AN ABSTRACT OF THE THESIS OF

Charles David Sturdavant for the degree MASTER OF SCIENCE
(Name) (Degree)

in GEOLOGY presented on June 2, 1975
(Major Department) (Date)

Title: SEDIMENTARY ENVIRONMENTS AND STRUCTURE OF THE CRETACEOUS ROCKS OF SATURNA AND TUMBO ISLANDS, BRITISH COLUMBIA

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Seven formations of the Upper Cretaceous Nanaimo Group sedimentary rocks are exposed on Saturna and Tumbo Islands. These formations are, from oldest to youngest, the Extension-Protection, Cedar District, DeCourcy, Northumberland, Geoffrey, Spray, and Gabriola. The rocks represent four successive cycles of deltaic sedimentation, the oldest and the youngest of which are incompletely exposed in the thesis area. A composite section of maximum thickness for the formations exposed on Saturna and Tumbo Islands is 9,776 feet; however, the formations vary significantly in thickness along strike.

The Extension-Protection Formation, consisting of conglomerates and lithic wackes, represents the upper part of a delta complex. The lower part of the cycle is not exposed in the thesis area. The

conglomerates are interpreted as having been deposited in the bed load and point bar subenvironments of highly competent streams. The sandstones overlying the conglomerates are interpreted as marine topset sands.

The Cedar District Formation, the lower part of the Cedar District-DeCourcy deltaic cycle, overlies the Extension-Protection Formation with an angular discordance of about 5°. The Cedar District Formation consists of repetitively interbedded and normally graded sandstones, siltstones, and mudstones, which were probably deposited as turbidites. The Cedar District strata are interpreted as delta-slope deposits.

Conformably overlying and intertonguing with the Cedar District Formation are the channel-mouth bar arkosic and lithic wackes of the DeCourcy Formation. Distributary channel conglomerates overlie the marine sandstones which are in turn overlain by marine channel-mouth bar sandstones. Paleocurrent data indicate that the Cedar District-DeCourcy deltaic complex prograded in an east-southeasterly direction.

The Northumberland Formation, the lower part of the Northumberland-Geoffrey deltaic cycle, conconformably overlies the DeCourcy Formation. Most of the Northumberland Formation was deposited as prodelta mudstones. However, the lower and upper parts of the formation were deposited in delta-slope environments, indicating a transition from and to the marine sandstones of the DeCourcy and Geoffrey Formations, respectively. The Geoffrey Formation intertongues with the Northumberland Formation and consists almost entirely of channel-mouth bar sandstones with local distributary channel conglomerates. The source of the sediments for the Northumberland-Geoffrey deltaic cycle was to the west or northwest. Paleocurrent data indicate that the sandstones of the Geoffrey Formation were distributed in a north to south direction around the mouths of distributary channels by longshore currents.

Overlying and intertonguing with the Geoffrey Formation is the predominantly mudstone Spray Formation, most of which is not exposed in the thesis area. The Spray Formation was deposited as turbidites and/or seasonal flood deposits in a delta-slope environment.

Overlying and intertonguing with the Spray Formation is the Gabriola Formation, the youngest formation exposed in the thesis area. The Gabriola Formation consists of bed load and point bar fluvial conglomerates, marine channel-mouth bar arkosic and lithic arenites, and topset conglomerates. Lithologies of the sandstones, pebble counts of the conglomerates, and sedimentary structures indicate a paleocurrent dispersal direction to the east or northeast for the Spray-Gabriola deltaic cycle.

At least two major episodes of structural deformation have been recorded on Saturna Island. The first episode of structural deformations resulted in a series of north-south trending faults. The second episode of structural deformation resulted in a series of east-west trending faults and related folds (the Kulleet Syncline).

Sedimentary Environments and Structure of the Cretaceous
Rocks of Saturna and Tumbo Islands,
British Columbia

by

Charles David Sturdavant

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1976

APPROVED:

Redacted for privacy

Professor of Geology

in charge of major

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Date thesis is presented June 2, 1975

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ACKNOWLEDGMENTS

I thank Dr. Keith F. Oles for his guidance and help in the completion of this thesis, Mr. Dana Braislin and Union Oil Company of California for financial assistance and field visitations, and Dr. J. G. Johnson for critically reading the manuscript. I also thank Dr. Alan R. Niem for taking such an active interest in my education and for being more of a friend than a professor. The suggestions and comments of all of these men were instrumental in the completion of this manuscript.

This thesis could not have been completed without the encouragement, field assistance, and typing ability of my loving and devoted wife, Theresa.

I further thank all the wonderful people of Saturna Island, especially the Vincents and the McDonalds.

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INTRODUCTION

Purposes and Methods of Investigation

Saturna and Tumbo Islands, two of the Gulf Islands of Canada, are located in southwestern British Columbia (Figure 1). The bedrock of the islands is composed of Cretaceous Nanaimo Group sandstones, mudstones and conglomerates. The sedimentary rocks lie unconformably over the Karmutsen volcanic rocks and Sicker Group granitic rocks on Vancouver and Saltspring Islands.

The purposes of this project were to compile a geologic map of the bedrock, to study the stratigraphic sequence, structure, and sedimentary petrology in detail, to determine the depositional paleoenvironments and paleocurrent dispersal patterns, and to interpret possible source areas for the Cretaceous rocks of Saturna and Tumbo Islands.

Field work was conducted between June 16, 1974 and August 25, 1974. The base map (scale 1 inch = 1/4 mile) and aerial photographs (scale 1 inch = 1/4 mile) were obtained from the Surveys and Mapping Branch of the British Columbia Department of Lands, Forests, and Water Resources. Field observations were plotted on the map with the aid of the aerial photographs.

Collection of field data was accomplished with the aid of a 20x hand lens, a Rock-Color Chart of the Geological Society of America (1963), a Brunton compass, a sand gauge based on the Wentworth size scale, and dilute hydrochloric acid. Stratigraphic terms from McKee and Weir (1953), the sorting terms of Folk (1968), and rounding terms from Powers (1953) were used in describing the rocks. Sections were measured with a Jacob's staff and Abney level, a 50-foot tape measure, and a rope where impassible cliffs were encountered.

Paleocurrent measurements were obtained from festoon troughs, planar foresets, drag marks, parting lineations, and flute casts. All measurements were recorded and the strata were rotated to horizontal via a FORTRAN computer program developed at the University of Rhode Island and modified by Dr. Alan R. Niem and Ken Spitze of Oregon State University (1974). The data were then plotted on rosette diagrams, and grand means were calculated to illustrate the general paleocurrent flow directions.

Pebble counts were conducted on the conglomerates in two of the coarse-grained formations. Clast lithologies were determined with the aid of a stereoscopic binocular microscope, and the pebble counts were then tabulated (Appendix E). A total of 30 petrographic thin sections were cut and examined microscopically. Point counts were performed on 13 slides and the results were tabulated (Appendix D).

The sandstones were classified using the Gilbert method (Williams, Turner, and Gilbert, 1954). The argillaceous limestones were classified according to Folk's (1959) classification.

Location and Accessibility

Saturna and Tumbo Islands are the southeasternmost islands of the British Columbia Gulf Island chain (Figure 1). The islands are located approximately 30 miles west of Bellingham, Washington, on an east-west line between Bellingham and Fulford Harbor, British Columbia. They straddle 48° 46' N. latitude, and 123° 8' W. longitude. The islands cover approximately 15 square miles.

Saturna Island can be reached by ferries from either Swartz Bay on Vancouver Island or Tsawwassen on the mainland. Because Tumbo Island is so small (about 1/4 square mile) it must be reached via private boat.

Saturna Island has a network of roads, most of which are gravel surfaced, connecting most parts of the island. Logging roads are extensive and they provide some important road cuts within the interior parts of the island. The entire southern coastline was accessible only by descending the 800-foot thick DeCourcy Sandstone sea cliffs of Brown Range, or by boat.

Much of the interior of Saturna and Tumbo Islands is covered by dense vegetation, but mountains with cliffs do provide some exposures of the more resistant units. Most of the data, however, were accumulated along the coastlines of the two islands.

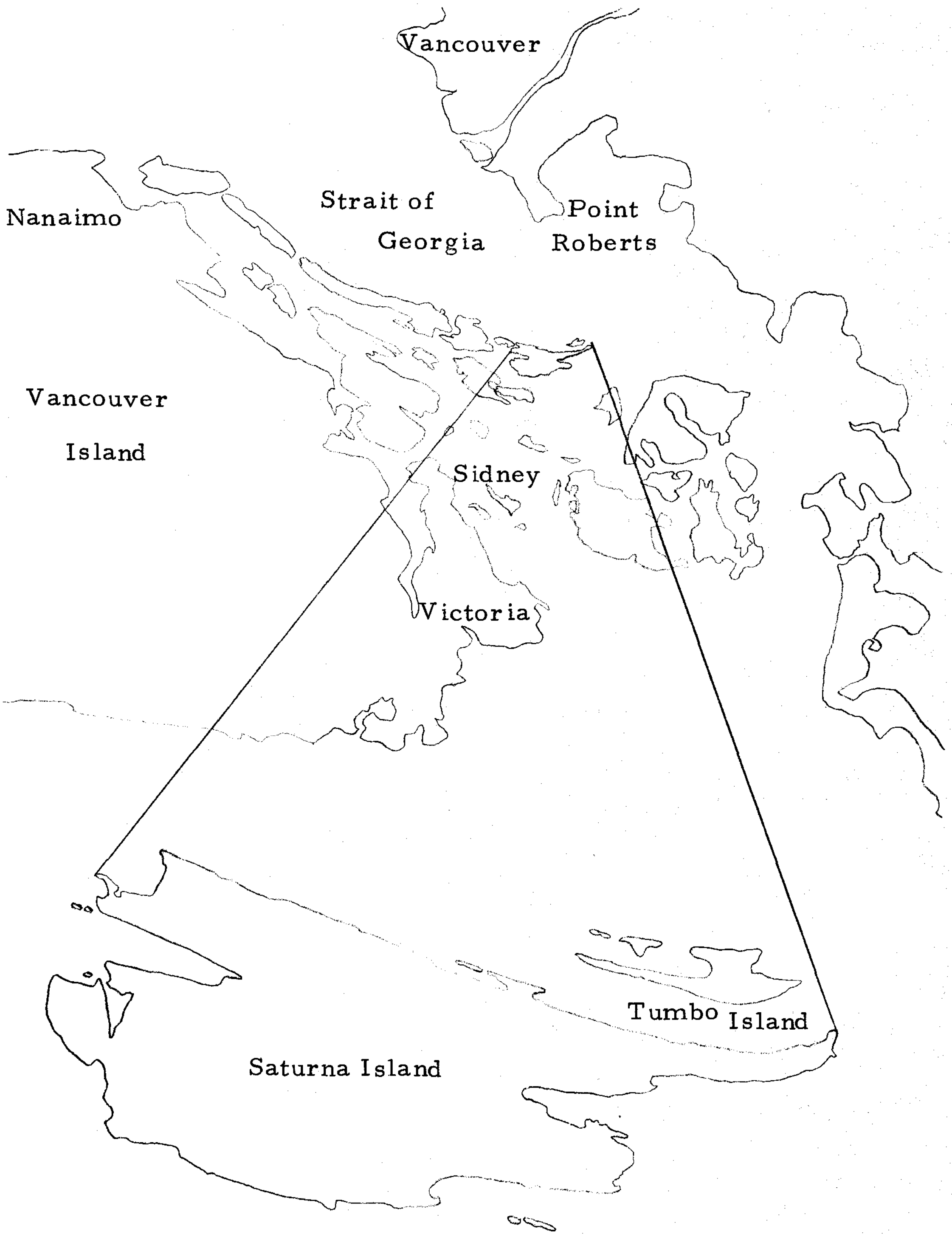


Figure 1. Index map of thesis area.

STRATIGRAPHY

Previous Work

The discovery of coal in the Nanaimo and adjacent areas on Vancouver Island first prompted interest in the Nanaimo Basin, attracting both geologists and paleontologists. Dr. W.F. Tolmie was the first to discover the existence of coal in the Suquash area, on the northeastern part of Vancouver Island, in 1835. Exploration for coal in the Suquash area was accomplished during the years 1849-1853, but no notable discoveries were made. In 1850, J.W. McKay, of the Hudson's Bay Company, discovered coal in the Nanaimo area and attention was focused there (Dawson, 1890). Production began in 1852 and by 1915 the area had produced over 25,000,000 tons of coal (Clapp and Cooke, 1917).

The first geologic work in the Nanaimo area was accomplished by J.S. Newberry (1857). In the course of Lieutenant Williamson's northern California and Oregon exploratory expedition Newberry collected fossils, including some new species, which he dated as Cretaceous in age. This was the first attempt at dating the rocks of the Gulf Island and Vancouver Island area. J. Hector (1861) published his work of a reconnaisance survey from Lake Superior to the Pacific Ocean. In his report he described the rock outcrops at Nanaimo, and he furnished a geologic sketch map of the area showing the locality and the extent of the coal seams. He listed several fossils that were collected at Nanaimo, and he verified the Cretaceous age first reported by Newberry (1857).

James Richardson (1872, 1878) conducted the first extensive geologic investigation of the Vancouver Island coal areas. His work laid the foundation for later, more detailed studies. He was the first to distinguish between the three basins of deposition: the Nanaimo, the Comox, and the Cowichan Basins. He established the structure of the area and was the first to delineate the stratigraphy, designating the various stratigraphic units which later were named as formations.

G.M. Dawson (1890) proposed the name "Nanaimo Group" for the strata of the area around Nanaimo.

Clapp (1911, 1912, 1914) conducted extensive geologic work on the southeast coast of Vancouver Island. He compiled geologic maps of the area, cross sections, and detailed measured and described sections. He was the first to establish formal names for the various formations within the Nanaimo Group.

MacKenzie (1922) studied the adjacent Comox Basin. Williams (1924) established names for Richardson's stratigraphic subdivisions. Usher (1949, 1952) made a detailed study of the Late Cretaceous ammonite faunas of Vancouver Island and vicinity. In the course of his study, he developed the biostratigraphy of the Nanaimo Group. Bell (1957), a palynologist, studied the various plant fossils of the area and drew some general conclusions on the age of the sedimentary rocks. McGugan (1964) studied the foraminifera of the mudstones of Vancouver Island and his biochronologic correlations showed that the coal seams of the Comox and Nanaimo Basins were not formed at the same time.

Muller and Jeletsky (1970) modified and standardized the names of the stratigraphic units of the Nanaimo Basin and the adjacent Comox Basin, determining that the formations in the two basins are correlative because of the facies and time relationships that exist. They published a geologic map of Vancouver Island and vicinity to a reconnaissance scale of 1:250,000.

The most recent detailed stratigraphic and paleoenvironmental studies of the Nanaimo Group have been accomplished by students from the Department of Geology at Oregon State University. Packard (1972) studied the depositional paleoenvironments of the Cretaceous rocks of Gabriola Island. Rinne (1973) examined the geology of the Duke Point-Kulleet Bay area on the east shore of Vancouver Island. Simmons (1973) investigated the stratigraphy and depositional paleoenvironments of Thetis and Kuper Islands. Hudson (1974) analyzed the stratigraphy and paleoenvironments of North and South Pender Islands, two miles west of Saturna Island. Hanson (1975) is currently completing a doctoral thesis on the structure, stratigraphy, and paleoenvironments of the Cretaceous rocks of Saltspring Island.

Regional Stratigraphy

The basement complex of Vancouver and Saltspring Islands, consisting of the Sicker Group, the Vancouver Group, and the Island Intrusions, is unconformably overlain by the Nanaimo Group sedimentary rocks. The Pennsylvanian to Permian Sicker Group consists of three parts: a lower member containing greenstones and greenschist derived from andesitic pyroclastic rocks; a middle member composed of metamorphosed graywacke sandstones, argillites, and conglomerates; and an upper member, called the Buttle Lake Formation, consisting of metamorphosed limestone with local chert. The total thickness of the Sicker group is about 13,000 feet (Muller and Carson, 1969).

Overlying the Sicker Group is the Triassic and Early Jurassic Vancouver Group, which is divided into the Karmutsen Formation, the Quatsino Formation, and the Bonanza Subgroup. The Karmutsen Formation is composed of low-grade metamorphosed pillow basalts, pillow breccias, and basalt flows, and the formation ranges in thickness from 7,000 to 20,000 feet. The Quatsino Formation consists of metamorphosed limestones and ranges in thickness from 500 to 2,000 feet. The Bonanza Subgroup contains metamorphosed limestones, argillites, and andesitic pyroclastic rocks, and ranges in thickness from 2,000 to 3,000 feet (Muller and Carson, 1969).

The Island Intrusions, composed of granodioritic to quartz monzonitic rocks, have intruded both the Sicker Group and the Vancouver Group. Potassium-argon dates suggest the Island Intrusion were emplaced in Middle Jurassic time (Muller and Carson, 1969).

Overlying these older rocks with angular unconformity are the sedimentary rocks of the Cretaceous Nanaimo Group. The most comprehensive study of these sedimentary rocks was published by Muller and Jeletsky (1970). In their study, they divided the group into nine formations which comprise five successive transgressive-regressive cycles, the last of which is incomplete. The formations and cycles are as follows:

<u>Fifth Cycle</u> (incomplete)

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

disconformity

<u>Fourth Cycle</u>

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

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

disconformity

Third Cycle

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

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

disconformity

Second Cycle

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

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

disconformity

First Cycle

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

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

Areal Stratigraphy

Seven formations of the Nanaimo Group are exposed on Saturna and Tumbo Islands. From oldest to youngest these formations are the Extension-Protection, Cedar District, DeCourcy, Northumberland, Geoffrey, Spray, and Gabriola. These units represent the second through the fifth sedimentary cycles as described by Muller and Jeletsky (1970).

When interpreted according to modern concepts of deltaic sedimentation, the stratigraphy of the formations exposed on Saturna and Tumbo Islands represents four cycles of deltaic progradation, but the lowermost cycle is incompletely exposed. Thickness variations, lateral facies changes, intertonguing, cyclic sedimentation, upward coarsening of grain size in each cycle, sedimentary structures, and the similarity of these rocks to those of ancient and modern delta systems all suggest that these Cretaceous formations were deposited in a deltaic environment.

Extension-Protection Formation

Nomenclature. Clapp (1912) named several formations within the coal measures of the Nanaimo area. The sequence, from oldest to youngest, is the East Wellington Formation, the Wellington Seam, the Extension Formation, the Cranberry Formation, the Newcastle Seam, the Newcastle Formation, the Douglas Seam, and the Protection Formation. Because these formations are indistinguishable outside the coal mining area, Muller and Jeletsky (1970) considered all these formations as one and gave them one name, the Extension-Protection Formation.

General Stratigraphy. The Extension-Protection Formation is the least exposed of the formations on Saturna Island. Only the upper 20 feet of it are exposed at Murder Point and at two small points 1/4 mile west and 1/2 mile west of Murder Point (Plate 1 and Figure 2). These are the only outcrops of the formation known on Saturna Island. Murder Point and the other two unnamed points are composed of northerly dipping, resistant strata which protect the overlying less resistant Cedar District Formation mudstone slopes from the destructive forces of the waves.

