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Title: STRATIGRAPHY AND PALEOENVIRONMENTS OF THE CRETACEOUS ROCKS, NORTH AND SOUTH PENDER ISLANDS, BRITISH COLUMBIA

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Dr. Keith F. Oles

The bedrock of North and South Pender Islands, the southernmost islands of British Columbia's Gulf Islands chain, is formed entirely by six formations of the Late Cretaceous Nanaimo Group. These six formations are, from oldest to youngest, the Extension-Protection, Cedar District, DeCourcy, Northumberland, Geoffrey, and Spray Formations. A composite section of maximum thicknesses for these formations totals approximately 11,600 feet. The formations, however, vary in thickness significantly along strike. These formations represent four cycles of deltaic progradation, the youngest and oldest of which are incompletely exposed.

The Extension-Protection Formation is considered to be the upper part of a west- to northwest-prograding delta complex, the lower part of which is not exposed within the thesis area. The fluvial

conglomerates of the Extension-Protection Formation, inferred to be topset beds, are overlain on South Pender Island by an interval of shallow marine arkosic and lithic sandstones. This shallow marine interval pinches out to the northwest and is absent on North Pender Island. The mineralogy of the conglomerates and sandstones suggests that the Extension-Protection Formation was derived from the pre-Cretaceous rocks of Vancouver Island.

The Extension-Protection Formation intertongues with and grades into the Cedar District/DeCourcy delta. Prodelta muds of the lower Cedar District Formation are overlain by distal bar turbidites. The turbidite deposits are conformably overlain by arkosic delta-front sheet sands or river mouth bars of the lower DeCourcy Formation. Continued basin subsidence, possibly combined with lower sedimentation rates, caused a transgression over the lower DeCourcy Formation and a return to prodelta deposition of the upper Cedar District Formation. The upper Cedar District and upper DeCourcy Formations follow a depositional cycle similar to that of the lower Cedar District and lower DeCourcy Formations, with the exception that fluvial conglomerates inferred to be topset beds intertongue with and overlie the shallow marine delta-front sheet sands or river mouth bars. Paleocurrent data, lateral thinning and facies changes, and mineralogy suggest that the Cedar District/DeCourcy delta sediments were derived from a source, to the northwest on Vancouver Island, which was composed of the Vancouver Group and the Island Intrusions.

The vertical succession of prodelta muds, distal bar turbidites, delta-front sheet sands or river mouth bars, and fluvial conglomerates is the same for the Northumberland/Geoffrey deltaic cycle as for the upper Cedar District/DeCourcy deltaic cycle. Paleocurrent data, lateral thinning and facies changes, and mineralogy suggest that the Northumberland/Geoffrey delta sediments were derived from a source area to the northwest, which was either the same source area as that of the Cedar District/DeCourcy delta, or one similar to it.

The Spray Formation, the lower part of the youngest deltaic cycle exposed in the thesis area, consists of distal bar turbidites. The Northumberland/Geoffrey delta intertongues with the Spray Formation, although this intertonguing may be related to the overlying Gabriola Formation.

At least three episodes of faulting have deformed the rocks of North and South Pender Islands, forming the Kulleet Syncline and other subordinate folds. The major faults trend west-northwest, with minor faults trending northwest to northeast.

Stratigraphy and Paleoenvironments of the Cretaceous Rocks, North and South Pender Islands, British Columbia

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INTRODUCTION

Purposes and Methods of Investigation

The purposes of this investigation were to map the Cretaceous rocks, to determine the stratigraphy and structure, to describe in detail the sedimentary units present, to determine the paleoenvironments of deposition, and to determine the modes and directional properties for sediment dispersal of the Cretaceous rocks of North and South Pender Islands, the southernmost islands of British Columbia's Gulf Islands chain (Plate 1). The bedrock of North and South Pender Islands is formed entirely by rocks of the Late Cretaceous Nanaimo Group.

Field work was initiated on June 15, 1973 and ended on September 15, 1973. Field observations were plotted on aerial photographs (1 inch = 1/4 mile, 1 inch = 1/2 mile, and 1 inch = 1 mile) and data were transferred to a base map (1 inch = 1/4 mile). All maps and aerial photos were obtained from the Surveys and Mapping Branch of the British Columbia Department of Lands, Forests, and Water Resources.

Acquisition of field data was aided by the use of a 10X hand lens, sand gauge chart, Rock-Color Chart of The Geological Society of America (1963), Brunton compass, and Jacob's staff with Abney level. The stratification terms were modified from those proposed by McKee and Weir (1953).

Paleocurrent measurements of sole markings were rotated in the field to apparent original depositional position using the technique of Briggs and Cline (1967). When necessary, other paleocurrent indicators, such as parting lineations and foreset bedding, were rotated in the laboratory to apparent original depositional position using a stereonet. Rosette diagrams were constructed and grand means calculated to illustrate graphically the paleocurrent flow directions.

Conglomerate units from each of the coarse-grained units were randomly sampled for pebble counts. Pebble lithologies were identified using a binocular microscope. Petrographic thin sections of 32 samples were examined microscopically. Thirteen thin sections were point counted. Alkali feldspars were identified using a selective staining technique modified from Bailey and Stevens (1960). The Michel-Levy method for plagioclase determination was used. The sandstone classification of Gilbert (Williams, Turner, and Gilbert, 1954) was followed.

Samples from each of the mudstone units were examined using X-ray diffraction techniques to determine the mineralogy of the clay minerals present (see Appendix H for analytical techniques).

Geographic Setting

Location and Accessibility

North and South Pender Islands are the southernmost islands of British Columbia's Gulf Islands chain (Plate 1). Located off the east coast of Vancouver Island 18 miles north-northeast of Victoria, the Penders cover approximately 19 square miles. To the north the islands are bounded by Navy Channel, to the west and southwest lies Swanson Channel, to the east is Plumper Sound, and to the south lies Haro Strait which is traversed by the U.S.-Canada international boundary.

North and South Pender Islands are named after Staff Commander (later Captain) Daniel Pender, R. N. From 1857 to 1870 Captain Pender carried on the surveys of the British Columbia coast initiated earlier by Captain George Vancouver. These surveys were carried out aboard the vessels Plumper, Hecate, and the Beaver (Akrigg and Akrigg, 1969).

Access to North Pender Island is via ferry from Swartz Bay on Vancouver Island or from Tsawwassen on the Canadian mainland.

Both islands have adequate major road networks, with additional access to the interior provided by logging roads. A bridge provides vehicular access to South Pender Island. Because of the limited exposures and accessibility to the interior of the islands, most of the field work was accomplished along the coastlines of the two islands.

Principal Geographic Features

The north part of North Pender Island is dominated by George Hill, Dent Hill, and Mount Menzies (Plate 1), all southwest-dipping sandstone cuestas. The south part of North Pender is best described as three-pronged. Razor Point on the north, Wallace Point on the south, and an unnamed projection of land in between are separated by Port Browning on the north and Bedwell Harbor on the south.

South Pender Island consists of two major ridges separated by an intermediate valley. Mount Norman, the highest point of the two islands, is located on the western part of South Pender Island.

The topography of both islands is varied, ranging from rolling hills to steep cliffs. A few small lakes and swamps are found within the interiors, especially on the less resistant formations.

STRATIGRAPHY

Previous Work

Discovery of coal on Vancouver Island in 1835 and the initial mining for coal in 1849 and 1850 (Usher, 1952) prompted much of the geologic research into the rocks associated with these economic deposits.

In 1857, Dr. J. S. Newberry, geologist with the northern California and Oregon exploratory expedition led by Lt. Williamson, dated the coal-bearing rocks of Vancouver Island as Cretaceous. J. Hector (1861), physician and geologist with Captain J. Palliser on his exploration from Lake Superior to the Pacific Ocean, mapped, described, and collected fossils he dated as Cretaceous from the rocks at Nanaimo. While passing by canoe between North Pender Island and adjacent Saturna Island, Hector noted a syncline which extends between the two islands.

From 1857 to 1861, F. B. Meek conducted paleontological work on the Cretaceous rocks of this area, concentrating mainly on Vancouver and Sucia Islands (Usher, 1952). James Richardson (1872, 1878), after extensive investigations of the Vancouver Island coal-fields for the Geological Survey of Canada, constructed detailed maps and cross-sections of the coal basins. Richardson correlated the rocks of North and South Pender Islands with his lower "productive coal measures" and suggested that the coal-bearing strata of the Nanaimo coal field lie to the southwest of the Penders.

The first comprehensive work on the invertebrate fossils of the Late Cretaceous rocks of Vancouver Island was published in 1879 by J. F. Whiteaves, paleontologist with the Geological Survey of Canada (Usher, 1952).

Dawson (1890) first proposed the name Nanaimo Group for the Late Cretaceous sedimentary succession of Vancouver Island as a replacement for the previously used "Vancouver Group" suggested in 1889 by C. A. White (Usher, 1952).

Extensive and detailed geologic work on Vancouver Island was carried out by C. H. Clapp from 1908 to 1917. Clapp (1911) coined the formational names of the Nanaimo Group based on the previous subdivisions of Richardson and Dawson (Figure 1). In addition to his studies of the coal-bearing strata, Clapp also reported on the pre- and post-Cretaceous geology of the region (Clapp, 1914; Clapp and Cooke, 1917).

Additional stratigraphic studies of the coalfields of Vancouver Island were conducted by Dowling (1915) and Buckham (1947) (Figure 1).

Usher (1949, 1952) conducted detailed paleontological investigations of the Nanaimo Group on Vancouver Island and the Gulf Islands. Usher collected fossil mollusks on North and South Pender Islands, and reported the presence of the Cedar District, DeCourcy, and

Clapp 1911-1917	Buckham 1947 Usher 1952			Muller & Jeletzky 1969 and this thesis		Stratigraphic column
Nanaimo Basin		Nanaimo Basin	Comox Basin		Nanaimo Basin Comox Basin	
Northumber-land	Maestrichtian	Northumber-land	Spray	Maes.	Spray	
			Geoffrey	Campanian	Geoffrey	
			Lambert		Northumberland	
De Courcy	Campanian	De Courcy	Denman		De Courcy	
Cedar District		Cedar District	Trent River		Cedar District	
Protection		Protection	Comox		Extension-Protection	
Newcastle		Newcastle	Qualicum			
Cranberry		Cranberry				
Extension		Extension				
East Wellington		East Wellington			East Wellington Member	

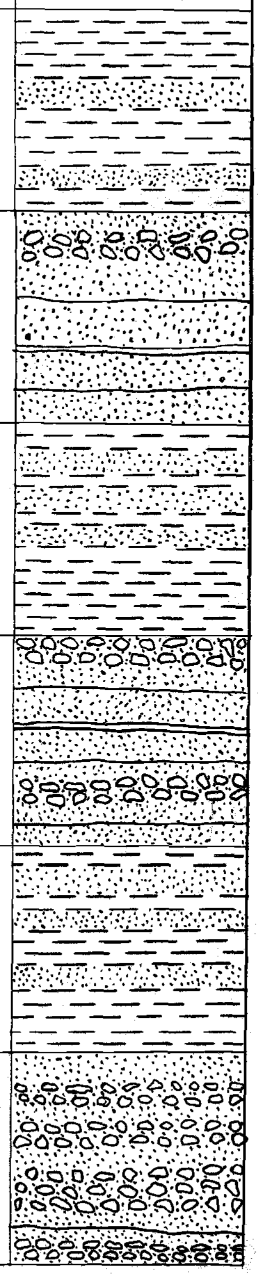


Figure 1. Correlations of the Nanaimo and Comox Basins (after Muller and Jeletzky, 1970), and generalized stratigraphic column (column not to scale).

Northumberland Formations (Figure 1). Usher also noted the presence of a syncline on North Pender Island. Studies of the fossil flora of the Nanaimo Group were published by Bell (1957).

The most recent and comprehensive work on the Nanaimo Group has been conducted by Muller and Jeletzky (1970). In addition to standardization of the formational nomenclature of the Nanaimo Group and a 1:250,000 geological map of the Gulf Islands and vicinity, Muller and Jeletzky also proposed a cyclic transgressive-regressive mechanism for the deposition of the alternating coarse- and fine-grained clastic sedimentary units of the Nanaimo Group.

Master of Science theses from Oregon State University concerning the Gulf Islands and Nanaimo Group include those of John A. Packard (1972), Richard W. Rinne (1973), and Michael S. Simmons (1973). Research on the geology of Saltspring Island is currently being conducted by O. S. U. doctoral candidate William B. Hanson.

Regional Stratigraphy

The oldest rocks exposed on Vancouver Island are those of the Sicker Group (Muller and Carson, 1969). The Sicker Group has been divided into three parts. The unnamed lower part, dated as being no younger than Pennsylvanian, includes greenstone and greenschist derived from andesitic-composition pyroclastic rocks. A minimum thickness for this part of the Sicker Group has been estimated at

10,000 feet. Overlying the basal unit is the clastic middle part of the Sicker Group. This unnamed Pennsylvanian age deposit includes 1,000 to 2,000 feet of graywacke sandstones, argillites, and local conglomerates, all metamorphosed. The upper part of the Sicker Group is known as the Buttle Lake Formation. This formation includes up to 1,000 feet of metamorphosed bedded Early Permian limestone with local chert. All parts of the Sicker Group have been intruded by basic sills and dikes (Muller and Carson, 1969).

Overlying the Sicker Group is the Vancouver Group. Included within the Vancouver Group are the Karmutsen Formation, the Quatsino Formation, and the Bonanza Subgroup. The Karmutsen Formation is the oldest part of the Vancouver Group and includes pillow basalts, pillow breccias, and basalt flows of sub-greenschist metamorphic rank. Thicknesses for the Karmutsen Formation range from 7,000 to 20,000 feet. Approximately 1,000 feet below the top of the Karmutsen Formation are limestones interbedded with the lavas. These limestones have been dated as early Late Triassic (late Karnian) (Muller and Carson, 1969).

Overlying the Karmutsen Formation are the massive to thickly bedded metamorphosed limestones of the Quatsino Formation. The Quatsino Formation is late Karnian in age and ranges from 500 to 2,000 feet in thickness (Muller and Carson, 1969).

The uppermost part of the Vancouver Group is the Bonanza Subgroup. These Late Triassic (Norian) rocks include thin-bedded metamorphosed limestones and argillites overlain mainly by metamorphosed pyroclastic rocks of andesitic composition. Thicknesses for the Bonanza Subgroup range from 2,000 to 3,000 feet (Muller and Carson, 1969).

Both the Sicker Group and the Vancouver Group are intruded by Middle and Late Jurassic granodioritic to quartz monzonitic rocks known as the Island Intrusions. Potassium-argon dates of the Island Intrusions give a date of intrusion as approximately 160 mybp (Muller and Carson, 1969).

Nonconformably overlying these older rocks are the sedimentary rocks of the Late Cretaceous Nanaimo Group. The Nanaimo Group extends from Campbell River, Vancouver Island to Orcas Island, Washington, a distance of 150 miles, with an outcrop area of approximately 1,500 square miles (Usher, 1952). The two major loci of Nanaimo Group deposition are the Comox Basin and the Nanaimo Basin. The Comox Basin extends from Nanoose Bay on the south to Campbell River on the north. The Nanaimo Basin includes the Late Cretaceous rocks extending south and southwest from Nanoose Bay through the Gulf Islands.

Muller and Jeletzky (1970) recognized four successive transgressive cycles in the Nanaimo Group consisting of eight formations and an uppermost non-marine formation, the Gabriola Formation. The cycles, formations, and their facies designations after Muller and Jeletzky (1970) are as follows:

Fifth Cycle (incomplete)

Gabriola Formation--Deltaic
600 to 3,000 feet of sandstone, conglomerate, minor mudstone.

disconformity

Fourth Cycle

Spray Formation--Marine
330 to 1,770 feet of mudstone, siltstone, minor sandstone.

Geoffrey Formation--Deltaic
400 to 1,500 feet of sandstone, conglomerate, minor mudstone.

disconformity

Third Cycle

Northumberland Formation--Marine
250 to 1,000 feet of mudstone, siltstone, minor sandstone.

DeCourcy Formation--Deltaic
130 to 1,400 feet of sandstone, conglomerate, minor mudstone.

disconformity

Second Cycle

Cedar District Formation--Marine
1,000 feet of mudstone, siltstone, minor sandstone.

Extension-Protection Formation--Deltaic to lagoonal
200 to 1,900 feet of conglomerate, sandstone, minor mudstone, and coal.

disconformity

First Cycle

Haslam Formation--Marine
100 to 500 feet of mudstone, siltstone, sandstone.

Comox Formation--Lagoonal to fluvial
100 to 1,300 feet of sandstone, mudstone, conglomerate, and coal.

Areal Stratigraphy

Six formations of the Nanaimo Group are present in the thesis area. From oldest to youngest, these formations are the Extension-Protection, Cedar District, DeCourcy, Northumberland, Geoffrey, and Spray Formations, representing Muller and Jeletzky's (1970) second, third, and fourth sedimentation cycles.

The stratigraphy of these formations, when interpreted according to modern concepts of deltaic sedimentation, actually represents four cycles of deltaic progradation, the youngest and oldest of which are incomplete due to lack of exposures. Particularly suggestive of the deltaic depositional environment are the cyclicity of sedimentation, the overall trend of grain size coarsening upward in each cycle, lateral facies changes and thickness variations, the sedimentary structures present, and the similarities of these rocks to those of ancient deltas and the sediments of modern deltas.

Extension-Protection Formation

Nomenclature. Clapp (1911) named five formations within the coal mining area of Nanaimo. These formations are, from oldest to youngest, the East Wellington Formation (with overlying Wellington coal seam), Extension Formation, Cranberry Formation (with overlying Newcastle coal seam), Newcastle Formation (with overlying Douglas coal seam), and the Protection Formation. These formations are indistinguishable outside the coal mining area and were grouped together as a single formation, the Extension-Protection Formation, by Muller and Jeletzky (1970).

General Stratigraphy. The Extension-Protection Formation crops out in a narrow strip from Thieves Bay to Wallace Point on North Pender Island (Plate 1 and Figure 2). The resistant conglomerates and sandstones form northeast-dipping cuestas as at Oaks Bluff, with the antidip slopes of the cuestas forming steep cliffs along the southwest coastline of North Pender Island from Boat Nook to Smugglers Nook.

On South Pender Island, the Extension-Protection Formation underlies the southern one-third of the island, where the section is repeated by faulting (Plate 1). As on North Pender Island, the resistant conglomerates and sandstones form northeast-dipping cuestas or hogbacks: one dipping 14°-49° in the Tilly Point-Drummond Bay-

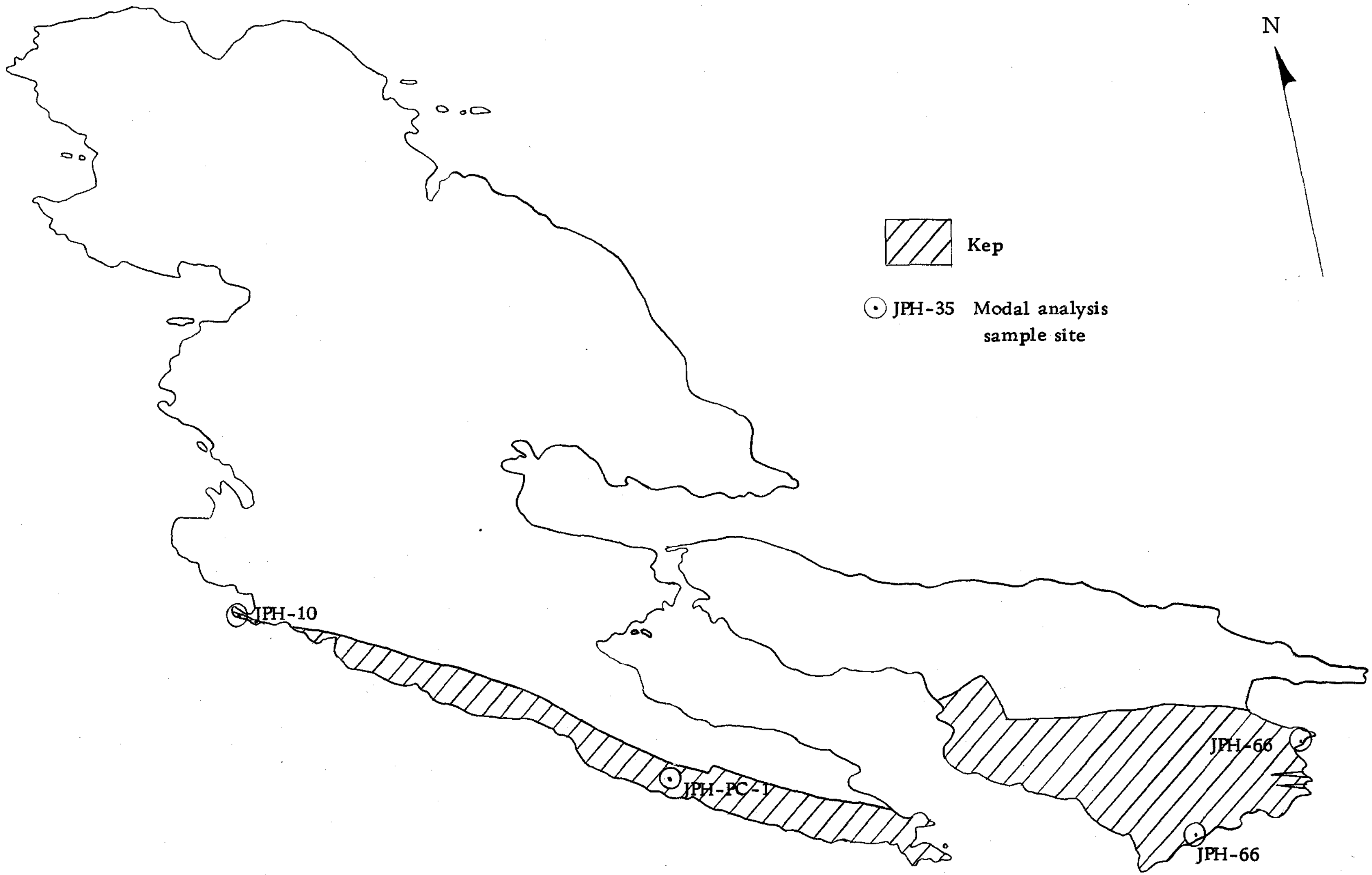


Figure 2 . Extension-Protection Formation distribution and sample sites for modal analyses and pebble counts.

Gowlland Point area, and two others dipping 26°-74° which form Stanford Hill and Curtis Peak.

Outcrops of the Extension-Protection Formation are almost continuous along the coastlines of both North and South Pender Islands. Some of these outcrops, however, are inaccessible because of the sheer cliffs rising from the channels in some areas. Outcrops in the interior of the islands are well exposed on the antidip slopes of cuestas, and there are local outcrops in road cuts and quarries. All other areas underlain by rocks of the Extension-Protection Formation are covered by a mantle of glacial deposits.

The basal contact of the Extension-Protection Formation is not exposed within the thesis area. The upper contact, separating pebble conglomerates and coarse-grained sandstones of the Extension-Protection Formation from the mudstones and fine-grained sandstones of the lower Cedar District Formation, is best exposed at the Thieves Bay navigation light on North Pender Island (Plate 1 and Figure 3). Here, over an interval of approximately 150 feet, thick-bedded pebble conglomerates and coarse-grained sandstones grade upward into interbedded medium- to fine-grained channeled sandstones and mudstones, finally passing into structureless mudstones. The lower 30 feet of the gradational interval contain zones of complex channel scour-and-fill (Figure 4). The upper contact of the Extension-Protection Formation can also be observed on the northwest shore of

Figure 3. Upper contact of the Extension-Protection Formation. Thick-bedded pebble conglomerates on left grade upward to mudstones of the lower Cedar District Formation on the right. Looking N. 56° W. at the Thieves Bay navigation light, North Pender Island.

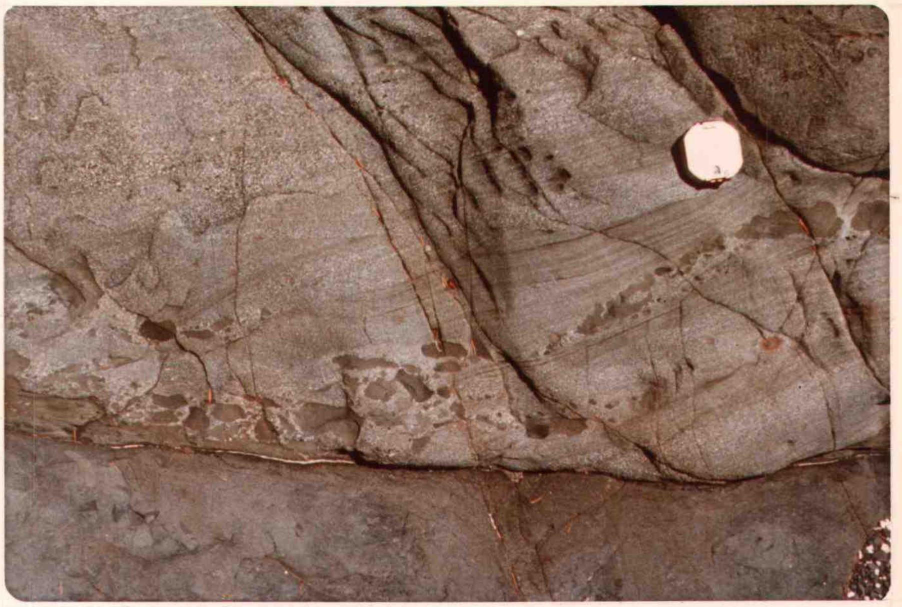


Figure 4. Part of a channel in the gradational zone between the Extension-Protection and Cedar District Formations. Note mud ripups and festooned bedding. At Thieves Bay navigation light, North Pender Island.

the Wallace Point area, North Pender Island, and in the southwest corner of Camp Bay, South Pender Island (Plate 1). At all locations the same general gradational sequence was observed, except no conglomerates are present at the upper contact of the Extension-Protection Formation on South Pender Island.

A reference section (Appendix A) was measured in the Oaks Bluff area (Plate 1) to provide a description of the typical development of the Extension-Protection Formation. Because the base is not exposed, the total actual thickness of the Extension-Protection Formation is unknown. A thickness of 1, 900 feet, derived from the known thickness of the Extension-Protection Formation in the Nanaimo Coal Basin, was used satisfactorily in constructing the geological cross-sections (Plate 1) and appears compatible with outcrop data.

The lower Extension-Protection Formation, best exposed on South Pender Island, is characterized by laterally extensive pebble and cobble conglomerates (Figure 5) which are not confined to discrete channels. These conglomerates are very thickly bedded and commonly display foreset bedding up to five feet thick (Figure 6). Basal contacts of the conglomerates are gently undulating to scour-and-fill, with channels two to five feet across and up to two feet deep.

The most striking feature of the conglomerates is their color. The conglomerates are commonly pale red (5R 6/2) to moderate red (5R 4/6) in gross aspect (Figures 5 and 6). This red color is generally

Figure 5. Typical pebble conglomerate from the Extension-Protection Formation. Note imbrication of clasts suggesting current from right to left. Bedding horizontal. End of Craddock Road, South Pender Island.

