribution pattern of sediments in the Strait of Georgia has interesting palaeogeographic implications. If all that was available for study was a section of intermittently exposed outcrops or a series of drill cores along the length of the Strait, and assuming the facies and mineralogy were the same as they are now, it would be impossible to detect the presence of land to the west (Vancouver Island). Also, the impression gained from study of the sand:silt:clay facies maps, or mean grain-size changes along the length of the Strait, is that the source lay to the southeast, since direction of fining of sediment is from southeast to northwest. The interpretation would be that transport of sediment was longitudinal down the axis of the Strait, whereas in fact the source is on one side and transport is at first lateral, then longitudinal. If the Roberts Swell sediments were interpreted as old delta deposits, the final analysis would be that the river supplying the Strait flowed into it from the southeast.

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APPENDIX I
SEDIMENT TEXTURAL PARAMETERS FOR STRAIT OF GEORGIA SAMPLES

NO.	X	Y	%G	%S	%Z	%C	S/M	D	MD	MZ	S.D.	SK.	K.	K'
10	1626	221	2.	58.	23.	16.	1.5	201.	3.6	4.8	2.99	.65	1.58	.61
13	1742	223	44.	34.	13.	9.	3.5	214.	0.7	.	.	.	.	.
19	1900	288	2.	53.	26.	20.	1.2	146.	3.6	4.5	3.72	.44	.87	.46
21	1909	337		93.	4.	3.	13.2	27.	2.0	2.0	.98	.17	1.82	.64
23	1909	402		60.	25.	15.	1.5	49.	3.6	4.8	2.38	.83	1.58	.61
25	1912	482		35.	45.	19.	0.6	27.	4.8	5.7	2.86	.56	1.24	.55
40	1741	268	4.	60.	24.	13.	1.8	194.	2.9	3.7	3.37	.41	1.31	.56
42	1722	342	15.	38.	30.	17.	1.4	201.	3.8	3.7	4.73	.01	1.29	.56
44	1712	408		40.	40.	21.	0.7	130.	4.8	5.7	2.78	.59	1.14	.53
45	1706	456		17.	57.	27.	0.2	77.	5.8	6.1	3.43	.54	1.27	.55
46	1637	449	21.	48.	18.	13.	2.2	31.	1.7	2.2	4.51	.21	1.12	.52
48	1632	345		70.	17.	14.	2.3	128.	3.4	4.4	2.49	.73	1.53	.60
50	1628	268		73.	15.	11.	2.6	150.	3.0	4.0	2.39	.76	1.94	.65
53	1610	156		29.	40.	31.	0.4	104.	5.8	6.6	3.27	.42	.81	.44
54	1484	187		64.	18.	17.	1.8	132.	3.6	5.0	2.89	.77	1.41	.58
56	1494	255		71.	19.	11.	2.4	132.	3.5	4.2	1.84	.91	2.09	.67
58	1511	336		73.	17.	10.	2.7	115.	3.4	4.0	1.98	.73	2.84	.73
60	1516	405		61.	23.	16.	1.6	104.	3.8	4.9	2.64	.81	1.74	.63
62	1523	461		68.	18.	13.	2.1	69.	3.2	4.3	2.49	.76	.90	.43
73	1327	217		16.	41.	44.	0.2	77.	7.4	7.4	3.23	.09	.88	.46
75	1340	255		31.	43.	26.	0.4	177.	5.0	6.4	3.28	.68	1.04	.50
76	1347	277		33.	42.	25.	0.5	168.	5.1	6.2	3.09	.59	.80	.44
77	1361	308		33.	43.	25.	0.5	161.	5.1	6.2	2.73	.60	.98	.49
79	1376	368		43.	36.	21.	0.8	146.	4.4	5.7	2.93	.75	1.18	.54
81	1389	425		69.	15.	16.	2.2	115.	2.4	4.1	3.14	.81	1.07	.51
82	1395	447		100.	.	.	100.0	77.	1.8	1.8	0.42	.18	.33	.24
83	1315	452		99.	1.	.	99.0	86.	2.2	2.2	0.39	.04	1.06	.51
85	1299	400		55.	27.	18.	1.2	174.	3.7	4.9	3.06	.64	1.01	.50
86	1288	373		24.	52.	24.	.3	187.	5.2	6.3	3.06	.72	1.13	.53
87	1274	333		10.	59.	31.	.1	201.	6.0	6.9	3.09	.49	.94	.48
88	1267	299		17.	53.	30.	.2	203.	5.9	6.8	3.17	.50	.92	.47
89	1254	256		15.	52.	33.	.2	205.	6.4	7.1	3.18	.38	.90	.47
93	1112	217	11.	46.	25.	17.	1.3	79.	3.6	4.2	.	.	.	.
96	1150	320		4.	56.	40.	0.0	282.	7.1	7.4	2.65	.21	.83	.45
97	1159	341		5.	55.	41.	0.1	282.	7.2	7.9	3.13	.35	.90	.43
98	1170	379		3.	64.	33.	0.0	245.	6.4	7.2	2.87	.47	.92	.47
100	1199	452		38.	37.	25.	.6	196.	5.3	5.8	3.37	.29	.85	.45
102	1220	498		37.	48.	15.	.6	79.	4.7	5.4	2.34	.53	1.15	.53
103	1182	543		24.	57.	19.	.3	90.	5.3	5.7	2.51	.37	1.11	.50
104	1171	622		5.	66.	29.	.1	79.	6.4	7.0	2.42	.41	1.07	.52
106	1125	550		13.	63.	24.	.1	155.	5.8	6.4	2.61	.43	1.12	.53
108	1092	493		22.	52.	26.	.3	241.	5.9	6.6	3.09	.41	1.05	.51
109	1077	484		17.	53.	30.	.2	260.	6.2	6.8	3.01	.37	.97	.49

111	1151	498		17.	60.	23.	.2	170.	5.6	6.3	2.66	.46	1.09	.52
113	1119	446		14.	54.	32.	.2	251.	6.4	6.9	2.92	.32	.96	.49
114	1104	433		7.	61.	33.	.1	267.	6.4	6.9	2.74	.41	.96	.49
115	1028	393		2.	52.	46.	0.0	316.	7.6	7.8	2.55	.19	.85	.46
116	1051	360		.	48.	52.	0.0	333.	8.1	8.7	2.79	.36	.97	.49
118	1013	313		1.	46.	53.	0.0	223.	8.2	8.4	2.28	.13	.91	.47
119	986	273		17.	39.	43.	.2	115.	7.3	7.3	3.30	.03	.91	.47
121	979	290		3.	43.	55.	0.0	177.	8.4	8.4	2.54	.04	.99	.50
123	940	343		1.	49.	51.	0.0	289.	8.1	8.2	1.96	.08	.94	.48
124	1004	392		1.	49.	50.	0.0	278.	8.0	8.2	2.35	.14	.94	.48
125	1023	421		1.	53.	46.	0.0	326.	7.8	8.1	2.60	.24	.90	.47
126	1034	463		3.	63.	34.	0.0	311.	6.9	7.3	2.34	.31	.99	.50
127	1056	521		12.	55.	33.	.1	263.	6.6	7.1	3.07	.27	1.05	.51
128	1066	556		6.	62.	31.	.1	205.	6.6	7.1	2.64	.33	.99	.50
129	1075	580		6.	64.	30.	.1	163.	6.4	6.9	2.60	.34	.93	.48
130	1080	596		3.	63.	34.	0.0	168.	6.8	7.3	2.53	.33	.75	.43
131	1083	615		3.	63.	34.	0.0	216.	6.8	7.3	2.51	.36	.99	.50
132	1090	629		3.	61.	36.	0.0	199.	6.8	7.3	2.47	.45	1.00	.50
133	1100	664		2.	61.	37.	0.0	170.	7.0	7.5	2.41	.37	.93	.48
134	1110	697		2.	59.	38.	0.0	137.	7.2	7.7	2.47	.32	.98	.49
135	1119	730		3.	62.	35.	0.0	91.	6.9	7.4	2.45	.33	1.00	.50
141	965	453		1.	47.	53.	0.0	347.	8.2	8.4	2.36	.13	.93	.48
145	914	349		1.	43.	57.	0.0	201.	8.6	8.7	2.42	.10	.98	.49
147	905	318		22.	39.	38.	.3	113.	6.6	7.1	3.26	.28	.76	.43
148	817	404	24.	25.	20.	31.	1.0	128.	4.1	4.1	5.77	.04	.72	.42
149	839	433	15.	16.	23.	46.	.4	201.	7.7	6.2	.	.	.	.
151	878	473		2.	39.	59.	0.0	366.	8.6	8.6	2.19	.	1.02	.51
152	891	439		1.	45.	54.	0.0	375.	8.3	8.4	2.38	.09	.88	.47
153	950	505		1.	51.	49.	0.0	362.	8.0	8.2	2.45	.17	.84	.46
154	914	516		1.	53.	46.	0.0	357.	7.7	8.1	2.52	.27	.92	.48
156	960	575		2.	57.	41.	0.0	307.	7.3	7.5	2.11	.18	.89	.47
158	1012	641		1.	57.	42.	0.0	269.	7.4	7.9	2.60	.31	.91	.47
160	1066	709		1.	56.	43.	0.0	192.	7.6	8.0	2.33	.25	.94	.48
161	1098	747		1.	53.	45.	0.0	143.	7.8	8.2	2.27	.28	.95	.49
162	1066	848		6.	58.	36.	0.1	68.	7.0	7.4	2.60	.25	1.01	.50
163	1060	829		3.	50.	47.	0.0	106.	7.9	8.1	2.50	.19	.92	.48
164	1047	814		2.	50.	48.	0.0	157.	7.9	8.2	2.44	.17	.96	.49
165	1036	777		.	48.	52.	0.0	225.	8.1	8.2	2.09	.09	.94	.49
166	1014	753		.	47.	53.	0.0	243.	8.2	8.7	2.56	.30	.97	.49
167	989	712		.	49.	51.	0.0	282.	8.0	8.4	2.35	.25	.94	.49
168	972	676		1.	47.	52.	0.0	293.	8.1	8.4	2.41	.24	.93	.48
169	951	640		1.	55.	44.	0.0	293.	7.6	8.0	2.58	.22	.92	.48
170	930	606		1.	55.	44.	0.0	313.	7.6	8.0	2.63	.29	.92	.48
171	892	583		.	53.	46.	0.0	338.	7.7	8.1	2.58	.27	.90	.48
175	851	536		.	37.	63.	0.0	371.	9.0	9.0	2.49	.06	.93	.48
182	955	774		1.	42.	57.	0.0	192.	8.4	8.6	2.12	.11	.94	.49
183	970	806		.	45.	54.	0.0	245.	8.2	8.4	2.06	.15	.95	.49
184	980	836		4.	46.	50.	0.0	253.	8.0	8.2	2.20	.15	1.01	.50
185	993	859		1.	50.	50.	0.0	161.	7.9	8.2	2.36	.22	.96	.49
186	1011	898		3.	52.	45.	0.0	154.	7.8	8.1	2.33	.23	1.07	.51
190	871	771		.	40.	60.	0.0	174.	8.6	8.8	2.12	.15	.94	.49
193	842	655		.	43.	57.	0.0	342.	8.5	8.9	2.31	.25	.90	.48
196	796	549		.	42.	58.	0.0	375.	8.4	8.6	1.98	.23	.95	.49
200	743	535		.	43.	57.	0.0	384.	8.4	8.7	1.98	.26	.95	.49