The basal contact is not exposed in the thesis area. The upper contact with the overlying Cedar District Formation shows an angular discordance of about 5° (Figure 5). This discordance probably was caused by distributary channel abandonment and migration, which resulted in a cessation of coarse clastic deposition as the basin continued to subside. According to Hubert and others (1972) a delta surface, after distributary migration, subsides by compaction of the thick prodelta sequence of water-saturated mud, and an angular discordance commonly develops. The contact separates conglomerates and coarse- to medium-grained sandstones of the Extension-Protection Formation from the overlying mudstones, siltstones, and very fine-grained sandstones of the Cedar District Formation. All exposures of the Extension-Protection strata are essentially the same because of their close proximity to one another. At all localities the

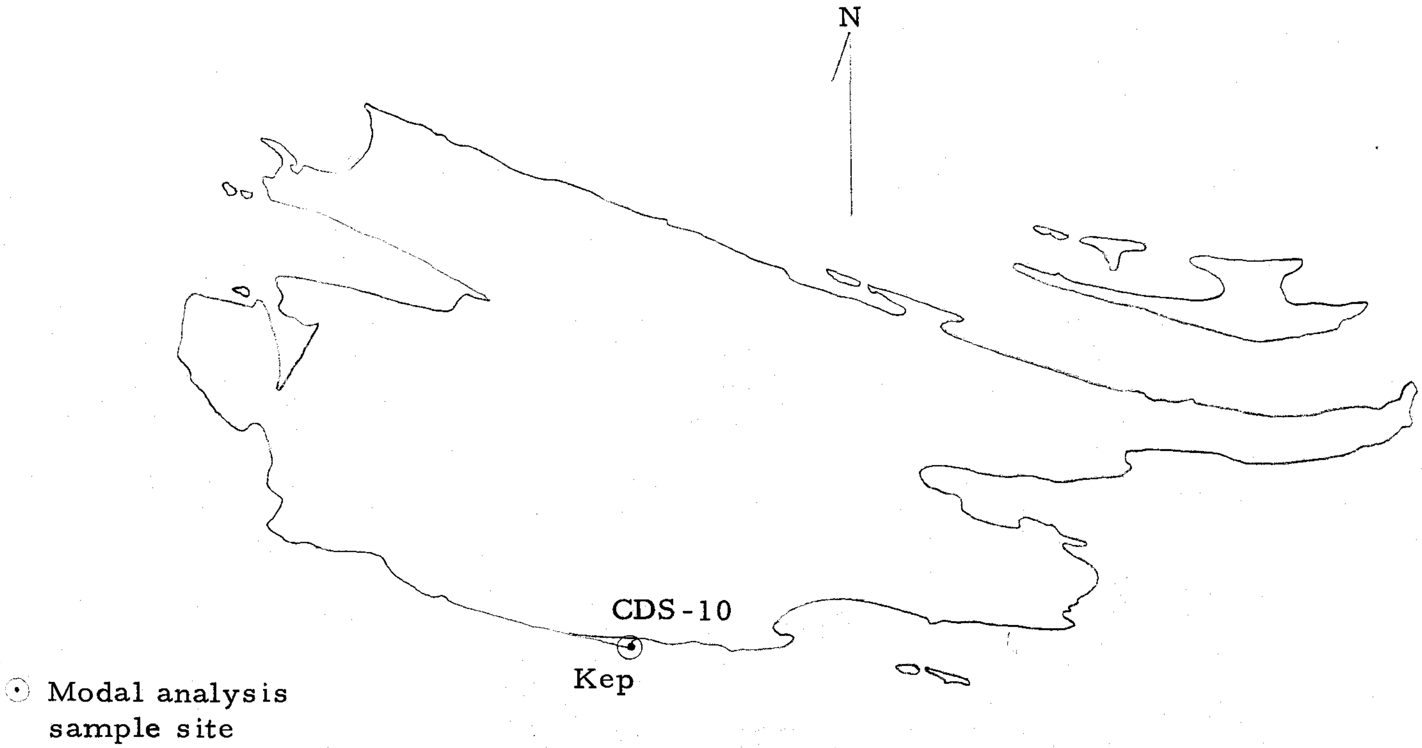


Figure 2. Extension-Protection Formation distribution and sample site for modal analysis.

lower 16 feet are composed of channel conglomerates that exhibit festoon cross-bedding and scour-and-fill structures. Overlying this interval is a calcareous, medium-grained sandstone, about 4 feet thick, which forms the uppermost part of the formation.

Because of the limited exposures of the Extension-Protection Formation, no stratigraphic section was measured. A sample of the uppermost sandstone was obtained and a petrographic point count was performed (Appendix D). The total thickness of the formation on Saturna Island is unknown because most of it lies underwater, but Hudson (1974) estimated a thickness of 1,900 feet on North and South Pender Islands. This thickness was used satisfactorily in the construction of geologic cross-sections on Saturna Island (Plate 1).

The conglomerates of the Extension-Protection Formation are dark gray (N 3) to medium dark gray (N 4). This dark color is primarily the result of an abundance of dark basalt and argillite cobbles and pebbles, and the dark lithic sandstone matrix, which also is composed of abundant basalt and argillite fragments.

The sandstones are commonly light brown (5YR 6/4) to grayish orange (10YR 7/4) on weathered surfaces, whereas on fresh surfaces they are light gray (N 7). Basal contacts are generally sharp and planar, but at places they exhibit scour-and-fill. The sandstones are thinly bedded to laminated and show crude grading from coarse-grained sandstone up into medium-grained sandstone.

Sedimentary structures in the conglomerates of the formation include thick bedding, crude normal grading, and festoon and planar cross-bedding. Sedimentary structures in the sandstones include scour-and-fill, normal grading, and calcareous sandstone concretions. The calcareous concretions range in diameter from 4 to 12 inches, are nearly spherical, and weather out as knobs on exposed surfaces.

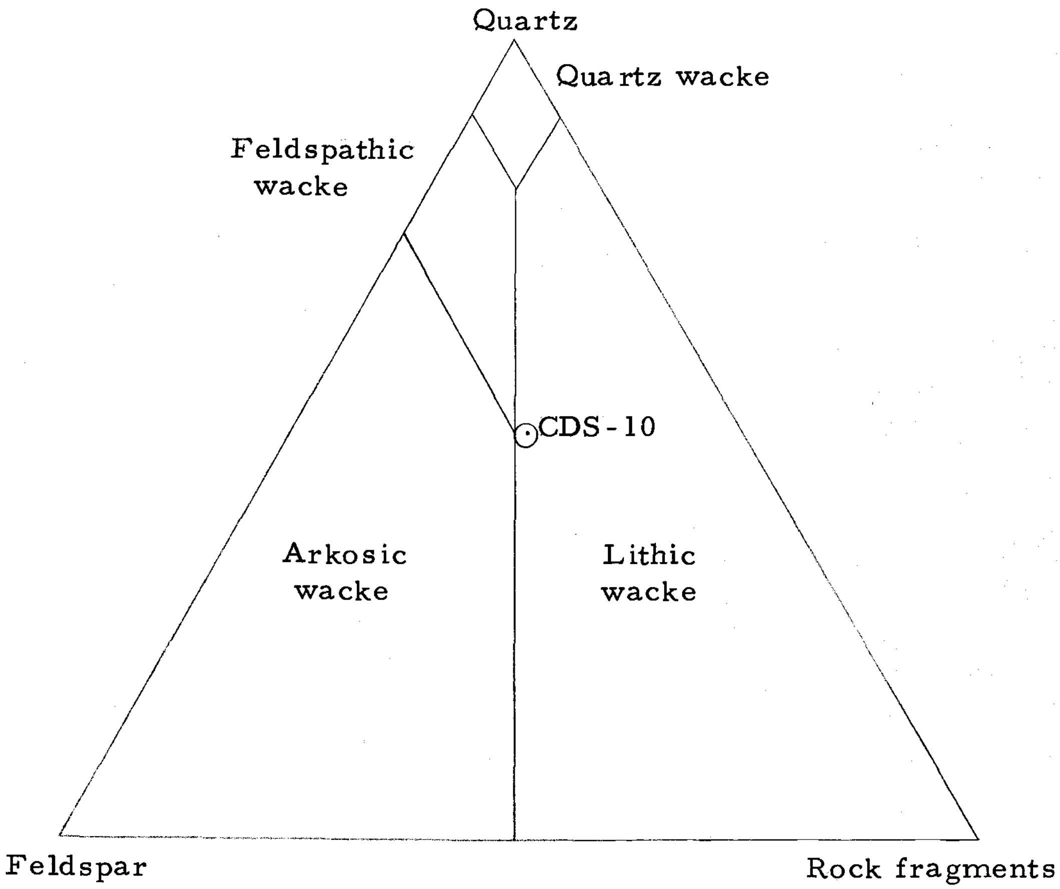
Lithology. The most striking feature of the Extension-Protection Formation conglomerates is the white quartzite clasts that stand out against a black matrix. Closer examination of the conglomerates reveals that most of the cobbles and pebbles are composed of dark argillite and basalt, and only a small percentage are composed of quartzite. An approximate breakdown of pebble lithologies is: argillite - 50%, basalt - 30%, gneiss - 10%, quartzite - 5%, and greenstone - 5%. Minor constituents include chert and rhyolites. The matrix, composed of dark gray (N 3) sandstone, is composed also of abundant argillite and basalt fragments. The conglomerates are very well cemented and cobbles cannot be obtained without breaking them, so a valid pebble count could not be performed.

One sample of the uppermost sandstone bed was obtained for petrographic analysis. A six-hundred point modal analysis (Appendix D) was performed on the thin section of the sample. The results reveal a texturally and compositionally immature sandstone according to Folk's (1951) concepts of maturity. The sandstone is a moderately sorted lithic wacke, with angular to rounded framework grains (Figure 3). The matrix content, which is in part detrital and in part diagenetic, is about 12%.

The framework grains of this sample predominantly consist of quartz, plagioclase, potassium feldspar, rock fragments, polycrystalline quartz, biotite, and chlorite. Minor constituents include muscovite, orthopyroxene, clinopyroxene, chert, limonite, hematite, magnetite, zircon, sphene, leucoxene, and almandite. Orthoclase is the dominant potassium feldspar, whereas microcline is rare. Andesine is the dominant plagioclase feldspar. Sericite, calcite, and chlorite are common alteration products of the feldspars. Most feldspars show signs of alteration, but some are unaltered. Perthite, myrmekite, and micrographic intergrowths, although rare, were observed. Chlorite is a common alteration product of biotite and is common in the greenstone fragments. Most of the hematite has altered from magnetite as evidenced by remanent magnetite inclusions within the hematite.

Detrital micas include biotite, chlorite, and muscovite. Rock fragments include phyllite, schist, basalt, and greenstone.

The cement in the sample is calcite, which accounts for 24% of the total composition of the rock. Calcite commonly has replaced quartz, chert, and feldspar framework grains, indicating a secondary



CDS-10: Upper Extension-Protection Formation (Murder Point, Saturna Island)

Figure 3. Classification of Extension-Protection Formation sandstone (after Gilbert, 1954).

origin for the cement.

Environments of Deposition. The tight packing, festoon cross-beds, and scour-and-fill structures of the conglomerates of the Extension-Protection suggest that the sediments were deposited in a fluvial environment. It is true that alluvial fans and beach gravels possess these same features, but such are generally more limited in extent than the conglomerates of the formation elsewhere in the Nanaimo Basin. Also alluvial fans generally have more angular clasts, and beach gravels display better sorting. The large size of the cobbles and boulders indicates a transporting medium of high competence. The sedimentary structures indicate that the cobbles were transported partly in the bed load and partly deposited in point bar subenvironments.

Overlying the conglomerates is a 6-foot coarse- to medium-grained sandstone. This sandstone closely resembles the present day topset beds of the Fraser River delta described by Johnston (1922). According to Johnston, the topset beds of the modern Fraser River delta are composed of sand, are generally laminated, and show upward finning. Petrographic analysis of a sample of this sandstone reveals little evidence of reworking or sorting and indicates rapid deposition and burial. The presence of fresh feldspars indicates a relatively close source area and rapid mechanical erosion (Pettijohn and others, 1972). Slow chemical weathering tends to destroy all feldspars and break them down into clays.

Cedar District Formation

Nomenclature. The marine mudstones overlying the Nanaimo Basin coal measures were named the Cedar District Formation by Clapp and Cooke (1917). The type section, 1,010 feet thick and exposed along the coast south of Dodd Narrows, was measured and described by Muller and Jeletsky (1970).

General Stratigraphy. The Cedar District Formation on Saturna Island is composed of a lower and an upper part separated by a tongue of DeCourcy Formation (Plate 1 and Figure 4). The strata are non-resistant, consequently the formation is a slope- and valley-former.

The lower Cedar District Formation underlies the western part of the Lyall Creek valley from Lyall Harbor to the northeast quarter of section 9 where it is terminated by a fault that juxtaposes the lower Cedar District Formation with the upper DeCourcy Formation (Plate 1). The lower Cedar District Formation apparently underlies most of Lyall Harbor; the only outcrop in this area occurs on the south bank of the mouth of Lyall Creek. The southern coastline of Saturna Island from Trueworthy Bight to within one half mile of Taylor Point is composed almost entirely of the lower Cedar District Formation.

The upper Cedar District Formation underlies the eastern part of the Lyall Creek valley, and extends from the northwestern corner

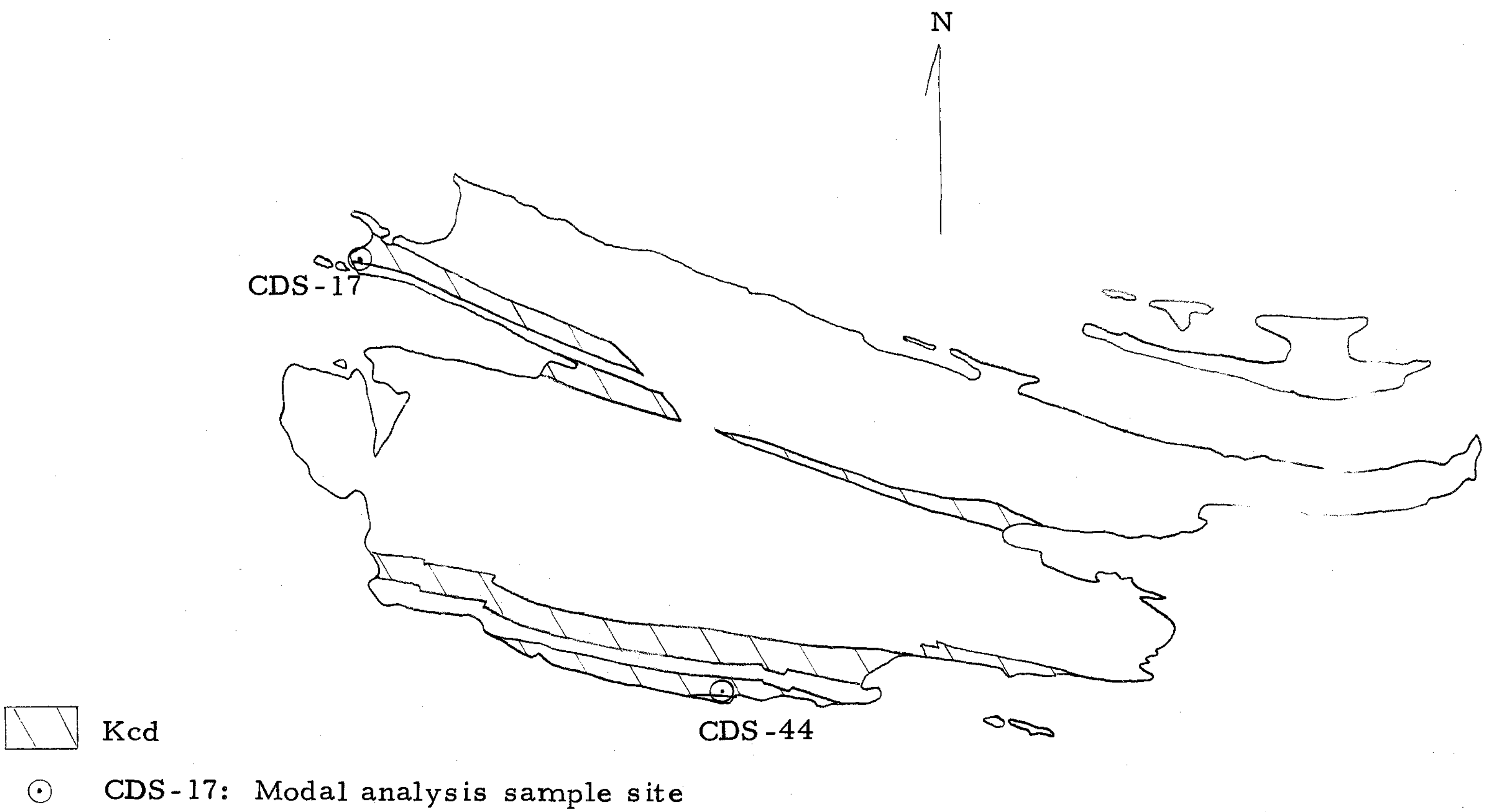


Figure 4. Cedar District Formation distribution and sample sites for modal analyses.

of section 10 to Narvaez Bay. The upper part also underlies the waters of Narvaez Bay, and outcrops occur on both the north and the south shores of the bay. The upper Cedar District Formation, in addition, underlies the relatively flat bench on the south shore of Saturna Island that extends from Saturna Beach to Bruce Bight. Exposures there are limited to the north and south sides of Saturna Beach and the north shore of Bruce Bight. The best exposures of the upper Cedar District Formation occur at Digby Point and Veruna Bay. The formation underlies a swampy area that extends from Veruna Bay in an east southeast direction to the southeast quarter of section 17, where it is terminated by the fault described previously. The upper Cedar District Formation is also exposed as tongues in the DeCourcy Formation between Bruce Bight and Monarch Head (Appendix C), and also at Mikuni Point (Appendix A).

The basal contact of the lower Cedar District Formation with the Extension-Protection Formation has been discussed in the preceding section. The upper contact, separating the thickly bedded sandstones of a lower DeCourcy Formation tongue from the normally graded sandstone-siltstone-mudstone sequences of the lower Cedar District Formation, is best exposed in the southeast quarter of section 5, along the southern coast of Saturna Island. Here the contact is well exposed and there is gradation over a 15-foot interval with an upsection increase in the thickness and number of sandstone beds.

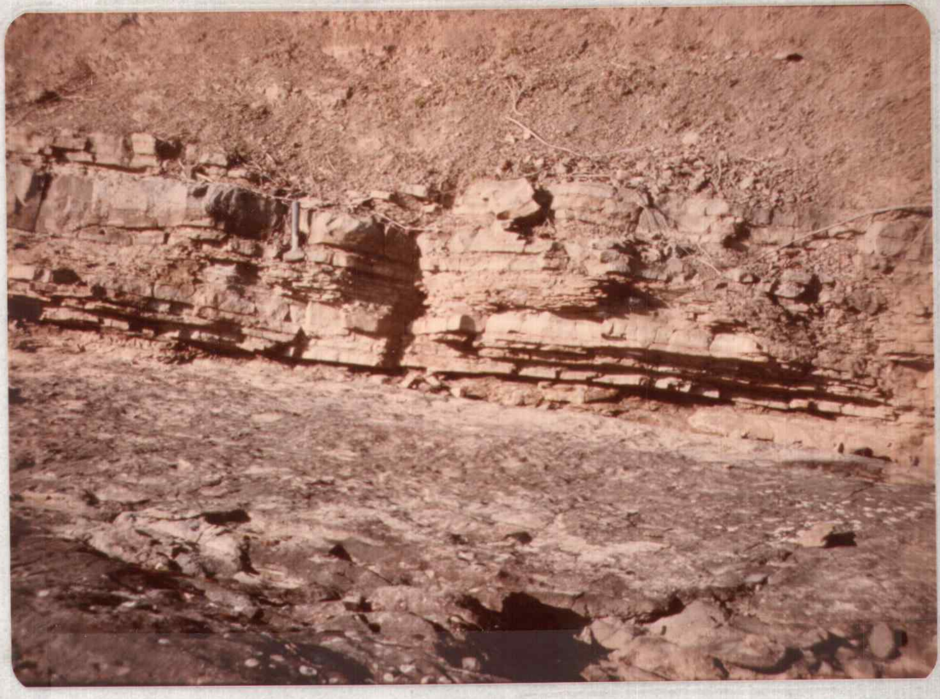


Figure 5. Contact of the Extension-Protection Formation with the overlying lower Ceder District Formation at Murder Point. Note the angular discordance between the two formations and the sandstone channel within the Cedar District Formation at the left side of the photograph.

Figure 6. Normally graded sandstone-siltstone-mudstone bed typical of the lower Cedar District Formation at Murder Point.

The lower contact of the upper Cedar District Formation with the underlying lower DeCourcy Formation tongue is exposed at Saturna Beach and between Digby Point and Lyall Harbor. At both localities the contact is gradational and shows a complex intertonguing relationship. There is an overall increase in the amount of mudstone upsection. For a more detailed description of the interval, see Appendix A.

The upper contact of the upper Cedar District Formation with the overlying upper DeCourcy Formation is exposed at Veruna Bay and at the southwestern quarter of section 1 along the southern coastline of Saturna Island between Bruce Bight and Monarch Head (Figure 15). The contact at Veruna Bay is gradational and displays an intertonguing relationship (Appendix A). The contact seen between Bruce Bight and Monarch Head, however, is sharp and planar and shows no intertonguing relationship (Appendix C and Figure 15). There is a sharp change from the interbedded sandstone, siltstone, mudstone sequences of the upper Cedar District Formation to the overlying cliff-forming sandstones of the DeCourcy Formation.

The Intertonguing relationships between the various tongues of the Cedar District and DeCourcy Formations are probably the result of normal deltaic processes. The intertonguing of marine mudstone of the Cedar District Formation and coarse- to medium-grained sandstones of the DeCourcy Formation probably represent distributary channel abandonment and migration. Intermittent deltaic progradation, which would result from deltaic distributary migration, fluctuations in the rate of basin subsidence, periodic tectonic uplift of the source area, or possibly major fluctuations in sea level, may have contributed to the intertonguing relationship.

One section of the upper Cedar District Formation was measured and described (Appendix A), and the lower Cedar District Formation was measured for interval thickness but not described. The thickness of the lower Cedar District Formation is 440 feet, whereas the upper part of the formation is 687 feet thick. If the 210 feet of the lower DeCourcy Formation tongue are included in the composite thickness, the total thickness of the Cedar District Formation is 1,337 feet.