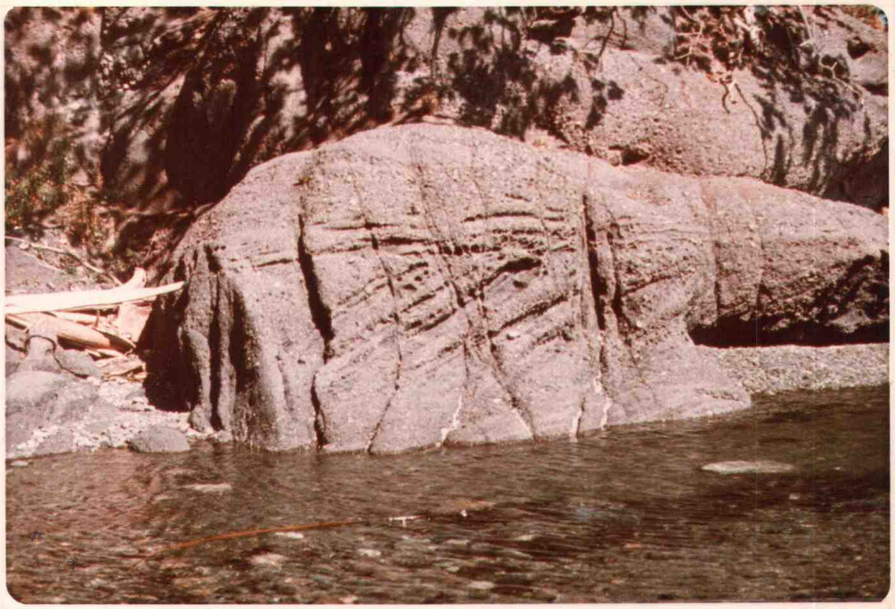


Figure 6. Planar foresets in Extension-Protection Formation pebble conglomerate. Current from right to left. Also note reddish color of outcrop (the color reproduction does not accurately portray the color of the rock). Height of cross-bedded interval is approximately five feet. End of Craddock Road, South Pender Island.

continuous over the entire outcrop, although locally it occurs as discontinuous patches in gray- or olive-colored surrounding rocks. Muller and Jeletzky (1970) attribute this color to the presence of abundant jasperoid chert. Thin section analysis, however, shows that a pervasive hematitic stain in the carbonate cement and matrix of the rocks produces the color.

Interbedded with the conglomerates are medium- to coarse-grained, poorly sorted, angular to subangular sandstones and rare thin beds of mudstone. The sandstones commonly appear brownish gray (5YR 4/1) to pale red (5YR 5/2) on weathered surfaces, with fresh surfaces light brownish gray (5YR 6/1) to light olive gray (5Y 6.5/1). The sandstones are thin- to thick-bedded and crudely graded upward over four to eight inches into similarly colored mudstones. Basal contacts of the sandstones are generally sharp and planar.

The upper Extension-Protection Formation, as exposed from Gowlland Point north on South Pender Island, is characterized by very thick-bedded conglomerates interbedded with very thick-bedded medium- to coarse-grained sandstones. Bedding thicknesses for both the conglomerates and the sandstones range from 10 to 40 feet. The conglomerates are similar in texture and composition to those of the lower Extension-Protection Formation, but lack the red color. Weathered surface colors for these conglomerates range from dark yellowish orange (10YR 6/6) to pale greenish yellow (10Y 8/2) in gross aspect.

The thick-bedded sandstones associated with these conglomerates appear medium dark gray (N 4) to yellowish olive gray (5Y 6/2) on weathered surfaces and medium light gray (N 5.5) to light olive gray (5Y 6.5/1) on fresh surfaces. The sandstones are medium- to coarse-grained, rarely pebbly or contain rare mud ripups, poorly to moderately sorted, and angular to subangular. Basal contacts of the sandstones are sharp and planar to gently undulating with less than three inches of relief. The upper 4- to 12-inch interval of each sandstone bed is crudely graded through similarly colored siltstone to dark gray (N 3) to olive gray (5Y 4/1) weathered mudstone. Isolated calcareous concretions up to 18 inches in diameter are found in these sandstones.

Sandstones become more abundant upward at the expense of conglomerates, in this interval on South Pender Island, until, at the top of the Extension-Protection Formation at Higgs Point (Plate 1), the formation is composed entirely of sandstone. However, on North Pender Island this sandstone interval is non-existent and the upper Extension-Protection Formation is characterized by thick beds of conglomerate alternating with thinner beds of sandstone and mudstone. For a more complete description of this interval, see Appendix A.

In the Gowlland Point area of South Pender Island two coves occur in what is interpreted as tongues of non-resistant Cedar District Formation mudstones. This is the only place on either island where intertonguing in the Extension-Protection Formation with the Cedar District Formation can be demonstrated on a large scale.

Sedimentary structures in the conglomerates of the Extension-Protection Formation include imbrication (Figure 5), graded bedding, scour-and-fill (Figure 7), planar foreset bedding (Figure 6), and load casts (Figure 7). Sedimentary structures in the sandstones of the Extension-Protection Formation include graded bedding, scour-and-fill, parting lineation, planar and festooned cross-bedding (Figure 4), parallel laminations, mud ripups (Figure 4), calcareous sandstone concretions, and convolute bedding. Woody fragments are common in the uppermost sandstones of the Extension-Protection Formation at Thieves Bay, North Pender Island.

Wave action and spray have produced wave-cut notches, caverns, and waffle-like patterns of honeycomb weathering in many of the sandstones of the Extension-Protection Formation.

Lithology. Pebbles from an Extension-Protection Formation conglomerate were obtained from a deeply weathered outcrop on the southeast side of Oaks Bluff, North Pender Island (Figure 2). The major lithologies identified from the sample include andesite, basalt, medium- to coarse-grained sandstones, and chert. Minor

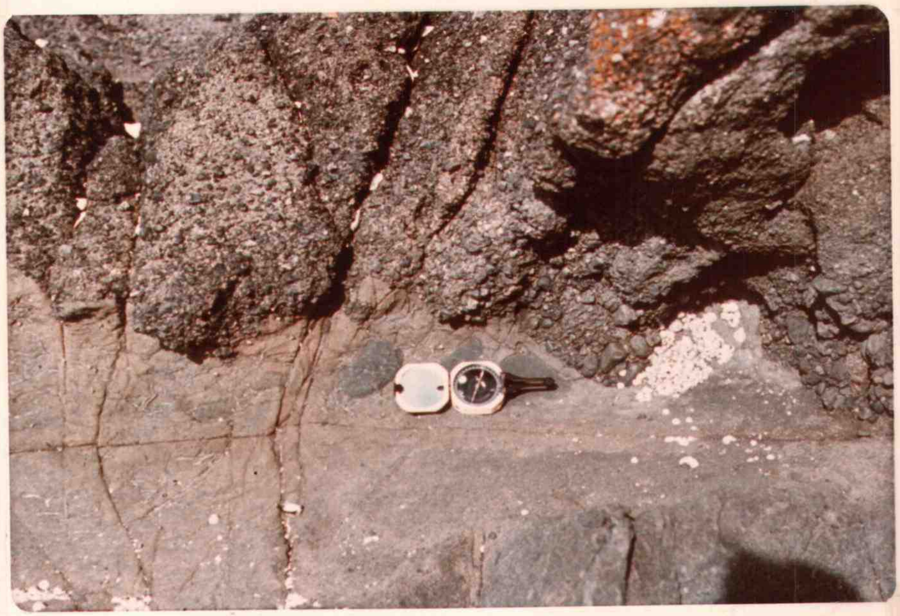


Figure 7. Loaded scour-and-fill bedding contact of Extension-Protection Formation pebble conglomerate over coarse-grained sandstone. Near Peter Cove, North Pender Island.

constituents include granitic and dioritic plutonic pebbles, greenstone, rhyolite, and foliated metamorphics. A breakdown of pebble count lithologies is presented in Appendix G.

Five thin sections of Extension-Protection Formation sandstones were examined microscopically. Six-hundred point model analyses (Appendix F) were performed on three of these samples. The results indicate that the sandstones are compositionally immature and texturally immature to submature, following Folk's (1951) concept of textural maturity. The sandstones are poorly to moderately sorted, angular to subangular lithic arenites and poorly sorted, subangular arkosic wackes (Figure 8). Matrix contents range from 2.7% to 11.8%. The clay matrix appears to be in part detrital and in part diagenetically derived from alteration of volcanic rock fragments.

Framework grains of these sandstones are dominantly quartz, chert, plagioclase, potassium feldspar, rock fragments, chlorite, and polycrystalline quartz. Minor constituents include magnetite, hornblende, and apatite. Types of plagioclase feldspar include andesine, with rare albite and oligoclase. The dominant potassium feldspar is orthoclase. Sericite, calcite, and chlorite are common alteration products of the feldspars. Generally the feldspars of the Extension-Protection Formation are highly altered. Detrital micas include muscovite and minor amounts of biotite. Rock fragments found in these sandstones include andesitic volcanic, medium- and

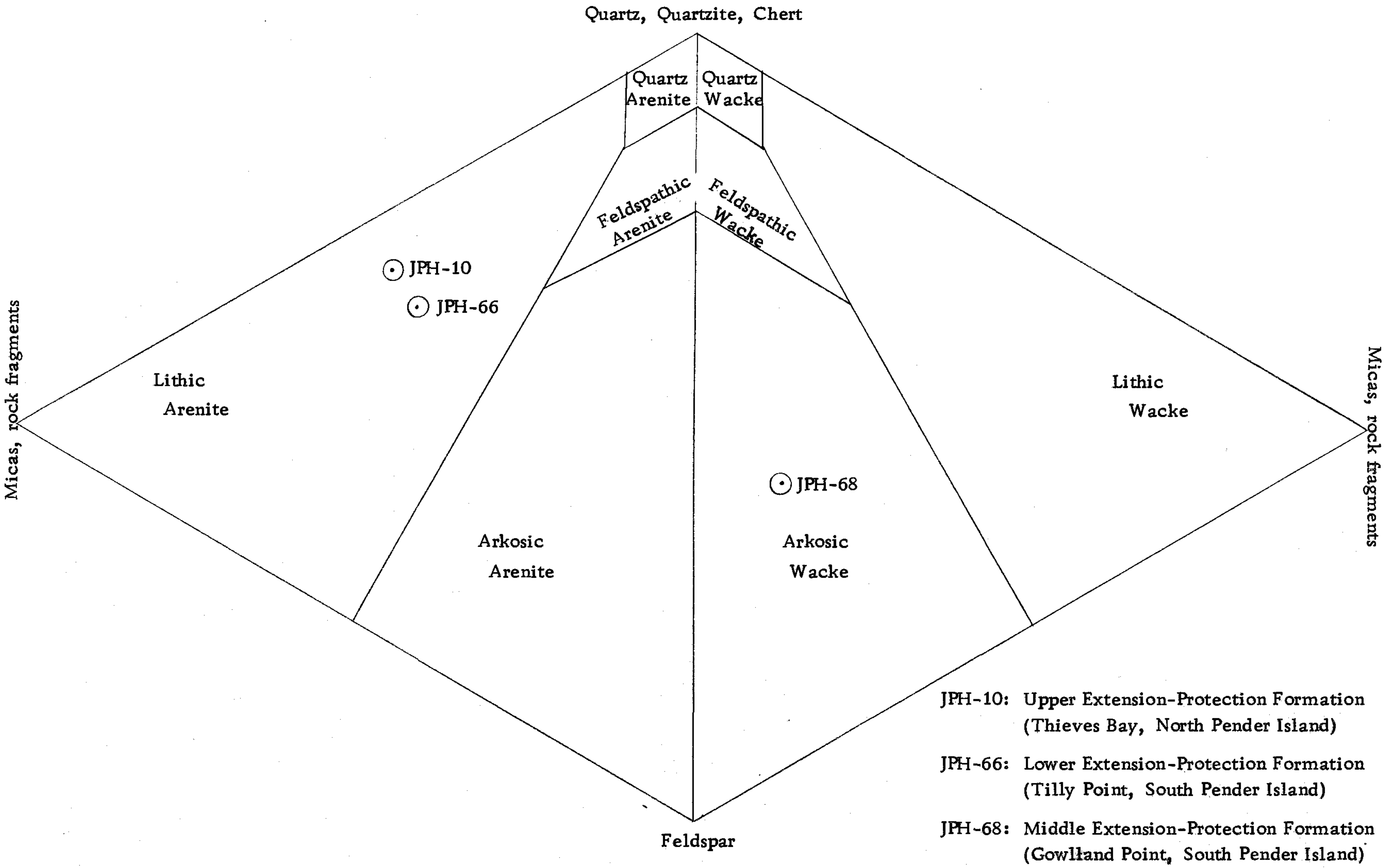


Figure 8 . Classification of Extension-Protection Formation sandstones (after Gilbert, 1954).

fine-grained sandstones, phyllite, schist, granitic, and mudstone fragments.

The cement found in the two lithic arenites examined is calcite. Numerous areas in the thin sections were noted where the calcite cement is replacing quartz, chert, volcanic rock fragments, and feldspar.

Environments of Deposition. Tight packing and imbrication of the well-rounded clasts in the conglomerates of the lower Extension-Protection Formation suggest fluvial deposition. The large size of the clasts and the occurrence of large-scale planar foresets (Figure 6) suggest that this fluvial medium was of high energy with a nearby source area. Wilkinson and Oles (1968) state that laterally extensive and apparently nearly horizontally deposited conglomerates such as these may indicate that the conglomerate sedimentation units are topset beds. The red color of the conglomerates and interbedded sandstones, though not in itself evidence for subaerial exposure, serves to support the topset bed hypothesis for the origin of these rocks.

At Gowlland Point, the top of the red conglomerates is marked by the intertonguing with the less resistant rocks of the Cedar District Formation. This is interpreted as alternating periods of fluvial and marine sedimentation, as would occur at the margins of the delta-front platform and the prodelta slope (Allen, 1970).

The return to fluvial sedimentation is marked by the recurrence of pebble conglomerates stratigraphically above the Cedar District Formation tongues. Though these conglomerates lack the red color of the lower Extension-Protection Formation conglomerates, they are still interpreted as being fluvially deposited topset beds. These conglomerates intertongue with and are succeeded by thick-bedded, evenly laminated sandstones which closely resemble those of the delta-front platform of the modern Niger River Delta (Allen, 1970).

Laterally equivalent rocks on North Pender Island lack the thick delta-front platform sandstone interval found on South Pender Island. Here, thick-bedded conglomerates of probable fluvial origin alternate with thick interbeds of sandstone and mudstone (Figure 9). The upward fining sequence of conglomerate-sandstone-mudstone, with its scour-and-fill base is similar to the alluvium of a braided river (Selley, 1970). It is also possible that the sandstone and mudstone interbeds are environmentally equivalent to prodelta slope deposits of the modern Niger Delta (Allen, 1970). Thinning of conglomerate beds and the probable pinching out of the delta-front platform sandstone interval from South Pender Island to North Pender Island suggest deltaic progradation from the southeast to the northwest.

The alternations between fluvial and shallow marine sedimentation which occur in the Extension-Protection Formation are probably related to a variety of factors. These factors include variations in

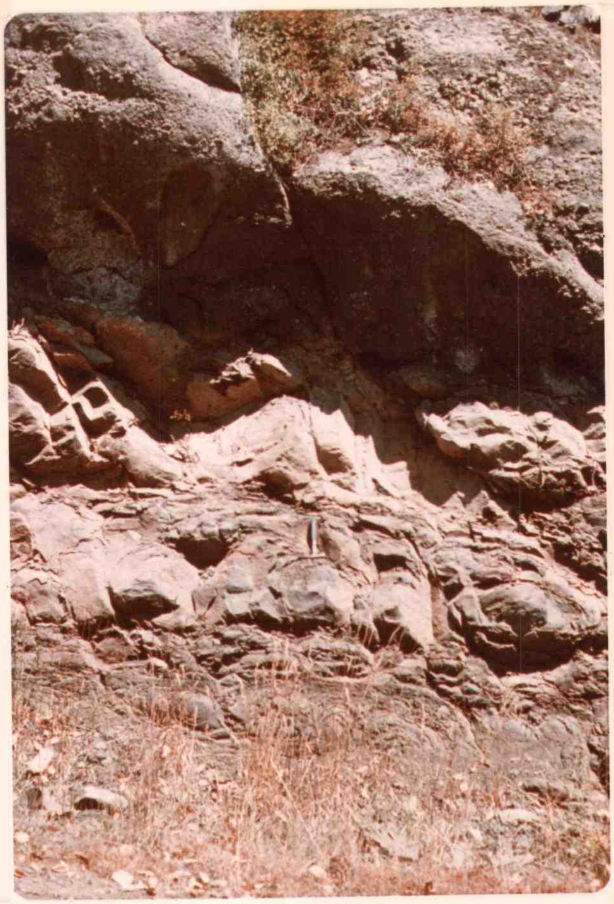


Figure 9. Sandstone and mudstone interbed underlying Extension-Protection Formation pebble conglomerate. Note spheroidal weathering of mudstones and scour-and-fill lower bedding contact of conglomerate. Oaks Bluff area, North Pender Island.

the rate of basin subsidence, tectonic events in the source area, or normal processes of deltaic sedimentation, especially channel abandonment and swinging of major sediment distributaries. Major fluctuations in sea level, while improbable, could also contribute to this phenomenon. In any case, sediment deposition and burial was very rapid, with no evidence of reworking by littoral processes.

Cedar District Formation

Nomenclature. Clapp and Cooke (1917) designated the name Cedar District Formation for the marine mudstones which overlie the Nanaimo Basin coal measures. Muller and Jeletzky (1970) measured and described a 1,010-foot section at Dodd Narrows, which is considered the type section for the formation.

General Stratigraphy. The Cedar District Formation underlies two strips of land on the southern part of North Pender Island. The lower Cedar District Formation extends from Thieves Bay to Bedwell Harbor (Plate 1 and Figure 10) and underlies most of Magic Lake. The upper Cedar District Formation, separated from the lower part of the formation by a tongue of DeCourcy Formation sandstone, underlies a valley extending from 1/4 mile north of Boat Nook to Medicine Beach and along the southwest shore of Bedwell Harbor. The Cedar District Formation is also exposed as tongues in DeCourcy Formation

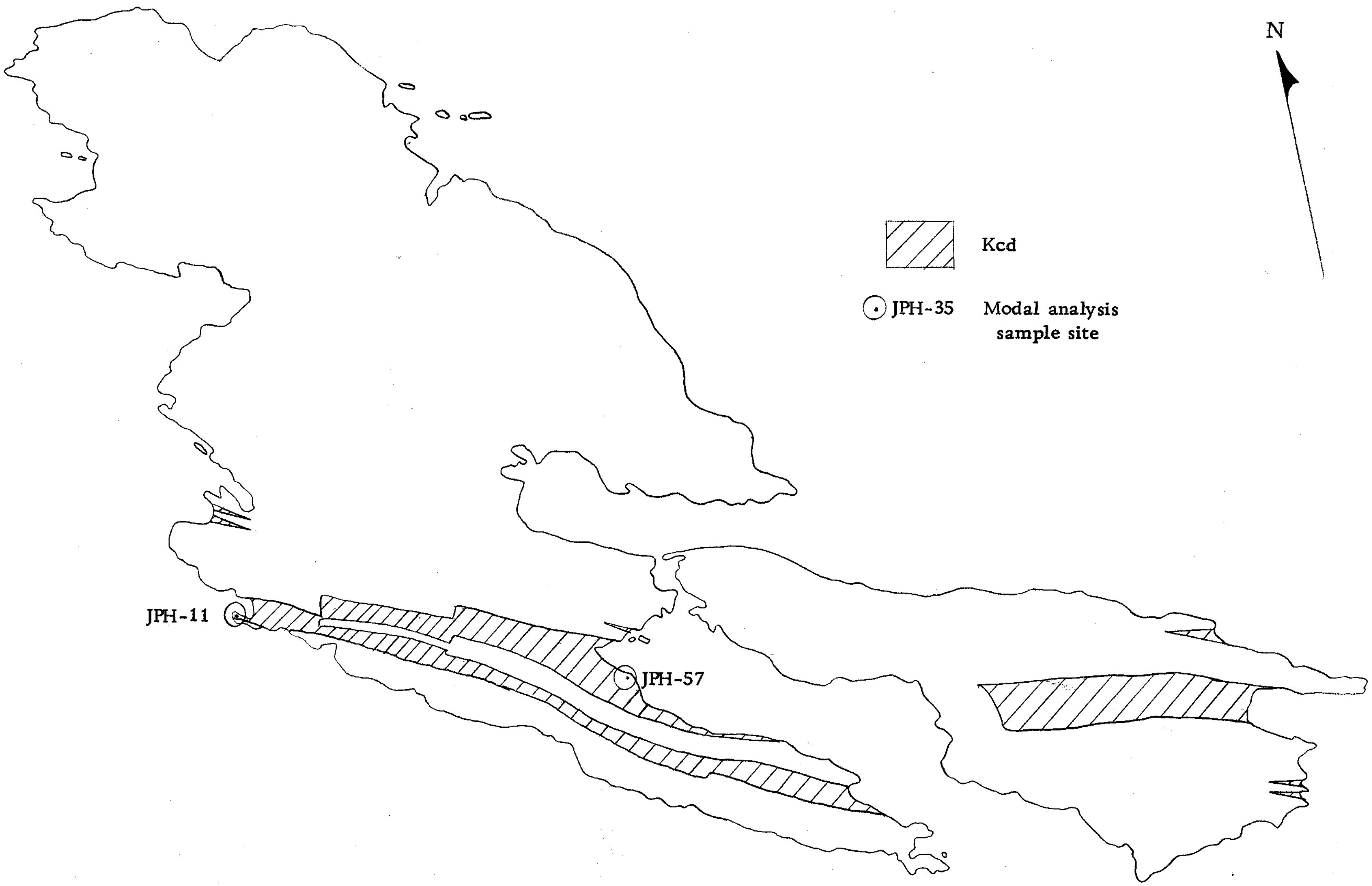


Figure 10. Cedar District Formation distribution and sample site for modal analyses.

sandstones along the southeast shore of Shingle Bay and north of Medicine Beach, North Pender Island (Plate 1 and Figure 10).

On South Pender Island, the Cedar District Formation underlies the valley between Curtis Peak and Spalding Hill and extends under Camp Bay (Plate 1 and Figure 10). Other exposures of the Cedar District Formation occur as tongues in the Extension-Protection Formation in the Gowlland Point area and as a tongue in the DeCourcy Formation north of Hermit Hill.

Because it is non-resistant, the Cedar District Formation forms limited outcrops. The best exposures are at Medicine Beach and Thieves Bay on North Pender Island. Limited exposures occur at Shingle Bay, and in road cuts and quarries in the interior of the islands. At all other places, the Cedar District Formation is covered by a mantle of glacial debris.

The basal contact of the lower Cedar District Formation with the Extension-Protection Formation has been described in the preceding section. The upper contact, separating the thick-bedded sandstones of Tongue 1 of the DeCourcy Formation from the normally graded sandstone-siltstone-mudstone sequence of the lower Cedar District Formation is best exposed in Section 6, near the southeast tip of North Pender Island (Plate 1). Here, presumably massive mudstone is overlain by and interbedded with normally graded sandstones and siltstones of probable turbidite origin. Although the contact with the lowermost sandstone of the DeCourcy Formation is covered, the general overall increase in sandstone upsection suggests a gradational contact. For a more complete description of this interval, see Appendix B.

The lower contact of the upper Cedar District Formation is exposed only along the southwest coastline of Bedwell Harbor in Sections 21 and 6, North Pender Island (Plate 1). Here, the contact separating the DeCourcy Formation sandstones from the mudstones and siltstones of the upper Cedar District Formation is sharp and essentially planar. The upper contact of the upper Cedar District Formation is best exposed at Medicine Beach, North Pender Island. As with the lower Cedar District Formation, presumably massive mudstones are overlain by normally graded sequences of sandstone-siltstone-mudstone. The percentage of sandstone increases upward in the section until, at the top of the formation the outcrop is 60% to 65% sandstone (Figure 11). Although the contact with the overlying DeCourcy Formation sandstones is sharp and conformable, the interval below the contact is considered as a gradational transition between the two formations. A similar sequence was observed in roadcuts on South Pender Island at the top of the Cedar District Formation.

Two sections (Appendices B and C) were measured and described in the Cedar District Formation to establish its stratigraphic relationships with the underlying and overlying formations. The total

Figure 11. Sandstone-siltstone-mudstone sequence of probable turbidite origin in the uppermost part of the upper Cedar District Formation. Note general overall increase in thickness of sandstone beds upsection. Northwest corner of Medicine Beach, North Pender Island.

thickness of the Cedar District Formation, as exposed on North and South Pender Islands, is estimated as a minimum of 2,200 feet.

The lower part of the lower Cedar District Formation consists of sandy mudstone and non-resistant, presumably massive mudstone. Exposures of the non-resistant mudstone are poor to non-existent. The sandy mudstones yielded a few specimens of fossil pelecypods, particularly external molds and shell fragments of Inoceramus. The upper part of the lower Cedar District Formation is dominantly composed of rhythmically bedded, normally graded sandstone-siltstone-mudstone sequences (Figure 12). Individual graded units range from three to seven inches in thickness. Bottom contacts of the graded units are generally sharp and planar to gently undulating; upper contacts are generally gradational over one to four inches. Parallel laminations and convolute laminations observed in these graded units may represent divisions B and C or divisions C and D of incomplete Bouma sequences (Bouma, 1962).

The lower part of the upper Cedar District Formation is dominantly composed of massive mudstone with minor thin beds of siltstone and normally graded sandstone-siltstone-mudstone sequences. The upper part of the upper Cedar District Formation is formed entirely by normally graded sandstone-siltstone-mudstone sequences similar to those of the upper part of the lower Cedar District Formation except that the individual graded units increase in thickness up to 12 inches.

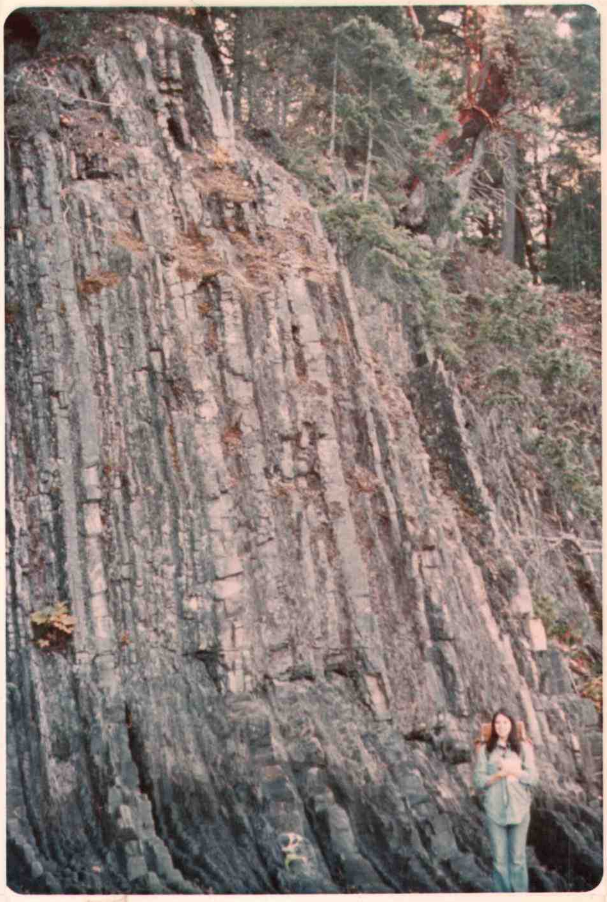


Figure 12. Vertically dipping normally graded sandstones and mudstones of the Cedar District Formation. Near Shingle Bay, North Pender Island.

Intertonguing of the Cedar District Formation with the Extension-Protection Formation has been described previously. Tongues of Cedar District mudstones and sandstones in the DeCourcy Formation occur on the southeast side of Shingle Bay and are particularly well exposed northeast of Medicine Beach, North Pender Island (Plate 1). These alternations of coarse- and fine-grained sedimentation probably reflect channel abandonment and migrating distributaries in the deltaic model of sedimentation. Other factors possibly contributing to this phenomenon might include variations in the rate of basin subsidence, tectonic events in the source area, and the remote possibility of major fluctuations in sea level.