201	750	575		.	41.	59.	.0	375.	8.4	8.5	1.80	.12	.91	.48
202	758	617		.	45.	55.	0.0	366.	8.4	8.4	1.88	.08	.95	.49
203	767	651		.	45.	55.	0.0	342.	8.3	8.4	1.95	.14	.92	.48
204	787	714		.	47.	53.	0.0	315.	8.2	8.3	2.06	.10	.96	.49
207	808	796		.	38.	62.	0.0	152.	8.7	8.8	1.98	.08	.95	.49
209	825	843		1.	35.	64.	0.0	293.	8.9	9.0	2.08	.03	1.00	.50
212	758	901		.	27.	72.	0.0	121.	9.3	9.3	1.98	-.01	1.00	.50
213	744	864		.	32.	68.	0.0	174.	9.0	9.1	2.06	1.10	.92	.48
214	735	830		.	30.	70.	0.0	155.	9.2	9.3	2.05	.07	.93	.48
215	725	793		2.	27.	71.	0.0	119.	9.2	9.3	2.23	.07	.96	.49
217	716	745		.	36.	64.	0.0	287.	8.8	9.0	2.05	.16	.90	.47
219	704	696		1.	34.	65.	0.0	228.	8.8	8.8	2.07	.02	1.01	.50
220	703	685	1.	7.	27.	65.	0.1	238.	9.1	9.1	3.17	-.09	1.23	.55
221	693	644		.	38.	62.	0.0	329.	8.6	8.7	1.79	.09	1.01	.50
222	676	580		.	38.	62.	0.0	379.	8.7	8.9	2.27	.16	.95	.49
223	666	532		.	33.	66.	0.0	384.	9.0	9.1	1.83	.14	.72	.42
225	657	489		1.	27.	72.	0.0	201.	9.2	9.2	1.96	.00	1.03	.51
228	639	649		1.	33.	66.	0.0	267.	8.8	8.9	2.00	.10	.97	.49
229	646	680		2.	30.	69.	0.0	176.	9.2	9.2	2.31	.01	1.03	.51
230	643	693		.	29.	71.	0.0	152.	9.2	9.4	2.04	.11	.95	.49
231	647	703		.	29.	70.	0.0	210.	9.1	9.2	1.80	.08	.95	.49
232	656	735		1.	30.	69.	0.0	265.	9.1	8.9	1.57	-.12	.95	.49
233	661	764		.	32.	68.	0.0	210.	9.0	9.2	2.04	.15	.87	.47
234	664	783		2.	32.	66.	0.0	137.	9.0	9.1	2.45	.01	1.03	.51
236	668	810		1.	23.	76.	0.0	132.	9.4	9.5	2.09	.08	.92	.48
237	679	850		.	29.	71.	0.0	165.	9.2	9.3	1.90	.04	1.29	.56
238	639	885	5.	41.	17.	37.	.9	73.	4.7	5.8	4.26	.27	.86	.46
251	565	575		.	35.	65.	0.0	399.	8.8	9.0	2.05	.16	.93	.48
255	455	451	1.	31.	29.	39.	.5	165.	6.0	6.5	3.41	.16	.79	.44
257	466	566		.	33.	67.	0.0	402.	8.8	9.1	2.06	.20	.95	.49
259	498	643		.	26.	74.	0.0	338.	9.3	9.4	1.81	.15	.83	.46
261	511	677		.	29.	71.	0.0	316.	9.2	9.3	2.03	.06	.86	.46
262	515	701		1.	28.	72.	0.0	204.	9.3	9.4	2.06	.06	.95	.49
263	516	719		37.	17.	47.	.6	97.	7.6	7.2	3.63	-.06	.64	.39
264	520	730		7.	28.	65.	.1	187.	9.0	9.0	2.38	0.00	1.0	.50
265	526	759	2.	8.	24.	67.	.1	139.	9.1	9.0	.	.	.	.
267	544	832		.	27.	73.	0.0	168.	9.4	9.3	1.80	-.05	1.03	.51
268	554	870	20.	18.	20.	42.	0.6	97.	5.0	5.4	5.77	-.32	.77	.43
269	453	876		61.	13.	26.	1.6	91.	3.2	5.0	3.61	.70	.94	.48
280	386	552		.	28.	72.	0.0	406.	9.2	9.3	1.92	.09	.89	.47
282	373	476		.	20.	80.	0.0	348.	9.6	9.6	1.83	.01	.98	.50
284	363	447		2.	26.	72.	0.0	274.	9.4	9.5	2.89	.04	1.14	.53
286	353	414		90.	6.	4.	9.0	82.	3.2	3.2	.85	.37	2.24	.69
287	280	420	24.	47.	14.	15.	2.4	104.	2.2	2.9	4.63	.30	1.21	.55
289	303	525		.	24.	76.	0.0	408.	9.3	9.3	1.74	-.01	1.01	.50
290	316	590		.	27.	72.	0.0	402.	9.2	9.2	1.69	.01	1.01	.50
291	320	611		1.	25.	74.	0.0	384.	9.2	9.2	1.83	.03	.98	.50
292	325	637		.	20.	80.	0.0	342.	9.6	9.6	1.80	0.00	.98	.50
293	329	649		.	26.	74.	0.0	366.	9.4	9.4	1.83	-.01	.98	.50
294	334	676	9.	21.	16.	53.	.4	279.	8.2	6.9	5.06	-.24	.90	.47
295	336	683	2.	16.	19.	63.	.2	223.	9.0	8.0	4.26	-.29	1.25	.56
297	336	702		.	24.	76.	0.0	375.	9.4	9.4	1.83	-.01	.98	.50
298	341	720		.	25.	75.	0.0	292.	9.4	9.4	1.90	-.01	.99	.50
299	350	766		1.	26.	73.	0.0	170.	9.4	9.4	2.23	-.02	1.04	.51

300	362	818		14.	24.	62.	.2	210.	8.8	8.3	3.33	-.19	1.18	.54
301	366	848		3.	27.	21.	0.0	177.	9.2	9.1	2.05	-.07	1.02	.51
302	290	832		10.	23.	66.	.1	137.	9.2	8.6	3.16	-.20	1.12	.53
303	280	773		.	24.	76.	0.0	216.	9.4	9.4	1.84	-.03	1.00	.50
305	268	704		.	23.	77.	0.0	304.	9.4	9.5	1.98	.12	.99	.50
309	262	624		3.	23.	74.	0.0	324.	9.4	9.5	2.22	0.00	1.08	.52
311	238	512		.	24.	76.	0.0	408.	9.4	9.7	2.25	.22	.97	.49
313	231	465		16.	27.	57.	.2	195.	8.6	8.0	3.31	-.15	.72	.42
315	234	433		66.	24.	10.	1.9	77.	3.7	3.9	1.86	.41	3.48	.78
317	186	501		.	22.	78.	0.0	408.	9.4	9.6	1.78	.14	.81	.45
321	196	666		.	27.	73.	0.0	393.	9.2	9.2	2.14	-.14	1.31	.57
326	200	762		.	23.	76.	0.0	210.	9.6	9.6	2.11	.02	.96	.49
327	204	796		.	22.	77.	0.0	220.	9.4	9.5	2.00	.11	.97	.49
328	152	772		4.	25.	71.	0.0	192.	9.3	9.3	2.32	-.08	1.12	.53
329	144	727		.	25.	75.	0.0	338.	9.4	9.4	1.98	-.03	1.00	.50
330	134	669		.	25.	75.	0.0	397.	9.2	9.3	1.90	.04	.99	.50
331	129	618		6.	22.	72.	0.0	256.	9.4	9.3	2.51	-.08	1.22	.55
332	126	604		.	23.	77.	0.0	238.	9.6	9.7	2.26	.06	1.02	.50
334	116	561		.	25.	75.	0.0	244.	9.7	9.7	2.39	.01	.96	.49
335	112	531		.	23.	77.	0.0	402.	9.6	9.7	2.15	.11	.91	.48
336	103	502		3.	20.	77.	0.0	248.	9.6	9.5	1.33	-.12	1.24	.56
337	94	479	17.	51.	14.	18.	2.1	73.	2.7	3.1	.	.	.	.
340	51	504	13.	22.	15.	50.	.5	265.	8.0	6.3	4.94	-.45	.74	.42
341	50	516	7.	42.	11.	40.	1.0	326.	5.2	5.6	4.51	.08	.76	.43
342	52	536	14.	9.	18.	59.	.3	322.	8.8	7.4	4.88	-.42	1.16	.54
343	51	571		22.	19.	58.	.3	262.	9.6	.	.	.	.	.
345	53	621		.	22.	78.	0.0	280.	9.4	9.5	1.91	.06	.94	.49
347	53	653		9.	22.	68.	0.0	247.	11.0	.	.	.	.	.
349	73	707		.	25.	75.	0.0	388.	9.3	9.3	1.80	.04	.91	.48
350	84	747		1.	24.	76.	0.0	356.	9.2	9.2	1.63	.08	.94	.49
351	98	802		80.	10.	10.	.	132.	3.4	3.6	1.90	.56	5.18	.84