The lower and upper Cedar District Formations are lithologically similar. Both are composed of rhythmically interbedded very fine-grained sandstone, siltstone, and mudstone, with mudstone intervals up to 20 feet thick. Mudstone comprises approximately 60% of both parts of the formation. The individual normally graded sandstone-siltstone-mudstone packets range in thickness from 5 to 25.5 inches, and incomplete Bouma sequences are well displayed. The lower parts of the graded packets usually display parallel laminations (division B of the Bouma sequence) which grade upward into micro-trough cross-laminations (division C of the Bouma sequence). Overlying division C are either parallel silt laminations, or graded siltstones, representing division D of the Bouma sequence. Division D grades upward into mudstone, which is part E of the Bouma sequence. The BCDE sequence is the typical development of the graded beds of the Cedar District Formation. Less commonly, parts CDE and DE of the Bouma sequence occur alone, and if interpreted as turbidite deposits, these would represent either interdistributary or distal turbidite deposits on a prodelta. Bottom markings on the sandstone beds include load casts, flames, and flute casts. Most commonly however, the lower contacts are sharp and planar. Upper contacts grade into mudstone over an interval of one half to three inches.

Shell fragments and external molds of the pelecypod Inoceramus occur locally in both the upper and lower Cedar District Formation; however, the lower part of the formation is by far the more fossiliferous of the two.

The formation is predominantly composed of mudstone. The mudstone, because it is non-resistant, weathers out as 1/4 to 1-1/4 inch chips which obscure any sedimentary structures that may be present. However, fresh outcrops of the mudstone display fine laminations. Weathered outcrop colors range from light gray (N 7) to dusky yellow (5Y 6/4), whereas fresh samples range in color from medium dark gray (N 4) to light olive gray (5Y 6/1).

Four argillaceous limestone beds, ranging in thickness from 2 to 5-1/2 inches, were described in the measured section of the upper Cedar District Formation (Appendix A). The fresh colors range from medium dark gray (N 4) to medium gray (N 5), and weathered colors range from grayish orange (10YR 7/4) to light gray (N 7). Sedimentary structures within the argillaceous limestones include laminations (up to 6 per inch), festoon and planar cross-laminations, vertical burrows, and upper contacts that grade within 1 inch into the overlying mudstone.

The sandstones of the Cedar District Formation generally show laminations and cross-laminations, with micas concentrated on bedding planes, which separate individual laminae. Grain sizes range from fine- to very fine-grained sand, and sorting is poor to moderate. Framework grains are angular to subrounded. The sandstone beds, more resistant to weathering than the mudstone, stand out as ribs in the outcrops. Weathered outcrop colors range from dark yellowish brown (10YR 4/2) to grayish orange (10YR 7/4). Fresh colors range from medium dark gray (N 4) to very light olive gray (5Y 6/2). Siltstones are identical to the sandstones, except for grain size. Pyrite concretions occur in some of the sandstone beds of the upper Cedar District Formation. The concretions are usually spherical, with a maximum diameter of one inch, but some are elongate, with maximum dimensions of one by three inches. The sandstone around the concretions is stained yellow with limonite.

Sedimentary structures observed in the formation include laminations (Figure 7), festoon and planar cross-laminations (Figure

7), graded bedding (Figure 6), load deformations, scour-and-fill (Figure 7), flames and ball-and-pillow structure (Figure 8), controted laminations, convoluted bedding (Figure 10), sandstone dikes (Figure 13), load casts, and rare parting lineations and flute casts.

Organic remains observed in the Cedar District Formation include vertical and horizontal burrows, including Thalassinoides, fragments of pelecypod shells, including crushed Inoceramus shells, external molds of Inoceramus, and carbonaceous debris.

Lithology. X-ray diffraction analysis of the mudstones in the lower Cedar District Formation reveals kaolinite, mica, chlorite, and montmorillonite as the clay minerals present, whereas the upper Cedar District Formation mudstones contains kaolinite, mica, chlorite, montmorillonite, vermiculite, and antigorite. See Appendix E for the tabulated results of the clay mineralogies and Appendix F for the analytical techniques.

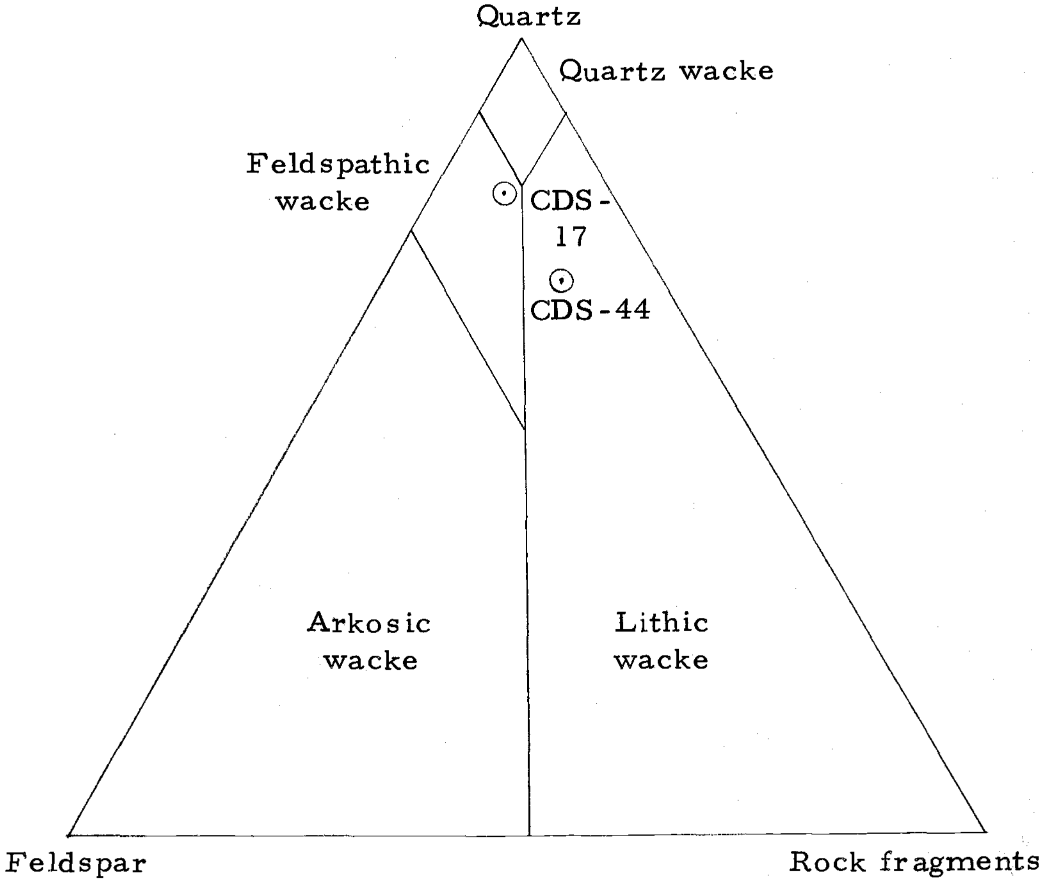
Four thin sections of Cedar District Formation sandstones were examined microscopically. Six-hundred point modal analyses were performed on two thin sections, one from the lower part of the formation, and one from the upper part (Appendix D). The results indicate that the lower Cedar District Formation sandstones are both texturally and compositionally immature according to Folk's (1951) concepts of maturity. The upper Cedar District Formation, although texturally immature, is compositionally submature. The sandstones are poorly

Figure 7. Parallel laminations, festoon cross-laminations and scour-and-fill in a sandstone bed within the lower Cedar District Formation. Note the crushed Inoceramus shells in the lower left corner and the pyrite concretion near the center of the photograph.

Figure 8. Flames and ball-and-pillow structure of the upper Cedar District Formation south of Digby Point. West is to the left.

Figure 9. Festoon troughs in a sandstone bed of the upper Cedar District Formation at Digby Point that yielded many paleo-current directions. South is to the left.

Figure 10. Contorted bedding of the upper Cedar District Formation at Bruce Bight. Note that the overlying strata has been little affected by the deformations below. West is to the left.



CDS-17: Upper Cedar District Formation (south of Digby Point, Saturna Island)
CDS-44: Lower Cedar District Formation (Murder Point, Saturna Island)

Figure 11. Classification of Cedar District Formation sandstones (after Gilbert, 1954).

Figure 12. Vertical burrows (Thalassinoides) in the upper Cedar District Formation at Veruna Bay, indicating an outer shelf environment.

Figure 13. Four-foot wide sandstone dike in the upper Cedar District Formation at Veruna Bay. Note the continuity of the bedding from one side of the dike to the other.

sorted, calcareously cemented lithic wackes, and feldspathic wackes (Figure 11), with angular to well rounded grains. The matrix content ranges from 11.3 to 12.7 percent. Many of the volcanic rock fragments in the thin section show indistinct boundaries and have been partially altered to clays. The cementing clay minerals surrounding the altered volcanic grains are of the same color and texture as the clays within the grains, indicating that some of the cementing clays are diagenetic. Some of the clays, however, are of a different color than those of the volcanic fragments, and are not associated with any lithic fragments, indicating that some of the clays are detrital in origin. Porosity of the sandstones ranges from less than 1% to 3.3%.

The framework grains predominantly consist of quartz, biotite, plagioclase, chlorite, and rock fragments (Appendix D). Minor constituents include polycrystalline quartz, chert, orthoclase, muscovite, orthopyroxene, pyrite, hematite, magnetite, sphene, leucoxene, garnet, laumontite, and sericite. Andesine is the dominant plagioclase feldspar. Myrmekite intergrowths were found in samples from both parts of the Cedar District Formation. Sericite, calcite, and rare laumontite are alteration products of the feldspars. Hematite is a common alteration product of magnetite and biotite. Biotite also is commonly altered to chlorite, as are many of the greenstone fragments.

Detrital micas include biotite, chlorite, and muscovite. Detrital rock fragments include phyllite, schist, greenstone, and mudstone.

The cement found in all samples is calcite, and it comprises from 26.6% to 33% of the total composition of the rocks. Echinoid spines and shell fragments were observed in sample CDS-44. The calcite cement, in many places, has partially replaced quartz and feldspar grains.

Three thin sections of the argillaceous limestone beds in the upper Cedar District Formation were examined microscopically. The limestones consist of from 50% to 70% microcrystalline calcite and from 50% to 30% very fine-grained sand to clay-sized detrital grains, including quartz, plagioclase (andesine), muscovite, augite, chlorite, and biotite. Most of the detrital grains occur in discrete laminae and are in grain support, but some are in matrix support. The argillaceous limestones also contain pyrite, plant debris, and a small amount of sapropel. Most of the calcite appears to be of secondary origin, because it has partially replaced many quartz grains.

Environments of Deposition. The Cedar District Formation represents a return to marine sedimentation. The presence of the marine pelecypod Inoceramus confirms this conclusion. Much of the formation is dominated by interbedded sandstone, siltstone, and mudstone, and closely resembles the delta-slope facies of the Hamilton Group, described by Mazzullo (1973). Allen (1970) and Coleman and

Gagliano (1965) have described modern delta-slope deposits that are similar to those of the Cedar District Formation. According to these authors, the delta-slope deposits consist of graded sandstones and shales, often associated with flute casts, groove casts, and cross-laminations.

Many of the sandstone beds of the lower Cedar District Formation were deposited by turbidity currents. The beds display normal grading, incomplete Bouma sequences, and bottom markings, such as flute casts, drag marks, sole marks, and many beds contain broken and disarticulated pelecypod shells. Dott (1966) and Allen (1970) recognize turbidity currents as important sand transporting mechanisms in the development of delta-slope deposits in their deltaic models.

The sandstone beds of the upper Cedar District Formation cannot be positively identified as turbidite deposits. The sandstones are usually graded and commonly display incomplete Bouma sequences, but this is insufficient to confirm a turbidite origin. These same sedimentary structures can also be formed during seasonal storms as the discharge of the rivers increases and coarser sediments are deposited farther from shore than normal. As the flood subsides, finer particles are deposited on top of the coarse clastics, resulting in a graded deposit. Such a process has been described on the modern Fraser River delta by Johnston (1922).

The thick, laminated mudstones of the Cedar District Formation were probably deposited in a low energy, below wave base environment. The wide-spread occurrence of the trace fossil Thalassinoides supports this suggestion. Chamberlain (written commun., 1975) states that this trace fossil occurs in an outer shelf environment. The presence of pyrite concretions indicates that at least part of the formation was deposited under reducing conditions (Krauskopf, 1967). It is suggested that the turbidite units and the interbedded sandstone-siltstone-mudstone sequences of the formation were deposited in shallow marine waters because they vertically grade upward into shallow marine and fluvial sandstones of the DeCourcy Formation.

As mentioned previously, the Cedar District Formation is separated into two parts by a tongue of DeCourcy Formation sandstone. The sandstone is in part shallow marine in origin, as evidenced by the presence of the marine pelecypod Inoceramus, and is in part fluvial in origin, as indicated by the presence of pebbly sandstones, some of which are localized in channels (Appendix A). The sedimentary structures and fossils suggest that the lower and upper parts of this tongue were deposited as river-mouth bars (Allen, 1970), channel-mouth bars (Mazzullo, 1973), or distributary-mouth bars (Coleman and Gagliano, 1965); whereas, the middle part of the tongue closely resembles the distributary channel and subaerial levee deposits of the Mississippi River delta described by Coleman and Gagliano (1965).

The geometry of the outcrops delineate an arcuate pattern as do those of their modern counterparts.

DeCourcy Formation

Nomenclature. The resistant sandstone and conglomerate formation that underlies the DeCourcy Islands was named the DeCourcy Formation by Clapp (1911). Muller and Jeletsky (1970) proposed that the name DeCourcy Formation be substituted for the Denman Formation, a name proposed by Williams (1924) for the equivalent strata in the Comox Basin.

General Stratigraphy. The DeCourcy Formation is a resistant sandstone unit containing local channel conglomerates. It is the most extensive formation on Saturna Island, comprising about one half of the total bedrock of the island (Plate 1 and Figure 14). The formation is composed of two major tongues, separated by the upper Cedar District Formation. The lower tongue (about 210 feet thick) is exposed from Croker Point to Taylor Point on the southern coast of Saturna Island. Sea cliffs up to 100 feet high have been formed where the formation intersects the waters of Plumper Sound. The cliffs on the north side of Lyall Harbor exposed from the King Islets to the northeast corner of section 9, are also composed of the lower DeCourcy Formation, as are the Java Islets.

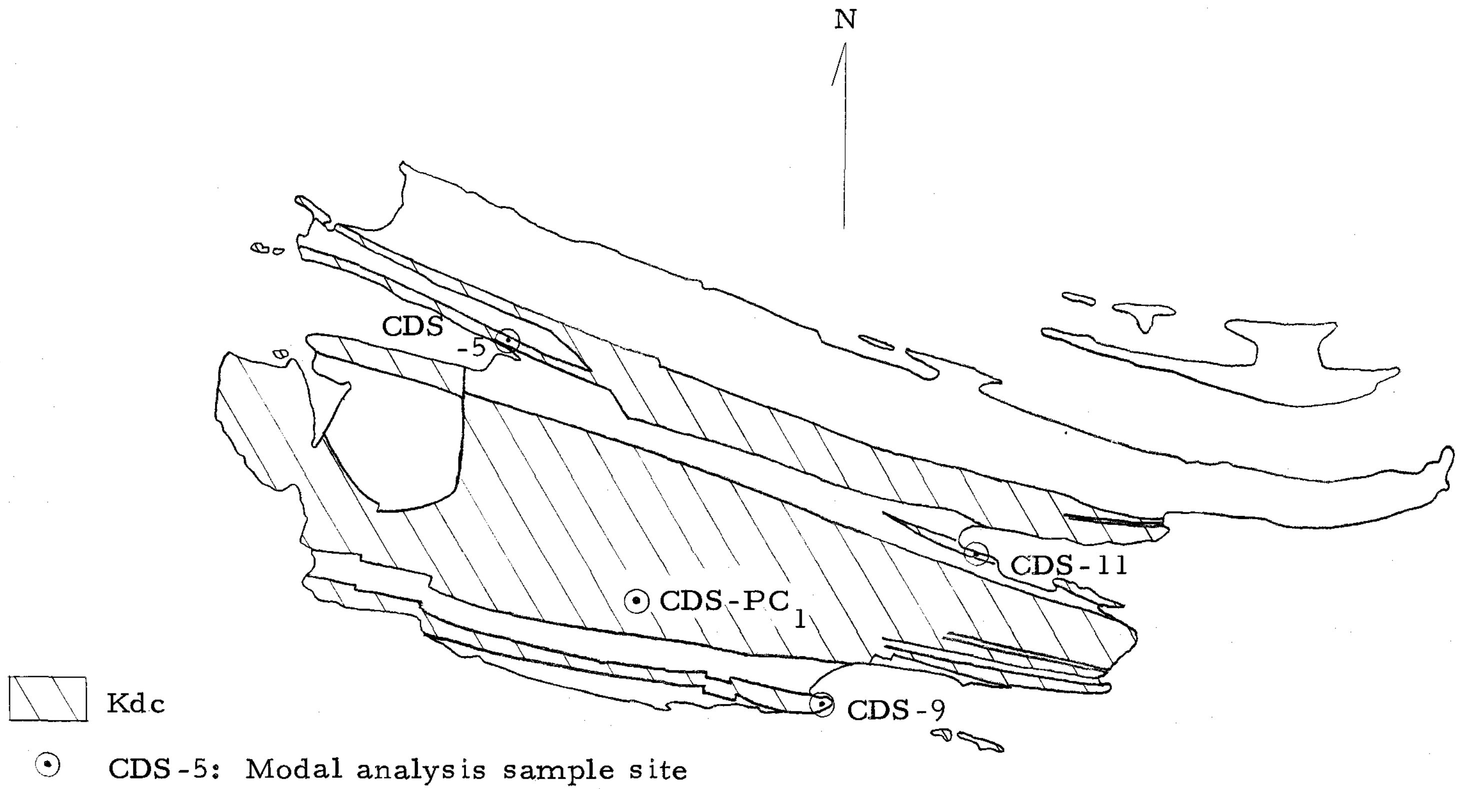


Figure 14. DeCourcy Formation distribution and sample sites for modal analyses and pebble counts.

The upper DeCourcy Formation is the thicker (at least 816 feet) and the more extensive of the two tongues of the formation. It crops out from Payne Point and Elliot Bluff to Monarch Head and supports the magnificent cliffs of Brown Ridge. The entire bedrock of this area, except for most of section 8, consists of the upper DeCourcy Formation. Mt. Warburton Pike, the highest point on Saturna Island, and Mt. Fisher, also are composed of the upper DeCourcy Formation. The upper unit also crops out from Minx Reef to Fiddler's Cove, forming the 600-foot high near vertical cliffs on the north side of the Lyall Creek valley.

The upper and lower contacts of the lower DeCourcy Formation have been described previously. The basal contact of the upper DeCourcy Formation with the underlying upper Cedar District Formation has been described in the previous section. The contact of the upper DeCourcy Formation with the overlying Northumberland Formation is exposed only during a minus tide on the southwest shore of Winter Cove between Mikuni Point and Church Cove (Appendix A) and at Fiddler's Cove during normal tides (Appendix B). The contact at Winter Cover is sharp and concordant, showing an abrupt change from medium- to coarse-grained sandstones of the DeCourcy Formation to the sandstone-siltstone-mudstone sequences of the Northumberland Formation. The contact at Fiddler's Cove (Appendix B) shows an apparent intertonguing of two tongues of the Northumberland

Figure 15. Sharp and concordant contact of the upper Cedar District Formation and the overlying upper DeCourcy Formation between Bruce Bight and Monarch Head. Note the abrupt change of lithology and the Jacob's staff for scale.

Formation, but the contacts here are covered.

A complete stratigraphic section of the upper DeCourcy Formation was not measured, but an incomplete section was described around Monarch Head (Appendix C) where it has a thickness of at least 816 feet. Trigonometric calculations of the thickness of the complete upper DeCourcy Formation at Mt. Fisher result in a thickness at 1,080 feet. Hudson (1974) estimated the thickness of the formation at 2,500 feet on North and South Pender Islands.

A partial section of the lower DeCourcy Formation was measured and described (Appendix A) south of Digby Point, where it is at least 150 feet thick. Muller and Jeletsky (1970) measured a section about 1/4 mile west of Taylor Point, and the total thickness is 210 feet.

The lower DeCourcy Formation is typified by thinly to thickly bedded (1-1/2 inches to 3 feet thick) medium- to coarse-grained pebbly sandstones and thinly laminated (up to 12 per inch) fine- to very fine-grained sandstones. Weathered outcrop colors range from grayish yellow (5Y 8/4) to pale yellowish brown (10YR 6/2). Fresh samples range from medium olive gray (5Y 4/2) to light olive gray (5Y 6/1).