The dominant lithology of the Cedar District Formation is mudstone. The mudstone is often laminated but usually weathers out as 1/4 to one inch chips which obscure any bedding which may be present. Weathered surface colors for the mudstones range from dark yellowish brown (10YR 4/2) to dark gray (N 3); fresh surface colors range from greenish black (5G 2/1) to light bluish gray (5B 6/1). Scattered lenses of micritic mudstone ranging from one to four inches thick and three inches to several feet in length are found in the mudstones, as are 1/2 to two-inch wide and one to three-inch long limonite-stained nodules and bands of pyrite-marcasite.

The sandstones of the Cedar District Formation are generally thinly laminated to laminated; many are cross-laminated. Grain sizes range from very fine-grained to medium-grained, with poor to moderate sorting and subangular to subrounded particles. Weathered surfaces are commonly yellowish gray (5Y 7/2) to light gray (N 6); fresh surfaces are commonly medium bluish gray (5B 6/1) to medium gray (N 4.5). Siltstones are thinly laminated to thin-bedded and display colors similar to those of the sandstones.

Sedimentary structures observed in the Cedar District Formation include graded bedding, parallel and cross-laminations, convolute bedding, calcareous mudstone concretions, pseudo-concretions (concentrically weathering mudstone concretions, lithologically similar to the encompassing unit), load casts, groove casts, current crescents, and parting lineation.

Organic structures found in the Cedar District Formation include whole and broken pelecypod shells (with original shell material preserved), external molds of *Inoceramus*, woody debris, and horizontal worm burrows.

Lithology. X-ray diffraction analysis of Cedar District Formation mudstone revealed chlorite, vermiculite, mica, and possibly kaolinite as the clay minerals present (see Appendix G for tabulated results and Appendix H for analytical techniques).

Four thin sections of Cedar District Formation sandstones were examined microscopically. Modal analyses (Appendix F) were performed on one sample each from the lower and upper Cedar District

Formation (Figure 13), showing that the sandstones are compositionally immature and texturally immature to submature following Folk's (1951) concept of maturity. The sandstones are either very fine- to medium-grained lithic wackes or medium- to coarse-grained arkosic arenites, with matrix contents ranging from 5.3% to 23.2% (Figure 13). All of the sandstones are poorly sorted, with angular to subangular particles. The framework grains are dominantly quartz, chert, plagioclase, potassium feldspar, rock fragments, and chlorite. Minor constituents include polycrystalline quartz, garnet (almandite), epidote, hornblende, and magnetite. Types of plagioclase feldspar include andesine, with minor oligoclase. The dominant potassium feldspar is orthoclase. Feldspars are commonly altered to sericite and calcite. Detrital micas include locally abundant biotite with less abundant muscovite. Andesitic volcanic, fine-grained sandstone, mudstone, diorite, schist, and phyllite rock fragments are also present.

Environments of Deposition. The massive mudstones of the lower parts of the lower and upper Cedar District Formation appear to represent marine deposition in a low energy environment, probably below wave base. The presence of unbroken and articulated fossil clams and *Inoceramus* suggests that these are shallow marine deposits and have not been redeposited by turbidity currents. In the deltaic models of sedimentation suggested by Coleman and Gagliano (1965)

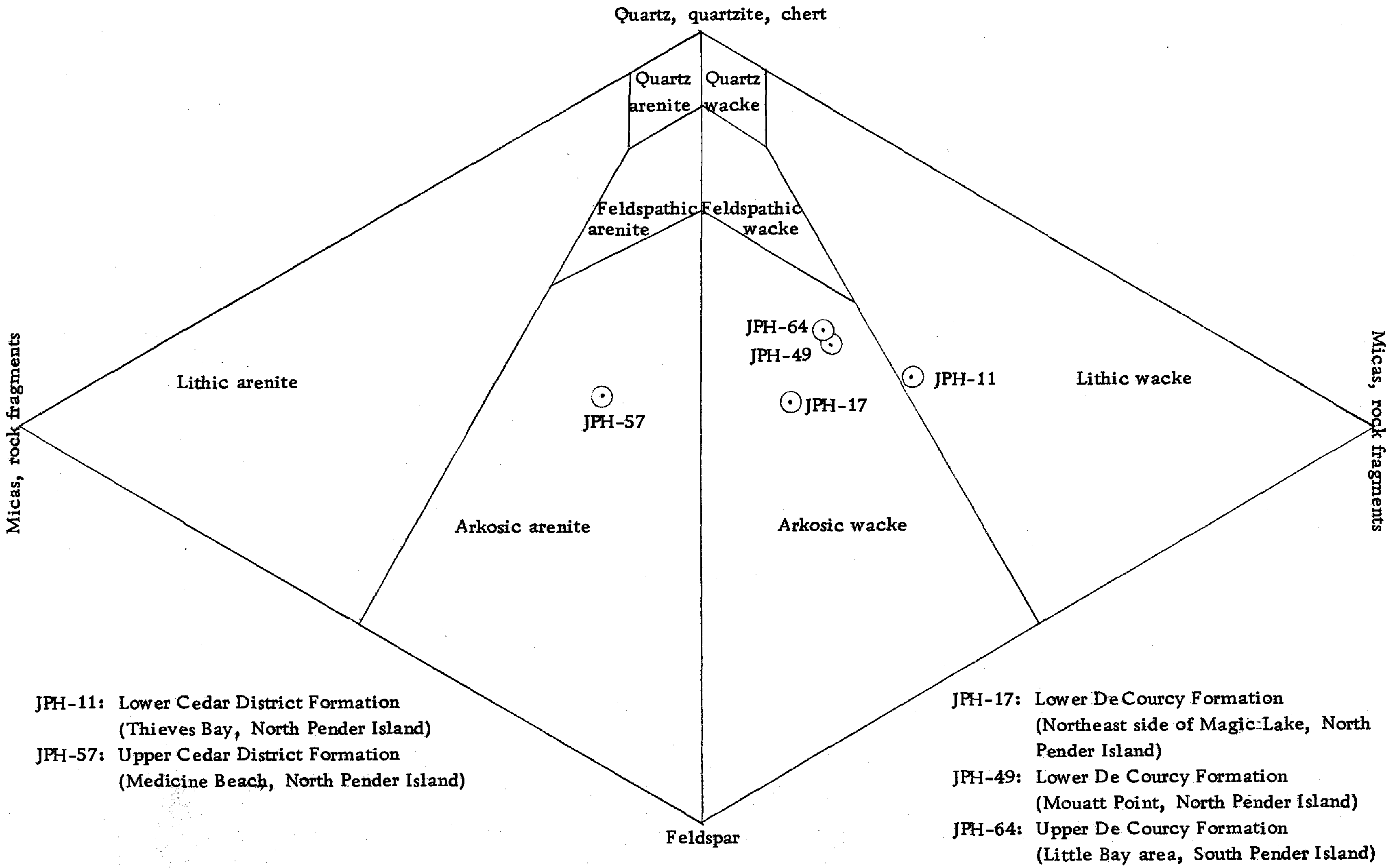


Figure 13. Classification of Cedar District and De Courcy Formation sandstones (after Gilbert, 1954).

and Visher (1965), these deposits are found in the prodelta environment.

The upper parts of the lower and upper Cedar District Formation probably represent the filling of a shallow marine depositional environment. This filling apparently was by sediment transported by turbidity currents as deltaic progradation overran the prodelta environment. Coleman and Gagliano (1965) recognize sedimentation of this type in their distal bar environment, while Allen (1970), Visher (1965), and Dott (1966) recognize turbidity currents as integral depositional modes in their deltaic sedimentation models. That this depositional environment was shallow is suggested by the upward transition of these turbidite sequences into shallow marine and fluvial rocks of the overlying DeCourcy Formation. The presence of pyrite-marcasite as nodules and bands within the mudstones suggests that Cedar District deposition occurred at least in part under reducing conditions (Krauskopf, 1967).

DeCourcy Formation

Nomenclature. Clapp (1911) proposed the name, DeCourcy Formation, for the sandstones and conglomerates which overlie the Cedar District Formation. The name is derived from the DeCourcy Islands which are formed by this formation.

General Stratigraphy. The DeCourcy Formation is the most extensive formation on North and South Pender Islands (Plate 1 and Figure 14). The lower DeCourcy Formation underlies the resistant ridge extending from 1/4 mile north of Boat Nook to the southwest coastline of Bedwell Harbor, Section 6, North Pender Island. The upper DeCourcy Formation forms a fault block in the Irene Bay-Cramer Hill area and extends from the Shingle Bay-Thieves Bay area, under Lively Peak, to the Aldridge Point-Medicine Beach area, North Pender Island.

The lower DeCourcy Formation pinches out to the southeast and is absent on South Pender Island. The upper DeCourcy underlies the northern half of the island, from the Mortimer Spit-Ainslie Point area to Teece Point (Plate 1 and Figure 14). Mount Norman, the highest elevation on the two islands, Spalding Hill, Hermit Hill, and Blunden Islet are all underlain by the DeCourcy Formation.

Outcrops of the DeCourcy Formation are nearly continuous along the coastlines of both North and South Pender Islands. Outcrops in the interiors of both islands are found along ridge-crests, in road cuts, and along fault scarps such as the southwest side of Mount Norman and Richardson Bluff (Plate 1).

The basal and upper contacts of the lower DeCourcy Formation and the basal contact of the upper DeCourcy Formation have been described previously. The upper contact of the upper DeCourcy

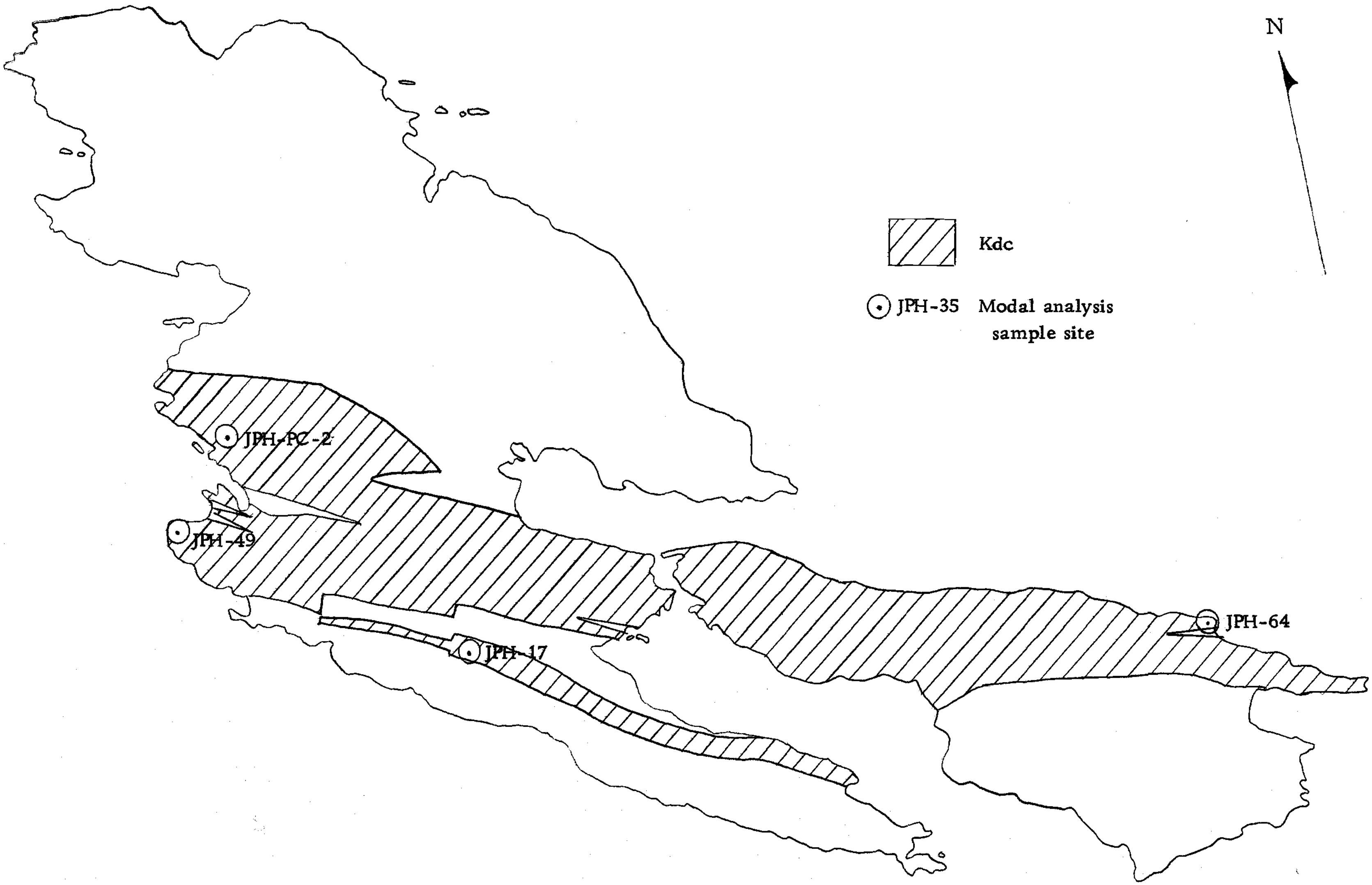


Figure 14. De Courcy Formation distribution and sample sites for modal analyses and pebble counts.

Formation has been faulted out of the stratigraphic sequence and was not observed in the thesis area. Muller and Jeletzky (1970) consider the upper contact to be gradational into the overlying Northumberland Formation. Simmons (1973) reported a sharp and conformable contact at the top of the DeCourcy Formation on Thetis and Kuper islands.

A complete stratigraphic section was not measured in the DeCourcy Formation because of faulting. An estimated total thickness of the formation, as exposed on North and South Pender islands, is 2,500 feet. This figure is based on both the known thicknesses of the measured intervals (Appendices B and C) and outcrop evidence.

The lower DeCourcy Formation is characterized by very thick-bedded (2 to 15 feet), resistant sandstones which form the linear ridge extending from 1/4 mile north of Boat Nook to the southwest coastline of Bedwell Harbor, Section 6, North Pender Island (Plate 1 and Figure 14). The dominant sedimentary structures within this almost 300-foot thick tongue are parallel laminations. The lower contacts of the sandstone beds which form this tongue are sharp and planar to gently undulating. Load casts (Figure 15), groove casts, and flute cases were observed on the lower bed surfaces, but are not abundant. The upper bedding contacts are gradational over three to seven inches to siltstone or mudstone partings. For a more complete description of this interval, see Appendix B.

Figure 15. Load casts on the bottom of over-turned DeCourcy Formation sandstone beds. North side of Irene Bay, North Pender Island.

Figure 16. Typical DeCourcy Formation pebble and cobble conglomerate. Note large mudstone ripup in left center of photo. One-quarter mile northeast of Medicine Beach, North Pender Island.

The upper DeCourcy Formation, separated from the lower DeCourcy by the mudstone tongue of the upper Cedar District Formation, is characterized by sandstones similar to those of the lower DeCourcy. The upper DeCourcy Formation is a minimum of 2,200 feet thick within the thesis area. At least three conglomerate intervals, represented by pebble and cobble conglomerates (Figure 16), are interbedded with the sandstones. These conglomerate intervals are best exposed 1/8 mile and 1/2 mile northeast of Medicine Beach and from Shingle Bay to Teece Point (Plate 1). Conglomerates underlie much of Lively Peak, Mount Norman, Spalding Hill, and Hermit Hill. The lower and middle conglomerate intervals are 25 and 15 feet thick, respectively. The upper conglomerate interval is a minimum of 800 feet thick. None of the conglomerate intervals are confined to discrete channels. Tight packing, imbrication, and a high degree of rounding of the clasts suggest that these conglomerates are of fluvial origin. See Appendix C for a more detailed description of the upper DeCourcy Formation.

Sandstone is the dominant lithology of the DeCourcy Formation. The sandstones are commonly yellowish gray (5Y 8/1) to very pale orange (10YR 8/2) on weathered surfaces, and light olive gray (5Y 6/1) to yellowish olive gray (5Y 6/2) on fresh surfaces. The sandstones are medium- to coarse-grained, poorly to moderately sorted, with subangular to subrounded particles. A 2 1/2 foot diameter calcareous sandstone concretion was also observed.

The conglomerates of the DeCourcy Formation are commonly olive gray (5 Y 4.5/1) to yellowish gray (5 Y 7/2) in gross aspect. Clasts range in size from fine pebbles to boulders, with medium pebbles being the dominant size. Roundness of the clasts ranges from subrounded to rounded.

Mudstones found in the DeCourcy Formation are generally shades of gray (N 3 to N 6) on both weathered and fresh surfaces. The mudstones are commonly laminated, but any bedding present is obscured where the mudstones weather to 1/4 to one inch chips.

Sedimentary structures observed in the conglomerates of the DeCourcy Formation include imbrication, mud ripups, and scour-and-fill. Sedimentary structures observed in DeCourcy Formation sandstones include planar and festooned cross-bedding, convolute bedding, flame structures (Figure 17), parallel laminations, groove casts, flute casts, load casts, parting lineation, mud ripups, scour-and-fill, graded bedding, and calcareous sandstone concretions. Organic structures observed in the DeCourcy Formation include horizontal worm burrows, woody debris, and a 3/4 inch thick coal bed found near Thieves Bay, North Pender Island. Wave action and spray have produced wave-cut notches, caverns, and waffle-like patterns of honeycomb weathering in many DeCourcy sandstones, similar to those found in the Extension-Protection Formation.

Figure 17. Flame structures in medium-grained sandstone of the lower DeCourcy Formation. Southwest coastline of Bedwell Harbor, Section 6, North Pender Island.

Lithology. Pebbles from a deeply weathered outcrop of DeCourcy Formation conglomerate were obtained from near the top of the 425-foot high hill on the east side of Shingle Bay, North Pender Island (Figure 14). The dominant lithologies present include andesite, chert, basalt, granodiorite, and diorite. Minor amounts of quartzite, vein quartz, rhyolite, greenstone, schist, phyllite, sandstone, and mudstone were also found. A breakdown of pebble count lithologies is presented in Appendix C.

Eleven thin sections of DeCourcy Formation sandstones were examined microscopically. Modal analyses were performed on three of these samples (Appendix F). The results indicate that the sandstones are texturally and compositionally immature. The sandstones are poorly sorted, angular to subangular, arkosic and lithic wackes (Figure 13). Matrix contents range from 10.7% to 20.0%. The matrix appears to be in part detrital and in part derived from diagenetic alteration of volcanic rock fragments.

The dominant framework grains found in these sandstones include quartz, plagioclase, potassium feldspar, rock fragments, chert, and mica. Minor constituents include polycrystalline quartz, chlorite, sphene, epidote, augite, garnet (almandite), zircon, and disseminated carbonaceous organic matter. Types of plagioclase feldspar include andesine, with minor oligoclase and rare albite. The dominant potassium feldspar is orthoclase, with rare microcline.

Sericite and calcite are common alteration products of the feldspars. Compared with the feldspars of the Extension-Protection Formation, these feldspars are generally quite fresh and, in some cases, show no signs of incipient alteration. Detrital micas include biotite, with minor amounts of muscovite. Rock fragments found in the DeCourcy Formation sandstones include andesite, mudstone, fine-grained sandstone, phyllite, schist, and small amounts of granitic and dioritic plutonic rock fragments.

Very little chemical cement was observed in the DeCourcy Formation sandstones. What little was observed was dominantly calcite. Only in one instance were silica overgrowths on quartz grains noted.

Environments of Deposition. The thick-bedded sandstones of the lower DeCourcy Formation are probably of shallow marine origin, and closely resemble the river-mouth bars described by Allen (1970) from the modern Niger River delta. The river-mouth bars described by Allen are U-shaped in plan, but limited outcrops in the thesis area prevented any accurate determination of the geometry of these deposits. Deposits in the modern Mississippi River delta similar to those of the lower DeCourcy Formation have been described by Gould (1970) as delta-front sheet sands, and by Coleman and Gagliano (1965) as distributary mouth bars.

The upper DeCourcy Formation thick-bedded sandstones are considered environmentally equivalent to the lower DeCourcy Formation sandstones. The conglomerates of the upper DeCourcy are laterally extensive, particularly the uppermost conglomerate unit, which is continuous over both islands. The similarity of the DeCourcy conglomerate units to the conglomerates of the Extension-Protection Formation suggests that the DeCourcy conglomerates were also deposited as topset beds.

Throughout the DeCourcy Formation it is apparent that deposition and burial were rapid. No evidence was found to suggest any substantial reworking by littoral processes.

The intertonguing relationship between the DeCourcy Formation and the Cedar District Formation, described under the preceding formation, is evident throughout much of the DeCourcy Formation. The intertonguing is probably the result of normal processes of channel abandonment and distributary migration in the deltaic model of sedimentation. Other factors possibly contributing to this phenomenon include variations in the rate of basin subsidence, tectonic events in the source area, and the remote possibility of major fluctuations in sea level.

Northumberland Formation

Nomenclature. The Northumberland Formation is named for the exposures on the southwest side of Gabriola Island along the Northumberland Channel. When first proposed by Clapp in 1911, the Northumberland Formation included upper and lower mudstone members and a middle sandstone and conglomerate member. In 1970, Muller and Jeletzky redefined the Northumberland Formation and restricted it to the lower mudstone member of Clapp, with the Geoffrey and Spray Formations assigned to the middle sandstone and conglomerate member and the upper mudstone member, respectively.

General Stratigraphy. The Northumberland Formation is exposed only on North Pender Island. Here, the low-lying areas east and southeast of Cramer Hill and south-southwest of Mount Menzies are underlain by the formation (Plate 1 and Figure 18). The Northumberland Formation also underlies the north coastline of North Pender Island from 3/4 mile west of Clam Bay to Colston Cove. Also underlain by the formation are coves and adjacent low-lying areas near Stanley Point, the Colston Cove-Welcome Cove-Hope Bay area, and narrow strips of land east of the Bald Cone-Mount Menzies area, and from Pollard Cove to Razor Point.

The non-resistant nature of the Northumberland Formation limits the opportunities for good exposures. The best outcrops occur from Clam Bay to Colston Cove, east of the Bald Cone-Mount Menzies area, and north of Razor Point (Plate 1). Limited exposures exist

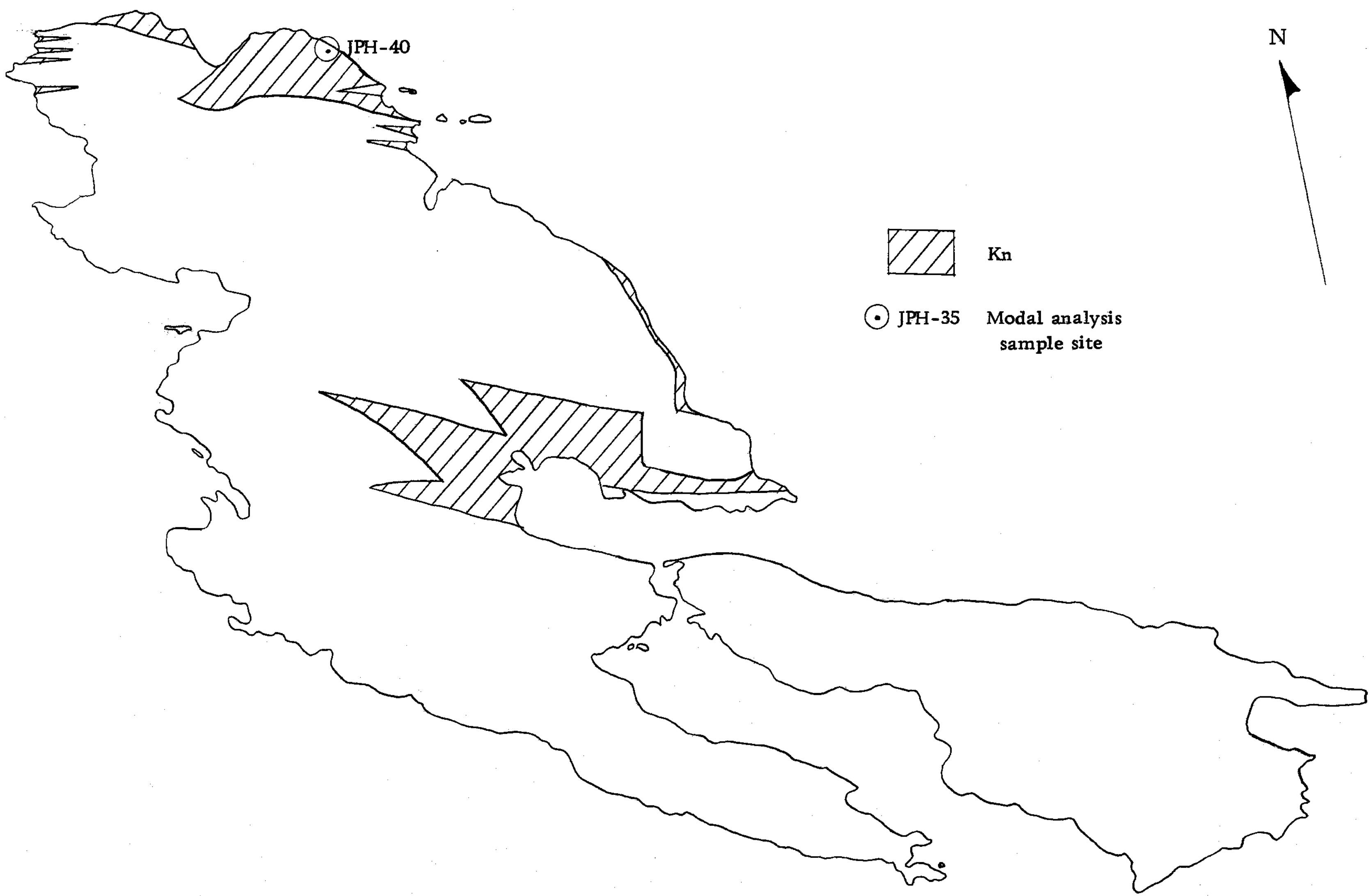


Figure 18 . Northumberland Formation distribution and modal analysis sample site.

near Stanley Point and in the Hamilton Beach-Brackett Cove area. Exposures in the interior of the island are almost non-existent and are limited to fresh road cuts.

The basal contact of the Northumberland Formation, not exposed within the thesis area because of faulting, has been discussed under the DeCourcy Formation. The upper contact, separating the overlying sandstones and pebble conglomerates of the Geoffrey Formation from the underlying sandstone-siltstone-mudstone sequence of the Northumberland Formation, is best exposed at Colston Cove, North Pender Island (Plate 1). Here, the upper contact is sharp and gently undulating. The underlying sandstone-siltstone-mudstone sequence, however, shows a general overall increase in sandstone thickness and abundance upwards in the interval. This gradual increase in the sandstone content of the outcrop suggests that this interval is a gradational transition between the two formations, similar to the Cedar District-DeCourcy Formation contact described previously. The only other location where the upper contact of the Northumberland Formation was observed is on the west side of Clam Bay, North Pender Island (Plate 1). The contact here is scour-and-fill, with normally graded beds of fine pebble conglomerate of the Geoffrey Formation overlying Northumberland mudstone.

A described section of the Northumberland Formation (Appendix D) was measured from near Clam Bay to Hope Bay, North Pender

Island (Plate 1). The minimum thickness of the Northumberland Formation on North Pender Island, as determined from outcrop data, is 2,500 feet.

The Northumberland Formation can be divided into two parts. The lower part is the main body of the Northumberland Formation. The upper part includes tongues which interfinger with the Geoffrey Formation. The lower Northumberland Formation is dominantly formed by interbedded sandstone-siltstone-mudstone sequences (see Appendix D for a description of these sequences). The dominant sedimentary structures found in these sequences are repetitive normally graded bedding, parallel laminations, and convolute laminations. Basal bedding contacts are generally sharp and planar to gently undulating. Rare groove casts, flute casts, and load casts were observed on the bottom of beds. Upper bedding contacts are generally gradational over intervals ranging from 1/2 to five inches. Individual graded units range from 2 to 24 inches in thickness. The parallel laminations overlain by convolute laminations found in the normally graded sandstones may represent divisions B and C or divisions C and D of incomplete Bouma sequences. On the basis of these sedimentary structures and their similarity to the sandstones of the upper Cedar District Formation, the sandstones of the lower Northumberland Formation are interpreted as turbidity current deposits.