NO. = SAMPLE NUMBER; X,Y = X AND Y COORDINATES; % = WEIGHT PERCENT, G = GRAVEL, S = SAND, Z = SILT, C = CLAY; S/M = SAND TO MUD RATIO; D = DEPTH IN METRES; INCLUSIVE GRAPHIC MEASURES (FOLK AND WARD, 1957) ARE IN PHI UNITS: MD = MEDIAN, MZ = GRAPHIC MEAN, S.D. = INCLUSIVE GRAPHIC STANDARD DEVIATION, SK = INCLUSIVE GRAPHIC SKEWNESS, K = GRAPHIC KURTOSIS, K' = NORMALISED KURTOSIS (K/(1+K)).

APPENDIX II(A)
DATA MATRIX FOR FACTOR ANALYSIS

SAMPLE COORDS NO. X Y	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	>10
					PHI: WT%										
101626 221		1.34	0.89	0.63	1.39	2.30	17.69	35.87	7.67	7.57	48.0	3.41	3.21	3.09	10.14
131742 223	30.25	9.95	4.22	2.92	4.97	16.96	4.35	4.79	3.99	3.75	2.86	2.13	1.62	1.87	5.37
191900 288		0.53	0.99	0.45	6.88	31.77	6.23	7.92	6.96	8.09	5.95	4.41	3.89	3.60	12.26
211909 337				0.58	8.45	39.51	39.19	5.24	1.45	0.84	0.99	.45	.41	.49	1.77
231909 402						0.07	7.79	52.55	10.49	6.26	4.91	3.22	3.05	4.74	6.94
251912 482				0.05	0.05	0.5C	7.21	27.51	19.03	14.06	7.14	5.19	3.89	3.46	11.9
401741 268		0.76	2.79	4.33	5.53	18.67	18.77	12.44	8.96	7.01	4.33	3.28	2.54	2.69	7.91
421722 342	7.64	3.80	3.53	4.15	6.48	8.54	3.30	15.83	12.46	8.68	5.20	3.78	3.31	3.94	9.46
441712 408				0.01	0.05	0.07	2.16	37.42	14.21	13.20	7.44	4.90	4.90	3.45	12.18
451706 456					0.01	0.10	0.77	15.79	19.55	16.70	13.21	7.11	5.69	3.49	17.59
461637 449	9.76	5.50	6.15	7.16	10.74	15.14	9.79	5.06	5.27	5.66	4.19	2.87	2.48	2.71	7.52
481632 345			0.17	0.03	0.02	0.35	32.40	36.87	3.80	5.24	4.31	3.23	2.95	2.95	7.69
501628 268				0.10	0.23	1.71	47.74	23.29	3.99	5.27	3.35	2.85	2.38	2.57	6.52
531610 156					0.01	0.10	0.65	28.58	9.19	13.54	9.39	8.00	6.13	6.52	17.89

541484	187	0.07	0.09	0.03	0.33	16.82	46.82	4.52	6.38	3.73	3.80	3.59	3.94	9.89
561494	255			0.01	0.25	8.71	62.30	8.01	4.81	3.00	2.10	2.10	1.90	6.81
581511	336		0.16	0.08	0.59	22.56	49.55	7.38	4.51	3.08	2.05	1.95	1.95	6.15
601516	405				0.31	3.95	57.13	7.83	6.62	5.30	3.20	3.20	1.43	11.03
621523	461		0.03	0.06	1.26	38.93	27.88	4.94	5.18	5.43	2.90	3.02	2.59	7.77
731327	217			0.02	0.10	0.89	14.82	7.37	10.74	10.74	11.70	10.10	10.10	23.41
751340	255			0.04	0.48	0.63	29.77	18.03	12.19	6.86	5.84	4.57	4.57	17.02
761347	277				0.24	1.35	31.31	16.46	12.28	7.53	5.86	5.02	4.88	15.07
771361	308				0.05	0.77	31.83	15.40	13.14	7.70	6.49	5.29	4.68	14.65
791376	368				0.05	1.35	41.59	14.84	9.48	6.08	5.24	4.39	3.40	13.58
811389	425		0.01	0.25	26.90	39.13	2.58	2.36	3.81	4.65	4.27	3.51	2.98	9.54
821395	447			0.44	65.44	32.99	0.71	0.05	0.05	0.00	0.00	0.00	0.00	0.00
831315	452			0.15	29.72	65.92	2.81	0.33	0.2	0.2	.2	.2	.07	.2
851299	400			0.03	3.69	33.98	16.95	7.64	7.82	6.27	5.27	4.00	4.09	10.23
861288	373				0.03	0.26	23.30	23.29	14.04	8.08	6.51	4.97	4.28	15.24
871274	333				0.01	0.09	9.87	22.04	17.69	11.33	7.55	6.56	6.36	18.49
881267	299				0.02	0.17	16.37	21.33	13.52	9.87	8.77	6.21	4.57	19.18
891254	256				0.03	0.19	14.88	18.55	12.56	11.32	9.20	7.96	5.31	19.99

931112	217	7.81	0.90	2.62	2.05	3.38	5.71	10.21	25.05	6.46	4.13	9.56
5.17	5.68	4.65	6.62									
961150	320						0.02	0.09	4.32	16.13	14.18	14.42
11.00	10.51	12.22	17.11									
971159	341					0.01	0.01	0.06	4.68	11.02	15.09	16.03
12.53	8.76	7.81	24.11									
981170	379						0.02	0.12	2.62	20.10	20.97	13.50
9.40	7.47	7.47	18.32									
1001199	452					0.05	4.75	20.62	12.48	9.22	11.64	9.60
6.92	5.82	4.25	14.63									
1021220	498					0.04	0.21	4.16	32.16	18.65	14.46	9.33
5.83	4.20	2.33	8.63									
1031182	543			0.03	0.11	0.03	0.90	2.76	20.25	19.76	18.26	12.17
7.10	4.94	4.06	9.63									
1041171	622						0.02	0.19	4.40	12.93	21.59	22.11
9.62	8.58	6.24	14.31									
1061125	550					0.09	0.27	0.39	12.53	20.78	19.95	13.49
8.55	6.08	5.13	12.73									
1081092	493				0.02	0.04	0.17	1.13	20.40	14.57	15.02	13.55
8.98	5.06	5.39	15.67									
1091077	484					0.01	0.12	0.68	15.99	17.02	14.74	11.96
9.74	7.51	4.43	17.8									
1111151	498					0.03	0.09	1.23	16.07	21.57	18.19	12.03
7.84	5.88	4.48	12.60									
1131119	446					0.01	0.16	1.38	12.43	14.78	16.50	13.09
9.96	7.97	6.26	17.65									
1141104	433						0.02	0.17	6.37	18.34	18.51	14.15
9.80	8.71	7.62	16.33									
1151028	393								1.72	9.91	18.77	13.56
9.65	16.16	9.39	20.86									
1161051	360									2.62	10.73	17.54
17.28	13.61	8.90	29.32									
1181013	313								1.00	3.31	10.36	15.74
16.57	15.33	13.26	24.44									
119 986	273			0.43	0.74	0.58	1.63	5.06	8.81	9.97	8.34	9.59
11.10	11.10	10.91	21.25									

121 979 290								2.76	6.10	8.72	13.95
	13.95	13.52	16.13	24.85							
123 940 343								0.69	2.67	9.80	16.92
	19.15	16.92	15.59	18.26							
1241004 392								0.82	5.57	10.77	15.97
	16.72	14.86	11.89	23.40							
1251023 421								1.20	6.23	15.35	15.77
	15.36	11.42	10.17	24.49							
1261034 463								2.91	11.33	16.99	21.31
	13.22	10.25	8.9	15.10							
1271056 521								12.20	13.53	15.65	14.32
	11.41	8.75	7.16	16.98							
1281066 556					0.01	0.02	0.11	6.19	16.08	17.98	16.56
	11.59	8.04	7.33	16.08							
1291075 580					0.01	0.03	0.07	6.12	20.31	18.16	14.37
	10.84	8.67	6.78	14.64							
1301080 596					0.09	0.21	0.41	2.63	12.79	18.65	18.65
	11.10	9.99	8.21	17.31							
1311083 615								2.96	12.96	19.94	18.61
	11.96	9.31	7.64	16.62							
1321090 629								2.89	11.50	21.40	17.57
	12.78	8.94	8.63	16.29							
1331100 664								1.73	8.23	19.12	20.45
	13.01	10.36	9.03	18.06							
1341110 697								2.01	7.43	16.56	20.28
	15.21	10.81	8.11	19.60							
1351119 730								2.94	9.67	18.12	20.54
	14.10	10.47	6.44	17.72							
141 965 453								0.56	3.48	10.78	15.65
	16.69	13.91	12.17	26.77							
145 914 349								0.86	3.74	7.47	13.51
	17.82	13.79	14.37	28.45							
147 905 318					0.01	0.20	1.61	20.41	17.40	6.80	6.25
	8.97	9.24	10.33	18.76							
148 817 404	8.74	9.93	5.56	4.62	3.62	3.87	4.64	8.00	5.23	3.95	4.19
	6.28	6.98	6.98	17.44							