The coarse-grained sandstones and coarse-grained pebbly sandstone beds commonly grade upward into medium-grained sandstones. Contacts between consecutive beds are sharp and planar to slightly undulating. Rare mudstone beds, 6 inches to 2 feet thick, and mudstone lenses, up to 6 inches thick and 20 feet long, separate coarse- to medium-grained sandstone beds. These mudstones probably represent deltaic interdistributary overbank flood deposits and/or fine clastic fill of oxbow cutoffs. The sandstones directly above and below tongues of the Cedar District Formation are finer grained than most of the lower DeCourcy Formation, indicating a transition to prodelta deposition. These finer grained sediments of the lower DeCourcy Formation, are very fine-grained sandstones and siltstones that commonly display fine laminations, festoon cross-laminations, and less commonly contorted laminations. Sedimentary structures observed in the coarser grained beds include scour-and-fill, planar foresets, normal grading, laminations (up to 5 per inch), and rare groove casts (Figure 16).

Organic structures in the lower DeCourcy Formation include external molds of the pelecypod Inoceramus (Figure 17) and vertical and horizontal burrows in the fine- to very fine-grained sandstone beds.

The upper DeCourcy Formation is separated from the lower part by the 679-foot thick tongue of the upper Cedar District Formation. The upper DeCourcy Formation is characterized by thickly bedded, cliff-forming coarse- to medium-grained sandstones with laminated mudstones and very fine-grained sandstones separating the thick,

Figure 16. Groove casts on the base of a sandstone bed of the lower DeCourcy Formation in the cliffs northeast of Trueworthy Bight. The bidirectional paleocurrent direction indicated is nearly east-west.

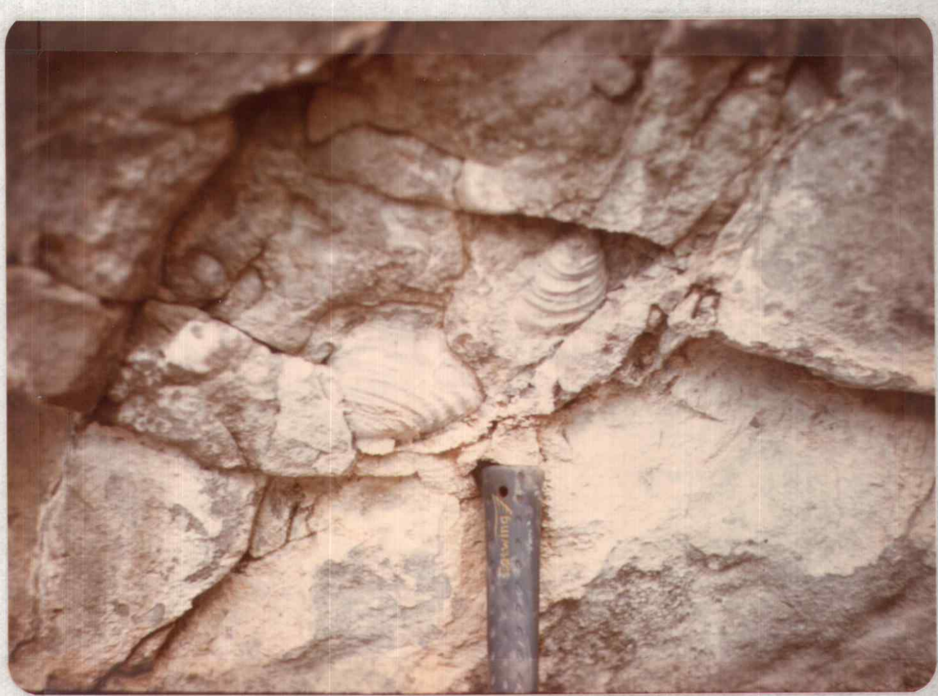


Figure 17. External molds of the pelecypod Inoceramus in a sandstone bed of the lower DeCourcy Formation. The outcrop is near the contact of the lower Cedar District Formation and the overlying lower DeCourcy Formation and is located in the cliffs northeast of Trueworthy Bight.

cliff-forming beds. Channel conglomerates occur on Brown Ridge southeast of Mt. Warburton Pike. The conglomerates resemble those of the Extension-Protection Formation in color and structure. They are dark gray (N 3) to medium dark gray (N 4) in color and they display festoon cross-bedding. The channels are lenticular in shape, are up to 10 feet thick and 200 feet wide, and cut shallow marine sandstones. Because they are exposed only in two dimensions, no accurate paleocurrent determinations could be obtained. Imbrication was not observed, probably because the outcrop exposures cross-cut the channel axis. If this is true, then the currents that deposited the conglomerates were flowing either north or south. Pebble elongation supports this north-south current direction. The lenticular channels, poor sorting, festoon cross-bedding, and high degree of rounding of the clasts indicate a fluvial origin for these conglomerates.

Coarse- and medium-grained sandstones are the dominant lithologies of the upper DeCourcy Formation on Saturna Island. These sandstones are commonly grayish yellow (5Y 8/4) to light dusky yellow (5Y 6/1) to light gray (N 7). Some of the coarse- and medium-grained sandstone beds contain matrix-supported pebbles of basalt, chert, and quartzite up to 1/4 inch in diameter. The coarse-grained sandstone commonly grades up into medium-grained sandstone, and almost as commonly up through very fine-grained sandstone into a mudstone interval of 1 to 13 inches in thickness. This normal grading occurs over an interval of 8 to 20 feet. Contacts between beds are generally sharp and planar, although there are local load deformed or scour-and-fill contacts.

Most of the cliff-forming coarse- and medium-grained sandstones of the upper DeCourcy Formation appear structureless from a distance. Some are structureless, but most show normal grading and crude bedding (1/2 inch to 9 feet thick). The lower parts of some beds contain mudstone clasts up to two inches in diameter. Other sedimentary structures observed in the coarse- and medium-grained sandstone beds are spherical calcareous sandstone concretions up to 6 feet in diameter, (Figure 21), festoon cross-beds, scour-and-fill, planar foresets (Figure 18), asymmetric ripple marks (Figure 19), and rare groove casts. Wave-cut notches (galleries) and honeycomb weathering (Figure 20) have been produced in the wave and spray zones of the DeCourcy Formation.

The fine- and very fine-grained sandstones of the upper DeCourcy Formation exhibit colors similar to those of the coarse- and medium-grained sandstone beds. These finer-grained sandstone beds are usually finely laminated (as many as 20 per inch), and many display micro-trough cross-laminations. Other sedimentary structures observed are contorted laminations, convolute bedding, flames, load casts, and meandering coarse-grained sandstone dikes up to one inch wide that cross-cut the laminae of the very fine-grained sandstones.

Figure 18. Planar foresets in the upper DeCourcy Formation between Mikuni Point and Church Cove. South is to the left.

Figure 19. Asymmetric ripple marks on top of a fine-grained sandstone bed of the upper DeCourcy Formation between Bruce Bight and Monarch Head. Attitude of the bedding is N. 75 W., 31°N. The paleocurrent transport direction indicated is north-northwest.

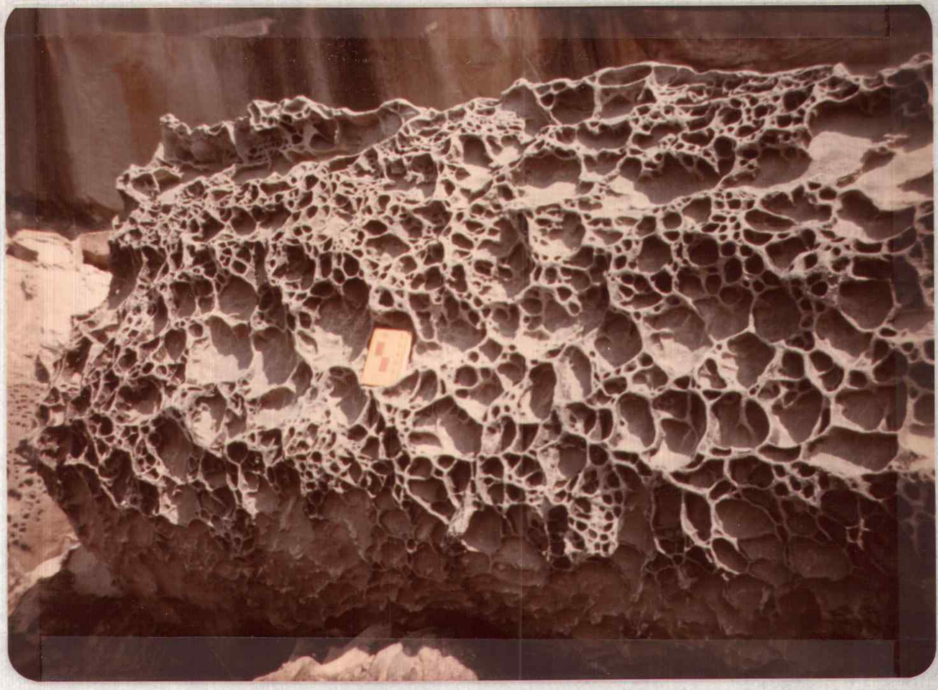


Figure 20. Well developed honeycomb weathering in a sandstone bed of the upper DeCourcy Formation west of Monarch Head.

Figure 21. Nearly spherical calcareous concretions in a coarse- to fine-grained sandstone bed of the upper DeCourcy Formation west of Monarch Head. The hammer in the foreground is 11 inches long.

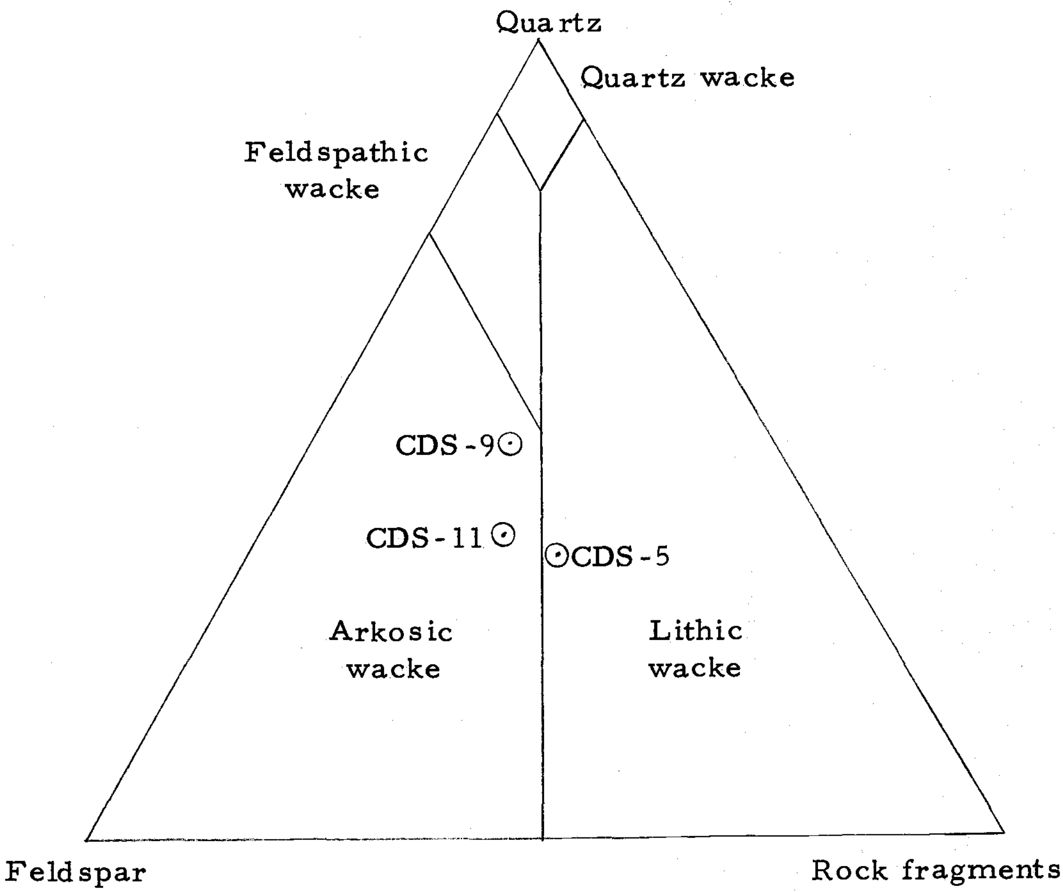
The mudstones of the upper DeCourcy Formation are generally light olive gray (5Y 6/1) in the weathered outcrop, whereas fresh samples range in color from medium dark gray (N 4) to medium gray (N 5). The mudstones are commonly thinly laminated; the upper contacts with overlying sandstone beds are usually load deformed or exhibit flames, but rarely they are sharp and planar. Vertical and horizontal burrows up to one inch in diameter occur in the mudstone intervals (Figure 22). Most mudstone beds are laterally discontinuous and wedge out within 1,300 feet (Figure 38). Some mudstone intervals are interbedded with very fine-grained sandstone and siltstone in normally graded packets similar to much of the Cedar District Formation, but small coal lenses up to about 2 inches thick and 5 feet long occur within them (Figure 24). This further supports the deltaic interdistributary environment for the mudstones.

Lithology. Pebbles from DeCourcy Formation conglomerates were obtained from the top of the Brown Ridge cliffs in the southwest quarter of section 3 and the southeast quarter of section 4. Over 200 pebbles were randomly chipped out of the conglomerates. In the laboratory, 100 pebbles were randomly picked from the sample and a pebble count was determined (Appendix B). Chert, limestone, basalt, quartzite, and greenstone are the dominant lithologies present. Minor clast lithologies include granite, granodiorite, gneiss, rhyolite, schist, phyllite, gabbro, mudstone, and petrified wood.

Figure 22. Mudstone with extensive burrowing in the upper DeCourcy Formation near Monarch Head.

Ten thin sections of DeCourcy Formation sandstones were examined microscopically. Six-hundred point modal analyses (Appendix D) were performed on three of these samples. The results indicate that these sandstones are texturally and compositionally immature, according to Folk's (1951) concepts of maturity. The sandstones are poorly to moderately sorted, angular to subrounded arkosic and lithic wackes (Figure 23). Matrix content ranges from 15.3% to 19.0%. The matrix appears to be in part detrital, but most appears to be derived from diagenetic alteration of feldspars, biotite, and volcanic rock fragments.

The dominant framework grains of the sandstones include quartz, plagioclase, potassium feldspar, biotite, chlorite, and rock fragments. Minor constituents include muscovite, orthopyroxene, clinopyroxene, limonite, hematite, magnetite, zircon, sphene, epidote, apatite, and garnet (almandite). Types of plagioclase include andesine and minor oligoclase and albite. The potassium feldspars are orthoclase and minor microcline. Rarely myrmekite intergrowths were observed in some of the feldspar grains. Common alteration products of the feldspars include sericite and kaolinite. Both fresh and altered feldspars are present in all samples. Chlorite and magnetite are common alteration products of biotite and volcanic rock fragments. Detrital micas include biotite and minor muscovite.



CDS-5: Lower DeCourcy Formation (road cut on East Point Road in SW 1/4, Sec. 17, Saturna Island)
CDS-9: Lower DeCourcy Formation (Taylor Point, Saturna Island)
CDS-11: Upper DeCourcy Formation (southwest corner of Narvaez Bay, Saturna Island)

Figure 23. Classification of DeCourcy Formation sandstones (after Gilbert, 1954).

Rock fragments found in the DeCourcy Formation sandstones include basalt, greenstone, sandstone, schist, polycrystalline quartz, chert, and minor phyilite and mudstone.

Most of the volcanic rock fragments in the thin section show indistinct boundaries, and clay minerals cementing the grains are the same color and texture as the clays in the volcanic fragments. The matrix was, therefore determined to be primarily of diagenetic origin.

Environments of Deposition. The sandstones of the DeCourcy Formation were probably deposited in a shallow marine environment and closely resemble the channel-mouth bar facies of the Hamilton Group described by Mazzullo (1973). According to Mazzullo, this facies contains thickly bedded sandstones that display festoon cross-bedding, burrows, current ripple marks, and scour-and-fill channels. All of these sedimentary structures were observed in the formation.

Other similar environments have been described as delta-front sheet sands by Gould (1970) on the Mississippi River delta, as river-mouth bars by Allen (1970) on the Niger River delta, and as distributary mouth bars by Coleman and Gagliano (1965) on the Mississippi River delta.

The general textural immaturity of the DeCourcy Formation suggests rapid burial with little reworking or winnowing of the sediments. The occurrence of fresh feldspars implies a close source area with steep relief and rapid mechanical erosion. The abundance of unstable rock fragments and polycrystalline quartz further support the idea of a close source area with steep relief and rapid deposition and burial with little reworking and abrasion of the grains.

The carbonaceous mudstone partings with abundant Diplocraterion burrows (Figure 22) and the thick coal-bearing sandstone-siltstone-mudstone sequences of the formation (Figure 24) are interpreted as interdistributary bay facies. According to Mazzullo (1973), the interdistributary bay facies consists of thinly bedded or bioturbated siltstone and mudstone. These finer deposits intertongue with the channel-mouth sandstones. Thin cross-laminations, plant remains, and burrows are common to such deposits. Further evidence for the interdistributary bay facies interpretation is the lateral discontinuity of the mudstone units (Figure 38). Similar deposits have been described by Gould (1970) and Coleman and Gagliano (1965) as marsh deposits on the Mississippi River delta. Another possible interpretation is a deep marine origin for these mudstones, but lateral discontinuity in outcrop, the relative thinness of the beds, and the absence of deep marine fossils and trace fossils forego any interpretations of this type. Mudflat deposits described by Coleman and Gagliano (1965) on the modern Mississippi River delta contain many of the sedimentary structures described in these mudstones, but they do not contain coal.

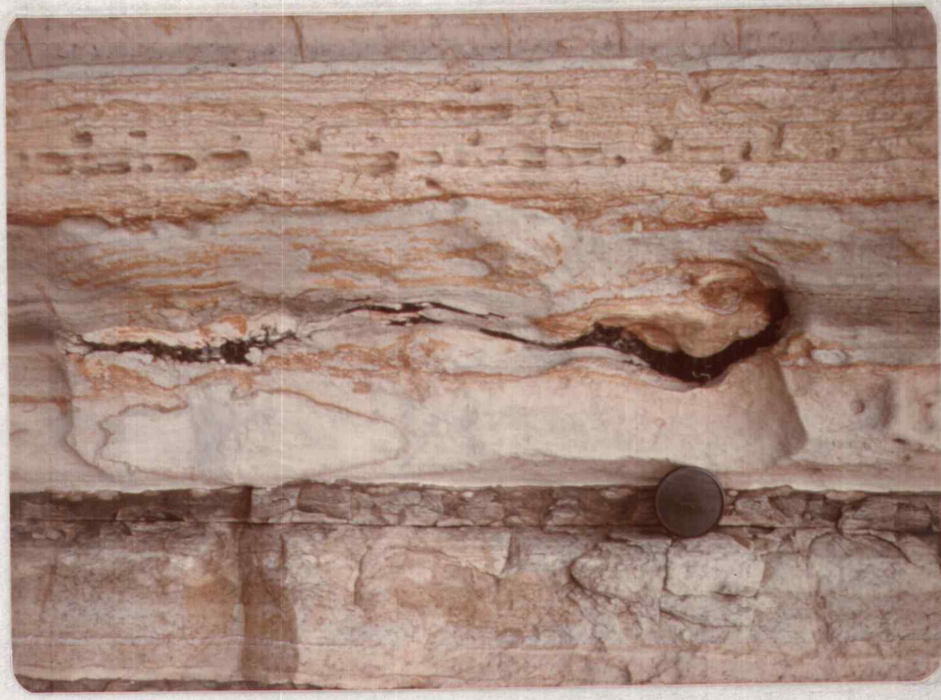


Figure 24. Small coal lens in an interdistributary bay facies of the upper DeCourcy Formation. Located west of Monarch Head.

Figure 25. Monarch Head as seen from the bluffs to the north. Note the projects of resistant sandstone, caused by intertonguing of the resistant DeCourcy Formation and the nonresistant Northumberland Formation.

The conglomerates of the DeCourcy Formation have been interpreted in the previous section as fluvial in origin, and appear to be localized in channels. The fact that they are surrounded by and cut into marine sandstones, suggests these may be distributary channels.

Both the upper Cedar District and Northumberland Formations intertongue with the upper DeCourcy Formation. For a more detailed description see described stratigraphic section in Appendix C. This intertonguing represents intermittent progradation of the delta, which may have been caused by deltaic distributary abandonment and the resultant diversion of clastic deposition to another part of the delta. As subsidence of the basin and transgression continued a prodelta mudstone (the Northumberland) sequence would then overlap the DeCourcy sandstones. Other possibilities which may have contributed to this intertonguing facies relationship are variations in the rate of basin subsidence, tectonic events in the source area, or possibly major fluctuations in sea level.