The upper Northumberland Formation is best exposed in the northern part of North Pender Island. Here, the formation is found as four dominantly mudstone tongues in the Stanley Point-Willey Point area (Figure 19), and as three tongues in the Colston Cove-Welcome Cove-Hope Bay area. The latter three tongues are 419.5, 120, and 127.5 (minimum) feet thick, respectively. The Northumberland Formation tongues in the Stanley Point-Willey Point area, though not measured directly, appear to be substantially thinner. Where exposed, the lower contacts of the Northumberland tongues are gradational over 5 to 12 inches into the underlying Geoffrey Formation sandstones. Upper contacts of the Northumberland tongues are generally sharp and gently undulating. The upper Northumberland tongues are lithologically similar to the lower Northumberland Formation, though bedding thicknesses are generally much thinner. For a more complete description of this interval, see Appendix D.

As in the Cedar District Formation, mudstone is the dominant lithology of the Northumberland Formation. Colors of the mudstones range from shades of gray (N 3 to N 6) on weathered surfaces to olive black (5Y 2/1) or dark gray (N 3) on fresh surfaces. The mudstones are commonly thinly laminated to thin-bedded; however, any bedding which may be present is obscured where the mudstone weathers to 1/4 to one inch chips. Other features of the Northumberland Formation mudstones include pseudo-concretions (concentrically

Figure 19. Non-resistant Northumberland Formation mudstones (inlets) intertonguing with resistant sandstones and conglomerates of the Geoffrey Formation (points). Northeast of Stanley Point, North Pender Island.

weathering mudstone concretions, lithologically similar to the enclosing unit), pyrite-marcasite nodules and bands up to two inches in length, and micritic mudstone concretions which generally occur as irregular ellipsoids two to six inches in length.

The sandstones of the Northumberland Formation are yellowish gray (5Y 7/2) to light olive gray (5Y 6/1) on weathered surfaces, and medium gray (N 5) to olive gray (5Y 4/1) on fresh surfaces. The sandstones are thinly laminated to thin-bedded and display abundant soft sediment deformation structures (Figure 20). Grain sizes range from very fine- to coarse-grained, with poor to moderate sorting and angular to subangular particles. Siltstones in the Northumberland Formation are colored shades of gray (N 4 to N 7) to brownish gray (5YR 3/1) on weathered surfaces, and light olive gray (5Y 6/1) to olive gray (5Y 4/1) on fresh surfaces, and are thinly laminated to thin-bedded.

Sedimentary structures found in the Northumberland Formation include graded bedding, parallel and convolute laminations, flame structures, convolute bedding (Figure 20), parting lineation, groove casts, flute casts, load casts, planar and festooned cross bedding, calcareous mudstone concretions, micritic mudstone lenses, and pyrite-marcasite nodules and bands. Organic structures in the Northumberland Formation include woody debris, abundant horizontal worm burrows, and an entire crushed <u>Inoceramus</u> (Figure 21).

Figure 20. Convolute bedding formed by soft sediment deformation in vertically dipping Northumberland Formation mudstones. Stratigraphic "up" to right of picture. Near Brackett Cove, Port Browning, North Pender Island.

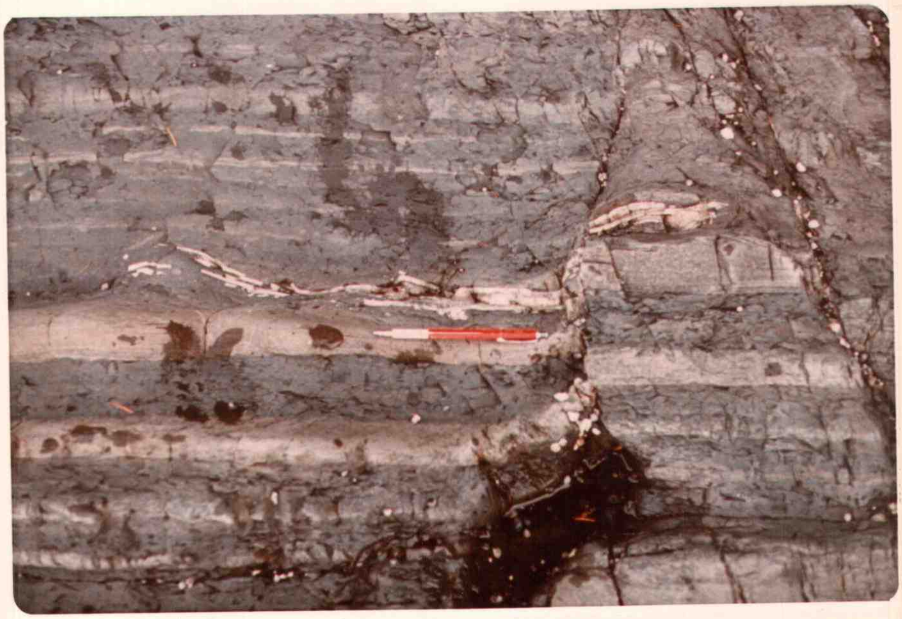
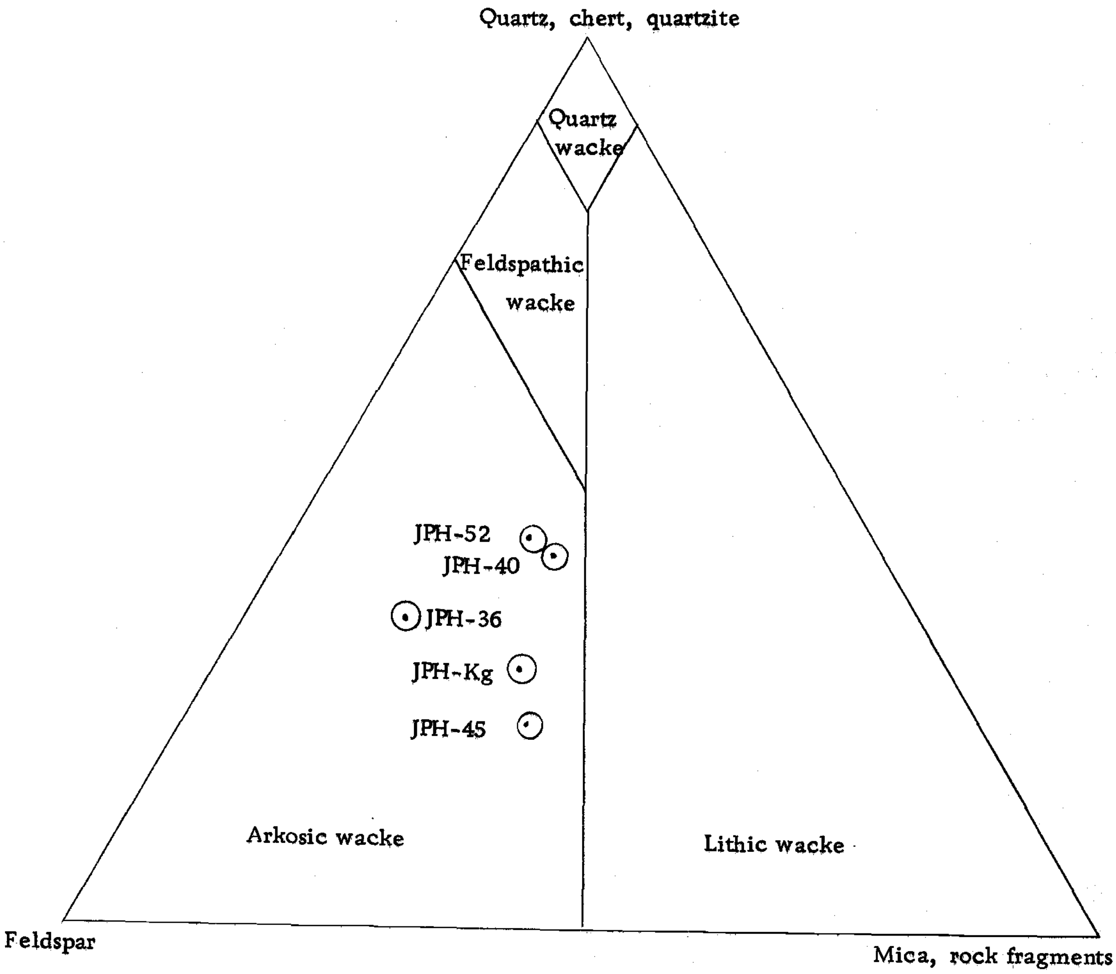


Figure 21. Crushed Inoceramus shell in normally graded siltstones and mudstones of the Northumberland Formation. Note small fault which offsets right end of shell. Pen is six inches long. One-half mile northwest of Razor Point, North Pender Island.

<u>Lithology.</u> X-ray diffraction analysis of Northumberland mudstone showed the presence of chlorite, vermiculite, mica, montmorillonite, and possibly kaolinite as the clay minerals (see Appendix G for tabulated results and Appendix H for analytical techniques).

Three samples of sandstones from the Northumberland Formation were examined microscopically. A modal analysis (Appendix F) of one of the samples showed that the sandstone is compositionally and texturally immature. The sandstone is a fine- to medium-grained arkosic wacke with a matrix content of 13.3% (Figure 22). The sandstone is poorly sorted, with angular to subangular particles. The predominant framework grains are quartz, plagioclase, rock fragments, and mica. Minor constituents include polycrystalline quartz, chert, potassium feldspar, chlorite, organic matter, and augite. Types of plagioclase feldspar include andesine, with minor oligoclase and albite. The dominant potassium feldspar is orthoclase, with rare microcline. The feldspars are commonly altered to sericite and calcite. Freshness of the feldspars is apparently intermediate between the much altered feldspars of the Extension-Protection Formation and the fresh feldspars of the DeCourcy Formation. Detrital micas are dominantly biotite, with minor muscovite. Andesite, mudstone, fine-grained sandstone, and schist rock fragments are present. The matrix of the sandstones is predominantly derived from diagenetic alteration of crushed volcanic rock fragments. Chemical cement



JPH-40: Middle Northumberland Formation (near cable crossing, Sec. 22, North Pender Island)

JPH-36: Lower Geoffrey Formation (Hope Bay, North Pender Island)

JPH-Kg: Middle Geoffrey Formation (Razor Point area, North Pender Island)

JPH-45: Upper Geoffrey Formation (Otter Bay, North Pender Island)

JPH-52: Lower Spray Formation (Otter Bay, North Pender Island)

Figure 22 . Classification of Northumberland, Geoffrey, and Spray Formation sandstones (after Gilbert, 1954).

found in the Northumberland Formation samples is entirely calcite.

Environments of Deposition. The Northumberland Formation is environmentally similar to the Cedar District Formation. The mudstones, siltstones, and minor sandstones with the crushed remains of Inoceramus probably represent deposition in a shallow marine environment such as the prodelta of Coleman and Gagliano (1965) and Visher (1965).

The normally graded sandstone-siltstone-mudstone sequences of the lower Northumberland Formation, with their incomplete Bouma sequences, probably represent deposition by turbidity currents in a shallowing depositional basin similar to that previously suggested for the upper Cedar District Formation. That this basin was shallow is suggested by the upward transition of the turbidite sequences into the shallow marine and fluvial rocks of the overlying Geoffrey Formation. Sedimentation of this type is recognized by Coleman and Gagliano (1965) in their distal bar environment. The presence of pyrite-marcasite nodules and bands suggests that Northumberland deposition occurred at least in part under reducing conditions (Krauskopf, 1967).

The upper Northumberland Formation, characterized by its intertonguing relationship with the overlying Geoffrey Formation, is the result of alternating periods of marine, fine-grained sedimentation and fluvial, coarse-grained sedimentation. These alternations probably reflect channel abandonment and migrating distributaries in the deltaic model of sedimentation. Other factors possibly contributing to this phenomenon might include variations in the rate of basin subsidence, tectonic events in the source area, and the remote possibility of major fluctuations in sea level.

Geoffrey Formation

Nomenclature. Usher (1952) used the name, Geoffrey Formation, to denote the thick sandstones and conglomerates exposed on Mount Geoffrey, Hornby Island. Muller and Jeletzky (1970) correlated this Comox Basin Geoffrey Formation with the middle sandstone and conglomerate member of Clapp's (1911) Northumberland Formation. The middle member is now known as the Geoffrey Formation in both the Nanaimo and Comox Basins.

General Stratigraphy. The Geoffrey Formation, along with the Northumberland Formation and the Spray Formation, is found only on North Pender Island. In the northern part of the island, the Geoffrey Formation extends from Stanley Point to Hope Bay, underlying George Hill and the unnamed 575-foot high hill in Section 22 (Plate 1 and Figure 23). The Geoffrey Formation also extends from James Point to 1/2 mile southwest of Hope Bay, underlying Dent Hill, and forms most of the coast line of North Pender Island from Hope Bay to Razor Point. The formation is also found within the Kulleet Syncline in the

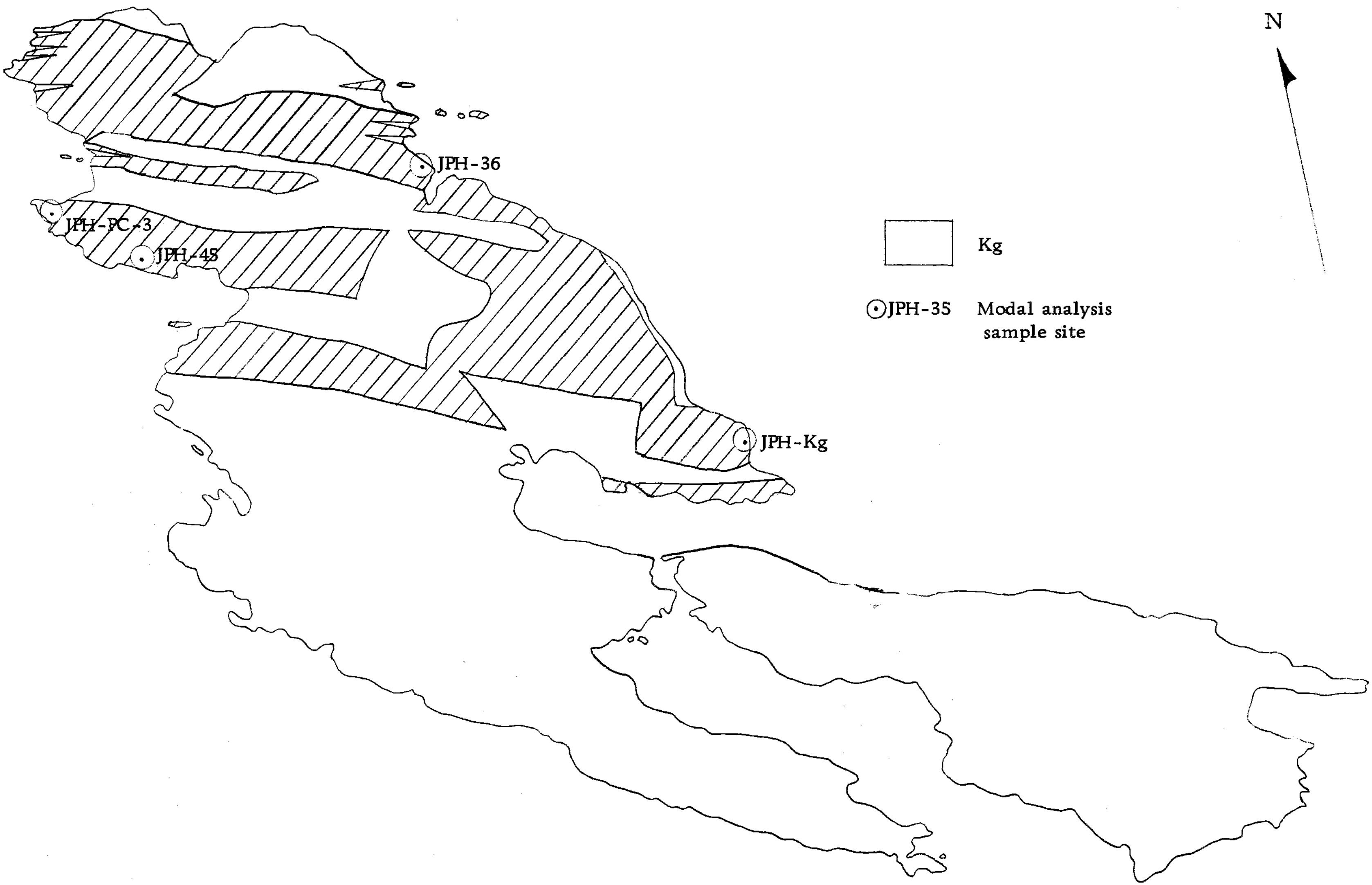


Figure 23. Geoffrey Formation distribution and sample sites for modal analyses and pebble counts.

Bald Cone-Mount Menzies area, as fault blocks in the Roe Islet-Ella Bay area and northwest of Razor Point, as tongues in the Northumberland Formation from Razor Point to Pollard Cove, and as tongues in the Spray Formation from Grimmer Bay 1 1/2 miles east-southeast towards the interior of the island.

Outcrops of the Geoffrey Formation are almost continuous where the formation occurs on the coastline. Particularly well exposed outcrops occur from Hope Bay to near Bald Cone, and dramatic Geoffrey Formation dip slopes form the shoreline at the Otter Bay ferry dock (Figure 24). Outcrops of the Geoffrey Formation in the interior of the island occur along ridge crests, in fault scarps, and in road cuts.

The basal contact of the Geoffrey Formation with the underlying Northumberland Formation has been described previously. The upper contact of the Geoffrey Formation is best exposed at the head of Otter Bay (Plate 1). Here, though the actual contact is covered, the upper surface of the uppermost Geoffrey sandstone is essentially planar, and the contact is inferred to be sharp and conformable. The contact closely resembles the upper contact of the lower DeCourcy Formation. The upper contact of the Geoffrey Formation was also observed at Percival Cove, near Port Washington, where it is also inferred to be sharp and conformable (Plate 1). The upper Geoffrey Formation intertongues with the overlying Spray Formation at Grimmer Bay.

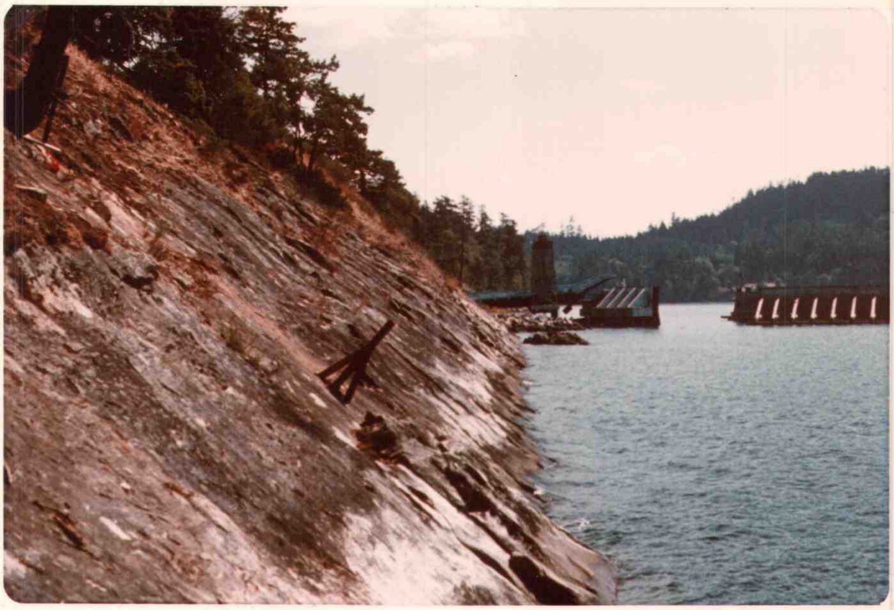


Figure 24. Dip slope of upper Geoffrey Formation sandstone at Otter Bay, North Pender Island. Otter Bay ferry dock in right background.

A described section, encompassing the lower part of the Geoffrey Formation, was measured from Colston Cove to the south side of Hope Bay (Plate 1 and Appendix D). The total thickness of the Geoffrey Formation, as exposed on North Pender Island, is 1,650 feet. This figure is derived from the section measurement and the estimated thickness of the remaining exposures.

The Geoffrey Formation can be divided into two parts: a lower part which intertongues with the underlying Northumberland Formation; and an upper part which forms the main body of the formation. The lower Geoffrey Formation is best exposed as resistant points in the Stanley Point-Willey Point area and the Colston Cove-Welcome Cove-Hope Bay area. Another Geoffrey Formation tongue occupies the same stratigraphic interval and extends from Pollard Cove to Razor Point.

The lower Geoffrey Formation is dominantly formed by sandstones similar to those of the DeCourcy Formation and of the upper marine interval of the Extension-Protection Formation. Bedding thicknesses range from 1 to 20 feet. Lower bedding contacts are sharp and planar to gently undulating, and display locally abundant groove casts, load casts, and flute casts. Upper bedding contacts are gradational over three to seven inches to siltstone or mudstone. The dominant sedimentary structure in these sandstones is faint parallel laminations. Pebble conglomerate was observed in one tongue of the Geoffrey Formation in the Stanley Point area.

The lower contact of each Geoffrey tongue is sharp and planar to gently undulating. The upper contact of each tongue is gradational over three to seven inches into the overlying Northumberland Formation tongue. For a more detailed description of this intertonguing relationship, see Appendix D.

The upper Geoffrey Formation is the main body of the formation. The sandstones of the upper Geoffrey (Figure 25) are similar to those of the lower Geoffrey tongues. Groove casts, load casts, and flute casts are exceptionally well preserved and abundant on the bottom of these beds (Figures 26 and 27). The only significant fluvial interval in the Geoffrey Formation occurs near the top of the formation. This is represented by tightly packed, well rounded, and rarely imbricated pebble conglomerates. The conglomerates are best exposed on Dent Hill near James Point, on James Point, in the Willey Point area, and they form the top of the cliffs from Bald Cone southward. Bedding thicknesses of the conglomerates range from 10 to over 30 feet.

Sandstones of the Geoffrey Formation are medium- to coarse-grained, poorly to moderately sorted, with angular to subrounded grains. The dominant sedimentary structures are parallel laminations. Colors of the sandstones range from light gray (N 8) to pale yellowish brown (10YR 6/2) on weathered surfaces and light bluish

Figure 25. Southwest-dipping, thick-bedded sandstones of the upper Geoffrey Formation. Looking northwest, 3/4 mile southeast of Hope Bay, North Pender Island.

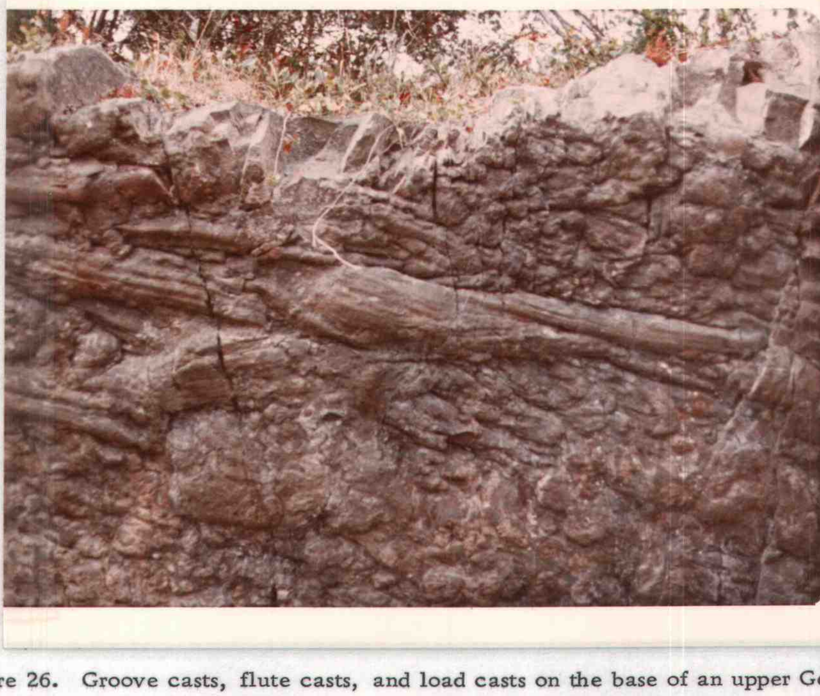


Figure 26. Groove casts, flute casts, and load casts on the base of an upper Geoffrey Formation sandstone bed. Large groove cast in center of photo is approximately 20 feet long. Current from right to left. One mile southeast of Hope Bay, North Pender Island.

Figure 27. Flute casts and groove cast on the base of an upper Geoffrey Formation sandstone bed. Current from left to right. One and one-quarter miles southeast of Hope Bay, North Pender Island.

gray (5B 6/1) to yellowish gray (5Y 8/2) on fresh surfaces. Siltstones in the Geoffrey Formation are generally laminated, rarely cross-laminated, and display colors similar to the sandstones.

Mudstones found in the Geoffrey Formation are shades of gray (N 3 to N 8) on fresh and weathered surfaces. The mudstones are laminated or weather to chips 1/4 to two inches in length which obscured any stratification present.

Sedimentary structures observed in the Geoffrey Formation sandstones include flute casts, groove casts, load casts (Figures 26 and 27), parallel laminations, planar and festooned cross-bedding up to one foot thick, convolute laminations (Figure 28), flame structures, scour-and-fill channels four inches to one foot wide and up to four inches deep, normally graded bedding, parting lineation, rare calcareous sandstone concretions, and mud ripups up to 1 1/2 feet in length. Sedimentary structures observed in the Geoffrey Formation conglomerates include imbrication, scour-and-fill channels six inches to two feet wide and up to eight inches deep, and graded bedding.

Organic structures in the Geoffrey Formation include zoophycos-like trace fossils (Seilacher, 1964), woody debris up to one foot long and six inches wide, and horizontal worm burrows.

Wave action and spray have produced wave-cut notches, caverns, and waffle-like patterns of honeycomb weathering in the Geoffrey

Figure 28. Convolute laminations produced by soft sediment deformation in a fine-grained sandstone of the upper Geoffrey Formation. Three-fourths mile southeast of Hope Bay, North Pender Island.

Formation similar to those found in the Extension-Protection and DeCourcy Formations.

Lithology. Pebbles from a deeply weathered outcrop of Geoffrey Formation conglomerate were collected near James Point. A pebble count of these samples indicates that chert, andesite, basalt, quartzite, and granitic rocks are the most abundant clasts in the conglomerate. Minor amounts of diorite, rhyolite, schist, phyllite, vein quartz, and greenstone rock fragments are also present. Complete pebble count data are presented in Appendix G.

Seven samples of sandstones from the Geoffrey Formation were examined microscopically. Modal analyses (Appendix F) were performed on three of these samples. The results indicate that the sandstones are texturally and compositionally immature. All of the samples are arkosic wackes (Figure 22), with matrix contents ranging from 11.8% to 14.8%. The matrix appears to be dominantly derived from diagenetic alteration of volcanic rock fragments.

The framework grains of these sandstones are dominantly quartz, plagioclase, rock fragments, and mica. Minor constituents include polycrystalline quartz, chert, potassium feldspar, chlorite, sphene, pyrite, augite, and zircon. Types of plagioclase feldspar include andesine, with minor oligoclase. The dominant potassium feldspar is orthoclase. Sericite and calcite are common alteration products of the feldspars. The Geoffrey Formation feldspars appear to be intermediate in alteration between the more altered feldspars of the Extension-Protection Formation and the fresher feldpars of the DeCourcy Formation. Detrital micas include biotite with subordinate muscovite. Rock fragments found in these sandstones include andesite, dioritic and granitic plutonics, mudstone, sandstone, schist, and phyllite.

Chemical cement found in the Geoffrey Formation samples is entirely calcite. Minute amounts of a greenish-colored, fibrous, radiating zeolite were observed as a pore-filling in two samples. The zeolite is probably laumontite and has been previously reported from the Geoffrey Formation on Gabriola Island by Packard (1972).