149	839	433	9.57	2.76	2.32	2.03	3.45	4.58	3.18	3.19	3.25	4.18	3.83
11.67	9.93	10.98	25.09										
151	878	473								1.63	2.86	6.80	12.88
16.45	15.38	13.24	30.76										
152	891	439								0.56	3.86	12.43	15.43
13.72	15.00	13.29	25.72										
153	950	505								0.53	4.50	14.26	16.89
15.01	12.76	11.26	24.77										
154	914	516								0.74	4.82	16.08	18.08
14.48	12.06	10.45	23.31										
156	960	575								2.04	8.08	17.46	17.78
13.58	17.14	9.38	14.55										
158	1012	641								1.39	7.61	17.47	16.90
14.93	10.14	9.30	22.26										
160	1066	709								0.93	5.01	15.02	18.44
17.39	11.59	10.01	21.61										
161	1098	747								1.09	3.02	10.78	21.55
18.10	12.50	9.70	23.27										
162	1066	848				0.01	0.57	1.62	0.48	3.12	9.34	17.05	17.96
14.11	9.53	8.43	17.78										
163	1060	829				0.02	0.32	0.47	0.63	1.09	4.36	11.92	17.36
16.85	13.11	10.04	23.83										
164	1047	814								1.71	6.31	8.08	17.30
18.11	13.26	10.67	24.57										
165	1036	777								0.48	4.96	8.02	16.93
17.82	15.78	8.40	27.62										
166	1014	753								0.41	3.24	6.35	17.84
19.46	12.97	10.68	29.05										
167	989	712								0.47	4.28	9.91	18.47
16.14	13.22	10.50	27.02										
168	972	676								0.61	1.92	11.69	17.05
16.50	12.65	11.96	27.63										
169	951	640								0.80	6.28	15.07	19.09
14.57	11.55	8.79	23.86										
170	930	606								0.90	4.73	18.02	17.79
14.41	11.26	8.33	24.55										

171 892 583	13.91 11.43 9.58 25.03						0.49	5.56	15.76	18.23
175 851 536	16.35 13.78 11.86 37.50						0.32	1.28	10.26	8.65
182 955 774	18.78 16.26 13.97 27.02						0.62	2.75	6.41	14.20
183 970 806	18.88 18.29 10.62 25.36						0.32	2.36	7.67	16.52
184 980 836	19.11 15.59 11.06 23.39		0.14	1.07	1.56	0.68	0.25	2.51	6.54	18.11
185 993 859	18.56 14.48 9.59 25.50						0.87	4.69	9.59	16.73
1861011 898	22.20 12.05 11.10 21.88	0.11	0.89	0.76	0.18	0.15	0.47	3.81	9.51	16.81
190 871 771	20.77 15.10 16.68 28.01						0.25	1.57	5.35	12.27
193 842 655	19.02 13.86 12.57 33.30						0.41	2.26	3.55	18.05
196 796 549	20.36 15.27 17.98 24.77						0.24	1.36	5.77	14.25
200 743 535	25.44 15.03 15.80 26.21						0.19	0.77	3.85	12.72
201 750 575	21.23 19.42 16.26 23.03						0.19	0.45	4.07	15.36
202 758 617	21.07 17.63 15.48 21.93						0.23	1.29	6.02	16.34
203 767 651	19.28 17.40 15.05 22.58						0.29	1.41	5.64	18.34
204 787 714	19.02 17.66 13.58 21.28						0.39	3.17	7.70	17.21
207 808 796	18.75 16.94 18.15 26.92						0.18	1.21	5.14	12.70
209 825 843	19.11 14.51 16.99 32.56						0.92	1.77	4.60	9.55
212 758 901	14.16 16.99 16.05 39.17						0.43	0.94	3.78	8.50

213 744 864							0.30	0.00	4.41	10.59
16.76 17.21 16.76 33.97										
214 735 830							0.20	0.00	3.70	9.98
15.89 17.00 17.00 36.22										
215 725 793		0.25	0.16	0.18	0.18	0.46	0.95	0.86	2.92	7.72
15.10 15.96 16.81 38.43										
217 716 745							0.20	0.80	3.62	12.88
18.51 16.90 15.69 31.39										
219 704 696							0.84	2.09	4.18	9.62
18.41 16.74 16.32 31.80										
220 703 685	0.66	0.38	0.77	0.85	1.64	2.65	1.10	2.15	4.43	8.15
12.59 11.87 14.87 37.90										
221 693 644							0.29	1.43	5.25	8.59
22.42 17.18 16.70 28.15										
222 676 580							0.12	0.61	7.31	10.96
19.18 16.44 14.92 30.45										
223 666 532							0.21	0.35	1.76	12.56
18.84 15.35 19.89 31.05										
225 657 489							0.94	1.42	2.83	6.72
15.92 16.27 19.81 36.09										
228 639 649							0.88	1.99	2.79	11.15
17.12 18.71 15.53 31.85										
229 646 680							1.71	2.73	2.39	8.19
16.38 15.02 17.07 36.52										
230 643 693								1.02	2.90	7.00
18.09 17.41 14.51 39.08										
231 647 703							0.39	0.49	1.94	9.72
17.01 18.95 18.47 33.04										
232 656 735							0.76	0.76	1.14	9.89
18.63 17.11 30.42 21.29										
233 661 764							0.08	1.84	0.41	11.65
17.98 16.76 16.14 35.15										
234 664 783							2.06	3.92	4.90	7.35
16.16 15.67 14.69 35.26										
236 668 810							0.68	1.57	1.05	6.81
13.89 16.77 17.03 42.19										

237 679 850	16.92	16.50	17.34	37.23								0.17	1.27	2.54	8.04
238 639 885	6.43	7.05	9.90	20.17	4.41	0.31	0.71	1.03	1.72	4.56	19.25	14.21	4.21	2.23	3.84
251 565 575	19.45	16.86	16.54	31.12								0.14	0.97	3.24	11.67
255 455 451	8.88	9.16	10.59	18.90			1.02	1.79	1.92	2.82	5.15	19.44	12.03	5.73	2.58
257 466 566	18.23	18.23	14.66	34.07								0.16	0.79	3.17	10.70
259 498 643	20.83	18.32	18.32	37.36								0.14	0.72	1.80	2.51
261 511 677	17.48	17.13	16.41	37.82								0.09	1.07	1.43	8.56
262 515 701	15.79	16.52	18.36	37.08								0.51	1.47	1.47	8.81
263 516 719	8.42	11.14	10.59	24.99					0.05	0.57	17.32	18.77	2.45	1.36	4.35
264 520 730	16.02	15.39	15.07	34.86								7.05	0.31	3.14	8.17
265 526 759	12.48	15.39	15.97	35.42			2.07					7.65	1.74	2.32	9.97
267 544 832	16.82	15.77	18.23	38.90								0.11	0.35	2.45	7.36
268 554 870	7.53	9.64	10.11	22.63	7.61	7.78	4.43	3.61	1.92	2.64	3.06	6.58	5.64	2.59	4.23
269 453 876	4.74	5.31	6.16	14.21				0.10	0.82	13.79	30.93	15.60	2.76	2.75	2.84
28C 386 552	16.64	19.23	15.90	36.98								0.15	1.11	1.48	8.51
282 373 476	12.03	18.90	18.90	42.10								0.33	1.29	0.86	5.59
284 363 447	8.13	15.88	12.78	43.76								2.03	3.87	3.87	9.68
286 353 414	.31	.94	.84	2.62					0.04	0.98	34.05	54.78	4.08	0.73	0.63

287	280	420	9.43	14.24	10.65	5.23	7.08	11.44	12.39	8.12	2.29	1.46	2.29	2.50	2.91	9.99
289	303	525							0.19	1.45	0.00	7.23	15.43	19.29	18.80	37.61
290	316	590							0.24	0.50	2.00	7.98	16.96	18.95	18.46	34.92
291	320	611							0.67	0.55	2.21	6.62	15.45	19.87	18.21	36.42
292	325	637							0.09	0.87	0.43	5.19	13.41	19.03	19.03	41.96
293	329	649							0.20	0.99	0.99	7.41	16.80	16.80	19.27	37.55
294	334	676	6.94	2.29	2.33	3.78	5.61	5.85	3.71	1.37	2.74	3.83	8.48	12.31	12.86	27.90
295	336	683	0.72	1.16	1.91	2.32	4.05	5.17	2.51	1.62	2.43	6.94	7.99	12.50	14.93	35.76
297	336	702							0.31	0.00	2.34	5.84	15.97	16.36	20.25	38.94
298	341	720							0.25	0.82	1.64	6.54	15.54	17.99	18.40	38.84
299	350	766							0.83	1.39	6.39	4.17	13.89	16.39	17.50	39.44
300	362	818				0.03	0.60	6.23	7.57	2.52	2.51	6.21	12.71	13.45	15.81	32.36
301	366	848							2.51	2.19	1.75	7.87	14.86	17.05	21.86	31.90
302	290	832			0.07	0.07	0.17	0.91	9.10	5.72	2.54	4.82	10.15	13.95	16.49	36.02
303	280	773							0.37	1.40	0.94	7.02	14.50	18.24	18.71	38.82
305	268	704							0.14	1.12	0.37	7.11	14.21	19.07	17.20	40.77
309	262	624				0.04	0.50	0.96	1.53	1.69	1.35	1.35	18.58	16.89	18.58	38.52
311	238	512							0.21	1.03	0.52	7.76	14.48	20.17	15.00	40.85