Northumberland Formation

Nomenclature. The mudstones which overlie the DeCourcy Formation and are exposed northeast of Northumberland Channel on the south coast of Gabriola Island were named the Northumberland Formation by Clapp (1911). The formation, as defined by Clapp, consists of a lower 500 feet of mudstone, a middle 400 to 1,000 feet of sandstone and coarse conglomerate, and an upper mudstone member. Muller and Jeletsky (1970) redefined the Northumberland Formation, and they restrict the name to the lower 500 feet of mudstone. The name Geoffrey Formation was assigned to the middle sandstone and conglomerate member, and the upper mudstone member was named the Spray Formation.

General Stratigraphy. The Northumberland Formation is a non-resistant, predominantly mudstone unit. It is a slope- and valley-former. The complete formation is exposed from Church Cove to Winter Point on Saturna Island and underlies the lowlands from this area to the northwest corner of section 17, where it intertongues with the Geoffrey Formation (Plate 1 and Figure 26). The formation also is exposed in Fiddler's Cove and underlies the lowlands to the west. Much of section 8 is underlain by the Northumberland Formation, and the slopes from Harris Road through the valley between Mt. Fisher and the peak 1,300 feet north of Mt. Fisher down to Boot Cove are also underlain by the formation. Exposures of the thick mudstones occur in road cuts along Boot Cove Road, Payne Road, and Harris Road. The Northumberland Formation also occurs as tongues in the DeCourcy Formation at Monarch Head (Appendix C and Figure 25) and along Narvaez Bay Road.

Because of its non-resistant nature, exposures of the Northumberland Formation are rather limited. The best exposures occur

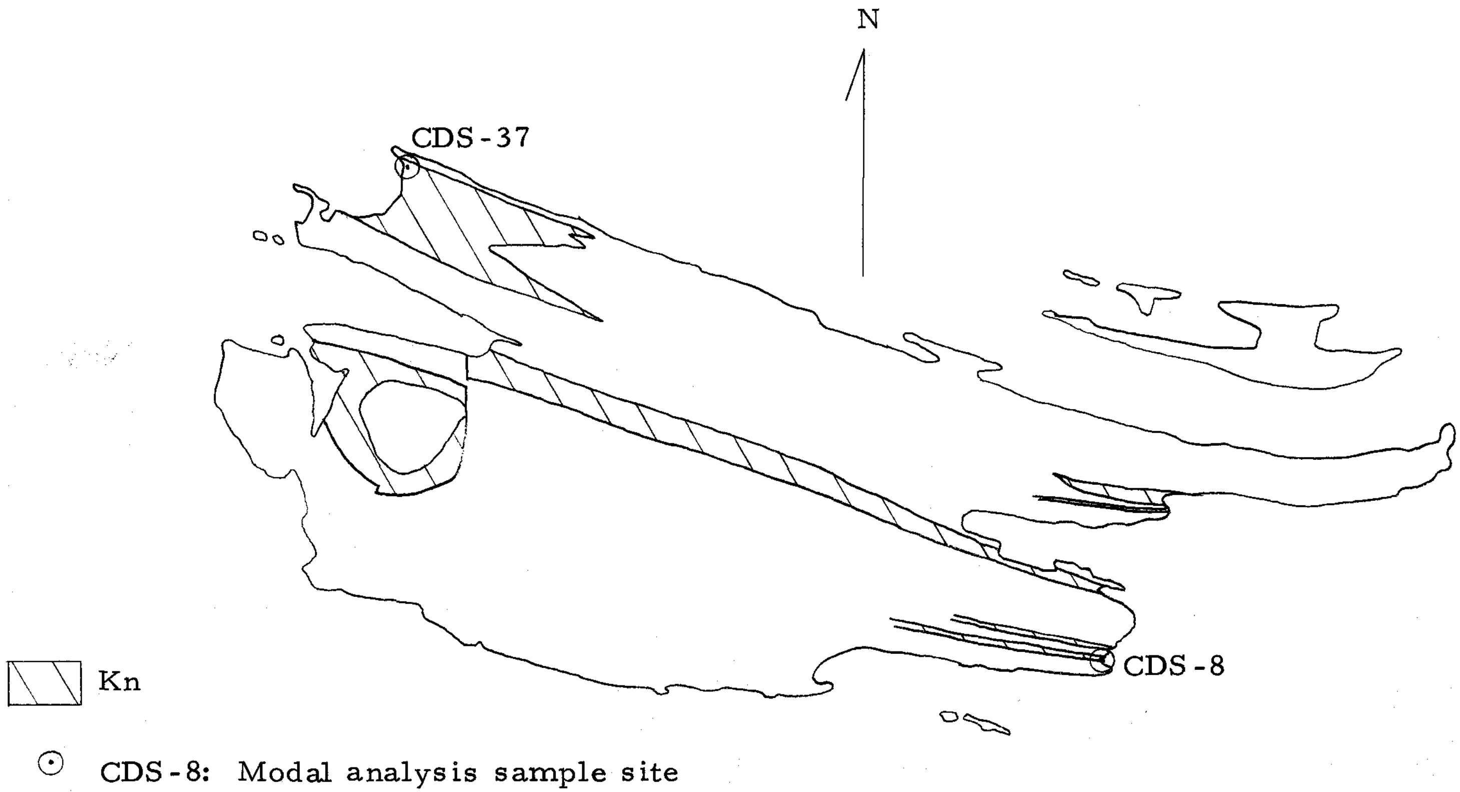


Figure 26. Northumberland Formation distribution and sample sites for modal analyses.

along the shore of Winter Cove from Church Cove to Winter Point, and tongues of the formation are particularly well exposed as Monarch Head during low tide.

The basal contact of the Northumberland Formation has been described in the previous section. The upper contact of the formation with the overlying sandstones of the Geoffrey Formation is best exposed at Winter Point (Appendix A and Figure 29). The contact here is sharp, planar, and concordant. There is an abrupt change from the interbedded sandstone-siltstone-mudstone sequences of the Northumberland Formation to the thickly bedded, medium- to coarse-grained sandstones of the overlying Geoffrey Formation.

Two sections of the Northumberland Formation were measured and described (Appendix A and B). A complete section was measured from Church Cove to Winter Point (Plate 1), and a total maximum thickness of 1669 feet was determined.

The Northumberland Formation can be divided into three units: a lower, a middle, and an upper part. The lower part consists of 348 feet of mudstone with intercalations of very fine-grained sandstone and siltstone that form graded packets ranging in thickness from 3 to 10 inches. Mudstone comprises between 50% and 70% of the interval. The very fine-grained sandstones are medium ligh gray (N 6) on the weathered outcrop, whereas fresh outcrops are medium gray (N 5). The sandstones are usually moderately sorted and are composed of angular to subangular grains. The sandstones are commonly laminated (up to 4 per inch), and as a rule display micro-trough cross-laminations. Upper contacts usually grade within one inch into the overlying siltstone, but locally are sharp and planar. Lower contacts generally are load deformed with a maximum relief of 1/2 inch, but also are locally sharp and planar. The siltstones are all thinly laminated, and weathered colors are usually brownish gray (5YR 4/1), with fresh outcrops being olive gray (5Y 4/1). Upper contacts grade within one inch into the overlying mudstone. The mudstones are thinly laminated, are olive gray (5Y 4/1) weathered, medium dary gray (N 4) fresh. Pseudoconcretions, a spheroidal onion-skin-like weathering phenomenon, are common in the mudstones, and clastic dikes up to two inches wide extend from the sandstone beds and cross-cut the mudstone beds. The mudstones typically weather out in chips 1 inch by 1-1/2 inches.

Bouma sequences observed in the sandstone beds in the lower part of the Northumberland Formation include BCDE, CDE, and DE. These represent a middle to distal or interdistributary turbidite deposit, if the sediments are interpreted as turbidite deposits.

The middle part of the Northumberland Formation is dominated by mudstone, which comprises 85% to 95% of this 745-foot thick interval. Intercalations of siltstone laminae up to 1/2 inch thick, beds of calcareous concretions, and argillaceous limestone beds occur sporadically throughout this part. The siltstones display laminations (up to 14 per inch) and micro-trough cross-laminations, and they form insignificant ribs in the mudstone. Colors are the same as the siltstones of the lower part of the formation. Lower contacts of the siltstones are sharp and planar, whereas upper contacts with the overlying mudstone are gradational over an interval of 1/4 inch. These could possibly represent divisions DE of the Bouma sequence.

The mudstones of the middle part of the formation are non-resistant and weather out in chips 3/4 by 1-1/4 inches. Fresh colors are usually medium gray (N 5), and weathered outcrops are light olive gray (5Y 6/1). The mudstones are laminated, but pseudoconcretions 3 to 20 inches in diameter commonly obscure any sedimentary structures.

Calcareous concretions occur as isolated nodules along bedding planes within the mudstone. They are ellipsoidal in shape and range in length from 6 to 12 inches and in thickness from 2 to 4 inches. The weathered color of the concretions is light gray (N 7), and the fresh color is medium gray (N 5). The concretions are composed predominantly of micrite (a calcareous mud) with a nucleus of sparry calcite crystals, which may be recrystallized fossils.

There are two types of limestone beds that occur in the middle part of the Northumberland Formation. One type is an argillaceous limestone with sharp and planar lower contacts, upper contacts that grade within 1/2 inch into the overlying mudstone, and have a mottled texture. The weathered color is light gray (N 7), whereas fresh samples exhibit a dary gray (N 3.5) color. Beds range in thickness from 5 to 10 inches. The second type of limestone is a sandy argillaceous limestone with sharp and planar lower contacts, thin laminations, and micro-trough cross-laminations. The weathered color is very light gray (N 8); the fresh color is medium light gray (N 6). Beds range in thickness from 1-1/2 to 7-1/2 inches. The sandy limestones are composed of subangular grains of quartz, biotite, and muscovite scattered in a matrix of sparry calcite. Both types of limestones are resistant rib-formers. The calcite appears to be mostly secondary in origin, because most of the detrital grains have been replaced and embayed by the calcite.

The upper unit of the Northumberland Formation resembles the lower in that sandstone and siltstone are more abundant than in the middle part. Mudstone in the upper unit comprises 50% to 70% of the 576-foot thick interval. The upper unit is distinguished by having spherical calcareous concretions up to 3 inches in diameter in the mudstone, and burrows about 1/2 inch in diameter parallel to bedding in the sandstones. The burrows were identified by C.K. Chamberlain (written commun., 1975) as *Thalassinoides*.

The Northumberland Formation, on Saturna Island, can be readily distinguished from the Cedar District Formation by the amount of mudstone. About 90% of the Northumberland Formation is composed of mudstone, while only about 60% of the Cedar District Formation is composed of mudstone. Also, the sandstone beds of the Cedar District Formation are generally thicker and display more complete Bouma sequences than the sandstones of the Northumberland Formation.

Sedimentary structures observed in the Northumberland Formation include laminations, micro-trough cross-laminations, normal grading, clastic dikes up to one inch wide that originate in sandstone beds, pseudoconcretions, load deformations, spherical calcareous concretions, ellipsoidal calcareous concretions, and rare reverse grading from mudstone through siltstone to sandstone within 1/2 inch.

Organic structures found in the formation include horizontal burrows (Thalassinoides), woody debris, one specimen of the pelecypod Mytilus, and one unidentified ammonite.

Lithology. X-ray diffraction analysis of Northumberland Formation mudstones reveals montmorillonite, chlorite, mica, antigorite, kaolinite, mixed layer clays, and possible vermiculite. See Appendix E for the tabulated results of the clay mineralogies and Appendix F for the analytical techniques.

Four thin sections of Northumberland Formation sandstones were examined petrographically. Modal analyses (Appendix D) of two of the samples indicate that the sandstones are compositionally and texturally immature. The sandstones are poorly to moderately sorted, arkosic wackes and calcareous arkosic arenites with angular to subrounded grains (Figure 27). Matrix content ranges from 2.4% to 28.1%, and is composed of detrital and diagenetic clays. The diagenetic clays have been derived from the alteration of feldspars, biotite, and volcanic rock fragments.

Framework grains range in size from medium sand to silt, and are predominantly composed of quartz, plagioclase, orthoclase, biotite, muscovite, and rock fragments. Minor constituents include chlorite, orthopyroxene, clinopyroxene, pyrite, limonite, hematite, magnetite, sphene, epidote, leucoxene, garnet (almandite), and apatite. The dominant plagioclase feldspar is andesine, with minor oligoclase and albite. Kaolinite, sericite, and calcite are common alteration products of the feldspars. Both fresh and altered feldspars are present in all samples, and rare myrmekite intergrowths were observed in some of the feldspars. Biotite and volcanic fragments are commonly altered to chlorite. Sericite is also a common alteration product of volcanic rock fragments. Detrital micas include biotite and muscovite, whereas sericite and chlorite appear to be entirely diagenetic in origin.

Detrital rock fragments include phyllite, schist, greenstone, basalt, and granite.

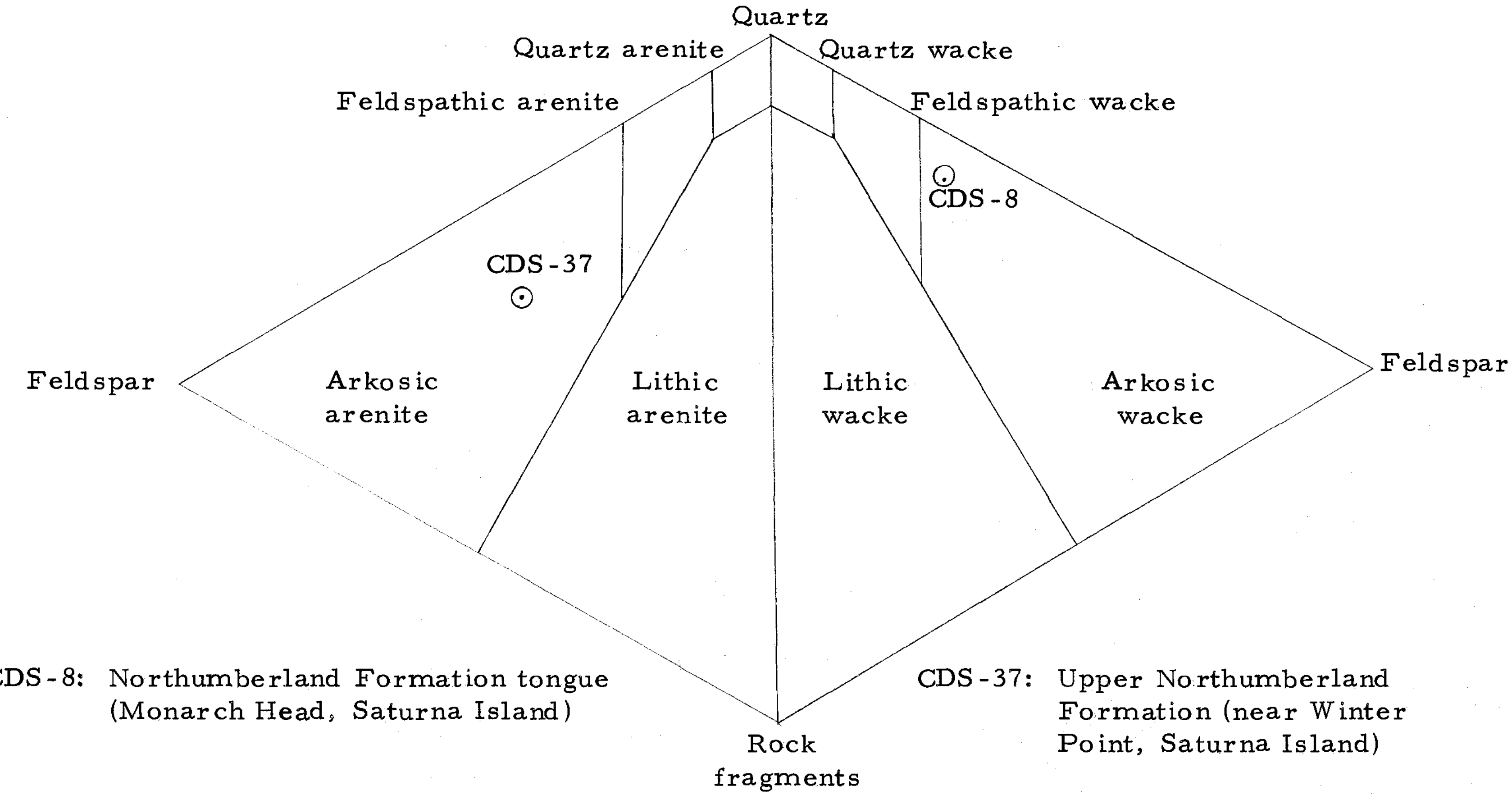


Figure 27. Classification of Northumberland Formation sandstones (after Gilbert, 1954).

The dominant cement in sample CDS-37 is calcite, which accounts for 26% of the sample; whereas, sample CDS-8 is cemented by clays. The calcite of the former sample commonly replaces quartz, chert, and feldspars.

One sample of the bedded calcareous concretions of the Northumberland Formation was examined petrographically. The sample is composed of 85% micritic calcite, 12% silt-sized quartz grains in matrix support, and 3% organic matter derived from plants. Much of the carbonaceous plant fragments has been replaced by pyrite. The concretions exhibit a mottled texture, which may possibly be fecal pellets.

One sample of a bedded argillaceous limestone from the Northumberland Formation was examined petrographically. The argillaceous limestone is composed of 60% micritic calcite, 30% silt-sized quartz, 5% silt-sized muscovite, plagioclase, and potassium feldspar, and 5% black stringy and disseminated organic matter, derived from both plants and animals. Much of the organic matter has been diagenetically replaced by pyrite. The detrital grains lie in both grain support and matrix support. These limestones also exhibit a mottled texture, which may possibly be fecal pellets. These limestones are classified as silty micrites according to Folk's (1959) classification.

<u>Environments of Deposition</u>. The lower and upper parts of the Northumberland Formation are environmentally similar to much of the Cedar District Formation. These sediments were probably deposited on a delta-slope similar to that described by Mazzullo (1973) for the Hamilton Group. The normally graded sandstone-siltstone-mudstone sequences, most of which display incomplete Bouma sequences, were probably formed as turbidities, although this cannot be demonstrated conclusively. These deposits could also have been formed during seasonal flooding as described on the Fraser River delta by Johnston (1922).

The middle part of the formation, which is composed predominantly of mudstone, probably represents a prodelta environment such as described by Visher (1965), Coleman and Gagliano (1965), Gould (1970), and Mazzullo (1973). According to these authors, sediments deposited in the prodelta environment are composed of a thick sequence of silty clays or muds with silty parallel and lenticular laminations. Coleman and Gagliano (1965) state that the silt laminations become thinner and less abundant in the seaward direction.

The overall sequence of the Northumberland Formation depicts a gradual transition from the thick shallow marine sandstones of the DeCourcy Formation to thin bedded delta-slope sandstone-siltstone-mudstone sequences and into the deeper marine mudstones of a prodelta environment. The sequence is reversed farther upsection, and the laminated prodelta mudstone sequence grades upward through the thin bedded delta-slope facies of the upper part of the formation and into the thick shallow marine sandstones of the overlying Geoffrey Formations. This sequence can be explained as the product of channel abandonment, shifting the deposition of coarser clastic particles elsewhere, followed by another distributary shift, bringing the deposition of coarser clastic particles back to the area. Other factors which may have contributed to this sequence are variations in the rate of basin subsidence, tectonic events in the source area, or possibly major fluctuations in sea level.

Geoffrey Formation

Nomenclature. The thick sandstones and conglomerates of Mt. Geoffrey on Hornby Island in the Comox Basin were named the Geoffrey Formation by Usher (1952). Muller and Jeletsky (1970) correlated the Geoffrey Formation of the Comox Basin with the laterally equivalent middle sandstone and conglomerate member of the Northumberland Formation in the Nanaimo Basin described by Clapp (1911). The middle member is now named the Geoffrey Formation in order to standardize the nomenclature between the two basins.

General Stratigraphy. The Geoffrey Formation is found at two localities on Saturna Island. The 1,050-foot high peak and cliffs 1,300 feet north of Mt. Fisher are held up by the formation. The entire north coastline of Saturna Island from Winter Point to East Point, except for a small tongue of Spray Formation, is composed of Geoffrey strata. Mt. David and Mt. Elford are supported by the resistant rocks of the formation (Plate 1 and Figure 28), and sea cliffs carved in the formation, as high as 150 feet, are exposed from Fiddler's Cove to East Point. These cliffs have been formed on the anti-dipslope of the strata, so the water is extremely deep at the foot of the cliffs, making much of the area inaccessible by foot. Cormorants of the area use these cliffs as nesting grounds, and in places the cliffs have been stained white by the guano.