Environments of Deposition. The Northumberland Formation-Geoffrey Formation deltaic cycle is the least complicated cycle of deltaic progradation observed within the thesis area. Lateral thickness and facies changes are evident, and the upward coarsening within the cycle, from Northumberland mudstones to pebble conglomerates at the top of the Geoffrey Formation, is almost uninterrupted. Selley (1970) considers this upward coarsening in each cycle to be a major clue to the identification of an ancient delta.

The thick-bedded sandstones of the Geoffrey Formation are interpreted as river mouth bar deposits similar to those described by Allen (1970) from the modern Niger Delta. Equivalent deposits in the modern Mississippi River delta are called delta-front sheet sands

(Gould, 1970) and distributary mouth bars (Coleman and Gagliano, 1965). In the lower Geoffrey Formation, these shallow marine deposits intertongue with the distal bar deposits of the upper Northumberland Formation.

The laterally extensive fluvial conglomerates of the upper Geoffrey Formation are interpreted as topset beds following the usage of Wilkinson and Oles (1968). The coarseness of the clasts suggests a nearby source drained by high energy streams. Throughout the Geoffrey Formation, the overall impression is of rapid deposition and burial, with no evidence for substantial reworking by littoral processes.

Spray Formation

Nomenclature. The Spray Formation was named by Usher (1952) after Spray Point in Tribune Bay, Hornby Island. The mudstones of the Spray Formation underlie the bay and adjacent areas on the island. Muller and Jeletzky (1970) correlated the Spray Formation from the Comox Basin with Clapp's (1911) upper mudstone member of the Northumberland Formation. The upper mudstone member is now known as the Spray Formation in both the Nanaimo and Comox basins.

General Stratigraphy. The Spray Formation underlies lowlying areas on North Pender Island extending from Grimmer Bay to one mile southeast of Hope Bay, from Otter Bay approximately 1/2 mile inland, and in the center of the Kulleet Syncline in Sections 14, 15, 18, and 19 Plate 1 and Figure 29). Outcrops of the Spray Formation are limited due to its non-resistant nature. The best outcrops are found on the beach at the head of Otter Bay. Limited outcrops are present at the head of Grimmer Bay. In the interior of the island, Spray Formation outcrops are limited to five fresh road cuts, the best of which is on the east side of the cemetery, Section 15, North Pender Island (Plate 1).

The basal contact of the Spray Formation with the underlying Geoffrey Formation has been described in the preceding section. The Spray is the youngest formation in the thesis area; therefore, the upper contact of the formation is not exposed.

A described section (Appendix E) was measured at the head of Otter Bay, North Pender Island. A fault interrupts the stratigraphic sequence at the top of this interval. The incomplete section totals 797 feet, and this is assumed to represent the minimum thickness of the Spray Formation as exposed on North Pender Island.

The Spray Formation, as with the Cedar District and Northumberland formations, is dominantly formed by mudstones. Weathered surface colors for the mudstones range from brownish black (5 YR 2/1) to very light gray (N 8), while fresh surfaces are olive gray (5Y 4/1) to dark gray (N 3). The mudstones are commonly laminated

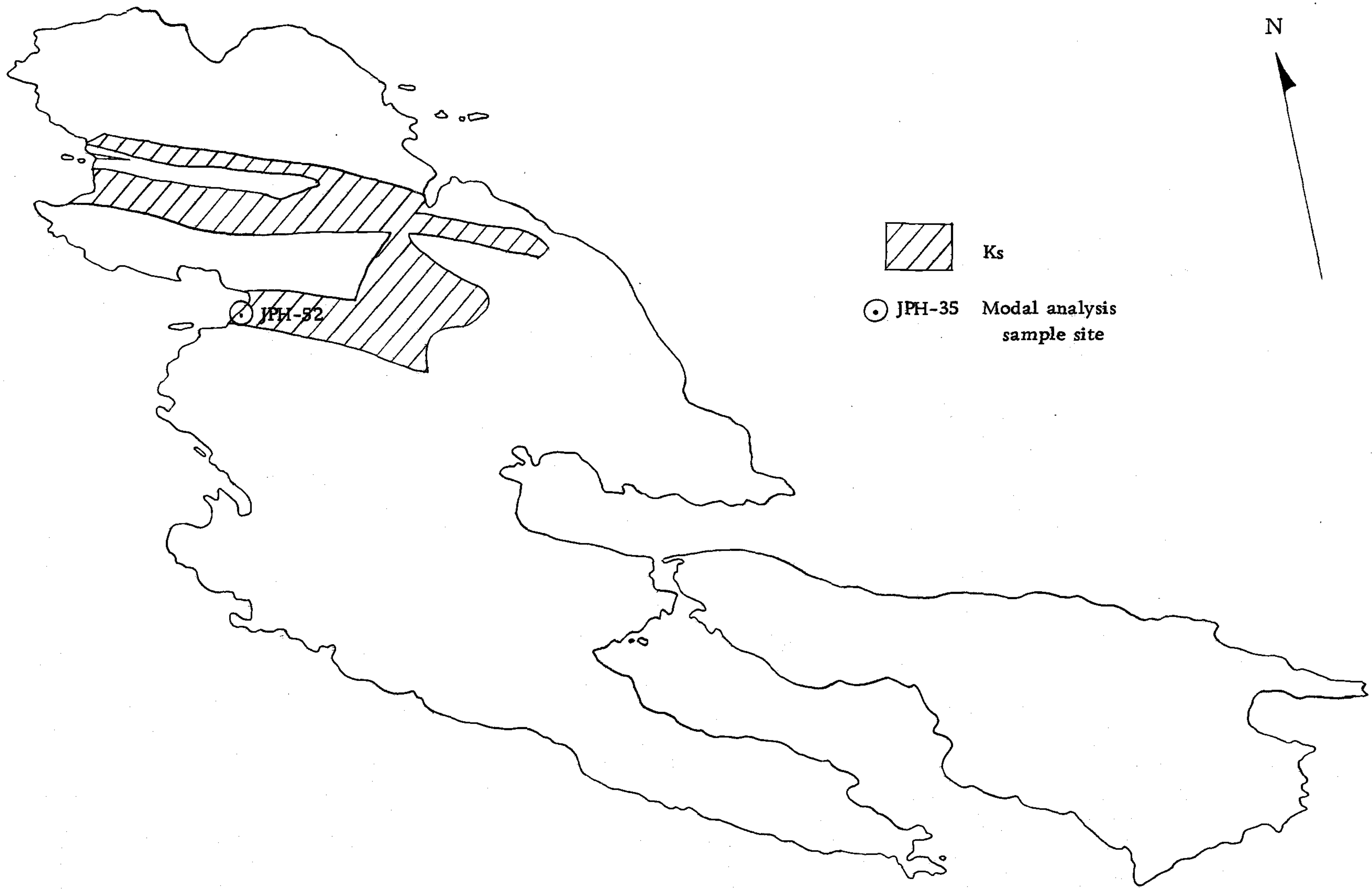


Figure 29. Spray Formation distribution and modal analysis sample site.

to thin-bedded. Bedding is obscured on many outcrops where the mudstone weathers to 1/4 to one inch chips. Brownish weathering nodules and bands of pyrite-marcasite up to three inches in length are common in the lower part of the formation.

Interbedded with the mudstones are thin- to thick-bedded sandstones and thin-bedded to thinly laminated siltstones. The sandstones are commonly light olive gray (5Y 6/1) to medium bluish gray (5B 5/1) on weathered surfaces, and dark yellowish brown (10YR 4/2) to grayish olive (10Y 4/2) on fresh surfaces. The sandstones are fine- to coarse-grained, poorly to moderately sorted, with angular to subrounded grains. Faint laminations are visible in the thicker-bedded sandstones. Parallel and convolute laminations found in many of the thinner, normally graded sandstones may represent divisions B and C or divisions C and D of incomplete Bouma sequences. Siltstones of the Spray Formation are generally thinly laminated to laminated, with coloring similar to that of the sandstones. For a more complete description of the Spray Formation, see Appendix E.

Sedimentary structures observed in the Spray Formation include graded bedding, convolute bedding, parallel and convolute laminations, pseudo-concretions (concentrically weathering mudstone concretions, lithologically similar to the enclosing unit), and pyrite-marcasite nodules and bands. Scour-and-fill structures and mudstone and fine-grained sandstone ripups were observed in the coarser-grained sandstones of the Spray Formation.

Lithology. X-ray diffraction analysis of the Spray Formation mudstone indicated that chlorite, vermiculite, mica, and possibly kaolinite are the clay minerals present (see Appendix G for tabulated results and Appendix H for analytical techniques).

One sample of sandstone from the Spray Formation was examined microscopically. A modal analysis (Appendix F) shows this sandstone to be an arkosic wacke (Figure 22). Matrix content of the sandstone is 11.5%. The matrix appears to be in part detrital and in part derived from diagenetic alteration of volcanic rock fragments. Sorting of the sample is poor, with angular to subrounded particles of medium- to coarse-grained size. The sandstone is texturally and compositionally immature. The framework grains are dominantly quartz, plagioclase, rock fragments, chert, potassium feldspar, and mica. Minor constituents include polycrystalline quartz and chlorite. Types of plagioclase feldspar include andesine, with rare oligoclase. The dominant potassium feldspar is orthoclase. The feldspars are commonly altered to sericite and calcite and resemble the feldspars of the Geoffrey Formation in degree of alteration. Detrital micas include subequal amounts of biotite and muscovite. Rock fragments present include andesite, mudstone, diorite, phyllite, schist, and fine-grained sandstone.

Environments of Deposition. Similarities between the lithologies, sedimentary structures present, and stratigraphic position at the base of a cycle of deltaic progradation suggest that the Spray Formation is environmentally equivalent to the lower Northumberland Formation and the upper parts of the lower and upper Cedar District Formation. The normally graded sandstones of the Spray Formation, with their incomplete Bouma sequences, probably represent the filling of a shallow marine environment by turbidity current deposits, a process which is recognized by Coleman and Gagliano (1965) in their distal bar environment. The presence of pyrite-marcasite as nodules and bands suggests that at least part of Spray Formation deposition took place under reducing conditions (Krauskopf, 1967).

The thick intervals of thick-bedded sandstones found within the section described at Otter Bay, though not mappable as distinct, separate tongues, may represent progradation of shallow marine sedimentation over the distal bar muds of the Spray Formation. These thick-bedded sandstones may be related either to the underlying Geoffrey Formation or to the overlying Gabriola Formation. If so, these sandstones may be the result of channel abandonment and distributary migration in the deltaic model of sedimentation. As with other intertonguing relationships between units observed within the thesis area, the same additional factors of variations in the rate of basin subsidence, tectonic events in the source area, and the remote possibility of major fluctuations in sea level, all apply.

STRUCTURE

Regional Structure

The structure of the Nanaimo Basin is dominated by generally northwest-striking faults and open folds. Richardson (1872, 1878), Clapp (1914), and Clapp and Cooke (1917) considered folding to be the major structural feature of the basin with faulting playing a minor role. Buckham (1947), Sutherland-Brown (1966), Muller and Carson (1969), and Muller and Jeletzky (1970) suggest that faulting is the dominant feature and that the folds are subordinate features controlled by the faulting.

The major faults in the Nanaimo Basin generally have a northeast downthrow so that northeast-dipping fault blocks of successively younger Late Cretaceous strata are exposed as the Georgia Strait is approached. Other faults, younger than the major ones, strike north and northeast. Muller and Jeletzky (1970) note that faulting is most pronounced in the southern Gulf Islands, of which North and South Pender islands are a part.

Clapp and Cooke (1917) named the major folds of the Nanaimo Basin. From southwest to northeast, they are the Kulleet Syncline, Thetis Anticline, Channel Syncline, and Trincomali Anticline. Muller and Carson (1969) note that folding is restricted to fault zones.

Sutherland-Brown (1966) suggests that the northwest-striking folds in the Late Cretaceous rocks of the Nanaimo Basin are surface expressions of basement fault movements.

Areal Structure

Faults

Faulting in the thesis area was recognized by aerial photo lineations, repetition of stratigraphy, juxtaposition of normally separated formations, linear fault-line scarps, offset of formational contacts, and by breaching of normally resistant sandstone formations. The time of faulting was before the last glaciation because fault-shattered zones and the less resistant formations have been glacially excavated and then filled with glacial debris.

The dominant structural feature of North and South Pender islands is a broad west-northwest-striking fault zone formed by five major faults. This fault zone extends from James Point to Shingle Bay on the west side of North Pender Island, and, on the east side, from Bald Cone on North Pender to Mount Norman on South Pender Island (Plate 1 and Figure 30). The fault zone is characterized by steeply dipping (greater than 50^{o}) strata, which are locally vertical to overturned. The four faults to the northeast are steeply dipping or vertical, with the northeast side downthrown relative to the southwest

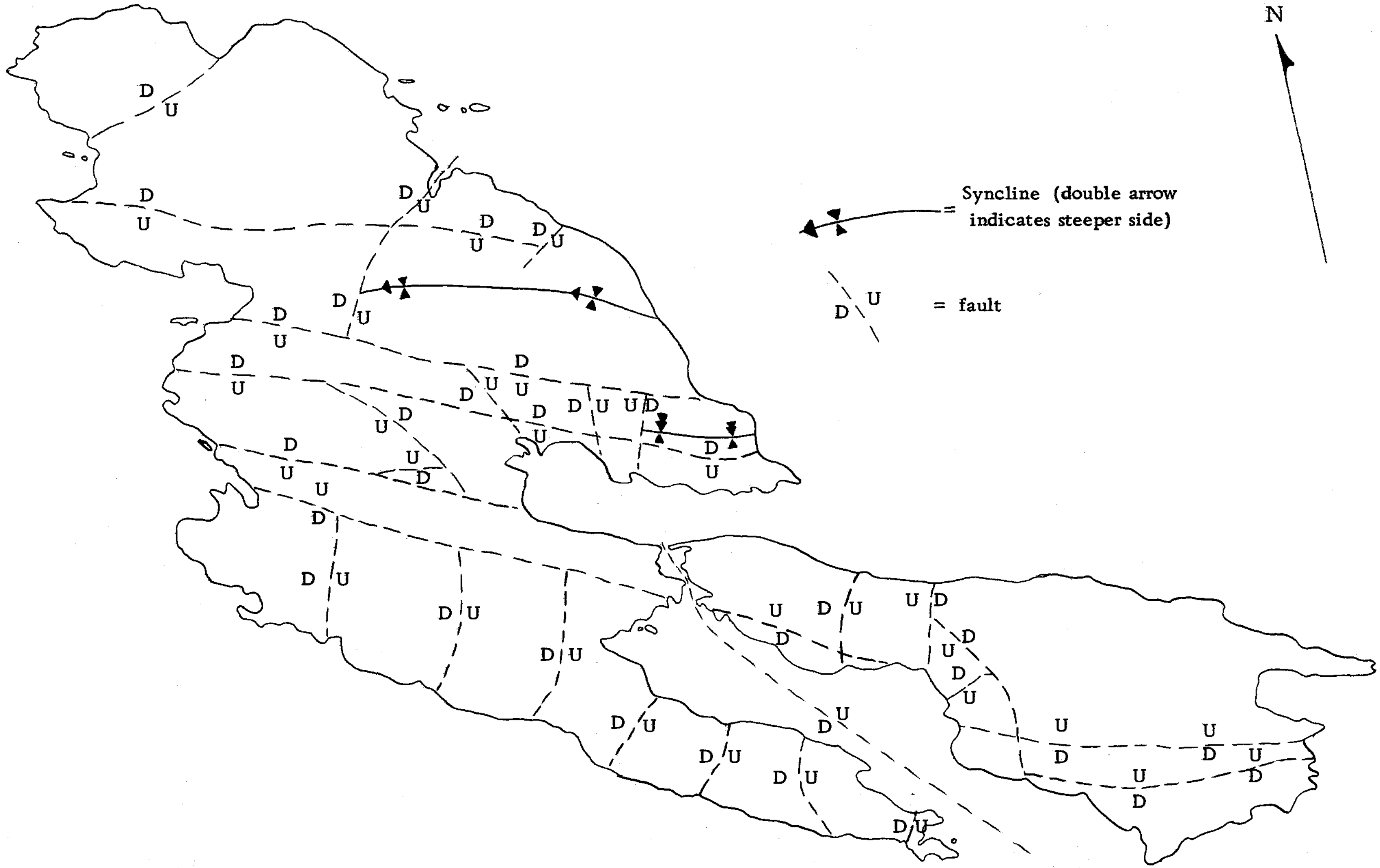


Figure 30 . Tectonic framework of North and South Pender Islands, B. C.

side. The southernmost fault is a north-east dipping reverse fault, which repeats part of the stratigraphy of the upper Extension-Protection Formation. North-northwest- and northeast-striking cross-faults further complicate the major fault zone. This major fault zone extends from North and South Pender islands to Saltspring Island, and probably extends under Ladysmith Harbor onto Vancouver Island (Hanson, pers. comm.).

Older faults which are cut by the major fault zone trend to the north or northeast. The general movement of these faults is the southeast side up relative to the northwest side. Faults younger than the major fault zone have variable relative movements and trend north-west to northeast. Offset of formational contacts suggest the presence of a major northwest-striking fault in Bedwell Harbor between North and South Pender islands. The relative motion of this fault is north-east side up relative to the southwest side. Adjacent to some of the major faults the rocks have been shattered. These areas, up to 150 feet wide, are less resistant and are commonly found as inlets or narrow valleys.

Folds

The only major fold in the thesis area is a syncline found in Sections 13, 14, 15, 18, and 19, North Pender Island (Plate 1 and Figure 30). The syncline occurs in the Northumberland, Geoffrey, and Spray Formations, and apparently is an extension of the Kulleet Syncline. The surface trace of the axis of this syncline strikes N. 63° W. at the east coast of the island, passes between Bald Cone and Mount Menzies (Figure 31), and then curves to the west to bear N. 80° W. in the northwest quarter of Section 14. The syncline is terminated by a fault 1/4 mile west of the cemetery in Section 15. Both of the flanks of the syncline dip approximately 15° to 20°; the syncline plunges 10° to 12° to the west-northwest. A fault truncates the southwest limb of the syncline along its entire length.

A secondary syncline in the Geoffrey Formation, bordered on three sides by faults, is found in Section 12, North Pender Island (Plate 1 and Figure 30). The surface trace of the axis of this syncline bears almost due west at the coastline. Approximately 1/4 mile inland the trace of the syncline swings to N. 70° W. A fault terminates the syncline 1/4 mile north-northwest of Pollard Cove. The syncline is asymmetrical; the northeast limb dips up to 40°, while the southwest limb dips only up to 19°. The only other folds in the thesis area occur in Section 13, North Pender Island (Plate 1 and Figure 30). These minor folds are a series of three anticlines and two intermediate synclines, all symmetrical and plunging 12° to 18° to the northwest.

Figure 31. The Kulleet Syncline as exposed on the east coast of North Pender Island. Cliff-forming unit is pebble conglomerate and sandstone of the upper Geoffrey Formation. Looking east-northeast from near Perry Rock.

GEOLOGIC HISTORY

Paleocurrent Data

General

Numerous types of sedimentary structures useful in paleocurrent determination were observed within the thesis area. These sedimentary structures include groove casts, flute casts, foreset beds, current crescents, imbricated pebbles, and channel axes. A total of 164 measurements were obtained from these paleocurrent indicators from the five oldest formations present in the thesis area. No paleocurrent indicators were found in the Spray Formation.

The paleocurrent measurements were plotted on rosette diagrams in two manners. The "unmodified" diagram represents the distribution of paleocurrent indicators when bidirectional indicators, such as groove casts and channel axes, are plotted as two measurements in opposing quadrants. The "modified" diagram represents the distribution of paleocurrent indicators when bidirectional indicators are plotted in a single quadrant, the direction of which is determined by the mean of the "unmodified" distribution and the paleocurrent direction suggested by the stratigraphic evidence within the formation, such as thinning or pinching out of a sandstone body. Means and standard deviations were calculated following the method suggested by Royse (1970).

Extension-Protection Formation

The Extension-Protection Formation is considered to be the upper part of a cycle of deltaic progradation. The lower part of this cycle is not exposed within the thesis area. Only five paleocurrent measurements, four of them bidirectional, were obtained from the Extension-Protection Formation, and this number is not sufficiently large to base any realistic assumptions upon it. The unmodified plot of these measurements has a mean of N. 90° W. with a standard deviation of 165° (Figure 32). The modified plot of these measurements, with a true current sense suggested by the mean of the unmodified plot, has a mean of S. 55°W. with a standard deviation of 39°. Lateral facies changes suggest an even more northwesterly direction of sediment transport. Outcrops from which these measurements were taken dip from 36° to 56°, and a significant error may have been introduced into these data when rotation to apparent original depositional position was accomplished with a stereonet.

Cedar District and DeCourcy Formations

The Cedar District and DeCourcy formations are considered as

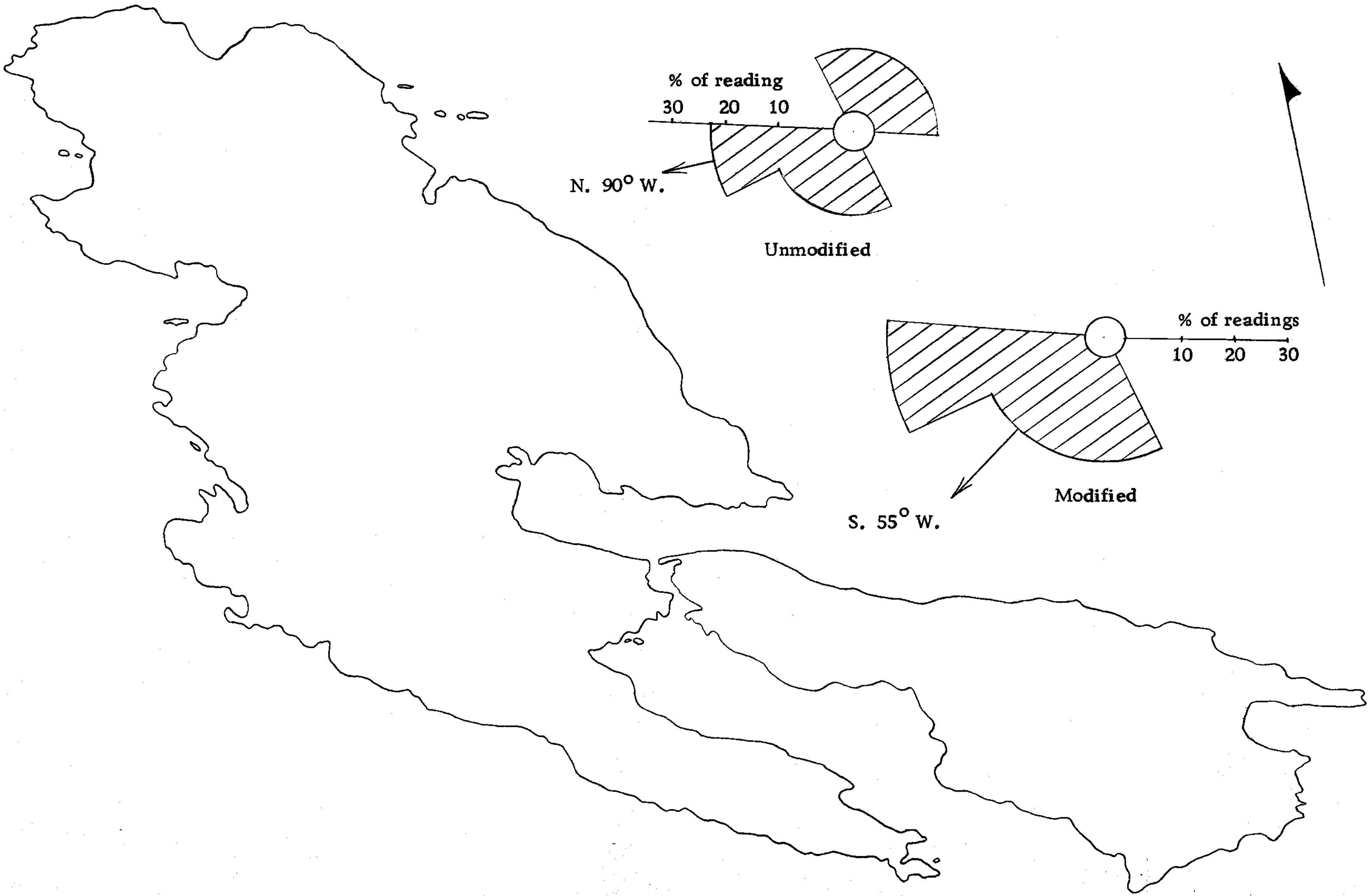


Figure 32. Paleocurrent data for the Extension-Protection Formation.

one complete cycle of deltaic progradation, and for this reason paleocurrent indicators for the two formations are combined. The unmodified plot of these measurements has a mean of S. 41° W. and a standard deviation of 157° (Figure 33). The modified plot, given a true directional sense by a preponderance of the unidirectional indicators and the stratigraphic evidence of lateral thinning and facies changes, has a mean of S. 37° E. and a standard deviation of 57°.

Northumberland and Geoffrey Formations

The Northumberland and Geoffrey formations represent the youngest complete cycle of deltaic progradation present in the thesis area. The unmodified plot of the paleocurrent indicators from these two formations has a mean of S. 60° E. and a standard deviation of 44° (Figure 34). The modified plot is similar to the unmodified plot, with the mean shifting only two degrees to S. 62° E. The modified plot has a standard deviation of 28°. The thinning of Geoffrey Formation sandstone tongues to the southeast supports this as a direction of sediment transport.

Postulated Source Areas

The pre-Cretaceous stratigraphy of Vancouver Island is formed by the Pennsylvanian-Permian Sicker Group, the Triassic-Jurassic

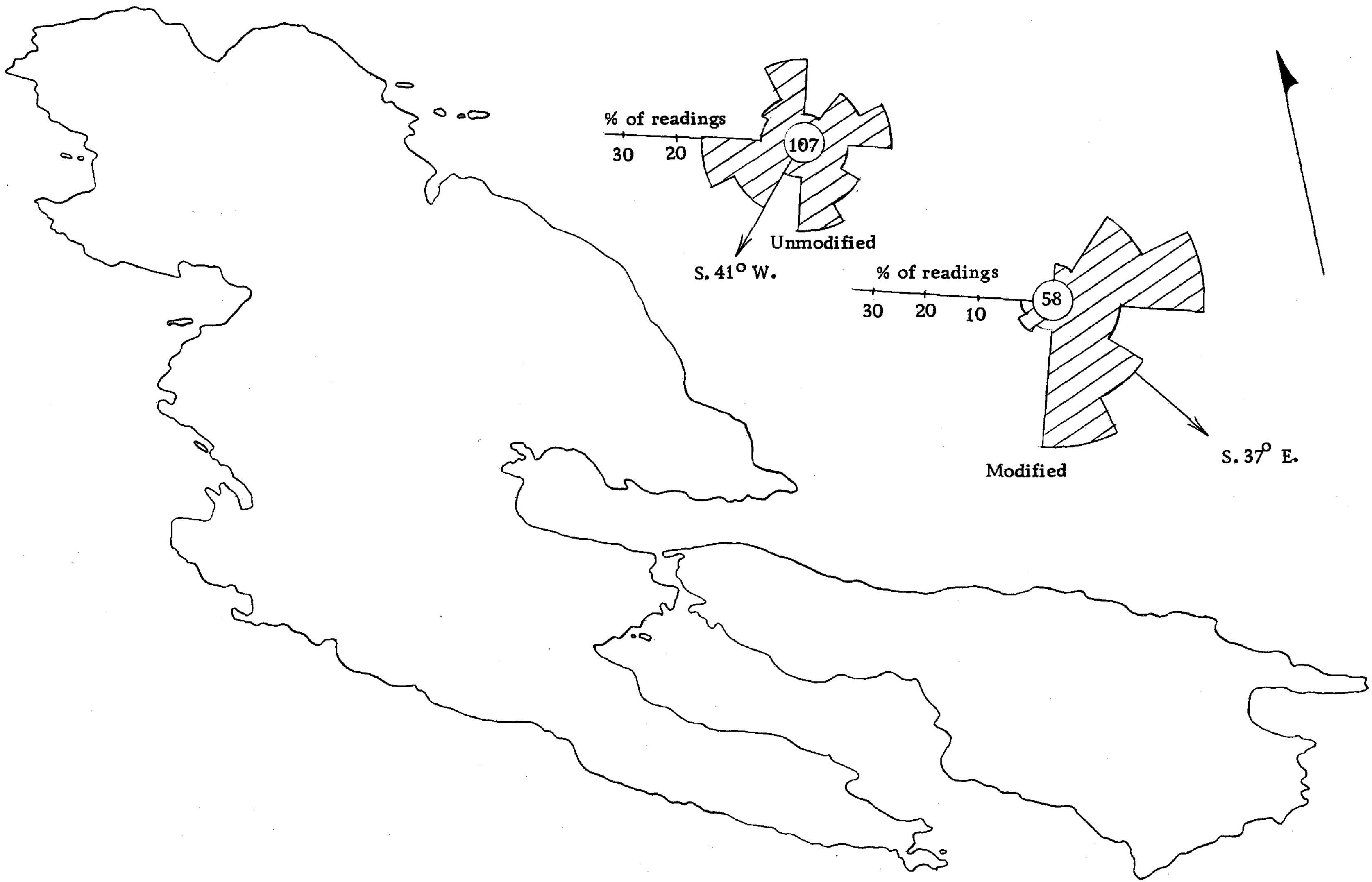


Figure 33. Paleocurrent data for the Cedar District/DeCourcy deltaic sequence.