313	231	465							1.59	14.14	9.51	4.42	4.42
8.50	12.91	13.93	30.58										
315	234	433				0.12	1.00	3.79	14.29	47.25	17.47	3.73	0.93
1.86	1.63	2.10	5.83										
317	186	501								0.23	0.38	1.50	5.25
15.00	19.13	18.76	39.76										
321	196	666								0.22	7.29	0.00	4.84
15.14	18.50	19.62	34.75										
326	200	762								0.35	1.40	1.40	6.99
13.64	15.73	17.48	43.01										
327	204	796								0.47	0.67	1.35	6.43
13.88	18.62	17.94	40.62										
328	152	772								3.77	3.31	2.53	5.25
14.39	16.14	17.30	37.33										
329	144	727								0.37	1.24	4.33	4.95
14.23	15.47	22.28	37.13										
330	134	669								0.33	0.00	4.09	7.35
13.89	17.16	22.88	34.31										
331	129	618								5.94	3.28	2.19	5.10
11.67	15.68	17.87	38.28										
332	126	604									3.31	2.11	4.22
13.86	16.87	17.17	42.47										
334	116	561									1.25	4.06	7.50
12.50	14.69	15.63	44.38										
335	112	531									1.76	1.31	5.24
14.85	16.59	16.16	44.11										
336	103	502								3.11	3.60	1.80	3.24
11.53	15.85	20.17	40.70										
337	94	479		15.93	1.01	0.75	2.63	12.14	24.64	11.10	7.73	1.82	2.05
2.27	3.86	4.77	9.32										
340	51	504		8.69	4.52	2.95	3.20	8.82	3.90	3.22	4.92	2.07	1.55
6.47	11.65	13.20	24.85										
341	50	516		4.58	2.02	2.24	4.01	16.93	16.12	2.72	1.01	1.53	2.80
5.85	9.41	10.43	20.35										
342	52	536	3.48	7.38	3.22	0.87	0.18	0.92	2.66	4.51	2.32	2.69	3.85
9.36	10.26	14.49	33.83										

343 51 571	11.52 6.50 3.54 48.44	0.41	0.96	4.13	8.49	8.44	4.32	1.77	1.48
345 53 621	13.28 19.50 18.67 39.42						1.66	2.08	5.39
347 53 653	11.96 1.81 7.98 58.36		0.07	0.46	1.88	7.00	2.87	2.90	4.71
349 73 707	16.95 18.73 20.52 35.68					0.10	1.34	1.34	5.35
350 84 747	15.70 20.35 23.84 31.40					0.58	0.58	1.16	6.40
351 98 802	1.89 0.0 2.83 6.84		0.06	2.23	22.64	55.28	6.14	0.00	2.12

APPENDIX II(B)

VARIMAX FACTOR MATRIX

No.	X	Y	COMM.	1	2	3	4
10	1626	221	0.5139	0.6552	-0.2460	0.0336	-0.1517
13	1742	223	0.5599	0.3707	0.2938	0.1836	0.5499
19	1900	288	0.4768	0.5141	0.3348	0.1537	0.2772
21	1909	337	0.6224	0.5263	0.4497	0.3721	0.0689
23	1909	402	0.8495	0.4702	0.5612	-0.3136	-0.4638
25	1912	482	0.9902	0.5823	0.3248	-0.6862	-0.2732
40	1741	268	0.7905	0.6202	0.4722	0.1593	0.3969
42	1722	342	0.9017	0.5529	0.4100	0.0212	0.6538
44	1712	408	0.9211	0.5444	0.3510	-0.6178	-0.3461
45	1706	456	0.5831	0.5463	-0.0306	-0.8159	-0.1342
46	1637	449	0.9106	0.4758	0.3550	0.2356	0.7090
48	1632	345	0.9316	0.5545	0.5767	0.0821	-0.5333
50	1628	268	0.8204	0.5486	0.5195	0.1887	-0.4626
53	1610	156	0.8289	0.5093	0.1975	-0.6150	-0.3902
54	1484	187	0.8919	0.4919	0.6039	-0.0904	-0.5263
56	1494	255	0.8221	0.4449	0.5922	-0.2240	-0.4726
58	1511	336	0.9485	0.5336	0.6322	-0.0969	-0.5048
60	1516	405	0.7708	0.4488	0.5261	-0.2858	-0.4592
62	1523	461	0.8863	0.5776	0.5297	0.1210	-0.5074
73	1327	217	0.8515	0.2239	-0.1829	-0.7229	-0.4953
75	1340	255	0.9657	0.4569	0.3542	-0.7515	-0.2583
76	1347	277	0.9594	0.4919	0.3413	-0.7143	-0.3013
77	1361	308	0.9435	0.5056	0.3025	-0.7066	-0.3117
79	1376	368	0.8842	0.4629	0.4548	-0.5703	-0.3714
81	1389	425	0.6311	0.5156	0.4112	0.3585	-0.2601
82	1395	447	0.4272	0.4208	0.3700	0.3214	-0.0992
83	1315	452	0.7080	0.5021	0.4648	0.3889	-0.2975
85	1299	400	0.8192	0.6220	0.4597	0.0519	-0.4671
86	1288	373	0.9601	0.4509	0.2156	-0.8277	-0.1591
87	1274	333	0.9605	0.4222	-0.0439	-0.8824	-0.0395
88	1267	299	0.9329	0.4255	0.0923	-0.8519	-0.1329
89	1254	256	0.9344	0.4240	0.0187	-0.8541	-0.1571
93	1112	217	0.7327	0.6327	0.4445	0.1576	0.3317
96	1150	320	0.8505	0.2814	-0.3752	-0.7937	-0.0240
97	1159	341	0.9404	0.3855	-0.5748	-0.6725	-0.0956
98	1170	379	0.9360	0.4517	-0.2661	-0.8318	-0.0221
100	1199	452	0.8339	0.7412	0.2708	-0.1849	-0.4206
102	1220	498	0.9727	0.6179	0.2389	-0.6690	-0.2936
103	1182	543	0.9925	0.6313	0.0142	-0.7520	-0.1680
104	1171	622	0.5582	0.5624	-0.5552	-0.5749	-0.0564
106	1125	550	0.9837	0.5508	-0.1427	-0.8086	-0.0790
108	1092	493	0.9768	0.6199	-0.0482	-0.7256	-0.2523
109	1077	484	0.9721	0.5234	-0.0597	-0.8124	-0.1858
111	1151	498	0.9812	0.5479	-0.0319	-0.8159	-0.1197
113	1119	446	0.9971	0.5408	-0.2040	-0.7973	-0.1654
114	1104	433	0.9632	0.4516	-0.2845	-0.8228	-0.0356
115	1028	393	0.7097	0.1816	-0.5369	-0.6230	0.0184

116	1051	360	0.8788	−0.0980	−0.9229	0.0769	−0.1074
118	1013	313	0.9713	−0.2679	−0.9406	0.0751	−0.0961
119	986	273	0.5780	0.4056	0.1967	−0.6116	0.0276
121	979	290	0.7873	−0.4511	−0.7392	−0.1723	−0.0877
123	940	343	0.8640	−0.2186	−0.8765	0.1990	−0.0914
124	1004	392	0.9804	−0.1410	−0.9718	−0.0866	−0.0928
125	1023	421	0.9222	0.1511	−0.8746	−0.3599	−0.0699
126	1034	463	0.9723	0.4666	−0.7187	−0.4825	−0.0732
127	1056	521	0.9984	0.5219	−0.3356	−0.7627	−0.1782
128	1066	556	0.9809	0.5052	−0.4241	−0.7357	−0.0673
129	1075	580	0.5407	0.4584	−0.2829	−0.8059	−0.0331
130	1080	596	0.9649	0.4745	−0.5863	−0.6284	−0.0327
131	1083	615	0.9790	0.4866	−0.5909	−0.6256	−0.0411
132	1090	629	0.9471	0.4668	−0.6112	−0.5951	−0.0389
133	1100	664	0.9488	0.4235	−0.7629	−0.4293	−0.0565
134	1110	697	0.9860	0.3853	−0.8467	−0.3344	−0.0933
135	1119	730	0.9899	0.4753	−0.7468	−0.4461	−0.0854
141	965	453	0.9812	−0.2328	−0.9578	0.0251	−0.0945
145	914	349	0.9604	−0.5474	−0.7904	0.1635	−0.0970
147	905	318	0.8259	0.1586	0.4122	−0.7533	−0.2517
148	817	404	0.8624	0.3471	0.3670	0.1985	0.7535
149	839	433	0.7019	0.1680	0.3335	0.2937	0.6901
151	878	473	0.9805	−0.6579	−0.7002	0.2145	−0.1065
152	891	439	0.8550	−0.2139	−0.8892	−0.1286	−0.0444
153	950	505	0.5273	0.0494	−0.9376	−0.2027	−0.0677
154	9914	516	0.9109	0.1910	−0.8958	−0.2604	−0.0649
156	960	575	0.8096	0.2605	−0.7822	−0.3569	−0.0510
158	1012	641	0.9306	0.3090	−0.7978	−0.4416	−0.0602
160	1066	709	0.9706	0.2032	−0.9444	−0.1673	−0.0976
161	1098	747	0.9472	0.1091	−0.9529	0.0910	−0.1379
162	1066	848	0.9666	0.5075	−0.7123	−0.4477	−0.0351
163	1060	829	0.9790	0.0812	−0.9819	−0.0249	−0.0882
164	1047	814	0.8820	−0.0985	−0.9223	−0.0079	−0.1472
165	1036	777	0.8206	−0.1783	−0.8772	0.0726	−0.1186
166	1014	753	0.8470	−0.2380	−0.8456	0.2378	−0.1369
167	989	712	0.9288	−0.0698	−0.9540	0.0021	−0.1101
168	972	676	0.9108	−0.1318	−0.9371	0.0707	−0.1017
169	951	640	0.9460	0.2562	−0.8848	−0.3027	−0.0769
170	930	606	0.8530	0.2661	−0.8274	−0.3061	−0.0627
171	892	583	0.8982	0.2121	−0.8662	−0.3154	−0.0589
175	851	536	0.6295	−0.6443	−0.4562	0.0727	−0.0298
182	955	774	0.9637	−0.5251	−0.7703	0.2910	−0.1001
183	970	806	0.8900	−0.2999	−0.8486	0.2609	−0.1088
184	980	836	0.8634	−0.1058	−0.8362	0.3911	−0.0022
185	993	859	0.9308	−0.1126	−0.9484	0.0467	−0.1270
186	1011	898	0.7621	0.0368	−0.8388	0.2254	0.0798
190	871	771	0.9076	−0.6206	−0.6152	0.3706	−0.0815
193	842	655	0.8051	−0.4337	−0.6984	0.3427	−0.1088
196	796	549	0.8829	−0.5257	−0.6807	0.3693	−0.0829
200	743	535	0.7978	−0.4885	−0.5989	0.4352	−0.1053
201	750	575	0.8848	−0.4891	−0.6648	0.4419	−0.0913
202	758	617	0.9040	−0.3861	−0.7753	0.3789	−0.1017
203	757	651	0.9079	−0.3412	−0.8032	0.3675	−0.1061
204	787	714	0.9021	−0.2765	−0.8706	0.2397	−0.1013