No section of the Geoffrey Formation was measured and described because of the lack of control and adequate exposure. At Winter Point, the thickness is at least 50 feet, but the strata dip below sea level. Directly to the east, however, the formation thickens markedly as a result of intertonguing with the Northumberland Formation (Plate 1). The maximum thickness, which was calculated trigonometrically, occurs at Mt. David and is about 2,000 feet. Hudson (1974) measured and described a section of Geoffrey Formation on North Pender Island, the thickness there being 1,650 feet.

The lower contact of the Geoffrey Formation with the Northumberland Formation at Winter Point has been described in the previous section. The intertonguing relationship between the Geoffrey and Northumberland Formations northwest of Mt. David has been

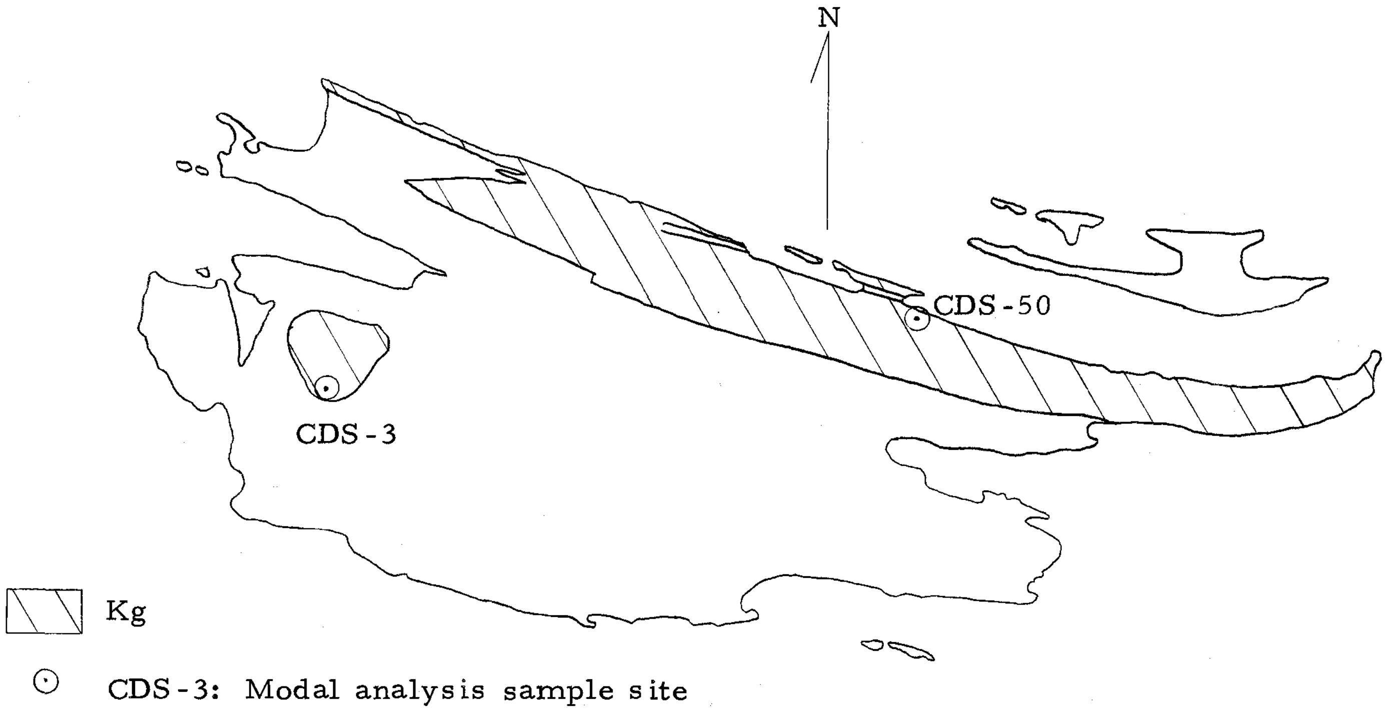


Figure 28. Geoffrey Formation distribution and sample sites for modal analyses.

mentioned previously, but not explained. In this area (Plate 1) the Geoffrey Formation consists of two tongues that extend westward into and terminate within 1/2 mile in the Northumberland Formation. This intertonguing probably was caused by distributary channel abandonment and migration, which resulted in a cessation of coarse clastic deposition and gradual marine transgression of finer clay clastics. Other factors which may have contributed to this relationship include variations in the rate of basin subsidence, tectonic events in the source area, and major fluctuations in sea level. The upper contact of the Geoffrey with the overlying Spray Formation is nowhere exposed on Saturna Island, the contact lying somewhere below sea level along the north shore.

The Geoffrey Formation is composed predominantly of medium- to coarse-grained, poorly to moderately sorted sandstone with angular to subrounded grains. The sandstones are commonly bedded (1/2 inch to 15 feet thick) and generally display parallel laminations. Other sedimentary structures observed include rib-and-furrow, festoon cross-beds, convolute bedding, crude normal grading from coarse- to medium-grained sand in the thick sandstone beds, spherical calcareous concretions up to 3 feet in diameter, and mudstone ripups to 3 feet in length. The weathered colors range from grayish orange (10YR 7/4) to yellowish gray (5Y 7/2), whereas fresh surfaces are usually light gray (N 6) in color.

The beds of Geoffrey Formation sandstone are separated by mudstone partings up to three feet thick. The mudstones are all finely laminated and contain laminae of siltstone. The mudstone is non-resistant and weathers out in chips 1/4 by 1 inch. Weathered colors range from olive gray (5Y 4/1) to light olive gray (5Y 6/1), whereas fresh colors are always medium dark gray (N 4). Upper and lower contacts of the mudstone intervals with the thinner sandstone beds are most commonly sharp and planar.

Conglomerates are rare in the Geoffrey Formation on Saturna Island. The only conglomerate found is located on the south side of Mt. Elford where it consists predominantly of pebbles of chert, quartzite, and basalt, up to one inch in diameter, suspended in a matrix of medium-grained sandstone. The conglomerate is localized in a channel twelve feet wide and three feet deep, that shows elongation in a northwest-southeast direction. Sedimentary structures observed in the channel include scour-and-fill, normal grading of the pebbles, and pebble elongation (elongate in a northwest-southeast direction).

A subaqueous debris flow in the Geoffrey Formation crops out in the cliff directly east of the East Point lighthouse. The outcrop consists of blocks of mudstone ranging in size from one inch to over three feet in diameter suspended in a matrix of structureless medium- to coarse-grained sandstone. The mudstone clasts display no preferred orientation and are rounded, but show no obvious signs of having been transported any great distance. Mudstone is non-resistant and tends to break into smaller pieces when transported very far in a turbulent medium.

Organic structures observed in the Geoffrey Formation include vertical and horizontal burrows (Thalassinoides) and carbonaceous plant debris.

Weathering features of the Geoffrey Formation that are common to the wave and spray zone include honeycomb weathering wave-cut notches (galleries) (Figure 30), and calcareous knobs (concretions) up to three feet in diameter.

Lithology. Three thin sections of Geoffrey Formation sandstones were examined petrographically. Modal analyses (Appendix D) were performed on two of the samples. The results indicate that the sandstones are texturally and compositionally immature arkosic arenites and arkosic wackes, with matrix contents that range from 8.8% to 14.9% (Figure 31). The clays appear to be dominantly derived from diagenetic alteration of biotite, feldspars, and volcanic rock fragments. Detrital clays less commonly were observed.

The framework grains of the Geoffrey Formation sandstones are mainly quartz, plagioclase, orthoclase, biotite, chlorite, muscovite, clinopyroxene, orthopyroxene, hornblends, and rock fragments. Minor constituents include pyrite, hematite, magnetite, sphene,

Figure 29. Sharp and concordant contact between the Northumberland Formation and the overlying Geoffrey Formation at Winter Point.

Figure 30. "Gallery" or wave-cut notch in the Geoffrey Formation sandstone cliffs below the East Point lighthouse. The cliff is approximately 50 feet high.

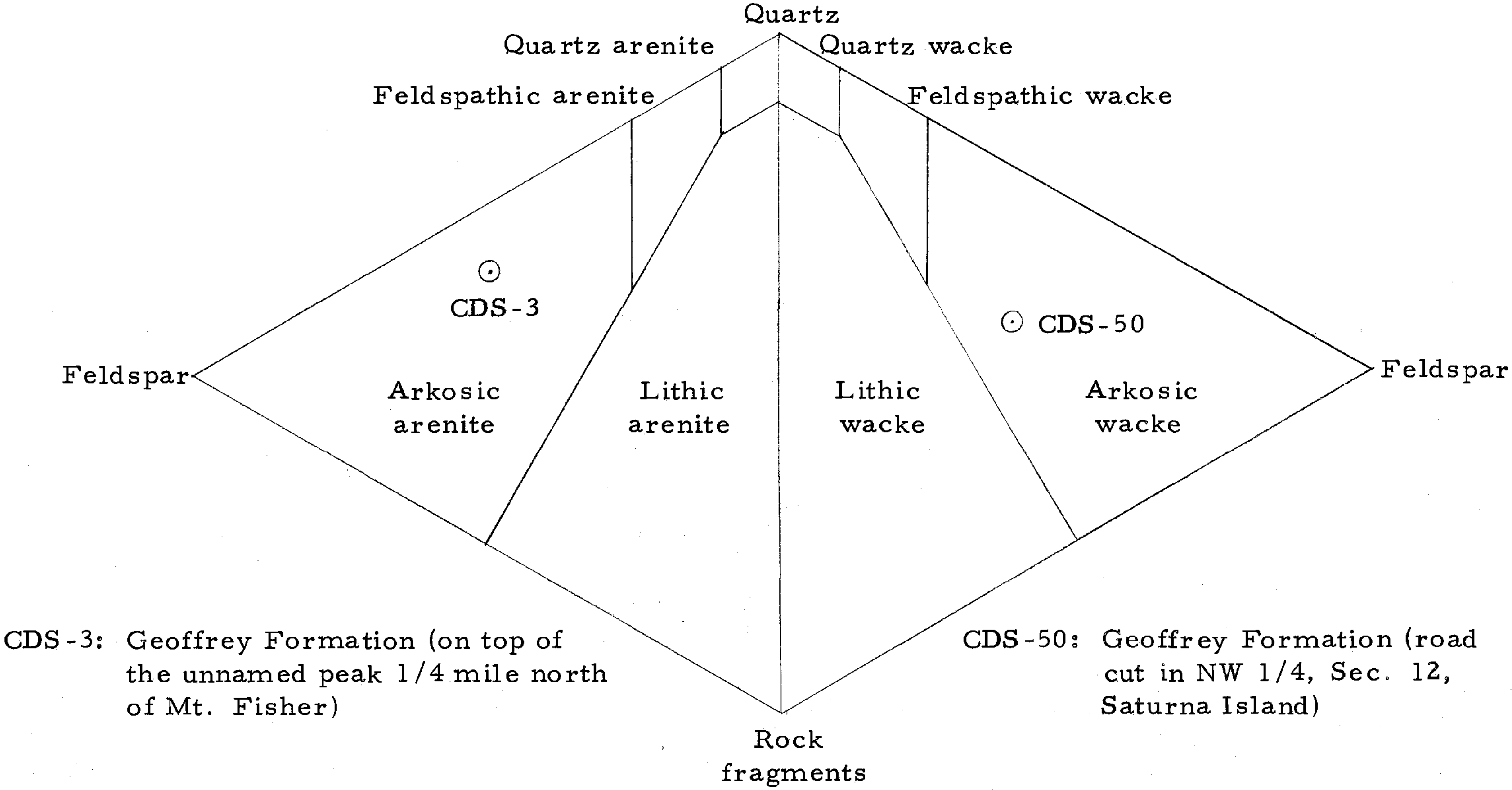


Figure 31. Classification of Geoffrey Formation sandstones (after Gilbert, 1954).

epidote, garnet (almandite), and apatite. Types of plagioclase include andesine and minor oligoclase and albite. Rare myrmekite intergrowths were observed in some of the feldspar grains. Common alteration products of the feldspars include sericite and kaolinite; however, both fresh and altered feldspars were observed. Volcanic rock fragments frequently have been altered to chlorite and sericite, and biotite often has been altered to chlorite or magnetite.

Rock fragments found in the Geoffrey Formation sandstones include phyllite, schist, gneiss, basalt, greenstone, sandstone, polycrystalline quartz, and chert.

The cementing agents in all sandstone samples are clays which are dominantly diagenetic and less commonly detrital in origin. Calcite or quartz overgrowths were not observed in any of the samples.

The one mineral that distinguishes the Geoffrey Formation from the DeCourcy Formation is hornblende. Hornblende occurs in amounts up to 1% in the Geoffrey Formation, whereas none was observed in any of the 10 petrographic thin sections of the DeCourcy sandstones.

Environments of Deposition. The petrology, sedimentary structures, intertonguing relationship with marine mudstones, and arcuate shape of the thick-bedded sandstones of the Geoffrey Formation, which resemble those of the DeCourcy Formation, are interpreted as channel-mouth bar deposits similar to those described by Mazzullo (1973) from the Hamilton Group. Modern deposits that are environmentally similar to the sandstones of the Geoffrey Formation occur on the Mississippi River Delta and are called delta-front sheet sands (Gould, 1970) and distributary mouth bars (Coleman and Gagliano, 1965). Allen (1970) has described such deposits from the modern Niger River delta and calls them river mouth bars.

One submarine slump deposit in the Geoffrey Formation was observed in the sea cliffs below the East Point lighthouse. According to Terzaghi (1962), these features are commonplace on the modern Fraser River delta front.

The general textural immaturity of the Geoffrey Formation sandstones suggests that the sediments were deposited and buried rapidly with little reworking, abrasion, or sorting of the grains. The abundance of polycrystalline quartz and rock fragments further supports the idea of a short history of transportation and reworking. The presence of fresh feldspars and chemically unstable rock fragments implies rapid mechanical erosion in high relief source area. Slow chemical weathering tends to alter and destroy all feldspars and rock fragments. Pyrite in the sandstones indicates that the Geoffrey Formation was, in part, formed under reducing conditions (Krauskopf, 1967).

Spray Formation

Nomenclature. The Spray Formation was the name applied by Usher (1952) to the mudstones cropping out in Tribune Bay on southeast Hornby Island. Muller and Jeletsky (1970) correlated the Spray Formation of the Comox Basin with the upper mudstone member of the Northumberland Formation in the Nanaimo Basin described by Clapp (1911), and redefined the upper mudstone member as the Spray Formation.

General Stratigraphy. The Spray Formation is a non-resistant, predominantly mudstone unit. It is exposed on Saturna Island as tongues within the Geoffrey Formation, which occupy small coves along the north shore (Plate 1 and Figure 32). Exposures of the Spray Formation are located in the northwest corner of section 12, the southeast and southwest corners of section 15, and during low tides at Russell Beach in the northeast corner of section 15. The Spray Formation, although not exposed, has been interpreted to be underlying the low-lying, swampy tombolo of Tumbo Island.

The lower contact of the Spray Formation is best exposed at Russell Beach during low tide. The contact here is gradational and shows an intertonguing relationship with the Geoffrey Formation. There is an overall upward increase in the amount of mudstone, and the sandstone beds become progressively thinner and less abundant

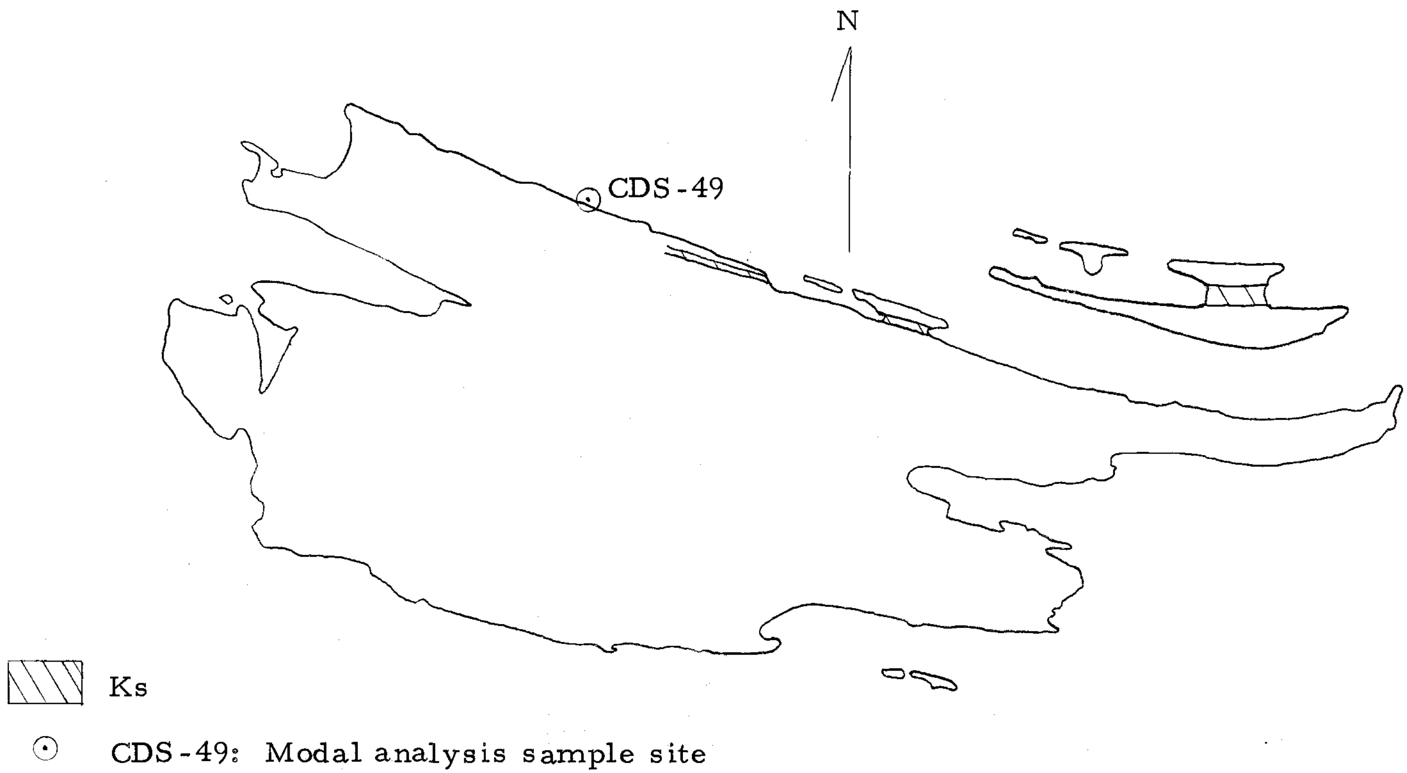


Figure 32. Spray Formation distribution and sample site for modal analysis.

upsection. The upper contact of the Spray Formation with the overlying Geoffrey Formation sandstone is best exposed in the small cove in the southwest quarter of section 15 on Saturna Island. At this locality, the contact is gradational and exhibits an intertonguing relationship. The sandstone beds increase in thickness upward and the mudstone beds become thinner.

The Spray Formation, as in the cases of the Cedar District and Northumberland Formations, is composed predominantly of mudstone (at least 60%). The weathered color of the mudstone is usually light gray (N 7), whereas the fresh color is commonly medium dark gray (N 4). The mudstone beds range in thickness from 1 to 10 inches and are as a rule thinly laminated. The mudstone is non-resistant and weathers out into 1/4 by 1/4 inch chips, obscuring any sedimentary structures that might be present. The upper contacts of the mudstone beds with the overlying sandstones or siltstones are usually sharp and planar, but locally load deformations and flames are present. The orientation of flames indicate a west to northwest paleoslope.

Interbedded with the mudstones of the Spray Formation are very fine-grained and moderately well to well sorted sandstones. They are resistant rib-formers that range in thickness from 1 to 12 inches, and most commonly display festoon cross-laminations. Other sedimentary structures observed in the sandstones include parallel laminations, spherical calcareous concretions up to two inches in diameter, and normal grading. The upper contacts of the sandstone beds usually grade within four inches through siltstone into the overlying mudstone. Repeated graded beds occur throughout the tongues of the Spray Formation. Most of the graded beds display incomplete Bouma sequences BCDE, CDE, or DE, where B is the lower parallel laminated sandstone, C is the micro-trough cross-laminated sandstone, D is parallel laminated siltstone, and E is mudstone.

The siltstones of the Spray Formation are similar in all respects, except for grain size, to the mudstones.