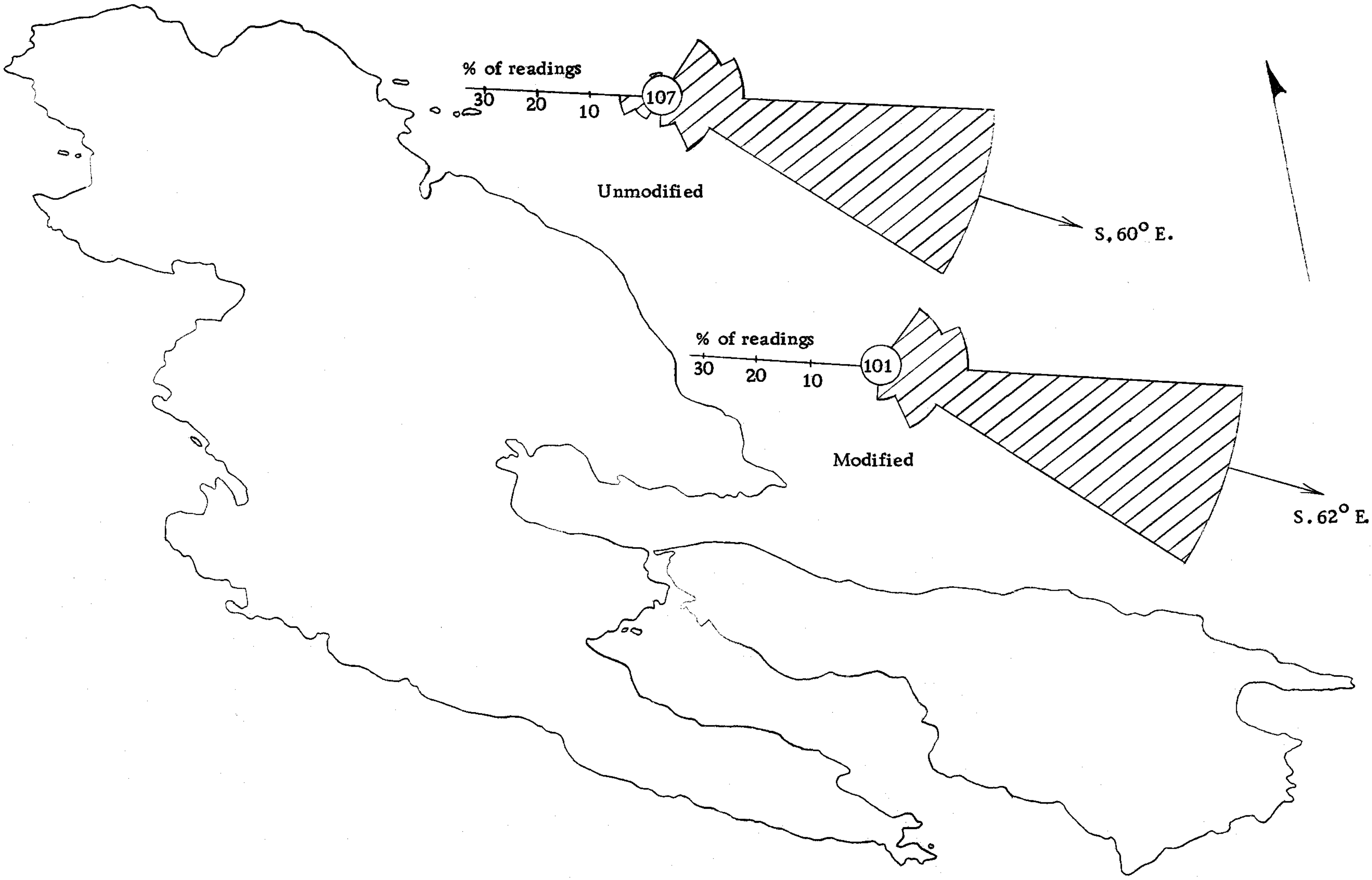


Figure 34. Paleocurrent data for the Northumberland/Geoffrey deltaic sequence.

Vancouver Group, and the Middle to Late Jurassic Island Intrusions. The Sicker Group is dominantly greenstone and greenschist derived from intermediate composition pyroclastics, and also contains limestones, graywackes, and local conglomerates (Muller and Carson, 1969). The Vancouver Group consists of andesitic pyroclastic rocks, pillow basalts, basaltic pillow breccias, basalt flows, and limestones, all of which have been metamorphosed (Muller and Carson, 1969). The Island Intrusions are granodioritic and quartz monzonitic batholiths.

A pebble count (Appendix G) from the Extension-Protection Formation shows an abundance of andesite, basalt, sandstone, and chert. Modal analyses (Appendix F) of Extension-Protection sandstones show an abundance of quartz, chert, plagioclase feldspar, volcanic and sedimentary rock fragments, and chlorite. This mineral assemblage could have been derived from the pre-Cretaceous rocks of Vancouver Island. Lateral facies changes and the scanty paleocurrent data suggest a sediment transport direction from the east or southeast. Whether these sediments actually had a source area to the east or southeast, or were deposited on a northwest-prograding lobe of a delta forming along Vancouver Island, is a matter of speculation.

A pebble count from the Cedar District/DeCourcy deltaic cycle shows abundant andesite, chert, basalt, and plutonic rock fragments. Modal analyses of sandstone samples show an abundance of quartz, chert, plagioclase and potassium feldspars, volcanic rock fragments, and chlorite. This mineral assemblage, combined with the relative decrease of sandstone and increase in plutonic rock fragments over the Extension-Protection Formation, suggests a source area in the Vancouver Group and the Island Intrusions. Paleocurrent data and lateral facies changes suggest that this source area was to the northwest of the thesis area, on Vancouver Island.

The Northumberland/Geoffrey deltaic cycle is mineralogically similar to the Cedar District/DeCourcy deltaic cycle. Again, andesite, chert, basalt, and plutonic rock fragments are the dominant lithologies in the conglomerates. Sandstone modal analyses show a relative decrease in quartz and an increase in volcanic rock fragments over the older deltaic cycle. Paleocurrent data and lateral facies changes suggest that the source area for the sediments of the Northumberland/Geoffrey deltaic cycle was to the northwest of the thesis area on Vancouver Island. This source area is either the same one as that of the Cedar District/DeCourcy deltaic cycle, or one similar to it.

Modal analysis of a sandstone from the Spray Formation shows little change from the mineralogy of the sandstones of the Northumberland/Geoffrey deltaic cycle. The mineral assemblage of the Spray Formation could have been derived from the pre-Cretaceous rocks of Vancouver Island. No paleocurrent data were collected, however, to substantiate this theory.

History

The six formations of the Late Cretaceous Nanaimo Group present in the thesis area were deposited in a subsiding marine basin off the northeast coast of Vancouver Island. The sediments deposited in this basin were poorly sorted, highly angular, and had high matrix contents. These factors suggest that erosion, deposition, and burial of these sediments was rapid, and that the sediments had little reworking by wave action.

Viewed in the context of plate tectonics, Monger, Souther, and Gabrielse (1972) call the Nanaimo Basin a "successor" basin formed after a collision of the North American plate with a Pacific plate. The presence of a lithospheric plate dipping below Vancouver Island was first suggested by Atwater (1970). Mckenzie and Julian (1971) also suggest the presence of a north-south striking, 50° east-dipping lithospheric plate in the Puget Sound, Washington area, and infer the presence of the same plate off the west coast of Vancouver Island.

Bell (1957), in his study of the flora of the Nanaimo Group, states that the climate on Vancouver Island during the Late Cretaceous was probably warm temperate, subtropical, or tropical. Most of the fossil flora collected by Bell were indicative of a warm temperate climate.

Sediments of the Comox and Haslam Formations were initially deposited in the Nanaimo Basin (Muller and Jeletzky, 1970) but are not exposed in the thesis area. The first record of deposition in the thesis area is the Extension-Protection Formation. These conglomerates were probably deposited as topset beds by high energy streams. The high energy streams either drained a source area to the east or southeast, or the conglomerates were deposited on a northwest-prograding lobe of a delta forming off the northeast coast of Vancouver Island. Regardless of where this source area was, it was apparently of high relief and tectonically active. Intertonguing of these conglomerates with tongues of Cedar District Formation mudstones on South Pender Island probably represents alternating periods of marine and fluvial deposition related to variations in the rate of basin subsidence, tectonic events in the source area, channel abandonment and the migration of major sediment distributaries, or improbable major fluctuations in sea level. Following deposition of the fluvial conglomerates, basin subsidence continued. Clastic deposition in the form of thick-bedded delta-front sheet sandstones occurred on South Pender Island. This sandstone interval is represented on North Pender Island by sandy mudstones and mudstones of the Cedar District Formation. apparently deposited in a farther offshore, prodelta environment.

Following the deposition of the Extension-Protection Formation, a major change in the direction of sediment transport took place. Sediments of the Cedar District/DeCourcy deltaic cycle began to prograde over the thesis area from a high relief, tectonically active source area to the northwest. Initially only the finer material carried by the high energy streams which drained the source area was deposited in the thesis area. These deposits are recognized in the lower Cedar District Formation as prodelta deposits. As deltaic progradation encroached over the area, turbidity current deposits were laid down over the prodelta muds. These turbidity currents were probably generated by slumping on the unstable slopes of the prograding delta, which apparently was the site of rapid deposition and little reworking of sediments. As the source of these turbidity currents approached the thesis area, the turbidite sandstone deposits became thicker and more abundant.

The filling and shallowing of the depositional basin was followed by the progradation of the delta-front sheet sands or river mouth bars of the lower DeCourcy Formation. Continued basin subsidence, possibly combined with lower sedimentation rates or abandonment of a deltaic lobe, caused a transgression over the delta-front sheet sands of the lower DeCourcy Formation and a return to prodelta deposition of the upper Cedar District Formation. Renewed progradation of the Cedar District/DeCourcy deltaic complex was initiated by turbidity current deposition similar to that of the lower Cedar District Formation. Following this deposition, the delta-front sheet sands or river mouth bars of the upper DeCourcy Formation prograded over the turbidites. Short periods of alternating prodelta and delta-front deposition are recorded as tongues of Cedar District mudstones in the sandstones of the DeCourcy Formation. Fluvial conglomerates deposited by high energy streams prograded over and alternated with the delta-front sheet sands in two intervals before the delta-front sheet sands were succeeded by the thick fluvial conglomerates of the upper DeCourcy Formation. These conglomerates probably represent topset beds and are the final depositional event during DeCourcy time observed in the thesis area.

The lower part of the Northumberland Formation was not observed in the thesis area, but it is apparent that the Northumberland/Geoffrey deltaic complex prograded from a high relief, tectonically active source area to the northwest which was drained by high energy streams. The source area of the Northumberland/Geoffrey deltaic cycle is either the same one as that of the Cedar District/DeCourcy deltaic cycle, or one similar to it. The earliest event recorded in the Northumberland/Geoffrey deltaic cycle is the deposition of turbidite sandstones over prodelta mudstones in a shallowing marine environment. These turbidite sandstones were deposited by turbidity currents probably generated in a manner similar to those of the Cedar District

Formation. As the locus of deposition encroached on the thesis area, the turbidite sandstones became thicker and more abundant.

Following the deposition of the turbidite sandstones of the Northumberland Formation, thick-bedded delta-front sheet sands or river mouth bars prograded over the thesis area. These sands of the lower Geoffrey Formation alternate with tongues of Northumberland muds in the Stanley Point-Willey Point area and the Colston Cove-Welcome Cove-Hope Bay area. These alternations of coarse-grained and fine-grained sedimentation probably reflect channel abandonment and migration of distributaries in the deltaic model of sedimentation. Other factors possibly contributing to this phenomenon are variations in the rate of basin subsidence, tectonic events in the source area, or the remote possibility of major variations in sea level.

The interval of intertonguing in the Northumberland and Geoffrey formations is succeeded by a thick sequence of thick-bedded sandstones which probably represent river mouth bars or delta-front sheet sands. These sands prograded toward the southeast and are overlain by an interval of fluvial conglomerates deposited as topset beds by high energy streams. Continued basin subsidence caused a transgression over the fluvial conglomerates and a short interval of shallow marine sand deposition followed.

Continued basin subsidence marked a return to marine conditions and the deposition of the distal bar muds of the Spray Formation.

These mudstones are punctuated by thin turbidite sandstone beds, probably related to the progradation of a tongue of shallow marine Geoffrey Formation sands into the thesis area. These sandstones are probably river mouth bars or delta-front sheet sands and mark a last progradation of the Northumberland/Geoffrey deltaic complex into the thesis area. Continued basin subsidence caused a return to deeper marine conditions, and the last Cretaceous event recorded in the thesis area is the deposition of Spray Formation mudstones. Overlying the Spray Formation is the dominantly sandstone Gabriola Formation (Muller and Jeletzky, 1970), which is not exposed within the thesis area.

Post-Cretaceous faulting has caused the sedimentary rocks of the Nanaimo Group to be folded and faulted along a west-northwesterly trend in the thesis area. The Kulleet Syncline and the minor syncline near Razor Point were probably formed at this time. Later north-northeast-trending faults terminated and truncated both of these synclines. Offsetting of faults suggests at least three episodes of faulting within the thesis area, but the exact number of episodes is not known.

Following the faulting, the thesis area was overridden by Pleistocene-age glaciers. These glaciers excavated the nonresistant mudstones of the Cedar District, Northumberland, and Spray Formations, stripped and grooved the sandstones and conglomerates of the Extension-Protection, DeCourcy, and Geoffrey Formations, and excavated the shattered rocks which border many of the fault zones. Thick deposits of glacial till now occupy the excavated areas. The most recent geologic events in the thesis area are the formation of wave-cut benches and notches, and honeycomb weathering caused by wave and spray action.

ECONOMIC GEOLOGY

Coal

Since its discovery on Vancouver Island in 1835 (Usher, 1952), coal has been the chief economic resource of the Nanaimo Group. Over 72 million metric tons of coal were mined from the Nanaimo Group from 1849 to the mid-1960's (Muller and Carson, 1969) before the mines were abandoned as uneconomical. Newer, more economical methods of mining, higher prices, and the proximity of the coal to water transport and major population centers may renew interest in the Nanaimo Group coal fields.

No economic deposits of coal were found on North and South Pender islands. Richardson (1872, 1878) suggested that additional coal-bearing strata of the Nanaimo coal field lie to the southwest of the Penders, but this is not confirmed.

Gravel and Clay Products

Gravel for road- and home-building is a valuable resource on the Gulf Islands. On North and South Pender islands, the gravel is removed from deposits of glacial till by screening. The only Cretaceous rocks currently used are the mudstones, which are sometimes used for roadbed material.

No clay products are currently being produced from the Cretaceous mudstones of the thesis area. A brick factory did operate at Colston Cove, North Pender Island, during the early years of this century. No evidence is left of this factory except for broken bricks which litter the nearby beaches.

Petroleum Potential

The Nanaimo Group presents a nearly ideal situation for the generation and entrapment of petroleum. Numerous structural traps, such as anticlines and faults, bring sandstones into contact with impermeable mudstones. Stratigraphic traps such as tongues of sandstone in mudstone also exist (in the thesis area this situation is displayed by DeCourcy Formation sandstones intertonguing with Cedar District Formation mudstones and Geoffrey Formation sandstones intertonguing with Northumberland Formation and Spray Formation mudstones). The potential source rocks would be the mudstones of the Cedar District, Northumberland, and Spray Formations.

The major barrier to the production of petroleum from the Nanaimo Group is the apparent lack of porosity and permeability in the sandstones. On outcrop, no porosity was ever observed. Modal analyses (Appendix F) of the sandstones within the thesis area indicated that 1.8% was the highest porosity achieved.

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APPENDICES

APPENDIX A

MEASURED SECTION A-B, EXTENSION-PROTECTION FORMATION

All sections were measured using a five-foot Jacobs staff mounted with an Abney level and a Brunton compass. Description of the measured intervals was aided by the use of a 10X hand lens and sand gauge chart. Colors are those of the Rock-Color Chart of the Geological Society of America (1963). Stratification terms are modified from McKee and Weir (1953).

Section A-B, encompassing a part of the upper Extension-Protection Formation, forms part of the southwest slope and the crest of Oaks Bluff on North Pender Island. The section was measured to provide a detailed description of the typical development of the Extension-Protection Formation. Steep cliffs, covering of part of the exposures by seawater, and a lack of structurally simple outcrops prevented the description of a more complete section.

Terminal point (B, Plate 1) is the upper surface of the conglomerate unit forming the crest of Oaks Bluff. Bearings from the terminal point to the highest elevation on Mt. Norman, South Pender Island, and the navigation light on Hay Point are N. 58° E. and S. 80° E., respectively.

Interval (feet)	Description
129-83.5	Conglomerate: resistant ridge-former; dark yellowish orange (10YR 6/6) to light olive gray (5Y 6/1) in gross aspect; crudely thickly bedded; some larger clasts current imbricated. Framework: fine pebbles to fine boulders, medium pebbles predominant; grain-supported; subangular to subrounded quartz, chert, sandstone, andesite, granite, diorite. Sandstone matrix: medium-grained to very coarse-grained, coarse-grained predominant; poorly sorted; subangular quartz, feldspar, lithic fragments.
83.5-50.5	Covered by vegetation.
50.5-37.5	Conglomerate: resistant cliff-former; as at 83.5; lower contact planar to gently undulating.
37.5-35.5	Sandstone: resistant rib-former; moderate yellowish brown (10YR 5/4) weathered; brownish olive gray (5YR 4/1) fresh; thin-bedded; medium-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, feldspar, lithic fragments. Lower contact gradational over four inches with underlying conglomerate.
35.5-32	Conglomerate: resistant ledge-former; pale greenish yellow (10Y 8/2) to light olive gray (5Y 5/2) in gross aspect; thick-bedded. Framework: fine to coarse pebbles, medium pebbles predominant; grain-supported; subangular to subrounded quartz, chert, andesite, basalt, coarse-grained sandstone, diorite. Sandstone matrix: medium- to coarse-grained, medium-grained predominant; subangular, quartz, feldspar, abundant lithic fragments. Lower contact scour, channels six inches to three feet across, three to seven inches deep.
32-28.5	Mudstone: non-resistant; moderate yellowish brown (10YR 5/4) weathered; olive gray (5Y 4/1) fresh; abundant pseudo-concretions (concentrically weathering mudstone concretions, lithologically similar to enclosing unit) in layers parallel to

Appendix A. (Continued)

Interval (feet)	Description
	bedding, three inches to two feet in diameter; weathers to chips 1/4 to 1 inch thick. Lower contact gradational over six inches with underlying sandstone.
28.5-27.5	Sandstone: resistant rib-former; light olive gray (5Y 6/1) weathered; light olive gray (5Y 5/2) fresh; thin-bedded; very coarse-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, lithic fragments. Lower contact scour, channels eight inches to two feet across, three to seven inches deep.
27.5-26.5	Mudstone: non-resistant; grayish moderate brown (5YR 3/3) weathered; olive gray (5Y 4/1) fresh; thin-bedded; abundant pseudo-concretions four to six inches in diameter; weathers to chips 1/4 to 1/2 inch thick.
26.5-0	Covered by slope debris and road bed; presumably non-resistant mudstone and sandstone.

Contact at A: within the Extension-Protection Formation; arbitrarily selected at the top of the underlying conglomerate bed.

Initial point (A, Plate 1) is the top of the conglomerate bed on the southwest side of the new road to Wallace Point, N.E. 1/4, N.W. 1/4, N.E. 1/4, Section 24, North Pender Island. Attitude at initial point is N. 62° W., 43° N.E., proceed N. 28° E. upsection.

APPENDIX B

MEASURED SECTION C-D, CEDAR DISTRICT FORMATION AND DE COURCY FORMATION

Section C-D encompasses part of the eastern shoreline of Section 6, North Pender Island. The section was measured to determine the approximate thickness of the lower Cedar District Formation and the lower De Courcy Formation and their stratigraphic relationships.

Terminal point (D, Plate 1) is on the northeast shore of the projection of land locally known as "Arbutus Point," Section 6, North Pender Island. Bearings from the terminal point to the highest elevation on Mt. Norman, South Pender Island, and the Hay Point navigation light are N. 03° E. and S. 79° E., respectively.

Contact at D: Within the lower De Courcy Formation; arbitrarily selected where vegetation and sea cliffs make further exposures inaccessible. Where observed, the contact between the lower De Courcy Formation and the overlying upper Cedar District Formation is sharp and essentially planar.

Interval (feet)	Description

De Courcy Formation, Tongue 1 (K_{dc1}).

726-691 — Sandstone: resistant ridge-former; olive gray (5Y 5/1) weathered; light olive gray (5Y 6/1) fresh; very thick-bedded (ten feet plus); groove casts on bottom surfaces; medium-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, feldspar, muscovite, biotite. Lower contact sharp, planar.

691-688.5 — Interbedded mudstone-sandstone sequence: non-resistant:

Mudstones: light olive gray brown (5Y 5/4) weathered; medium dark gray (N 4) fresh; abundant pseudo-concretions (concentrically weathering mudstone concretions, lithologically similar to enclosing unit) six inches to one foot in diameter arranged in layers parallel to bedding; mudstone weathers to chips 1/4 to 1/2 inch thick. Lower contacts gradational with underlying sandstone; upper contacts sharp, planar to gently undulating.

Sandstones: pale brown (5YR 5/2) weathered; light bluish gray (5B 6/1) fresh; laminated to cross-laminated (20-25 per inch); display minor soft sediment deformation folding; fine-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, muscovite, feldspar. Lower contacts sharp, planar to gently undulating; upper contacts gradational through siltstone to overlying mudstone.

Sequence:	(in.)
e. Mudstone	12
d. Sandstone	6
c. Mudstone	4
b. Sandstone	5
a. Mudstone	3

688.5-686.5 — Sandstone: resistant rib-former; yellowish gray (5Y 7/2) weathered; light olive gray (5Y 5/2) fresh; thin-bedded, thinly laminated in upper six inches of interval

Appendix B. (Continued)

Interval (feet)	Description
	(15-20 per inch); medium-grained; moderately sorted; non-calcareous; angular to subangular quartz, feldspar, muscovite, biotite; contains mud ripups up to two inches in length "floating" in the sandstone. Lower contact sharp, planar.
686.5-677.5	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones as at 688.5; upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-3 inches to underlying sandstones. Sandstones: yellowish gray (5Y 7/2) weathered; light gray (N 7) fresh; thinly laminated (10-15 per inch); exhibit rare soft sediment deformation folding; fine-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, muscovite, feldspar. Upper contacts gradational over 1-3 inches through siltstone to overlying mudstone; lower contacts sharp, planar to gently undulating.

Sequence:	(in.)
o. Mudstone	12
n. Sandstone	7
m. Mudstone	12
l. Sandstone	3
k. Mudstone	25
j. Sandstone	6
i. Mudstone	3
h. Sandstone	5
g. Mudstone	5
f. Sandstone	4
e. Mudstone	10
d. Sandstone	1
c. Mudstone	10
b. Sandstone	4
a. Mudstone	4

677.5-454.5	Sandstone: resistant ridge-former; yellowish olive gray (5Y 7/1) weathered; light olive gray (5Y 5/1) fresh; very thick-bedded (5-8 feet); medium- to coarse-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, muscovite, lithic fragments; contains rare mud ripups and calcareous concretions 2-4 inches in diameter; rarely faintly laminated to thinly laminated; rare scour-and-fill channels within sandstone beds; rare soft sediment deformation folds; rare flame structures; a few horizontal burrows noted on upper surfaces of sandstone beds; Lower contacts sharp, planar; upper contacts gradational over 4-8 inches through fine-grained sandstone to 3-8 inch thick beds of siltstone.

Contact: De Courcy Formation, Tongue 1 (K_{dc1}) and Cedar District Formation, Tongue 1 (K_{cd1}) covered.

Cedar District Formation, Tongue 1 (K_{cd1}) (Thickness = 454.5 feet).

454.5-399.5	Covered by sandstone boulder rubble and mudstone chips; assumed to be non-resistant mudstone.

Appendix B. (Continued)

Interval (feet)	Description
399.5-397.5	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones: light olive gray (5Y 6/1) weathered; olive gray (5Y 3/2) fresh; thin-bedded, rare pseudo-concretions 4-6 inches in diameter; weathers to chips 1/4 to 1/2 inch thick. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-2 inches to underlying sandstones. Sandstones: yellowish gray (5Y 7/2) weathered; medium dark gray (N 4) fresh; thinly laminated (15-25 per inch); fine-grained; well sorted; calcareous; subangular quartz, feldspar. Upper contacts gradational over 1-2 inches through siltstone to overlying mudstones; lower contacts sharp, planar to gently undulating.

Sequence: (in.)

Sequence	(in.)
d. Mudstone	6
c. Sandstone	5
b. Mudstone	7
a. Sandstone	6

Interval (feet)	Description
397.5-378	Mudstone as at 398; lower contact gradational over one inch.
378-374	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones as at 398; upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-3 inches to underlying sandstones. Sandstones: light olive gray (5Y 5.5/2) weathered; greenish gray (5GY 6/1) fresh; laminated to cross-laminated (10-12 per inch); very fine- to fine-grained; well sorted; calcareous; subangular quartz, feldspar. Upper contact gradational over 1-3 inches through siltstone to overlying mudstone; lower contacts sharp, planar to gently undulating.

Sequence	(in.)
i. Sandstone	2
h. Mudstone	8
g. Sandstone	4
f. Mudstone	3
e. Sandstone	2
d. Mudstone	2
c. Sandstone	3
b. Mudstone	21
a. Sandstone	3

Interval (feet)	Description
374-368.5	Mudstone as at 398; lower contact gradational over one inch to underlying siltstone.
368.5-367	Interbedded mudstone-siltstone sequence: non-resistant: Mudstones as at 398; upper and lower contacts gradational over 1/2 to 2 inches. Siltstones: olive gray (5Y 3/2) weathered and fresh; laminated to very thin-bedded; upper and lower contacts gradational over 1/2 to 2 inches.