207	808	796	0.9250	-0.6657	-0.5820	0.3737	-0.0594
209	825	843	0.9232	-0.8014	-0.4083	0.3321	-0.0625
212	758	901	0.9532	-0.9221	-0.1705	0.2716	-0.0051
213	744	864	0.9917	-0.8250	-0.4081	0.3865	-0.0408
214	735	830	0.9875	-0.8690	-0.3069	0.3706	-0.0271
215	725	793	0.9802	-0.9209	-0.1040	0.3453	0.0458
217	716	745	0.9821	-0.7112	-0.5397	0.4236	-0.0745
219	704	696	0.9674	-0.8280	-0.4087	0.3343	-0.0556
220	703	685	0.7420	-0.6999	0.1154	0.3580	0.3328
221	693	644	0.8225	-0.6841	-0.4718	0.3581	-0.0607
222	676	580	0.5417	-0.6689	-0.6142	0.3360	-0.0641
223	666	532	0.9076	-0.7363	-0.4067	0.4434	-0.0579
225	657	489	0.9734	-0.9381	-0.1059	0.2866	-0.0034
228	639	649	0.9463	-0.8042	-0.4038	0.3648	-0.0586
229	646	680	0.5747	-0.9350	-0.1554	0.2731	-0.0415
230	643	693	0.9281	-0.8800	-0.2067	0.3322	-0.0262
231	647	703	0.9719	-0.8536	-0.2843	0.4020	-0.0300
232	656	735	0.5870	-0.6549	-0.2190	0.3318	-0.0083
233	661	764	0.9355	-0.8093	-0.3318	0.4091	-0.0560
234	664	783	0.9522	-0.9419	-0.2108	0.1366	-0.0439
236	668	810	0.9679	-0.9484	0.0074	0.2615	0.0040
237	679	850	0.9946	-0.9179	-0.2002	0.3343	-0.0179
238	639	885	0.7849	0.3658	0.7352	0.3276	0.0564
251	565	575	0.9690	-0.7411	-0.4863	0.4230	-0.0671
255	455	451	0.6817	0.2802	0.7016	-0.2472	0.2230
257	466	566	0.9640	-0.7903	-0.4167	0.4031	-0.0571
259	498	643	0.8868	-0.8770	-0.0810	0.3331	-0.0084
261	511	677	0.9837	-0.8933	-0.2117	0.3742	-0.0257
262	515	701	0.9884	-0.9218	-0.1605	0.3355	-0.0172
623	516	719	0.9237	-0.0562	0.6957	0.3230	-0.5715
264	520	730	0.9471	-0.8709	-0.1394	0.3770	-0.1644
265	526	759	0.5646	-0.6842	0.0237	0.2823	0.1272
267	544	832	0.5815	-0.9167	-0.1493	0.3447	-0.0117
268	554	870	0.8035	0.2276	0.3863	0.1930	0.7518
269	453	876	0.8451	0.4661	0.6239	0.3336	-0.3569
280	386	552	0.9654	-0.8886	-0.2084	0.3630	-0.0231
282	373	476	0.9556	-0.9462	0.0741	0.2315	0.0337
284	363	447	0.5894	-0.7645	0.0589	-0.0356	0.0103
286	353	414	0.9579	0.4912	0.6609	0.0642	-0.5251
287	280	420	0.7023	0.3531	0.3502	0.1559	0.6563
289	303	525	0.9793	-0.5289	-0.0743	0.3330	0.0016
290	316	590	0.9841	-0.8942	-0.2080	0.3755	-0.0157
291	320	611	0.9677	-0.9203	-0.1166	0.3274	-0.0018
292	325	637	0.9797	-0.9497	0.0514	0.2727	0.0273
293	329	649	0.9912	-0.9232	-0.1209	0.3524	-0.0094
294	334	676	0.8065	0.0910	0.4085	0.3607	0.7079
295	336	683	0.7093	-0.2544	0.4332	0.3980	0.5464
297	336	702	0.9747	-0.9318	-0.0628	0.3201	0.0069
298	341	720	0.9976	-0.9435	-0.0777	0.3184	0.0035
299	350	766	0.8855	-0.9322	-0.0197	0.1230	0.0330
300	362	818	0.9708	-0.8262	0.2790	0.3565	-0.2884
301	366	848	0.8881	-0.8954	-0.0895	0.2791	-0.0193
302	290	832	0.9738	-0.8876	0.4152	-0.0695	-0.0935
303	280	773	0.9886	-0.9472	-0.0469	0.2986	0.0081
305	268	704	0.9671	-0.9333	-0.0366	0.3078	0.0066

309	262	624	0.9100	-0.9062	0.0682	0.2899	-0.0139
311	238	512	0.9099	-0.8951	-0.0842	0.3186	-0.0062
313	231	465	0.9685	-0.5749	0.6058	-0.4699	-0.2240
315	234	433	0.9422	0.5102	0.6765	-0.3269	-0.3434
317	186	501	0.9863	-0.9441	-0.0230	0.3068	0.0148
321	196	666	0.8725	-0.9272	0.0617	0.0857	0.0405
326	200	762	0.9512	-0.9428	0.0106	0.2493	0.0109
327	204	796	0.9774	-0.9438	-0.0194	0.2935	0.0108
328	152	772	0.9978	-0.9819	0.0651	0.1681	-0.0326
329	144	727	0.8884	-0.9218	-0.0103	0.1929	0.0384
330	134	669	0.6653	-0.8808	-0.1183	0.2737	0.0249
331	129	618	0.9805	-0.9609	0.2088	0.1081	-0.0442
332	126	604	0.9713	-0.9706	0.0880	0.1416	0.0396
334	116	561	0.8372	-0.8995	-0.0271	0.1638	0.0222
335	112	531	0.9505	-0.9449	0.0334	0.2374	0.0148
336	103	502	0.9708	-0.9529	0.2347	0.0837	0.0247
337	94	479	0.4839	0.3963	0.4308	0.1796	0.3300
340	51	504	0.8148	0.1371	0.4360	0.2367	0.7415
341	50	516	0.8728	0.3139	0.5353	0.4727	0.5140
342	52	536	0.5519	-0.0938	0.3669	0.2155	0.6017
343	51	571	0.3360	-0.1983	0.5300	0.0971	-0.0796
345	53	621	0.9616	-0.9531	0.0085	0.2278	0.0355
347	53	653	0.2340	-0.3691	0.2992	-0.0357	-0.0836
349	73	707	0.9659	-0.9275	-0.0766	0.3157	0.0099
350	84	747	0.8707	-0.8684	-0.0942	0.3279	0.0127
351	98	802	0.9401	0.4595	0.6815	-0.0167	-0.5140
			VARIANCE	38.533	26.534	16.769	6.371
			CUM.VAR.	38.533	65.068	81.837	88.208

APPENDIX II(C)

VARIMAX FACTOR SCORE MATRIX

Variable	Factor 1	2	3	4
-3	0.3696	0.2322	0.3023	0.9824
-2	0.4612	0.3413	0.3716	1.5604
-1	0.4281	0.3647	0.3169	1.5152
0	0.5023	0.3954	0.3564	1.5940
1	0.7074	0.4225	0.6392	1.4985
2	0.7458	0.4083	0.8699	0.3664
3	1.1103	0.8361	1.4264	-1.1315
4	0.5822	1.3087	-0.4041	-1.4183
5	0.3456	0.4202	-2.6347	0.4908
6	1.0848	-1.4298	-1.6597	0.4203
7	1.1419	-2.4323	0.3517	-0.0960
8	-0.4879	-1.7505	1.0208	-0.1690
9	-1.3772	-0.7239	0.4024	0.3097
10	-1.7289	-0.0147	0.1690	0.4917
>10	-1.9630	0.2893	-0.3108	0.5590

APPENDIX III

FRASER DELTA PROJECT

At the time this thesis was in its final stages of preparation results from a study of the Fraser Delta were beginning to emerge. The delta study was aimed at determining a sediment budget for the delta front. Preliminary results indicate that the delta has been actively, and vigorously, eroded south of Sand Heads, is in a more or less stable state between Sand Heads and North Arm, and is growing seaward just south of the North Arm Jetty. While some of the material contributing to outgrowth of the delta near the North Arm Jetty has been added artificially by dredging North Arm (and pumping the tailings to the south over the jetty), some must be added by longshore drift of sandy material from the south.