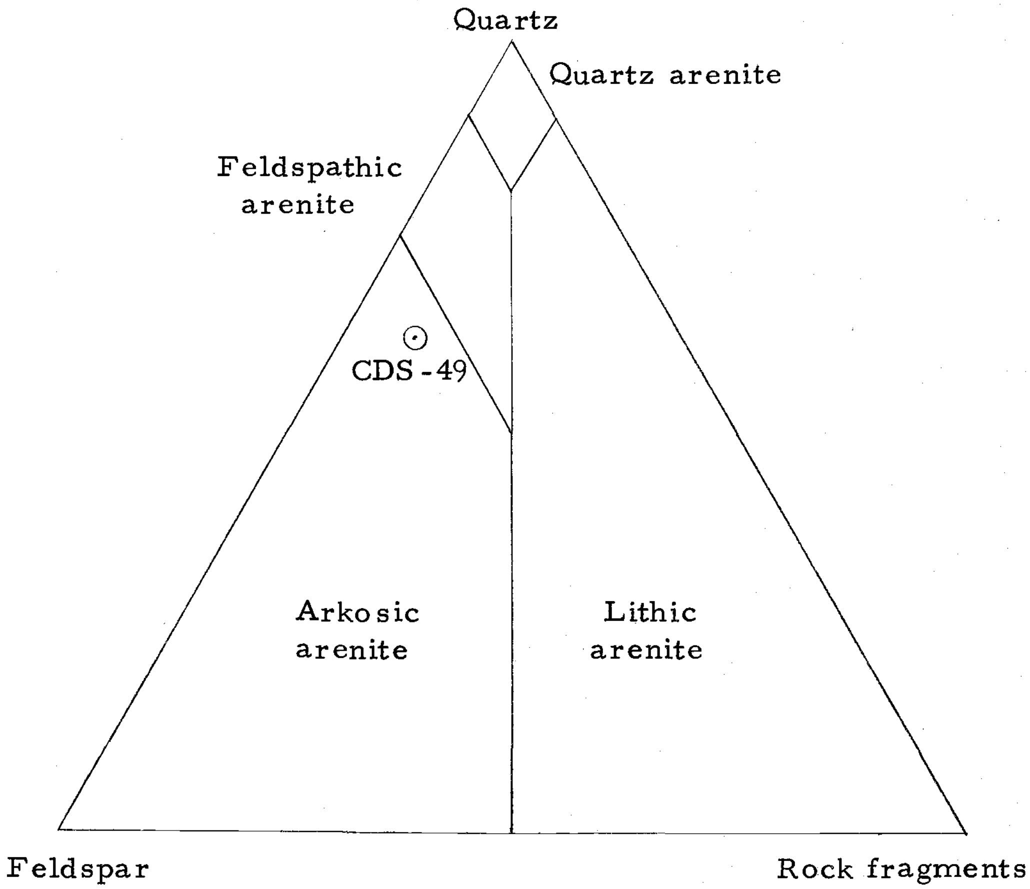
The thickness of the tongue of the Spray Formation in section 15 is about 40 feet. The total thickness of the Spray Formation in the locality of Saturna Island is unknown, because it is not completely exposed and probably underlies the waters of Tumbo Channel. Packard (1972) measured and described the Spray Formation on Gabriola Island and determined a thickness of 333 feet. Hudson (1974) measured and described the Spray Formation on North Pender Island, four miles west of Saturna Island, and determined a thickness of 797 feet. The Spray Formation evidently thickens to the southeast, so the formation between Saturna and Tumbo Island is probably about 800 feet thick.

Organic structures observed in the Spray Formation are vertical and horizontal burrows (Thalassinoides) and carbonaceous plant debris.

Lithology. X-ray diffraction analysis of Spray Formation mudstones reveals montmorillonite, chlorite, vermiculite, mica, kaolinite, and a mixed layer clay. See Appendix E for the tabulated results of the clay mineralogies and Appendix F for the analytical techniques.

One sample of Spray Formation sandstone was examined petrographically, and a modal analysis (Appendix D) was performed on it. The results indicate that the sandstones are texturally submature and compositionally immature. The sandstones are moderately well sorted, angular to subrounded, arkosic arenites with angular to subrounded grains and matrix content of 4.6% (Figure 33). The clay matrix appears to be predominantly detrital with a trace amount that has been derived from diagenetic alteration of feldspars, biotite, and volcanic rock fragments.

The framework grains range in size from very fine-grained sand to silt, and are predominantly composed of quartz, plagioclase, orthoclase, biotite, muscovite, pyrite, and rock fragments. Minor constituents include orthopyroxene, clinopyroxene, limonite, hematite, magnetite, zircon, and sphene. The dominant plagioclase feldspar is andesine, with minor oligoclase and albite. Kaolinite, sericite, and calcite are common alteration products of the feldspars. Both fresh and altered feldspars are present. The plagioclase in the volcanic rock fragments is commonly altered to sericite. Chlorite is



CDS-49: Spray Formation (Russell Beach, Saturna Island)

Figure 33. Classification of Spray Formation sandstones (after Gilbert, 1954).

a common alteration product of biotite and volcanic rock fragments. Detrital micas include biotite and muscovite, whereas, sericite and chlorite appear to be entirely diagenetic in origin.

Detrital rock fragments of the Spray Formation sandstones include basalt, greenstone, and phyllite.

Calcite cement in the Spray Formation sandstones comprises 25.7% of the total sample. The calcite, in many places, has embayed or completely replaced grains of quartz, chert, and feldspar.

Environments of Deposition. As mentioned previously, the Spray Formation is exposed only as tongues within the Geoffrey Formation. The repetitively interbedded sandstone-siltstone-mudstone sequences, some of which display incomplete Bouma sequences, resemble those of the upper Cedar District Formation. The bottoms of sandstone beds display no markings characteristic of turbidite deposits, and graded beds alone are suggestive but are not sufficient evidence to confirm turbidite deposition. The repeated graded beds were not necessarily deposited as turbidites, and may have been deposited in a delta-slope facies or proximal prodelta facies in much the same manner as the foreset and bottomset beds of the Fraser River delta described by Johnston (1922).

Thin section analysis and sedimentary structures of the sandstones indicates that the sediments were reworked and sorted by relatively weak traction currents. The fact that these sedimentary rocks grade vertically into shallow marine sandstones of the Geoffrey Formation indicates that the Spray Formation tongues were deposited in a shallow marine environment.

The occurrence of pyrite in the sandstones and mudstones indicates that the sediments were deposited, in part, under reducing conditions (Krauskopf, 1967).

Gabriola Formation

Nomenclature. The name Gabriola Formation was used by Clapp (1911) for the sandstones and conglomerates that cover much of Gabriola Island. The laterally correlative sandstones and conglomerates exposed at St. John Point, on Hornby Island in the Comox Basin, were called the St. John Formation by Williams (1924) and were renamed Hornby Formation by Usher (1952). Williams, however, used the name Hornby for a stratigraphically lower sandstone-conglomerate formation. Because of the ambiguities associated with the names St. John and Hornby Formation, Muller and Jeletsky (1970) proposed that the uppermost sandstone-conglomerate unit of both the Nanaimo and Comox Basins be called the Gabriola Formation.

General Stratigraphy. The Gabriola Formation is a resistant cliff- and mountain-forming sandstone-conglomerate unit In the thesis area, it is exposed only on Tumbo Island, Cabbage Island, and Pine Islets (Plate 1 and Figure 34).

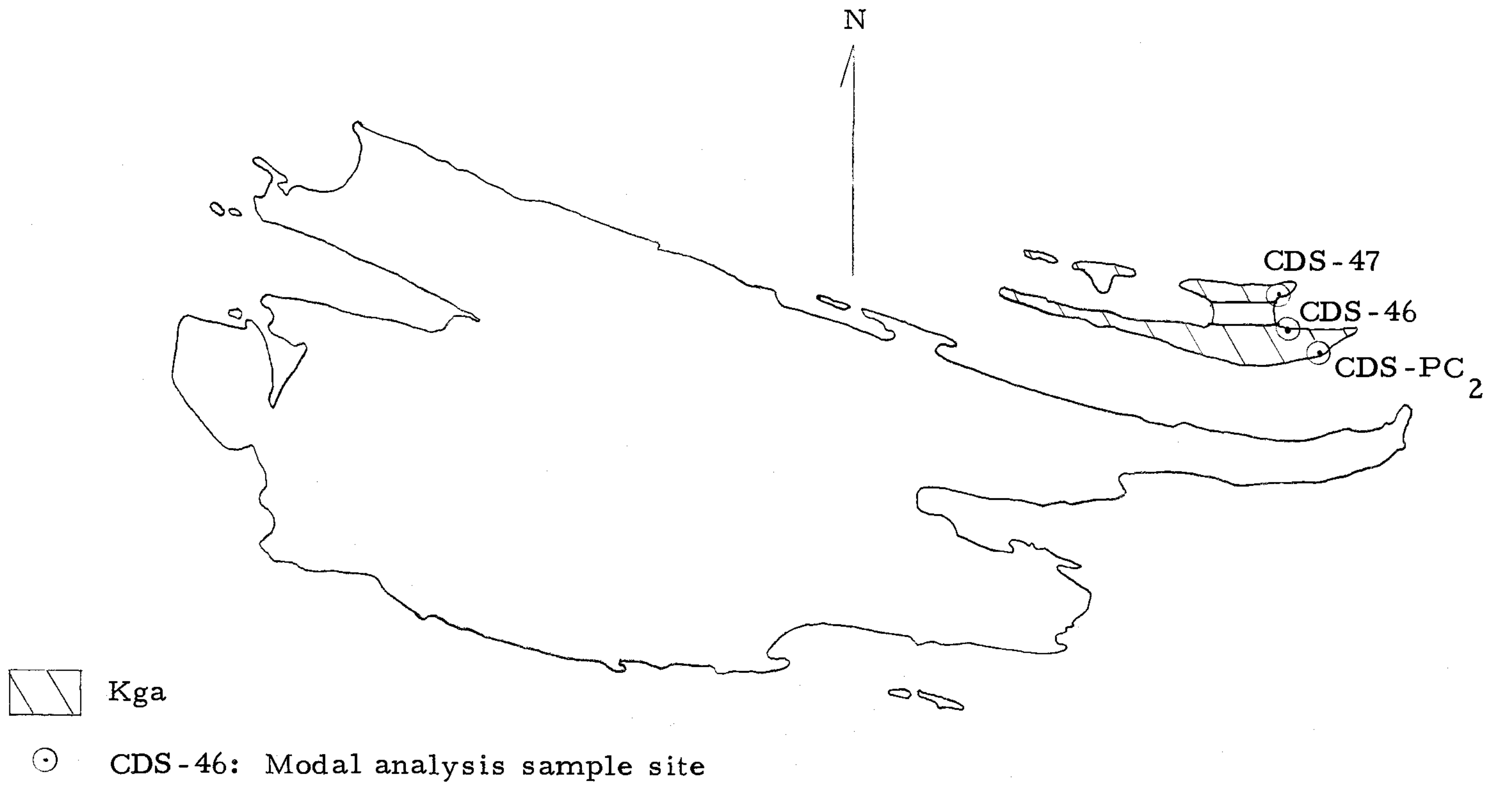


Figure 34. Gabriola Formation distribution and sample sites for modal analyses and pebble counts.

The lower contact of the Gabriola Formation with the underlying Spray Formation is nowhere exposed in the thesis area and probably lies below sea level in Tumbo Channel. Packard (1972) noted that the contact of the Gabriola and Spray Formations on Gabriola Island is remarkably sharp and planar. The upper contact also is not exposed on Tumbo Island and presumably lies beneath the waters of the Strait of Georgia.

The Gabriola Formation is composed predominantly of coarse- to fine-grained sandstones and conglomerates. The sandstones are usually well bedded, ranging from four inches to over five feet in thickness, and the dominant sedimentary structure is festoon cross-bedding. Nearly spherical calcareous concretions, up to four feet in diameter, project as knobs on weathered surfaces. Parallel laminations and less commonly contorted laminations occur in the fine-grained sandstone beds. Load casts, flames, and scour-and-fill occur at the contacts of coarse-grained sandstone and the underlying fine-grained sandstone. Normal grading from coarse-grained sandstone below to overlying fine-grained sandstone is common to most beds. The colors of weathered outcrops range from grayish orange (10YR 6/4) to yellowish gray, whereas fresh samples range in color from light olive gray (5Y 6/1) to light gray (N 7).

The southern shoreline of Tumbo Island is composed of channel conglomerates that display festoon cross-bedding, scour-and-fill, and normal grading upward into coarse-grained, festoon cross-bedded sandstones (Figure 35). Associated with these conglomerates are channel sandstones that also exhibit festoon cross bedding and scour-and-fill contacts.

The entire northern shoreline of Tumbo Island is composed of a thick, structureless pebble conglomerate. Pebble elongation was noted and the bidirectional paleocurrent direction indicated was north-south. Clasts range in size up to 12 inches and are composed predominantly of basalt, granodiorite, quartzite, and chert. For a more detailed breakdown of clast lithologies see Appendix E.

No section of the Gabriola Formation was measured and described because of the lack of proper control, the top and bottom of the formation not being exposed in the thesis area. Several samples, however, were obtained for thin-section analysis, and two were point counted. See Appendix D for the mineralogy of these samples.

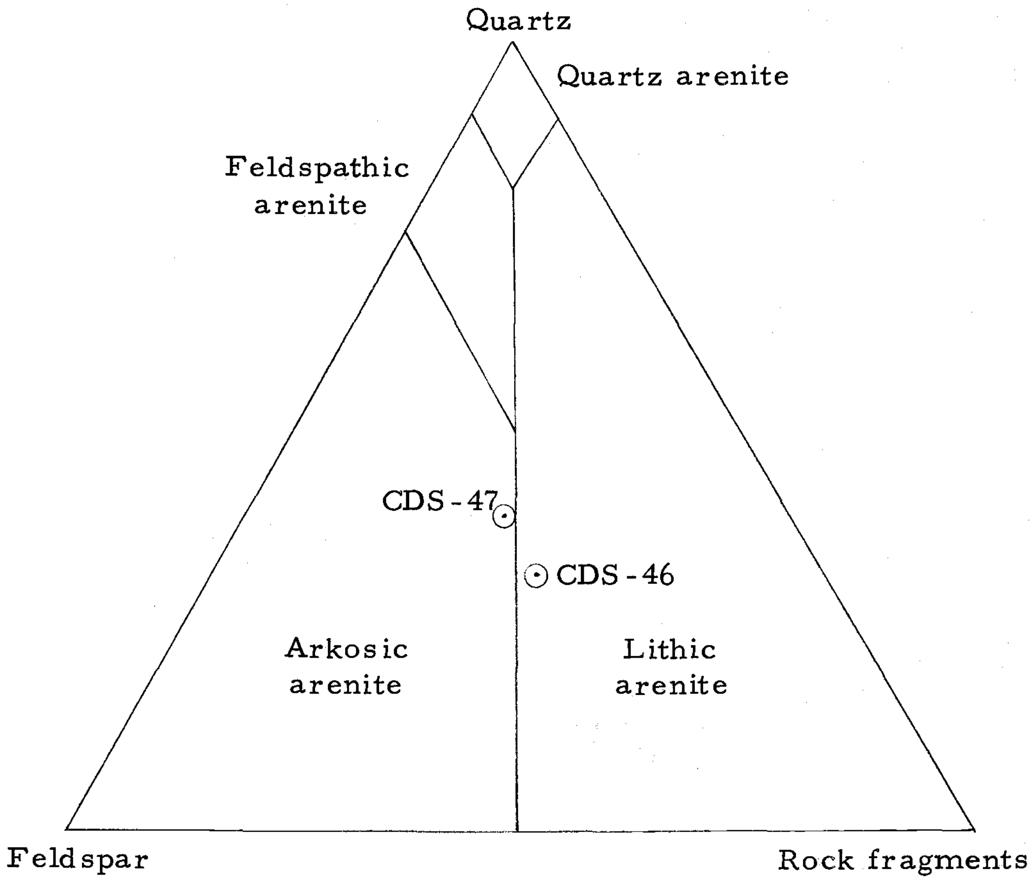
The weathering expression of the Gabriola Formation is similar to that of the Geoffrey Formation. Sea cliffs up to 125 feet high have been formed on the anti-dipslope of the formation, along the southern coastline of Tumbo Island. Where the steep cliffs intersect the water, there is no wave-cut bench, and deep water lies immediately at the foot of the cliffs. In the wave and spray zones honeycomb weathering, wave-cut notches or galleries (Figure 35), and calcareous concretions that project as resistant knobs have been formed.

Figure 35. Wave-cut notch in the cliffs of the Geoffrey Formation sandstones and conglomerates on the south shore of Tumbo Island. Note the festoon cross-bedding of the conglomerates and sandstones and the scour-and-fill structures.

Lithology. Pebbles from the lower part of the Gabriola Formation were collected from conglomerate outcrops along the southeastern coastline of Tumbo Island. A pebble count of the samples collected indicates that basalt, granodiorite, quartzite, and chert are the most abundant clasts in the conglomerates. Minor pebble litholigies include gabbro, andesite, greenstone, rhyolite, and gneiss. For a complete tabulation of the pebble count, see Appendix E.

Three thin sections of Gabriola Formation sandstones were examined petrographically. Modal analyses (Appendix D) were performed on two of the samples. The results indicate that the sandstones are texturally and compositionally immature, calcareously cemented, arkosic and lithic arenites (Figure 36), with matrix contents of about 2.3% and porosities that range from 0.6% to 4.0%. The clay matrix appears to be formed from the diagenetic alteration of biotite, feldspars, and volcanic rock fragments.

Framework grains of the Gabriola Formation sandstones are dominantly quartz, plagioclase, orthoclase, biotite, hornblende, magnetite, and rock fragments. Minor constituents include orthopyroxene, clinopyroxene, muscovite, pyrite, hematite, sphene, epidote, garnet (almandite), and apatite. Types of plagioclase feldspar include andesine with minor oligoclase and albite. Rare myrmekite intergrowths were found in some of the feldspar grains. Common alteration products of the feldspars include sericite and kaolinite;



CDS-46: Middle Gabriola Formation (west of Tumbo Point, Tumbo Island)
CDS-47: Upper Grbriola Formation (southwest of Savage Point, Tumbo Island)

Figure 36. Classification of Gabriola Formation sandstones (after Gilbert, 1954).

however, not all feldspars have been altered. Chlorite and sericite are common alteration products of the volcanic rock fragments, and biotite commonly has been altered to chlorite.

Rock fragments found in the Gabriola Formation include basalt, greenstone, schist, phyllite, sandstone, gneiss, polycrystalline quartz, and chert.

The cementing agent in all sandstones of the Geoffrey Formation is calcite, which accounts for from 19.3% to 24.3% of the total rock composition. Calcite, in many places, has partially replaced grains of quartz, chert, and feldspar.

Environments of Deposition. The Gabriola Formation was deposited in a variety of environments. The lower part of the formation, which is composed of festoon cross-bedded conglomerates and sandstones, with normal grading, was probably deposited in fluvial, point bar, and levee environments. The sorting and vertical succession of sedimentary structures is similar to those of the fluvial model as described by Visher (1965). According to Visher, these deposits display grading from the channel geavels upward through coarse- and medium-grained sandstone, and into fine-grained sandstone. The vertical succession of sedimentary structures is: sand waves or trough cross-bedding; current laminations; and fine ripple cross-laminations.

Overlying the fluvial sequence is a sequence of thick-bedded sandstones that display festoon cross-bedding. This section closely resembles the thick-bedded sandstones of the DeCourcy and Geoffrey Formations and also is similar to the Hamilton Group channel-mouth bar facies described by Mazzullo (1973). Beach and dune deposits have similar sedimentary structures, but a beach is a very narrow and restricted environment, and the deposits of the Gabriola Formation are too widespread. Also beach gravels display a higher degree of sorting. The sediments of a dune are more highly sorted, are compositionally more mature and are finer-grained than these sandstones. Modern analogs in the Mississippi River delta complex have been called delta-front sheet sands (Gould, 1970) and distributary mouth bars (Coleman and Gagliano, 1965).

Overlying the channel-mouth bar sandstones is an extensive covered interval. The covered interval is overlain by shallow marine, river-mouth bar sandstones, that are similar to those described previously. Because the covered interval lies stratigraphically between marine sandstones, it is interpreted as a tongue of marine Spray Formation.

Thick conglomerates overlie the marine sandstones. The tight packing, poor sorting, and large size of the well-rounded clasts suggests rapid deposition in a high energy fluvial environment. These laterally extensive and apparently nearly horizontally deposited conglomerates resemble those described by Wilkinson and Oles (1968) at topset beds in the deltaic Cretaceous Gable Creek Formation of central Oregon.

The general textural immaturity of the Gabriola Formation sandstones in thin section suggests rapid deposition with little or no evidence of reworking and abrasion. The presence of fresh feldspars indicates rapid mechanical erosion of a nearby source area, rapid deposition and rapid burial with little reworking of the grains. The abundance of polycrystalline quartz and rock fragments and the angularity of most of the grains further support a close source area and rapid deposition of the grains. The low matrix content of the sandstones, however, indicates either that the currents which deposited the sediments were selective or that the sediments were winnowed after deposition. The calcite appears to be a pore-filling cement and an alteration product, because many of the quartz, chert, and feldspar grains have been embayed and partially replaced by the calcite.