Appendix B. (Continued)

Interval (feet)	Description
	Sequence: (in.) e. Siltstone . . . . 2 d. Mudstone . . . . 4 c. Siltstone . . . . 3 b. Mudstone . . . . 5 a. Siltstone 4
367-333.5	Mudstone as at 398; lower contact gradational over three inches with underlying sandstone.
333.5-332	Sandstone: resistant rib-former; grayish orange (10YR 7/4) weathered; moderate yellowish brown (10YR 5/4) fresh; thin-bedded; fine- to medium-grained; well sorted; non-calcareous; subangular to subrounded quartz, feldspar. Lower contact sharp, planar.
332-319	Interbedded mudstone-siltstone sequence: non-resistant; same description as at 367. Lower contact of lowermost siltstone is sharp, planar.
	Sequence: (in.) r. Mudstone . . . . 36 q. Siltstone . . . . 4 p. Mudstone . . . . 24 o. Siltstone . . . . 4 n. Mudstone . . . . 6 m. Siltstone . . . . 2 l. Mudstone . . . . 12 k. Siltstone . . . . 3 j. Mudstone . . . . 12 i. Siltstone . . . . 3 h. Mudstone . . . . 9 g. Siltstone . . . . 2 f. Mudstone . . . . 2 e. Siltstone . . . . 2 d. Mudstone . . . . 4 c. Siltstone . . . . 4 b. Mudstone . . . . 23 a. Siltstone 4
319-309	Mudstone as at 398; lower contact gradational over two inches with underlying siltstone..
309-308.5	Siltstone: non-resistant; moderate brown (5YR 3.5/4) weathered; medium dark gray (N 4) fresh; laminated to cross-laminated (5-15 per inch); poorly sorted; calcareous. Lower contact sharp, planar.

Appendix B. (Continued)

Interval (feet)	Description
308.5-305.5	Mudstone as at 398; lower contact gradational over 1 1/2 inches with underlying sandstone.
305.5-305	Sandstone: resistant rib-former; yellowish olive gray (5Y 6/2) weathered; greenish gray (5GY 5/1) fresh; thin-bedded; very fine- to fine-grained; moderately sorted; calcareous; subangular quartz and feldspar. Lower contact sharp, planar.
305-303	Mudstone as at 398.
303-190	Covered by gravel beach; presumably non-resistant mudstone.
190-142	Sandy mudstone: non-resistant; yellowish gray (5Y 7/2) weathered; medium dark gray (N 4) fresh; weathers to chips 1/4 to one inch thick; contains numerous calcareous mudstone concretions as irregular ellipsoids and lenses ranging in size from one inch to 1 1/2 feet in length, concretions are aligned parallel to bedding. Lower contact gradational over eight inches with underlying sandstone.
142-140.5	Sandstone: resistant rib-former; olive black (5Y 2/1) weathered; olive gray (5Y 5/1) fresh; thin-bedded; very fine- to fine-grained; moderately sorted; very slightly calcareous; angular to subangular quartz and feldspar. Lower contact sharp, planar.
140.5-135.5	Sandy mudstone as at 142; contains rare pelecypod shell fragments and external molds of *Inoceramus*.
135.5-129.5	Covered by beach gravel, presumably non-resistant mudstone.
129.5-54.5	Mudstone as at 142 except mudstone concretions one inch to seven feet in length, up to eight inches thick. Lower contact gradational over two feet with underlying sandstone.
54.5-40.5	Sandstone with conglomeratic channel fill: resistant ridge-former: Sandstones: light olive gray (5Y 6/1) weathered; olive gray (5Y 4/1) fresh; very thin-bedded to thin-bedded, thicker beds in upper part of interval; medium-grained; moderately sorted; slightly calcareous; subangular to subrounded quartz, feldspar, lithic fragments. Conglomerates: light olive gray (5Y 6/1) in gross aspect; confined to channels five to eight feet in width, five to ten inches deep, in lower three feet of interval. Framework: fine to medium pebbles, fine pebbles predominant; grain-supported; subrounded to rounded andesite, basalt, quartz, chert, sandstone. Sandstone matrix: coarse- to very coarse-grained, coarse predominant; moderately sorted; subangular to subrounded quartz, feldspar, lithic fragments. Conglomeratic channels also contain rare rounded to well rounded medium pebbles of diorite and andesite up to eight inches in diameter. One conglomeratic channel is composed of mud ripups 1/4 to four inches in length.
40.5-26	Covered by beach gravel; presumably non-resistant mudstone.

Appendix B. (Continued)

Interval (feet)	Description
26-24.5	Sandstone: resistant rib-former; greenish gray (5GY 6/1) weathered; dark greenish gray (5GY 4/1) fresh; thin-bedded; medium-grained; moderately sorted; slightly calcareous; angular to subangular quartz, feldspar, biotite; rare calcarous concretions two to four inches in diameter. Lower contact sharp, gently undulating.
24.5-24	Sandstone: resistant rib-former; grayish black (N 2) weathered; light bluish gray (5B 6/1) fresh; laminated (4-8 per inch); very fine-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, feldspar. Lower contact sharp, gently undulating.
24-23	Sandstone as at 24.5; lower contact sharp, planar.
23-21	Sandstone as at 24; lower contact sharp, planar.
21-20	Sandstone as at 24.5; lower contact sharp, planar.
20-19.5	Sandstone as at 24.
19.5-13	Covered by beach gravel; presumably non-resistant mudstone.
13-4	Sandstone as at 24.5; lower contact sharp, gently undulating.
4-2.5	Sandstone as at 24.
2.5-0	Covered by beach gravel; presumably non-resistant mudstone.

Initial point (C, Plate 1) is the top of the lowest exposed rib of sandstone in the intertidal zone, about 300 feet northwest of the Trincomali housing development boat dock, North Pender Island. Bearings from the initial point to the highest elevation on Mt. Norman, South Pender Island, and the Hay Point navigation light are N. 07° W. and N. 49° E., respectively. Attitude is N. 60° W., 51° N.E.; proceed N. 30° E. upsection.

APPENDIX C

MEASURED SECTION E-F, CEDAR DISTRICT FORMATION
AND DE COURCY FORMATION

Section E-F, encompassing the upper part of the upper Cedar District Formation and the lower part of the upper De Courcy Formation, forms the shoreline extending from about 1800 feet southeast of Medicine Beach to about 1600 feet northeast of Medicine Beach, North Pender Island. The upper Cedar District Formation underlies Medicine Beach and the lowlying areas adjacent and southeast of the beach. The De Courcy Formation forms the shoreline northeast of Medicine Beach. The section was measured to provide a detailed description of the Cedar District Formation and the De Courcy Formation, and a description of their stratigraphic relationships.

Terminal point (F, Plate 1) is approximately 1600 feet northeast of the end of the Medicine Beach access road, North Pender Island. Bearings to the highest elevation on Mt. Norman, South Pender Island and the Hay Point navigation light are S. 77° E. and S. 51° E., respectively.

Contact at F: within the upper De Courcy Formation; arbitrarily selected where sea cliffs and faultings make accurate section description impossible.

Interval (feet)	Description
	De Courcy Formation, Tongue 4 (K_{dc4})
1854.5-1613.5	Sandstone: resistant ridge-former; yellowish gray (5Y 7/2) to light olive gray (5Y 5/2) weathered; medium light gray (N 6) fresh; very thick-bedded (5-10 feet plus); medium-grained; moderately sorted; slightly calcareous; angular to sub-rounded quartz, feldspar, lithic fragments, biotite, muscovite; rare scattered fine and medium pebbles; rare lenses of mud chips and pebbly sandstone 1/4 to eight inches thick.

Contact: De Courcy Formation, Tongue 4 (K_{dc4}) and Cedar District Formation, Tongue 4 (K_{cd4}); sharp, gently undulating.

Cedar District Formation, Tongue 4 (K_{cd4}) (Thickness = 341 feet).

1613.5-1503 Interbedded mudstone-sandstone sequence: non-resistant:

Mudstones: light olive gray (5Y 6/1) to grayish brown (5YR 3/2) weathered; olive gray (5Y 4/1) fresh; thin-bedded in bottom part of interval, decreasing to very thin-bedded in upper part of interval; moderately abundant pseudoconcretions (concentrically weathering mudstone concretions, lithologically similar to enclosing unit) 3-8 inches in diameter arranged parallel to bedding are found in all but the upper ten feet of the interval; rare calcareous mudstone concretions occur as irregular ellipsoids up to eight inches in length. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-3 inches with underlying sandstones.

Sandstones: yellowish gray (5Y 6.5/2) to light gray (N 7) to light olive gray (5Y 6/1) weathered; medium dark gray (N 4) to medium light gray (N 6) fresh; thin-bedded (3-18 inches); laminated to cross-laminated (10-24 per inch);

Appendix C. (Continued)

Interval (feet)	Description
	fine-grained; poorly to moderately sorted; slightly calcareous; subangular to subrounded quartz, feldspar, muscovite, biotite. Bottom of beds commonly display abundant flute casts and rare current crescents and load casts. Upper contacts gradational over 1-3 inches through siltstones to overlying mudstones; lower contacts sharp, planar to gently undulating. General overall increase in sandstone percentage upward in the interval. Typical sequence: (in.) j. Mudstone . . . . 12 i. Sandstone . . . . 12 h. Mudstone . . . . 3 g. Sandstone . . . . 3 f. Mudstone . . . . 1 e. Sandstone . . . . 2 d. Mudstone . . . . 30 c. Sandstone . . . . 18 b. Mudstone . . . . 2 a. Sandstone 7
1503-1428	Mudstone as at 1503.
1428-1365	Covered by gravel beach; presumably non-resistant mudstone.
1365-1272.5	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones: dark gray (N 4) weathered; olive black (5Y 2/1) fresh; thin-bedded (2-12 inches); contains moderately abundant calcareous mudstone concretions as irregular ellipsoids four to eight inches in diameter; weathers to chips 1/4 to 1/2 inch thick. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-3 inches with underlying sandstones. Sandstones: medium light gray (N 6) to light olive gray (5Y 6/1) weathered; medium gray (N 4.5) fresh; thin-bedded (2-12 inches); medium- to fine-grained; poorly sorted; calcareous; subangular to subrounded quartz, feldspar, biotite, muscovite, lithic fragments. Displays moderately abundant flute casts and load casts on bottom of beds. Upper contacts gradational over 1-3 inches through siltstones to overlying mudstones; lower contacts sharp, planar to gently undulating. General overall decrease in sandstone grain size upwards in the interval. Typical sequence: (in.) k. Mudstone . . . . 12 j. Sandstone . . . . 12 i. Mudstone . . . . 6 h. Sandstone . . . . 6 g. Mudstone . . . . 3 f. Sandstone . . . . 4 e. Mudstone 12

Appendix C. (Continued)

Interval (feet)	Description

d. Sandstone 2
c. Mudstone 8
b. Sandstone 2
a. Mudstone 2

Contact: Cedar District Formation, Tongue 4 (K_{cd4}) and De Courcy Formation, Tongue 3 (K_{dc3}); gradational over four inches.

De Courcy Formation, Tongue 3 (K_{dc3}) (Thickness = 158 feet).

1272.5-1255 — Sandstone: resistant ledge-former; medium light gray (N 6) to yellowish olive gray (5Y 7/1) weathered; dark greenish gray (5GY 5/1) fresh; thick- to very thick-bedded (2.5-5 feet); coarse-grained; poorly sorted; slightly calcareous; angular to subangular quartz, feldspar, biotite, muscovite, lithic fragments. Lower contact sharp, planar.

1255-1251 — Interbedded mudstone-sandstone sequence: non-resistant:

Mudstones: olive gray (5Y 4/1) weathered and fresh; thin-bedded (2-12 inches); weathers to chips 1/4 to 1/2 inch thick. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1/2-2 inches with underlying sandstones.

Sandstones: light olive gray (5Y 6/1) weathered; greenish gray (5GY 5/1) fresh; thin-bedded (2-8 inches); medium-grained; poorly sorted; moderately calcareous; subangular to subrounded quartz, feldspar, biotite, lithic fragments. Upper contacts gradational over 1/2-2 inches through siltstones to overlying mudstones; lower contacts sharp, planar to gently undulating.

Sequence: (in.)

j. Sandstone 3
i. Mudstone 2
h. Sandstone 2
g. Mudstone 3
f. Sandstone 2
e. Mudstone 9
d. Sandstone 4
c. Mudstone 13
b. Sandstone 8
a. Mudstone 2

1251-1250 — Sandstone: resistant rib-former; yellowish orange (10YR 7/6) weathered; light olive gray (5Y 6/1) fresh; thin-bedded; coarse-grained; poorly sorted; non-calcareous; subangular to subrounded quartz, feldspar, biotite, muscovite, lithic fragments. Displays groove casts on underside of bed. Lower contact sharp, gently undulating.

1250-1249 — Siltstone: non-resistant; grayish orange (10YR 7/4) to grayish brown (5YR 3/2) weathered; olive gray (5Y 4.5/1) fresh; laminated to cross-laminated (10-12 per

Appendix C. (Continued)

Interval (feet)	Description
	inch); poorly sorted; slightly calcareous. Lower contact gradational over three inches with underlying sandstone.
1249-1247.5	Sandstone: resistant rib-former; yellowish olive gray (5Y 7/1) weathered; medium gray (N 4.5) fresh; thin-bedded; normally graded; pebbly to very fine-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, feldspar, muscovite, lithic fragments. Lower contact scour-and-fill, channels 18-24 inches wide, 4-8 inches deep.
1247.5-1237.5	Pebbly sandstone: resistant ledge-former; yellowish gray (5Y 7/2) to olive gray (5Y 4/1) weathered; medium dark gray (N 3.5) fresh; very thick-bedded; normally graded; fine-grained to very fine-grained; very poorly sorted; non-calcareous; angular to subangular quartz, feldspar, muscovite. Conglomeratic clasts range from fine pebbles to medium cobbles, medium pebbles predominant; rounded to subrounded quartz, chert, with subordinate granite, andesite, sandstone, mudstone. Lower contact gradational over three feet with underlying sandstone.
1237.5-1227.5	Sandstone: resistant ledge-former; pale brown (5YR 5/2) to medium gray (N 5) weathered; dark yellowish brown (10YR 4/2) fresh; very thick-bedded; fine-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, muscovite. Lower contact gradational over one foot with underlying conglomerate.
1227.5-1202.5	Conglomerate: resistant ledge-former; olive gray (5Y 4.5/1) to yellowish gray (5Y 6/2) in gross aspect; structureless. Framework: fine pebbles to coarse cobbles, medium pebbles predominant; grain-supported in upper part of interval, lower ten feet of interval are matrix-supported; rounded to subrounded quartz, chert, subordinate diorite, mudstone, sandstone, andesite. Sandstone matrix: medium- to coarse-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, lithic fragments, biotite. Lower contact sharp, gently undulating.
1202.5-1192.5	Sandstone: resistant ledge-former; yellowish gray (5Y 7/2) weathered; medium light gray (N 6.5) fresh; thick- to very thick-bedded (1 1/2-6 feet plus); normally graded from coarse- to medium-grained; rare mud ripups; a few pebbly layers; medium-grained overall; poorly sorted; slightly calcareous; subangular to subrounded quartz, feldspar, biotite, lithic fragments. Lower contact sharp, planar.
1192.5-1187.5	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones: medium dark gray (N 4) weathered and fresh; very thin- to thin-bedded (1-8 inches); weathers to chips 1/4 to 1/2 inch thick. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-2 inches with underlying sandstones. Sandstones: medium light gray (N 6) weathered; light gray (N 7) fresh; laminated to cross-laminated (3-4 per inch); fine-grained; moderately sorted;

Appendix C. (Continued)

Interval (feet)	Description
	non-calcareous; angular to subangular quartz, feldspar, biotite. Upper contacts gradational over 1-3 inches through siltstone to overlying mudstones; lower contacts sharp, planar to gently undulating.

Typical sequence: (in.)

f.	Sandstone	10
e.	Mudstone	2
d.	Sandstone	4
c.	Mudstone	6
b.	Sandstone	12
a.	Mudstone	6

Interval (feet)	Description
1187.5-1185.5	Covered by beach gravel presumably non-resistant mudstone.
1185.5-1125	Sandstone: resistant ridge-former; yellowish olive gray (5Y 6/2) weathered; medium gray (N 5.5) fresh; thick-bedded to very thick-bedded (2-15 feet plus); medium-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, muscovite, biotite, lithic fragments; upper four to six inches of each bed normally graded into mudstone. Lower bedding contacts sharp, planar to gently undulating. Lower unit contact sharp, gently undulating.
1125-1119	Interbedded mudstone-siltstone sequence: non-resistant: Mudstones: dark olive gray (5Y 4.5/1) weathered; medium gray (N 5) fresh; very thin- to thin-bedded (1-5 inches); weathers to chips 1/4 to 1/2 inch thick; rare pseudoconcretions two to five inches in diameter. Upper contacts sharp, planar to gently undulating; lower contacts gradational with underlying siltstones. Siltstones: brownish black (5YR 2/1) weathered; medium gray (N 5) fresh; very thin- to thin-bedded (1-2 inches). Upper contacts gradational with overlying mudstones; lower contacts sharp, planar to gently undulating.

Typical sequence: (in.)

d.	Siltstone	3
c.	Mudstone	4
b.	Siltstone	2
a.	Mudstone	1

Interval (feet)	Description
1119-1114.5	Sandstone: resistant rib-former; light olive gray (5Y 5/2) weathered; medium gray (N 5) fresh; laminated (approximately eight per inch) with rare pebbly layers; coarse-grained; poorly sorted; calcareous; subangular to subrounded quartz, feldspar, biotite, lithic fragments.

Contact: De Courcy Formation, Tongue 3 (K_{dc3}) and Cedar District Formation, Tongue 3 (K_{cd3}); sharp, planar.

Appendix C. (Continued)

Interval (feet)	Description
	Cedar District Formation, Tongue 3 (K_{cd3}) (Thickness = 70.5 feet).
1114.5-1091	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones: medium dark gray (N 4) weathered; medium gray (N 4.5) fresh; very thin- to thin-bedded (1-12 inches); weathers to chips 1/4 to 1/2 inch thick. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1/2 to 3 inches with underlying sandstones. Sandstones: medium gray (N 5) to moderate brown (5YR 4/4) weathered; medium bluish gray (5B 6/1) fresh; thin-bedded (2-8 inches); fine-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, feldspar, muscovite. Upper contacts gradational over 1/2-3 inches through siltstone to overlying mudstones; lower contacts sharp, planar to gently undulating. General overall decrease in percentage of sandstone towards top of interval.

Typical sequence:

	(in.)
h. Sandstone	3
g. Mudstone	4
f. Sandstone	4
e. Mudstone	12
d. Sandstone	4
c. Mudstone	12
b. Sandstone	3
a. Mudstone	5

1091-1067	Covered by gravel beach presumably non-resistant mudstone.
1067-1044	Interbedded mudstone-sandstone sequence as at 1114.5; increase in sandstone percentage towards top of interval.

Contact: Cedar District Formation, Tongue 3 (K_{cd3}) and De Courcy Formation, Tongue 2 (K_{dc2}); gradational over three inches with underlying sandstone.

De Courcy Formation, Tongue 2 (K_{dc2}) (Thickness = 16.5 feet).

1044-1041.5	Sandstone: resistant ledge-former; yellowish gray (5Y 7/2) weathered; olive gray (5Y 5/2) fresh; thinly laminated (12-15 per inch); parting lineation on bedding surfaces; soft sediment deformation folding in upper part of interval; medium-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, feldspar, muscovite, lithic fragments. Lower contact sharp, planar.
1041.5-1030	Interbedded mudstone-sandstone sequence as at 1114.5; lower contact sharp, gently undulating.
1030-1027.5	Sandstone: resistant ledge-former; yellowish olive gray (5Y 6/2) to medium gray (N 5) weathered; olive gray (5Y 5/1) fresh; thin-bedded (5-12 inches); parting lineation on bedding surfaces; medium-grained; moderately sorted; moderately calcareous; subangular to subrounded quartz, feldspar, biotite, lithic fragments.

Appendix C. (Continued)

Interval (feet)	Description

Contact: De Courcy Formation, Tongue 2 (K_{dc2}) and Cedar District Formation, Tongue 2 (K_{dc2}); sharp, gently undulating.

Cedar District Formation, Tongue 2 (K_{cd2}).

1027.5-831.5 Interbedded mudstone-sandstone sequence: non-resistant:

Mudstones: dark olive gray (5Y 3/1) weathered and fresh; thin- to thick-bedded (2-36 inches); rare pseudo-concretions; weathers to chips 1/4 to 1/2 inch thick. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-3 inches with underlying sandstones.

Sandstones: yellowish gray (5Y 7/2) to light olive gray (5Y 5/2) weathered; medium gray (N 5) to medium light gray (N 6) fresh; thin-bedded (2-24 inches); thinly laminated to thinly cross-laminated (15-20 per inch); very fine-grained; moderately sorted; slightly calcareous; subangular quartz, feldspar, muscovite. Rare soft sediment deformation folding. Upper contacts gradational over 1-3 inches through siltstone to overlying mudstones; lower contacts sharp, planar to gently undulating.

General overall increase in sandstone bed thickness upward in the interval with a corresponding decrease in mudstone bed thickness.

Typical sequence:	(in.)
h. Mudstone	5
g. Sandstone	8
f. Mudstone	4
e. Sandstone	9
d. Mudstone	7
c. Sandstone	6
b. Mudstone	7
a. Sandstone	4

831.5-432.5 Covered by gravel beach; presumably non-resistant mudstone.

432.5-382.5 Interbedded mudstone-sandstone sequence: non-resistant:

Mudstones: dark gray (N 3) weathered; light bluish gray (5B 6/1) fresh; laminated (2-4 per inch); weathers to chips 1/2 to one inch thick; contains rare calcareous mudstone concretions as irregular spheres, ellipsoids, or lenses 3-10 inches in length. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-5 inches to underlying sandstones.

Sandstones: olive gray (5Y 4.5/1) weathered; medium gray (N 5) fresh; thinly laminated to thinly cross-laminated (15-20 per inch); rare soft sediment deformation folding; very fine-grained; moderately sorted; calcareous; subangular quartz, feldspar, muscovite. Upper contacts gradational over 1-5 inches through siltstone to overlying mudstones; lower contacts sharp, planar to gently undulating.

Appendix C. (Continued)

Interval (feet)	Description
	Typical sequence: (in.) f. Mudstone . . . . 48 e. Sandstone . . . . 2 d. Mudstone . . . . 12 c. Sandstone . . . . 3 b. Mudstone . . . . 36 a. Sandstone 4
382.5-380	Sandstone: resistant rib-former; light yellowish olive gray (5Y 7/1) weathered; light olive gray (5Y 5.5/2) fresh; laminated (four per inch); groove casts and flute casts on bottom of bed; coarse-grained; well sorted; calcareous; subangular to subrounded quartz, feldspar, biotite, muscovite, lithic fragments. Lower contact sharp, gently undulating.
380-344.5	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones: olive gray (5Y 4.5/1) weathered; olive gray (5Y 3.2) fresh; thin- to thick-bedded (3-48 inches plus); contains abundant pseudo-concretions three to twelve inches in diameter arranged in layers parallel to bedding; weathers to chips 1.4 to 1/2 inch thick. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-4 inches to underlying sandstones. Sandstones: medium gray (N 5) to medium light gray (N 6) weathered; yellowish gray (5Y 6/2) fresh; laminated to cross-laminated (10-12 per inch); rare soft sediment deformation folding; very fine-grained; moderately sorted; non-calcareous; subangular quartz, feldspar, muscovite. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-4 inches to underlying sandstones. Typical sequence: (in.) h. Sandstone . . . . 7 g. Mudstone . . . . 48 f. Sandstone . . . . 12 e. Mudstone . . . . 6 d. Sandstone . . . . 5 c. Mudstone . . . . 4 b. Sandstone . . . . 4 a. Mudstone 24
344.5-74	Covered by gravel beach; presumably non-resistant mudstone.
74-73.5	Sandstone: resistant rib-former; olive gray (5Y 4.5/1) weathered; medium gray (N 5) fresh; thinly laminated to thinly cross-laminated (15-20 per inch); rare soft sediment deformation folding; very fine-grained; moderately sorted; calcareous; subangular quartz, feldspar, muscovite. Lower contact sharp, planar.
73.5-72	Mudstone: non-resistant; dark gray (N 3) weathered; light bluish gray (5B 6/1) fresh; laminated (2-4 per inch); contains numerous calcareous mudstone

Appendix C. (Continued

Interval (feet)	Description
	concretions as irregular spheres, ellipsoids, and lenses 3-10 inches in length; also contains limonitic (?) streaks and nodules 1/2 to five inches in diameter; weathers to chips 1/2 to one inch thick. Lower contact gradational over one inch to underlying sandstone.
72-71.5	Sandstone as at 73.5; lower contact sharp, planar.
71.5-68.5	Mudstone as at 72; lower contact gradational over two inches to underlying sandstone.
68.5-68	Sandstone as at 73.5; lower contact sharp, planar.
68-66.5	Mudstone as at 72; lower contact gradational over four inches to underlying conglomerate.
66.5-65	Conglomerate: resistant rib-former; light olive gray (5Y 5.5/1) to brownish black (5YR 2/1) in gross aspect; crudely banded 2-3 inches thick. Framework: very coarse sand to fine pebbles, fine pebbles predominant; grain-supported; angular to subangular mudstone chips, very fine-grained sandstone, quartz, chert, diorite. Sandstone matrix: very fine- to medium-grained; poorly sorted; angular to subangular quartz, feldspar, biotite. Lower contact sharp, gently undulating.
65-0	Interbedded mudstone-sandstone sequence as at 382.5 except for more abundant calcareous mudstone concretions.

Contact at E: within the Cedar District Formation, Tongue 2 (K_{cd2}); sharp, planar.

Initial point (E, Plate 1) is the top of the ridge-forming fine-grained sandstone approximately 2600 feet south-southeast of the end of the Medicine Beach access road, North Pender Island. Bearings from the initial point to the highest elevation on Mt. Norman, South Pender Island, and the Hay Point navigation light are N. 73° E. and S. 66° E., respectively. Attitude is N. 57° W., 49° N.E., proceed N. 33° E. upsection.

APPENDIX D

MEASURED SECTION G-H, NORTHUMBERLAND FORMATION AND GEOFFREY FORMATION

Section G-H, encompassing the Northumberland Formation and the lower Geoffrey Formation, forms the coastline of North Pender Island from 1/4 mile east of Clam Bay to the southwest side of Hope Bay. The section includes the zone of intertonguing between the Northumberland Formation and the Geoffrey Formation. The four tongues of the Northumberland Formation form the coastline from the initial point to the point on the north side of Colston Cove, Welcome Bay, and Hope Bay. The four Geoffrey Formation tongues form the unnamed resistant points between the coves. The section was measured to provide a detailed description of the Northumberland Formation and the Geoffrey Formation and their stratigraphic relationships.

Terminal point (H, Plate 1) is the base of the cliff at the southeast corner of Hope Bay, North Pender Island. Bearings from the terminal point to the high water line on the unnamed point on the north side of Hope Bay and the eastern end of the government dock at Hope Bay are N. 71° E. and S. 49° E., respectively.

Contact at H: Geoffrey Formation, Main Member (K_{g4}) and Northumberland Formation, Tongue 4 (K_{n4}); covered, arbitrarily selected where vegetation and sea cliffs make accurate section description impossible.