The delta survey was conducted over the tidal flats and upper delta slopes, in shallower water than that from which samples 70-1-82 and 70-1-83 (this thesis) were collected. The soundings agree with sedimentological evidence obtained from samples 82 and 83, whose origin was interpreted as the result of erosion of older delta sediments.

APPENDIX IV

SAMPLE LOCATIONS

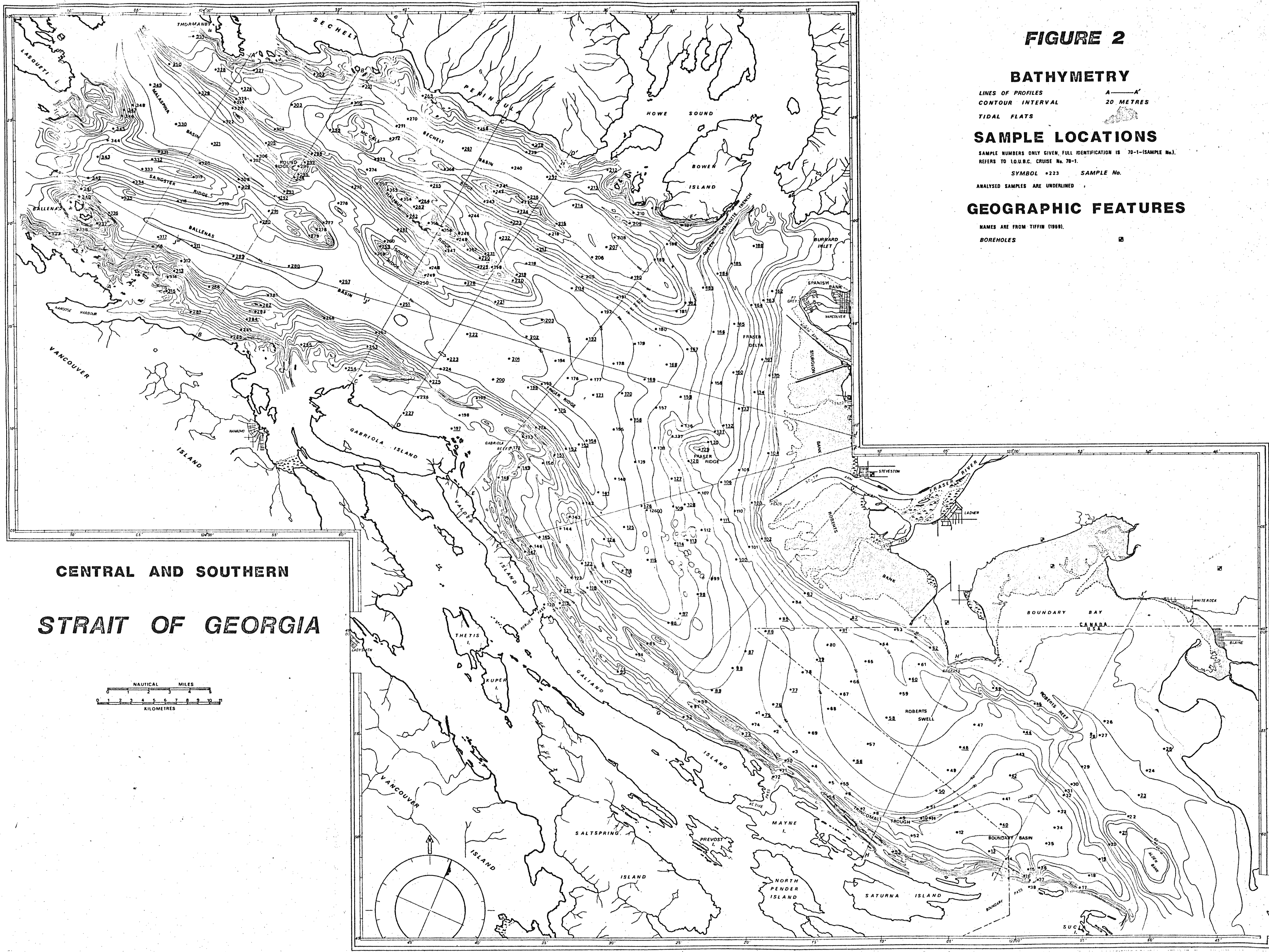
No.	Latitude (°N)	Longitude (°W)	No.	Latitude (°N)	Longitude (°W)
1	48°56'	123°19.1'	48	48°54.2'	123°04.1'
2	48°55.1'	123°17.8'	49	48°54.2'	123°05.0'
3	48°54.1'	123°16.4'	50	48°52.1'	123°05.9'
4	48°53.4'	123°15'	51	48°57.3'	123°06.6'
5	48°52.6'	123°13.7'	52	48°50.0'	123°07.7'
6	48°52'	123°13.7'	53	48°49.2'	123°09.1'
7	48°51.3'	123°11.4'	54	48°51.8'	123°13.9'
8	48°51.1'	123°10.4'	55	48°52.6'	123°12.8'
9	48°50.8'	123°08.55'	56	48°53.6'	123°12.0'
10	48°50.8'	123°07'	57	48°54.4'	123°10.0'
11	48°50.8'	123°06.3'	58	48°55.7'	123°09.5'
12	48°5o.1'	123°04.3'	59	48°56.86'	123°08.5'
13	48°49.2'	123°01.9'	60	48°57.6'	123°07.7'
14	48°48.8'	123°00.6'	61	48°58.28'	123°07.1'
15	48°48.3'	122°59.0'	62	48°59.1'	123°06.25'
16	48°48.0'	122°59.3'	63	49°00'	123°08.9'
17	48°47.4'	122°55.2'	64	48°59.2'	123°09.9'
18	48°48.0'	122°54.5'	65	48°58.46'	123°11'
19	48°48.8'	122°53.3'	66	48°57.5'	123°12.1'
20	48°49.5'	122°53.0'	67	48°56.8'	123°13'
21	48°50.1'	122°52.2'	68	48°56.1'	123°13.9'
22	48°50.9'	122°51.6'	69	48°55.1'	123°15.2'
23	48°51.9'	122°50.8'	70	48°53.6'	123°17'
24	48°53.1'	122°50.2'	71	48°53.2'	123°17.3'
25	48°54.08'	122°48.9'	72	48°52.8'	123°17.9'
26	48°55.5'	122°53.3'	73	48°54.9'	123°20'
27	48°54.8'	122°53.7'	74	48°55.4'	123°19.4'
28	48°54.9'	122°54.3'	75	48°55.9'	123°18.6'
29	48°53.3'	122°55.0'	76	48°56.4'	123°17.9'
30	48°52.4'	122°55.8'	77	48°57.2'	123°16.7'
31	48°52.1'	122°56.2'	78	48°58'	123°15.7'
32	48°51.9'	122°56.25'	79	48°58.6'	123°14.7'
33	48°51.1'	122°56.72'	80	48°59.3'	123°13.9'
34	48°50.35'	122°57.15'	81	49°00'	123°13'
35	48°49.55'	122°57.7'	82	49°00.6'	123°12'
36	48°48.3'	122°58.2'	83	49°01.9'	123°15.5'
37	48°47.8'	122°58.7'	84	49°01.4'	123°16.3'
38	48°47.4'	122°58.9'	85	49°006.'	123°17.3'
39	48°50.9'	123°02.3'	86	48°59.9'	123°18.4'
40	48°50.5'	123°01.0'	87	48°59'	123°20'
41	48°51.7'	123°00.8'	88	48°58.2'	123°20.9'
42	48°52.8'	123°00.2'	89	48°57.2'	123°22.4'
43	48°53.9'	122°59.8'	90	48°56.6'	123°23.3'
44	48°55'	122°59.3'	91	48°56.3'	123°23.9'
45	48°56.3'	122°58.5'	92	48°55.8'	123°24.5'
46	48°57'	123°01.6'	93	48°58.1'	123°29.3'
47	48°55.3'	123°03.1'	94	48°58.9'	123°28.0'