Interval (feet)	Description
	Northumberland Formation, Tongue 4 (K_{n4}) (Thickness = 127.5 feet).
1970.5-1930.5	Covered by gravel beach; presumably non-resistant mudstone.
1930.5-1925	Interbedded sandstone-siltstone sequence: non-resistant: Sandstones: yellowish gray (5Y 7/2) to light olive gray (5Y 5.5/2) weathered; light gray (N 7) fresh; thin-bedded; displays convolute soft sediment deformation folding; medium-grained; poorly sorted; calcareous; angular to sub-angular quartz, feldspar, biotite, abundant mud ripups 1-8 inches in length. Upper contacts gradational over 1-3 inches to overlying siltstones; lower contacts sharp, planar to loaded (1-4 inches relief). Siltstones: light gray (N 7) to light olive gray (5Y 5.5/1) weathered; olive gray (5Y 4.5/1) fresh; laminated to very thin-bedded (1/4 to 1 inch); weathers to chips 1/4 to 1/2 inch thick. Upper contacts sharp, planar to loaded (1-4 inches relief); lower contacts gradational over 1-3 inches to underlying sandstones.

Sequence:	(in.)
d. Sandstone	24
c. Siltstone	30
b. Sandstone	6
a. Siltstone	6

1925-1924	Sandstone: resistant rib-former; light gray (N 7) to light olive gray (5Y 5.5/1) weathered; olive gray (5Y 4.5/1) fresh; thin-bedded; medium-grained; poorly

Appendix D. (Continued)

Interval (feet)	Description
	sorted; calcareous; angular to subangular quartz, feldspar, biotite. Lower contact gradational over three inches to underlying siltstone.
1924-1920	Siltstone as at 1925; abundant wood and coaly fragments 1/16 to 1/4 inch long. Lower contact gradational over two inches with underlying sandstone.
1920-1919-5	Sandstone as at 1924; abundant platy mud ripups 1/8 to 1/2 inch in length; upper three inches of interval are laminated (8-10 per inch). Lower contact sharp, gently undulating.
1919.5-1918	Siltstone as at 1925. Lower contact gradational over two inches with underlying sandstone.
1918-1912	Sandstone: resistant ledge-former; medium light gray (N 6) to yellowish olive gray (5Y 7/1) weathered; light gray (N 7) fresh; thick-bedded; medium-grained; moderately sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, lithic fragments, rare mud ripups 1/4 to 3 inches in length.
1912-1843	Covered by gravel beach; presumably non-resistant mudstone.

Contact: Northumberland Formation, Tongue 4 (K_{n4}) and Geoffrey Formation, Tongue 3 (K_{g3}); covered.

Geoffrey Formation, Tongue 3 (K_{g3}) (Thickness = 100 feet).

1843-1743	Sandstone: resistant ridge-former; olive gray (5Y 4/2) to yellowish gray (5Y 7/2) weathered; yellowish gray (5Y 7/2) fresh; thick- to very thick-bedded (2-8 feet), upper 2-5 inches of each bed normally graded to mudstone; medium-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, feldspar, biotite, muscovite, lithic fragments, rare mud ripups 1/4 to 1 inch in length; rare pebbly layers; rare calcareous sandstone concretions exposed as resistant nodes 1-5 inches in diameter.

Contact: Geoffrey Formation, Tongue 3 (K_{g3}) and Northumberland Formation, Tongue 3 (K_{n3}); covered.

Northumberland Formation, Tongue 3 (K_{n3}) (Thickness = 120 feet).

1743-1623	Covered by gravel beach; presumably non-resistant mudstone.

Contact: Northumberland Formation, Tongue 3 (K_{n3}) and Geoffrey Formation, Tongue 2 (K_{g2}); covered.

Geoffrey Formation, Tongue 2 (K_{g2}) (Thickness = 105 feet).

1623-1518	Sandstone: resistant ridge-former; medium gray (N 5) to yellowish gray (5Y 7/2) weathered; light olive gray (5Y 5/1) fresh; thick- to very thick-bedded (2-15 feet

Appendix D. (Continued)

Interval (feet)	Description
	plus), upper 3-10 inches of each bed normally graded to mudstone; medium- to coarse-grained; moderately sorted; slightly calcareous; subangular to subrounded quartz, feldspar, biotite, lithic fragments, rare mud ripups 2-5 inches in length.

Contact: Geoffrey Formation, Tongue 2 (K_{g2}) and Northumberland Formation, Tongue 2 (K_{n2}); sharp, gently undulating.

Northumberland Formation, Tongue 2 (K_{n2}) (Thickness = 419.5 feet).

Interval (feet)	Description
1518-1517.5	Mudstone: non-resistant; medium dark gray (N 4) weathered; dark gray (N 3) fresh; thick-bedded; weathers to chips 1/4 to 3/4 inch thick. Lower contact gradational over two inches with underlying sandstone.
1517.5-1516.5	Sandstone: resistant rib-former; olive gray (5Y 5/1) weathered; light olive gray (5Y 7/1) fresh; thin-bedded; medium-grained; poorly sorted; calcareous; subangular to subrounded quartz, feldspar, biotite, lithic fragments. Lower contact sharp, gently undulating.
1516.5-1513.5	Mudstone as at 1517.5.
1513.5-1493.5	Covered by slope debris composed of medium-grained sandstone blocks 3-8 feet long.
1493.5-1440.5	Interbedded sandstone-siltstone sequence: non-resistant:

Sandstones: yellowish gray (5Y 6.5/2) weathered; medium light gray (N 6) fresh; thin-bedded (2-6 inches); very fine-grained; moderately sorted; calcareous; angular to subangular quartz, feldspar. Upper and lower contacts gradational over 1-4 inches into siltstone.

Siltstones: light gray (N 7) weathered; medium dark gray (N 4) fresh; laminated (8-12 per inch); weathers to small blocks 1-3 inches in length. Upper and lower contacts gradational over 1-4 inches into sandstone.

Typical sequence:	(in.)
j. Sandstone	4
i. Siltstone	8
h. Sandstone	3
g. Siltstone	4
f. Sandstone	2
e. Siltstone	18
d. Sandstone	3
c. Siltstone	24
b. Sandstone	4
a. Siltstone	24

Interval (feet)	Description
1440.5-1412.5	Covered by gravel beach.
1412.5-1408.5	Siltstone as at 1440.5.

Appendix D. (Continued)

Interval (feet)	Description
1408.5-1393.5	Covered by gravel beach.
1393.5-1328.5	Siltstone as at 1440.5; also contains rare limonitic (?) concretions 1/2 to 3 inches in length arranged parallel to bedding. Lower contact gradational over ten inches with underlying sandstone.
1328.5-1268.5	Interbedded sandstone-mudstone sequence: non-resistant: Mudstones: light gray (N 7) weathered; medium dark gray (N 4) fresh; laminated (8-10 per inch); weathers to chips 1/4 to 1/2 inch thick; contains rare limonitic (?) streaks 1/2 to 1 inch in length. Upper and lower contacts gradational over 1/2-4 inches into sandstone. Sandstones: yellowish gray (5Y 7/2) weathered; light olive gray (5Y 6/1) fresh; thin-bedded; very fine-grained; moderately sorted; calcareous; angular to subangular quartz, feldspar, biotite; displays abundant horizontal burrows on top bedding surfaces. Upper and lower contacts gradational over 1/2-4 inches through siltstone to mudstone.

Typical sequence:	(in.)
h. Sandstone	1
g. Mudstone	12
f. Sandstone	3
e. Mudstone	12
d. Sandstone	2
c. Mudstone	4
b. Sandstone	3
a. Mudstone	24

Interval (feet)	Description
1268.5-1266.5	Covered by beach gravel and shell debris.
1266.5-1263	Sandstone: resistant rib-former; light olive gray (5Y 6/1) weathered; light gray (N 6.5) fresh; laminated (2-4 per inch); medium-grained; poorly sorted; calcareous; angular to subangular quartz, feldspar, biotite, lithic fragments. Lower contact gradational over two inches with underlying mudstone.
1263-1243.5	Mudstone as at 1268.5.
1243.5-1138.5	Covered by beach gravel and shell debris; presumably non-resistant mudstone.
1138.5-1098.5	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones as at 1268.5. Upper and lower contacts gradational over 1-4 inches to sandstones. Sandstones: brownish gray (5YR 5/1) weathered; light olive gray (5Y 6/1) fresh; laminated (4-8 per inch); fine-grained; poorly sorted; non-calcareous; angular quartz, feldspar, muscovite. Upper and lower contacts gradational over 1-4 inches to mudstones.

Appendix D. (Continued)

Interval (feet)	Description
	Typical sequence: (in.) h. Sandstone . . . . 4 g. Mudstone . . . . 48 f. Sandstone . . . . 4 e. Mudstone . . . . 24 d. Sandstone . . . . 2 c. Mudstone . . . . 6 b. Sandstone . . . . 2 a. Mudstone 14

Contact: Northumberland Formation, Tongue 2 (K_{n2}) and Geoffrey Formation, Tongue 1 (K_{g1}); sharp, planar.

Geoffrey Formation, Tongue 1 (K_{g1}) (Thickness = 145 feet).

Interval (feet)	Description
1098.5-1088.5	Sandstone: resistant ledge-former; light gray (N 7) to light olive gray (5Y 5/1) weathered; light olive gray (5Y 6/1) fresh; thick-bedded (2-4 feet plus); medium-grained; moderately sorted; non-calcareous; subangular to subrounded quartz, feldspar, biotite, juscovite, lithic fragments.
1088.5-1087	Covered by slope debris composed of medium-grained sandstone blocks 1-4 feet in length.
1087-1084.5	Siltstone: non-resistant; brownish gray (5YR 3/1) weathered; light olive gray (5Y 6/1) fresh; laminated (6-10 per inch); poorly sorted.
1084.5-1080	Covered by slope debris composed of medium-grained sandstone blocks 1-4 feet in length.
1080-1002.5	Sandstone: resistant ridge-former; light gray (N 7) to medium gray (N 5) weathered; yellowish gray (5Y 6.5-2) fresh; thick- to very thick-bedded (3-5 feet plus); medium-grained; moderately sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, muscovite, lithic fragments; rare irregular limonitic (?) concretions one inch to two feet in length arranged parallel to bedding. Lower contact sharp, planar.
1002.5-967.5	Interbedded mudstone-sandstone sequence: moderately resistant: Mudstones: medium gray (N 4.5) weathered; dark gray (N 3) fresh; laminated (2-4 per inch); weathers to chips 1/2 to 1 inch thick. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 2-5 inches to underlying sandstones. Sandstones: light olive gray (5Y 5/1) weathered; olive gray (5Y 4/1) fresh; thick-bedded (2-4 feet); medium-grained; very poorly sorted; non-calcareous; angular to subrounded quartz, feldspar, biotite, lithic fragments. Upper contacts gradational over 2-5 inches through siltstone to overlying mudstones; lower contacts sharp, planar to gently undulating.

Appendix D. (Continued)

Interval (feet)	Description
	Typical sequence: (in.) f. Sandstone . . . . 24 e. Mudstone . . . . 18 d. Sandstone . . . . 20 c. Mudstone . . . . 44 b. Sandstone . . . . 16 a. Mudstone 38
967.5-953.5	Sandstone: resistant ledge-former; yellowish gray (5Y 7/2) weathered and fresh; thick- to very thick-bedded (3-5 feet plus), upper 5-8 inches of each bed normally graded to mudstone; medium-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, muscovite, lithic fragments.

Contact: Geoffrey Formation, Tongue 1 (K_{g1}) and Northumberland Formation, Main Member (K_{n1}); sharp, gently undulating.

Northumberland Formation, Main Member (K_{n1}) (Minimum thickness = 953.5 feet).

Interval (feet)	Description
953.5-953	Sandstone: resistant rib-former; yellowish orange (10YR 7/6) weathered; light bluish gray (5B 7/1) fresh; thin-bedded; coarse-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, muscovite, lithic fragments. Lower contact gradational over four inches to underlying siltstone.
953-952	Siltstone: non-resistant; yellowish gray (5Y 8/1) to grayish yellow-green (5GY 7/2) weathered; olive gray (5Y 4/1) fresh; thin-bedded; weathers as chips 1-2 inches thick. Lower contact gradational over two inches to underlying sandstone.
952-951	Sandstone: resistant rib-former; grayish dusky yellow (5Y 7/4) weathered; medium gray (N 5.5) fresh; thin-bedded; coarse-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, muscovite, lithic fragments. Lower contact sharp, gently undulating.
951-949.5	Mudstone: non-resistant; medium dark gray (N 4) weathered; olive black (5Y 2/1) fresh; laminated (3-4 per inch); rare calcareous mudstone concretions occur as irregular ellipsoids and lenses 2-6 inches in length arranged parallel to bedding; rare bands of limonitic (?) staining 1/2 to 3/8 inch thick parallel to bedding; weathers to chips 1/4 to 1/2 inch thick. Lower contact sharp, gently undulating.
949.5-949	Sandstone: resistant rib-former; grayish orange (10YR 7/4) weathered; light olive gray (5Y 6/1) fresh; thin-bedded; coarse-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, muscovite, lithic fragments. Lower contact sharp, gently undulating.
949-948	Sandstone: resistant rib-former; light olive gray (5Y 6/1) weathered; olive gray (5Y 4/1) fresh; thinly laminated (15-20 per inch); very fine-grained; moderately

Appendix D. (Continued)

Interval (feet)	Description
	sorted; non-calcareous; subangular to subrounded quartz, feldspar, muscovite, biotite. Lower contact gradational over three inches to underlying siltstone.
948-945	Siltstone: non-resistant; moderate yellowish brown (10YR 5/4) to grayish black (N 2) weathered; dark greenish gray (5GY 4.5/1) fresh; very thin-bedded (1/2 to 1 inch); poorly sorted; non-calcareous. Lower contact gradational over two inches to underlying sandstone.
945-943	Sandstone: resistant rib-former; light gray (N 7) to light olive gray (5Y 6/1) weathered; medium light gray (N 6) fresh; faintly thinly laminated to laminated (10-15 per inch); fine-grained; moderately sorted; non-calcareous, subangular quartz, feldspar. Lower contact sharp, gently undulating.
943-631	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones as at 949.5; limonitic (?) bands more abundant near calcareous mudstone concretions. Upper contacts gradational over 1-5 inches to sharp, gently undulating; lower contacts gradational over 1-5 inches to underlying sandstones. Sandstones: light olive gray (5Y 5/2) weathered; medium gray (N 5) fresh; laminated to cross-laminated (8-10 per inch), bedding becomes highly contorted and convolute in the upper part of the interval; fine- to medium-grained; moderately sorted; calcareous; subangular to subrounded quartz, feldspar, biotite, muscovite. Upper contacts gradational over 1-5 inches through siltstone to overlying mudstones; lower contacts gradational over 1-5 inches to sharp, gently undulating. General overall decrease in sandstone percentage and bed thickness upward in interval.

Typical sequence:	(in.)
h. Sandstone	2
g. Mudstone	4
f. Sandstone	2
d. Mudstone	84
d. Sandstone	6
c. Mudstone	33
b. Sandstone	2
a. Mudstone	5

Interval (feet)	Description
631-352.5	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones as at 949.5; display rare pseudo-concretions (concentrically weathering mudstone concretions, lithologically similar to enclosing unit). Upper contacts sharp, gently undulating; lower contacts gradational over 1-4 inches with underlying sandstones. Sandstones: light olive gray (5Y 5/2) weathered; medium light gray (N 6) fresh; thinly laminated to thinly cross-laminated (10-15 per inch); rare well-developed soft sediment deformation folding; top bedding surfaces display moderately abundant horizontal burrows; very fine- to fine-grained; moderately

Appendix D. (Continued)

Interval (feet)	Description
	sorted; calcareous; subangular to subrounded quartz, feldspar, biotite. Upper contacts gradational over 1-4 inches through siltstone to overlying mudstones; lower contacts sharp, gently undulating.

Typical sequence:	(in.)
j. Mudstone	35
i. Sandstone	5
h. Mudstone	8
g. Sandstone	2
f. Mudstone	60
e. Sandstone	3
d. Mudstone	25
c. Sandstone	12
b. Mudstone	30
a. Sandstone	12

352.5-0 Interbedded mudstone-sandstone sequence: non-resistant:

Mudstones as at 949.5. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-4 inches to underlying sandstones.

Sandstones: yellowish gray (5Y 7/2) weathered; medium gray (N 5) fresh; thinly laminated to thinly cross-laminated (8-15 per inch); fine-grained; moderately sorted; calcareous; subangular to subrounded quartz, feldspar, muscovite. Upper contacts gradational over 1-4 inches through siltstone to overlying mudstones; lower contacts sharp, planar to gently undulating.

General overall increase in thickness of sandstone beds and grain size of sandstones (to medium-grained) upward in interval.

Typical sequence:	(in.)
j. Mudstone	140
i. Sandstone	9
h. Mudstone	36
g. Sandstone	5
f. Mudstone	48
e. Sandstone	2
d. Mudstone	48
c. Sandstone	12
b. Mudstone	108
a. Sandstone	4

Contact at G: sharp, planar with underlying mudstone. Contact is within the Northumberland Formation.

Initial point (G, Plate 1) is located on the north shore of North Pender Island in the N.W. 1/4, S.W. 1/4, N.E. 1/4, Section 22, at the water level on a low tide of 3.6 feet. Bearing from the initial point to the waterline on the point on the west side of Clam Bay is N. 72° W. Attitude is N. 74° W., 47° S.W.; proceed S. 16° W. upsection.

APPENDIX E

MEASURED SECTION I-J, SPRAY FORMATION

Section I-J, encompassing the lower Spray Formation, forms the shoreline from the north side to the south side of Otter Bay, North Pender Island. The section was measured to provide a detailed description of the Spray Formation and its stratigraphic relationship with the underlying Geoffrey Formation.

Terminal point (J, Plate 1) is approximately 300 feet due east of the Roesland Resort boat dock, Otter Bay, North Pender Island. Bearing from the terminal point to the B.C. Ferries dock is N. 46° W.

Contact at J: within the Spray Formation where a fault interrupts the stratigraphic sequence.

Interval (feet)	Description
797-749.5	Mudstone: non-resistant; brownish black (5YR 2/1) weathered and fresh; thin-bedded; weathers to chips 1/4 to 1 inch thick. Lower contact sharp, planar.
749.5-747	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones as at 749.5. Upper contacts sharp, planar to gently undulating; lower contacts gradational over 1-3 inches to underlying sandstones. Sandstones: olive gray (5Y 5/1) weathered; medium dark gray (N 4) fresh; thin-bedded; medium-grained; poorly sorted; non-calcareous; angular to sub-angular quartz, feldspar, muscovite. Upper contacts gradational over 1-3 inches through siltstone to overlying mudstones; lower contacts sharp, planar to gently undulating.

Sequence:	(in.)
f. Sandstone	4
e. Mudstone	3
d. Sandstone	4
c. Mudstone	9
b. Sandstone	4
a. Mudstone	6

Interval (feet)	Description
747-742	Mudstone as at 749.5.
742-712	Interbedded mudstone-sandstone sequence: non-resistant: Mudstones as at 749.5. Upper and lower bedding contacts sharp, planar. Sandstones as at 750. Upper and lower bedding contacts sharp, planar.

Sequence:	(in.)
h. Sandstone	8
g. Mudstone	60
f. Sandstone	4
e. Mudstone	102
d. Sandstone	24

Appendix E. (Continued)

Interval (feet)	Description
	c. Mudstone . . . . 54 b. Sandstone . . . . 6 a. Mudstone 102
712-474	Covered by gravel beach; presumably non-resistant mudstone.
474-429	Sandstone: resistant ledge-former; medium bluish gray (5B 5/1) weathered; light olive gray (5Y 5/1) fresh; very thick-bedded; becoming thin-bedded (3-5 inches) at top of interval; fine- to medium-grained; poorly sorted; non-calcareous; subangular to sub-rounded quartz, feldspar, biotite, lithic fragments.
429-279.5	Covered by gravel beach; presumably non-resistant mudstone.
279.5-274.5	Sandstone: resistant ledge-former; medium dark gray (N 3) weathered; medium gray (N 5) fresh; thin-bedded at bottom of interval, becoming laminated (8-10 per inch) at top; very coarse-grained, upper two feet of interval grade normally to fine-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, lithic fragments.
274.5-265.5	Covered by beach gravel; presumably non-resistant mudstone.
265.5-261.5	Sandstone: resistant rib-former; olive gray (5Y 5/1) weathered; dark yellowish brown (10YR 4/2) fresh; thin-bedded; very coarse-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, biotite, abundant lithic fragments. Lower contact sharp, planar to gently undulating.
261.5-261	Mudstone: non-resistant; olive gray (5Y 4/1) weathered; dark gray (N 3) fresh; thin-bedded; weathers to chips 1/2 to 1 inch thick.
261-257.5	Covered by beach gravel and shell debris; presumably non-resistant mudstone.
257.5-255.5	Sandstone as at 261.5; fine pebbly channels 4-8 inches across and 1-3 inches deep in upper eight inches of interval.
255.5-253	Covered by beach gravel and shell debris; presumably non-resistant mudstone.
253-251	Sandstone: resistant rib-former; light olive gray (5Y 6/1) weathered; bluish gray (5B 6/1) fresh; very thin-bedded; fine-grained; moderately sorted; non-calcareous; subangular quartz, feldspar, biotite.
251-249	Covered by beach gravel and shell debris; presumably non-resistant mudstone.
249-220	Sandstone: resistant ridge-former; light olive gray (5Y 6/1) weathered; grayish olive (10Y 4/2) fresh; thick- to very thick-bedded (3-10 feet plus); coarse-grained, normally graded in upper six feet to fine-grained; poorly sorted; non-calcareous; angular to subangular quartz, feldspar, abundant mudstone, siltstone, and fine-grained sandstone ripups 1-30 inches in length, subangular to subrounded.

Appendix E. (Continued)

Interval (feet)	Description
220-86	Covered by gravel beach; presumably non-resistant mudstone.
86-31	Mudstone: non-resistant: very light gray (N 8) weathered; olive gray (5Y 4/1) fresh; highly sheared and fractured, no bedding visible; contains subrounded 2-8 inch diameter clasts of very fine-grained sandstone; rare limonithic (?) patches up to three inches in diameter.
31-0	Covered by gravel beach; presumably non-resistant mudstone.

Contact at I: covered by gravel beach; upper surface of underlying Geoffrey Formation sandstone is sharp and essentially planar.

Initial point (I, Plate 1) is located on the north shore of Otter Bay, North Pender Island, at the base of the prominent sandstone dip slope which forms the north side of the bay. Bearing from the initial point to the waterline on Roe Point is S. 78° W. Attitude is N. 61° W., 29° S.W.; proceed S. 29° W. upsection.

APPENDIX F

MODAL ANALYSES OF SANDSTONE SAMPLES

Sample / Mineralogy	Kcp			Kcd		Kdc			Kn	Kg			Ks
	JPH-10	JPH-66	JPH-68	JPH-11	JPH-57	JPH-17	JPH-49	JPH-64	JPH-40	JPH-36	JPH-45	JPH-Kg	JPH-52
Framework	64.9	59.7	86.5	76.1	87.9	88.5	87.7	89.3	81.5	83.9	88.2	84.2	88.5
Matrix	2.7	9.3	11.8	23.2	5.3	10.7	11.8	10.0	13.3	14.8	11.8	13.8	11.5
Cement	31.6	17.8	1.7	T	6.0	--	--	--	3.5	1.3	--	--	--
Fe alteration	0.8	13.2	--	0.7	0.8	0.8	0.5	0.7	1.7	--	T	2.0	T
Stable grains													
quartz	10.3	12.6	28.1	16.6	34.3	37.6	40.1	38.1	31.9	27.6	12.3	21.8	25.3
poly-x quartz	8.5	7.3	3.3	2.4	3.8	2.6	4.6	4.3	2.2	2.6	1.9	2.4	2.8
chert	23.1	19.5	5.2	11.2	6.6	4.5	4.0	7.8	5.5	3.4	6.6	4.5	12.8
Feldspars													
plagioclase	4.9	9.2	31.4	17.6	25.0	31.8	17.3	16.0	27.4	35.8	27.9	30.3	21.9
K-spar	T	2.2	17.3	2.2	9.1	7.2	12.2	11.6	2.9	12.3	13.3	9.5	8.7
Rock fragments													
sedimentary	7.7	2.8	T	3.7	1.1	0.7	1.5	2.2	1.6	--	0.6	T	2.5
volcanic	24.4	31.8	6.9	16.5	7.6	3.4	6.1	7.6	13.9	3.4	21.8	14.5	8.1
plutonic	6.4	0.6	1.3	T	1.7	0.8	1.3	0.6	0.5	T	1.1	0.9	2.3
metamorphic	0.5	T	T	1.1	1.1	0.9	1.5	1.9	1.2	1.4	0.9	--	1.1
Mica	--	T	2.9	0.9	2.7	6.6	7.8	4.7	6.1	9.1	6.3	12.7	7.8
Chlorite	12.3	10.6	1.5	23.9	4.4	2.8	2.5	3.5	3.9	2.2	6.1	2.4	6.2
Porosity	0.5	0.6	0.6	1.1	--	--	--	0.6	1.8	1.8	T	T	--
Others	1.3	2.2	0.6	2.4	2.6	1.1	1.1	1.1	1.0	T	0.9	T	T

APPENDIX G

PEBBLE COUNT LITHOLOGIES AND CLAY MINERALOGIES

Sample / Lithology	Extension-Protection JPH-PC-1	De Courcy JPH-PC-2	Geoffrey JPH-PC-3
Chert	12	18	21
Quartzite	-	6	12
Vein Quartz	-	3	4
Granitic	7	12	9
Andesite	28	31	21
Basalt	23	14	19
Greenstone	5	2	1
Foliated Metamorphic	2	1	1
Diorite	6	10	7
Sandstone	14	1	-
Rhyolite	3	3	5

Pebble Count Lithologies

Sample / Mineralogy	Cedar District	Northumberland	Spray
Chlorite	xx	xx	xx
Vermiculite	x	x	xx
Mica	x	x	x
Montmorillo-nite	-	x	-
Kaolinite	?	?	?

Clay Mineralogies

x = present; xx = common; ? = questionable occurrence

APPENDIX H

ANALYTICAL TECHNIQUES

X-ray Diffraction of Mudstones

Samples of mudstone from the Cedar District, Northumberland, and Spray Formations were prepared utilizing the following procedure:

Samples were crushed using a ceramic mortar and pestle and sieved through a 200 mesh sieve. Organic matter was removed by treating with hydrogen peroxide. Calcium carbonate was removed by treating with 0. 1 normal hydrochloric acid. The samples were then agitated with a rotary stirrer in a 2% solution of sodium carbonate for 15 minutes. The samples were boiled for five minutes and then centrifuged at high speed. The residue was rinsed and centrifuged three times with a 2% solution of sodium carbonate. A dispersing solution (Calgon) was added to the residue, which was then agitated for 15 minutes in a rotary stirrer. The sample was then placed in a beaker and allowed to settle for five hours. The dispersed sample was then transferred by pipette to a glass slide and dried at room temperature.

The mudstone samples were analyzed with the use of a Norelco X-ray diffractometer. Samples were scanned four times over a range of 3-30° 2θ. Treatments for each scan were as follows: 1) untreated, air dried; 2) ethylene glycolated for 24 hours; 3) heated to 400° Centigrade for 45 minutes; and 4) heated to 600° Centigrade for

45 minutes. Instrument settings were as follows:

Radiation:	Copper (Cu) ka (broad focus)
KV:	35
MA:	35
Filter:	Nickel

Rate Meter Settings

Multiplier:	1.0×10^3
Time Constant:	2.0 seconds
Scan rate:	2° 2θ/minute

Pyrite-Marcasite Determination by X-ray Diffraction

Limonite-stained concretions from the Cedar District, Northumberland, and Spray Formations were crushed using a ceramic mortar and pestle and screened through a 200 mesh sieve. This powder was packed in a powder pack tray and scanned from $25\text{-}60^{\circ}$ 2θ using a Norelco X-ray diffractometer. Instrument settings were the same as those for the analysis of the mudstones. Six peaks with d-spacings similar to those of pyrite (ASTM file card number 6-0710) and six peaks with d-spacings similar to those of marcasite (ASTM file card number 3-0799) were noted. Neither component appeared to be dominant. The sample was therefore identified as pyrite-marcasite.