No.	Latitude (°N)	Longitude (°W)	No.	Latitude (°N)	Longitude (°W)
95	48°59.4'	123°27.2'	145	49°04.7'	123°35.2'
96	49°00.4'	123°25.6'	146	49°04.2'	123°35.8'
97	49°00.9'	123°24.7'	147	49°03.9'	123°36.3'
98	49°01.8'	123°23.4'	148	49°07.6'	123°38.2'
99	49°02.6'	123°22.3'	149	49°08.1'	123°36.0'
100	49°03.3'	123°20.55'	150	49°08.3'	123°34.9'
101	49°04.1'	123°19.6'	151	49°08.7'	123°34.0'
102	49°04.55'	123°18.64'	152	49°09.0'	123°33.1'
103	49°06.3'	123°19.3'	153	49°09.2'	123°32.2'
104	49°08.7'	123°18.13'	154	49°09.4'	123°31.7'
105	49°07.9'	123°20.3'	155	49°09.9'	123°29.6'
106	49°07.3'	123°21.7'	156	49°10.4'	123°28.4'
107	49°06.85'	123°23.3'	157	49°11'	123°26.5'
108	49°06.25'	123°23.3'	158	49°11.5'	123°24.7'
109	49°06.2'	123°25.2'	159	49°12.2'	123°22.4'
110	49°05.9'	123°20.6'	160	49°12.7'	123°20.8'
111	49°05.5'	123°21.7'	161	49°13.3'	123°18.6'
112	49°05'	123°23.1'	162	49°16.6'	123°17.9'
113	49°04.5'	123°24.2'	163	49°16.2'	123°18.5'
114	49°04.3'	123°25.1'	164	49°15.9'	123°19.4'
115	49°03.6'	123°27.1'	165	49°15.1'	123°20.6'
116	49°03'	123°29'	166	49°14.7'	123°22.1'
117	49°02.5'	123°30.5'	167	49°13.8'	123°24.1'
118	49°02.2'	123°31.6'	168	49°13.2'	123°25.5'
119	49°01.4'	123°33.7'	169	49°12.4'	123°27.2'
120	49°01.3'	123°34.8'	170	49°11.7'	123°28.9'
121	49°02.0'	123°33.6'	171	49°10.7'	123°31.0'
122	49°02.7'	123°32.8'	172	49°09.1'	123°37.2'
123	49°03.4'	123°32.0'	173	49°09.6'	123°36.2'
124	49°04.6'	123°30.3'	174	49°10'	123°35.4'
125	49°05.2'	123°28.9'	175	49°10.8'	123°33.9'
126	49°06.2'	123°27.5'	176	49°11.4'	123°33'
126(2)	49°06.0'	123°27.1'	177	49°12.3'	123°31.2'
127	49°07.5'	123°25.3'	178	49°13.1'	123°29.6'
128	49°08.3'	123°24.3'	179	49°14.1'	123°27.9'
129	49°08.9'	123°23.2'	180	49°14.8'	123°26.4'
130	49°09.3'	123°22.7'	181	49°15.7'	123°24.8'
130(2)	49°08.9'	123°22.2'	182	49°16.1'	123°24.2'
131	49°09.7'	123°22'	183	49°16.8'	123°22.9'
132	49°10.1'	123°21.4'	184	49°17.5'	123°21.8'
133	49°10.9'	123°20.3'	185	49°18.0'	123°20.7'
134	49°11.7'	123°19.1'	186	49°18.8'	123°19.1'
135	49°12.5'	123°18'	187	49°19.8'	123°24.4'
136	49°10.1'	123°24.5'	188	49°18.9'	123°25.5'
137	49°09.6'	123°25.3'	189	49°18.2'	123°26.5'
138	49°09'	123°26.5'	190	49°17.25'	123°28.2'
139	49°08.3'	123°28'	191	49°16.4'	123°29.3'
140	49°07.5'	123°29.5'	192	49°15.7'	123°30.5'
141	49°06.9'	123°30.7'	193	49°14.4'	123°31.6'
142	49°06.3'	123°31.9'	194	49°13.3'	123°34'
143	49°05.7'	123°32.9'	195	49°12.2'	123°35'
144	49°05.1'	123°33.6'	196	49°12'	123°36'

No.	Latitude (°N)	Longitude (°W)	No.	Latitude (°N)	Longitude (°W)
197	49°10'	123°41.8'	249	49°17.5'	123°43.6'
198	49°10.6'	123°41.2'	250	49°17.1'	123°44.1'
199	49°11.5'	123°39.9'	251	49°16.1'	123°45.4'
200	49°12.3'	123°38.7'	252	49°14.7'	123°47.3'
201	49°13.5'	123°37.4'	253	49°14'	123°48'
202	49°14.5'	123°36.1'	254	49°12.9'	123°49.6'
203	49°15.3'	123°35.0'	255	49°14.1'	123°52.9'
204	49°16.8'	123°32.8'	256	49°15.4'	123°51.1'
205	49°17.4'	123°32.0'	257	49°17.2'	123°48.9'
206	49°18.3'	123°31.2'	258	49°18.5'	123°47.3'
207	49°18.8'	123°30.1'	259	49°18.9'	123°46.9'
208	49°19.3'	123°29.5'	260	49°19.1'	123°46.6'
209	49°19.9'	123°28.4'	261	49°19.7'	123°45.6'
210	49°20.4'	123°28.1'	262	49°20.3'	123°44.9'
211	49°20.7'	123°26.7'	263	49°20.8'	123°44.4'
212	49°22.5'	123°29.9'	264	49°21.05'	123°44.05'
213	49°21.7'	123°31.4'	265	49°21.8'	123°43.1'
214	49°20.8'	123°32.6'	266	49°22.6'	123°92.1'
215	49°19.9'	123°33.8'	267	49°23.6'	123°40.7'
216	49°19.4'	123°34.3'	268	49°24.6'	123°39.5'
217	49°18.7'	123°35.2'	269	49°26.1'	123°43.7'
218	49°18'	123°36.1'	270	49°25.0'	123°44.8'
219	49°17.5'	123°36.8'	271	49°24.7'	123°45.6'
220	49°17.2'	123°37.1'	272	49°24.1'	123°46.1'
221	49°16.2'	123°38.4'	273	49°23.1'	123°47.3'
222	49°14.6'	123°40.5'	274	49°22.6'	123°47.9'
223	49°13.4'	123°42.0'	275	49°21.7'	123°49'
224	49°12.9'	123°42.5'	276	49°21'	123°50'
225	49°12.3'	123°43.3'	277	49°20'	123°51.1'
226	49°11.5'	123°44.2'	278	49°19.7'	123°51.6'
227	49°10.7'	123°45.3'	279	49°10.4'	123°52.2'
228	49°17.1'	123°40.6'	280	49°17.92'	123°53.7'
229	49°12.9'	123°39.6'	281	49°16.5'	123°55.4'
230	49°18.3'	123°39.9'	282	49°16'	123°55.95'
231	49°18.5'	123°39.1'	283	49°15.7'	127°56.3'
232	49°19.3'	123°38'	284	49°15.3'	123°57'
233	49°20'	123°37.2'	285	49°14.8'	123°57.4'
234	49°20.5'	123°36.6'	286	49°14.5'	123°58.1'
235	49°21'	123°36.3'	287	49°15.7'	124°01.1'
236	49°21.2'	123°35.9'	288	49°16.9'	123°59.7'
237	49°22.2'	123°34.5'	289	49°18.4'	123°57.9'
238	49°23.8'	123°35.5'	290	49°20'	123°55.9'
239	49°23.4'	123°36'	291	49°20.55'	123°55.3'
240	49°22.6'	123°37.1'	292	49°21.15'	123°54.5'
241	49°21.8'	123°38.2'	293	49°21.5'	123°54.1'
242	49°21.55'	123°38.4'	294	49°22.2'	123°53.3'
243	49°21'	123°39.1'	295	49°22.35'	123°53.11'
244	49°20.3'	123°40.2'	296	49°22.7'	123°53.1'
245	49°19.5'	123°41.1'	297	49°22.9'	123°52.6'
246	49°19.2'	123°41.2'	298	49°23.3'	123°52.0'
247	49°18.7'	123°42.1'	299	49°24.5'	123°50.6'
248	49°17.8'	123°43.2'	300	49°25.8'	123°49.0'

No.	Latitude (°N)	Longitude (°W)	No.	Latitude (°N)	Longitude (°W)
301	49°26.5'	123°48.1'	330	49°24.8'	124°02.2'
302	49°27.2'	123°51.8'	331	49°23.5'	124°03.5'
303	49°25.6'	123°53.5'	332	49°23.1'	124°04'
304	49°24.5'	123°54.8'	333	49°22.6'	124°04.7'
305	49°23.9'	123°55.5'	334	49°22'	124°05.3'
306	29°23.2'	123°55.5'	335	49°21.2'	124°06.1'
307	49°23'	123°56.6'	336	49°20.5'	124°07.1'
308	49°22.1'	123°57.5'	337	49°20'	124°08'
309	49°21.7'	123°58.5'	338	49°19.7'	124°09.5'
310	49°20.85'	123°58.9'	339	49°19.5'	124°11.6'
311	49°18.9'	124°01.0'	340	49°21.3'	124°09.3'
312	49°18.2'	124°01.8'	341	49°21.7'	124°09.1'
313	49°17.2'	124°02.3'	342	49°22.2'	124°08.6'
314	49°17.4'	124°02.8'	343	49°23.2'	124°07.9'
315	49°16.7'	124°02.9'	344	49°24.0'	124°07.2'
316	49°18.9'	124°03.9'	345	49°24.6'	124°06.8'
317	49°19.3'	124°03.5'	346	49°25.2'	124°06.1'
318	49°21'	124°02'	347	49°25.5'	124°06.0'
319	49°22.2'	124°00.9'	348	49°25.7'	124°05.3'
320	49°22.85'	124°00.4'	349	49°26.7'	124°04.0'
321	49°23.8'	123°59.5'	350	49°27.7'	124°02.6'
322	49°24.87'	123°58.6'	351	49°29.0'	124°00.8'
323	49°25.5'	123°58'	352	49°21.9'	123°47.1'
324	49°25.8'	123°51.8'	353	49°21.6'	123°46.3'
325	49°26'	123°57.7'	354	49°21.1'	123°45.3'
326	49°26.5'	123°57.3'	355	49°20'	123°43.3'
327	49°27.3'	123°56.4'	356	49°19.6'	123°42.3'
328	49°27.4'	123°59.2'	357	49°18.7'	123°40.4'
329	49°26.3'	124°00.5'	358	49°17.8'	123°38.6'

Pharo



CENTRAL AND SOUTHERN

STRAIT OF GEORGIA

FIGURE 2