The occurrence of pyrite in one of the sandstones indicates that the Gabriola Formation was, in part, deposited under reducing conditions (Krauskopf, 1967).

The intertonguing relationship of the Gabriola Formation with the Spray Formation was probably the result of normal distributary channel abandonment, diverting the deposition of coarser sediments to another part of the delta. Other factors possibly contributing to this phenomenon are changes in the rate of basin subsidence, tectonic events in the source area, or eustatic changes in the sea level.

STRUCTURAL GEOLOGY

Regional Structure

Early investigators (Richardson, 1872, 1878; Clapp, 1914; Clapp and Cooke, 1917) considered folds to be the major structural features, with faults being subordinate to the folding. Recent workers (Buckham, 1947; Sutherland-Brown, 1966; Muller and Carson, 1969; Muller and Jeletsky, 1970) suggest that faults are the primary features with folding being subordinate features that are the result of drag related to the faulting.

Clapp (1914) described the structure as broad, open folds trending northwest-southeast. He suggested that compressional forces acted from the northeast because of the steeper northeast flanks of folds. He also believed that the folding occurred in post-Eocene time, but later investigations show that the time of folding may have been as early as Paleocene (Buckham, 1947).

Clapp and Cooke (1917) were the first to name the major folds of the Nanaimo Basin. They are, from northeast to southwest, Trincomali Anticline, Channel Syncline, Thetis Anticline, and Kulleet Syncline.

Buckham (1947), Sutherland-Brown (1966), and Muller and Jeletsky (1970) all believe that the faulting of the Nanaimo Group rocks is controlled by pre-existing faults of the basement complex.

Faluting is more abundant in the southern Gulf Islands (Muller and Jeletsky, 1970) which include Saturna Island.

Areal Structure

The structure of Saturna and Tumbo Islands is relatively simple (Plate 1, Figure 37). Tumbo Island has only low angle homoclinally north-dipping strata, whereas Saturna Island has one syncline (the Kulleet Syncline) and two major fault systems. There are many smaller faults throughout Saturna Island, most of which are related to the major fault systems or to the syncline.

Muller and Jeletsky (1970) accurately located the syncline, but were in error in the location of certain faults. For example, they ascertain there is a fault that trends north-south from Trueworthy Bight to Russell Reef. There is a fault present at Trueworthy Bight, but it continues only as far as Lyall Harbor. Muller and Jeletsky assumed that, because the Northumberland Formation laterally abuts the Geoffrey Formation, west of Mt. David, there must be a fault separating them. On the contrary, the Northumberland Formation intertongues with the Geoffrey Formation here, and there is no fault (Plate 1).

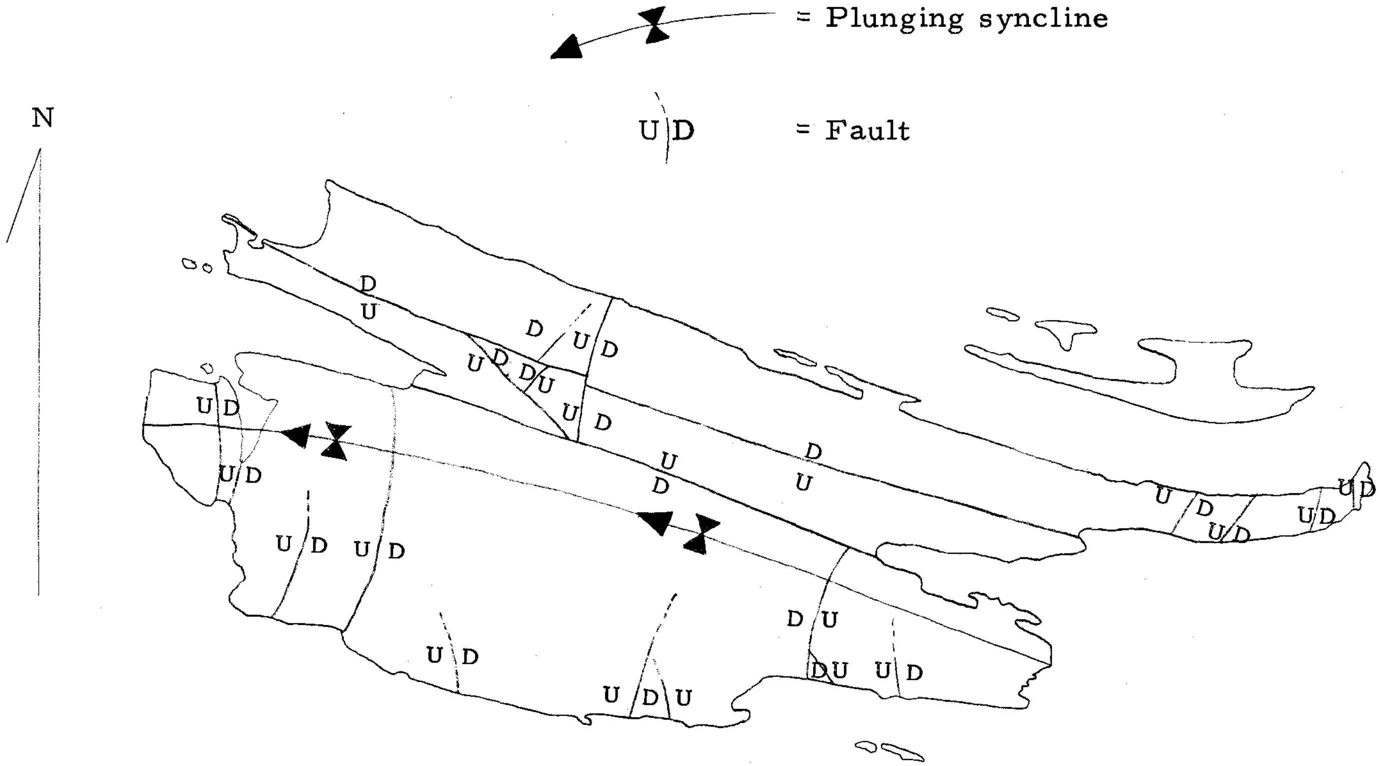


Figure 37. Tectonic framework of Saturna and Tumbo Islands, B.C.

Faults

Faults on Saturna Island were recognized by 1) termination of normally continuous strata, 2) juxtaposition of normally separated strata, 3) fracture zones in the sandstone, 4) dragged and warped strata, 5) lineations on aerial photographs, 6) troughs and valleys which cross-cut resistant formations, and 7) repetition of stratigraphy.

The two major faults on Saturna Island closely parallel each other and trend west-northwest. The larger of the two faults is located in the Lyall Creek valley. It extends from Lyall Harbor to Navaez Bay. It may be an oblique slip fault, with an apparent vertical displacement of at least 2,500 feet, and a right lateral strike-slip component of nearly one mile, or it may be a high angle reverse fault. If the latter is the case, the north block was uplifted relative to the south block. The displacement of the fault can only be hypothesized because of the lack of exposure near the fault, but work by more recent geologists (Muller and Carson, 1969; Muller and Jeletsky, 1970) indicate that the first hypothesis is more valid. I will refer to this fault as the Lyall Creek fault. The other major fault, a near vertical fault, extends from Mikuni Point to Fiddler's Cove. A fault-line scarp present on the southwest side of Mt. David, carved in resistant Geoffrey Formation sandstone, shows the reverse nature of the fault. The fault has created a zone of weakness, and weathering and erosion along the trace of the fault has created a trough from Mt. David to Fiddler's Cove. The fault, in this area, juxtaposes the DeCourcy Formation with the Geoffrey Formation, and the entire Northumberland Formation is missing from the section. The total vertical displacement is about 800 feet, with the south block having been uplifted relative to the north block.

There are several minor faults approximately perpendicular to the major faults, which trend north to north-northeast. One fault discussed above trends north from Trueworthy Bight to Lyall Harbor. It separates Mt. Fisher from Mt. Warburton Pike, and is marked by a valley through the DeCourcy Sandstone. The west block was uplifted relative to the east block with a vertical displacement of about 570 feet.

Separating Mt. David from Mt. Elford is a fault very similar to the one that separates Mt. Fisher from Mt. Warburton Pike. It has a similar displacement and relative movement. These two faults well may be the same fault, but displaced by the right lateral strike-slip movement of the younger Lyall Creek fault.

Drag along the north-trending faults which extend to Bruce Bight, on the south shore of Saturna Island, has created distorted bedding and warped strata. Normal faulting or possibly strike-slip faulting from Breezy Bay to Saturna Point has created Boot Cove by moving

DeCourcy Sandstone across strike until it rests laterally against the Northumberland Formation. The sandstone protects the non-resistant mudstone from rapid erosion, but some removal of the mudstone has occurred, creating the cove.

Folds

The only fold in the thesis area is a syncline. It extends the entire length of Saturna Island from a point 1, 300 feet north of Monarch Head to a point 1, 300 feet north of Elliot Bluff (Plate 1 and Figure 38). The syncline occurs in the DeCourcy, Northumberland, and Geoffrey Formations, and is probably an extension of the Kulleet Syncline of North Pender Island (Hudson, 1974). The axis of the syncline trends approximately N. 72 W through section 6, 1, 2, 3, 10, and 9, but in sections 7 and 8 it bends to the south and bears S. 80 W. at the western edge of section 7. The syncline is asymmetric and plunges gently to the west (8° maximum). The south flank of the syncline dips approximately 20° to 30°; whereas, the north flank dips 40° to 85°. The Kulleet Syncline appears to be related to the Lyall Creek Fault. The Kulleet Syncline may be a drag fold, created during uplift of the northern block of the Lyall Creek Fault. The fault, however, may be a rupture as compressional forces created the fold. The first hypothesis is probably more valid in light of recent investigations (Muller and Carson, 1969; Muller and Jeletsky, 1970).

Figure 38. Axis of the Kulleet Syncline 1/4 mile north of Monarch Head is located in the shallow marine sandstones of the DeCourcy Formation. Note the lateral discontinuity of the non-resistant mudstone units.

GEOMORPHOLOGY

Topography

The predominant factors controlling topography are structure and lithology. Oblique slip faulting and block faulting has tilted and folded the rocks of the area so that the more resistant strata today form prominent cuestas and hogbacks. The lowlands and valleys, such as the "shale plant" area and the Lyall Creek valley, are erosional lows carved in a non-resistant mudstone bedrock by fluvial processes and Pleistocene glaciation. Because the strata of Mt. David and Mt. Elford, which are composed of thick and resistant Geoffrey Formation sandstones, dip about 40° to the north, the mountains form giant hogbacks with steep antidipslopes, that are locally nearly vertical, 800-foot high cliffs. The strata of Mt. Warburton Pike and Brown Ridge, which are composed of resistant DeCourcy Formation sandstones and conglomerates, dip about 20° to the north and hold up a cuesta with a gentle dipslope and a steep antidipslope. The antidipslope varies in steepness from 45° to 90° and forms the 800-foot high cliffs that extend the length of southern Saturna Island (Plate 1). Grasses that turn brown in the summer sun and a few madrona, Douglas-fir and maple trees comprise the only vegetation on these cliffs. The cliffs are locally so steep and soil so thin that nothing is able to grow on them. Once domesticated, but now wild, goats inhabit the cliffs of Brown Ridge. They seem to roam freely about the cliffs and apparently have been unmolested by man.

The configuration of the shoreline perimeter of the islands is a manifestation of the lithology. The bays, harbors, coves, inlets, and pockets have been formed where the bedrock is composed of non-resistant mudstone. The points, reefs, and islets have been formed in the more resistant sandstones. This difference in resistance to erosion is clearly shown in the predominantly mudstone Cedar District Formation near Digby Point. Here the mudstone is interbedded with siltstone and very fine-grained sandstone. The more resistant sandstones weather out as ribs, and because the strata in this area are dipping about 23°, there is created a series of inclined steps.

The linearity of Saturna and Tumbo Islands is controlled by the strike of the strata, and erosional processes have been much more pronounced along strike in the softer units than across the strike.

Much of the interior of the islands is covered by dense vegetation, making geological investigation almost impossible. The Douglas-fir trees are the dominant vegetation type, but alders grow in areas that have been recently logged. Hemlock, madrona (arbutus), and vine maple are also common trees. The groundcover consists of salal, Oregon grape, salmonberries, blackberries, wild roses, and a variety of grasses, all of which effectively hinder travel through inland areas.

Weathering and Wave Action

Coastal Processes

Among the more noticeable features of Saturna and Tumbo Islands are the sea cliffs along the southern coastlines. The sea cliffs that lie along the southern shore of Saturna Island extend from Payne Point to Narvaez Bay. They are formed in the resistant lower and upper DeCourcy Formation, and range in relief from 25 feet near Croker Point to 350 feet at Monarch Head. The sea cliffs that extend from Fiddler's Cove to East Point are composed of the resistant Geoffrey Formation and range in height from 50 feet to 200 feet. The Gabriola Formation sandstones and conglomerates comprise the sea cliffs along the southern shore of Tumbo Island, and they range in elevation from 25 to 125 feet. These sea cliffs are all nearly vertical and have either a very narrow wave-cut bench or a vertical entrance to the deep water at their bases. This topographic barrier often hinders geological investigation, unless a boat is available. Jointing patterns and faults can be readily observed on these totally exposed coastlines. The jointing patterns in the sea cliffs were instrumental in the location of many minor faults. The outcrop colors range from a variety of oranges (moderate yellowish brown: 10YR 5/4 to grayish orange: 10YR 7/4) to a variety of grays (light olive gray: 5Y 6/1 to very light gray: N 8). Locally long, vertical light brown (5YR 5/6), limonite-stained streaks occur on the cliffs. Closer examination reveals that the streaks have been caused by runoff during times of rainfall. The cliffs on the southern border between sections 13 and 14, Saturna island, have been stained nearly white by the guano of the cormorants that use the area as a nesting ground.

Along the coastline, the most noticeable smaller-scale features of the sandstone formations are honeycomb weathering, large calcareous knobs (concretions) up to 6 feet in diameter, and wave-cut nips, often referred to as "galleries". These features are peculiar only to wave and spray zones and apparently are formed only at or near sea level. According to Muller and Jeletsky (1970), honeycomb weathering surfaces are the result of carbonate-filled networks of joints that weather out in relief. The carbonate-cemented sandstones are more resistant to the erosional effects of the waves and spray than those lacking carbonate; as a consequence, the latter are more deeply weathered and eroded (Figure 19). The large calcareous knobs (Figure 20) are calcareous concretions which, like the carbonate-filled joints of honeycomb weathering, are more resistant to weathering. Through time, the softer sandstone is weathered away, leaving the concretions as projecting knobs. "Galleries", or wave-cut notches, form at sea level as the waves and spray erode at the bases of sandstone cliffs and create cave-like features (Figure 27).

Bayhead beaches have formed at the heads of the bays, harbors and some coves. Bayhead beaches, in the thesis area, are underlain by less resistant mudstones and lie between points held up by resistant sandstone. The beaches are littered with cobbles and pebbles of basalt, sandstone, plutonic igneous rocks, and foliated metamorphics, which have been transported from other areas by Pleistocene glacial processes, presumably including ice rafting. Larger clasts, however, have been derived from the sandstone and conglomerate units on the island by fluvial and mass wasting processes. Many beaches on the islands are also littered with a variety of broken and disarticulated pelecypod shells, commonly oysters, and barnacles. The mud of the beaches supports a variety of pelecypods, many of which are edible. Narvaez Bay, Lyall Harbor, Reef Harbor, Fiddler's Cove, Bruce Bight, and Breezy Bay all have bayhead beaches.

Boat Passage, a narrow tidal passage about 100 feet wide, has been formed by wave, spray, current, and tidal action which have eroded and cut through a relatively thin tongue (about 50 feet thick) of the Geoffrey Formation. The passage connects Winter Cove with the Straight of Georgia. Because the tidal passage is narrow, the currents during tidal changes attain high velocities that pose a navigation hazard for boaters.

Church Cove has been created in much the same manner as Boat Passage. A relatively thin section (about 120 feet thick) of the

DeCourcy Formation has been breached by wave, spray, current, and tidal action, and part of the non-resistant Cedar District Formation has been removed by tidal currents, creating a small cove.

Tumbo Island consists of two parallel segments (Plate 1) that are connected by a tombolo. The tombolo, low-lying and swampy, is interpreted as being underlain by a tongue of the non-resistant Spray Formation. The Spray Formation was probably eroded below wave base, separating Tumbo Island into two islands and associated islets. Longshore drift later infilled the area with sand and mud, creating the tombolo that now connects the two parts of the island.

At the mouth of Lyall Creek, on the northeastern shore of Lyall Harbor, a small river-mouth bar has been formed. The bar is composed of sand and mud from the formations drained by Lyall Creek and is arcuate in shape, with the concave part facing Lyall Harbor. This bar forms a restricting barrier between the harbor and the creek.

Mass Wasting

Creep is a dominant mass wasting process on the Gulf Islands. On all slopes, bent or tilted tree trunks are very evident, the result of the slow downslope movement of regolith.

The high sandstone cliffs of Brown Ridge exhibit exfoliation much like granite. This phenomenon was also noted in other Gulf Islands

(Packard, 1972). It is independent of the bedding, but is more pronounced in the structurless units. It tends to round and smooth the surfaces of the cliffs.

Gravity is a dominant factor in mass wasting, resulting in talus cones at the bases of cliffs. These piles of sandstone blocks and boulders effectively obscure the outcrops at places along the coastline.

The regolith thickness is controlled by the lithology of the bedrock. Where sandstone is the bedrock, the cover is rubbly and less than 12 inches thick. The soil attains a much greater thickness where mudstone comprises the bedrock.

Glacial Processes

Pleistocene glaciation has carved and gouged the strata of Saturna and Tumbo Islands. The softer mudstone formations were carved more deeply along strike than the resistant sandstone and conglomerate formations, leaving the latter as remnant elongate highs. A thin veneer of glacial debris from the last glacial advance covers most parts of the islands, but is concentrated in the lowlands and along the coastlines. The debris consists predominantly of granitic, basaltic, and metamorphic cobbles and boulders. Glacial striations, although rare, were observed on the resistant sandstone beds of the upper Cedar District Formation at Veruna Bay.

Fluvial Processes

Fluvial processes are unimportant on Saturna and Tumbo Islands. The islands are too small to catch and retain sufficient rain water to produce perennial streams, and therefore, most streams are influent. All of the streams, except for Lyall Creek during unusually wet years, are intermittent, flowing only during the winter months and seasonal rain storms.

The drainage patterns are controlled by the strike of the strata, the structure, and the lithology. Most of the streams, like Lyall Creek, flow east-west, along strike, and on non-resistant impermeable mudstone, except where they are controlled by faults. Most of the faults on Saturna Island, because they are zones of weakness, have been incised by small intermittent streams. These small gullies were instrumental in the location of several inland faults. The gradient of the streams is controlled by the lithology. Streams flowing over sandstone have a higher gradient than those flowing over the more easily eroded mudstone. Therefore the creeks flowing over mudstone tend to reach base level more easily.

DEPOSITIONAL HISTORY

Paleocurrent Data

General

Festoon and planar cross-laminations and cross-beds, flute casts, groove casts, parting lineations, pebble elongation, and channel axes are the sedimentary structures observed in the thesis area that were useful in paleocurrent determinations. A total of 158 paleocurrent measurements was obtained from the Cedar District, DeCourcy, and Geoffrey Formations. Because of limited outcrop occurrence, paleocurrent measurements were not obtained from the Extension-Protection or Spray Formations. The Northumberland Formation did not contain sedimentary structures suited to paleocurrent determinations, and time and accessibility were the limiting factors in obtaining paleocurrent measurements from the Gabriola Formation.

Because most of the bedding planes from which paleocurrent measurements were obtained were inclined, they had to be rotated to horizontal in order to return them to their presumed depositional position and to determine true paleocurrent dispersal patterns. The inclined beds were rotated to horizontal with a FORTRAN program modified from a University of Rhode Island program. The data from each formation were then plotted on rosette diagrams and grand means were calculated following the method suggested by Royse (1970). Bidirectional data were supported by other sedimentary structures to determine an unidirectional transport direction.

Cedar District Formation

The Cedar District Formation is the marine member of the Cedar District-DeCourcy deltaic cycle. A total of 103 paleocurrent determinations were obtained from this formation, consequently there is good control of the paleocurrent dispersal pattern. The plot of these measurements has a grand mean of S.58° E. (Figure 39). Lateral outcrop thinning and intertonguing with the DeCourcy Formation to the west confirms this dispersal direction.

DeCourcy Formation

A total of 22 paleocurrent measurements were obtained from the DeCourcy Formation. The plot of these measurements has a grand mean of S.73° E. (Figure 40), which is consistent with the general offshore transport direction of the Cedar District Formation in the Cedar District-DeCourcy deltaic cycle.

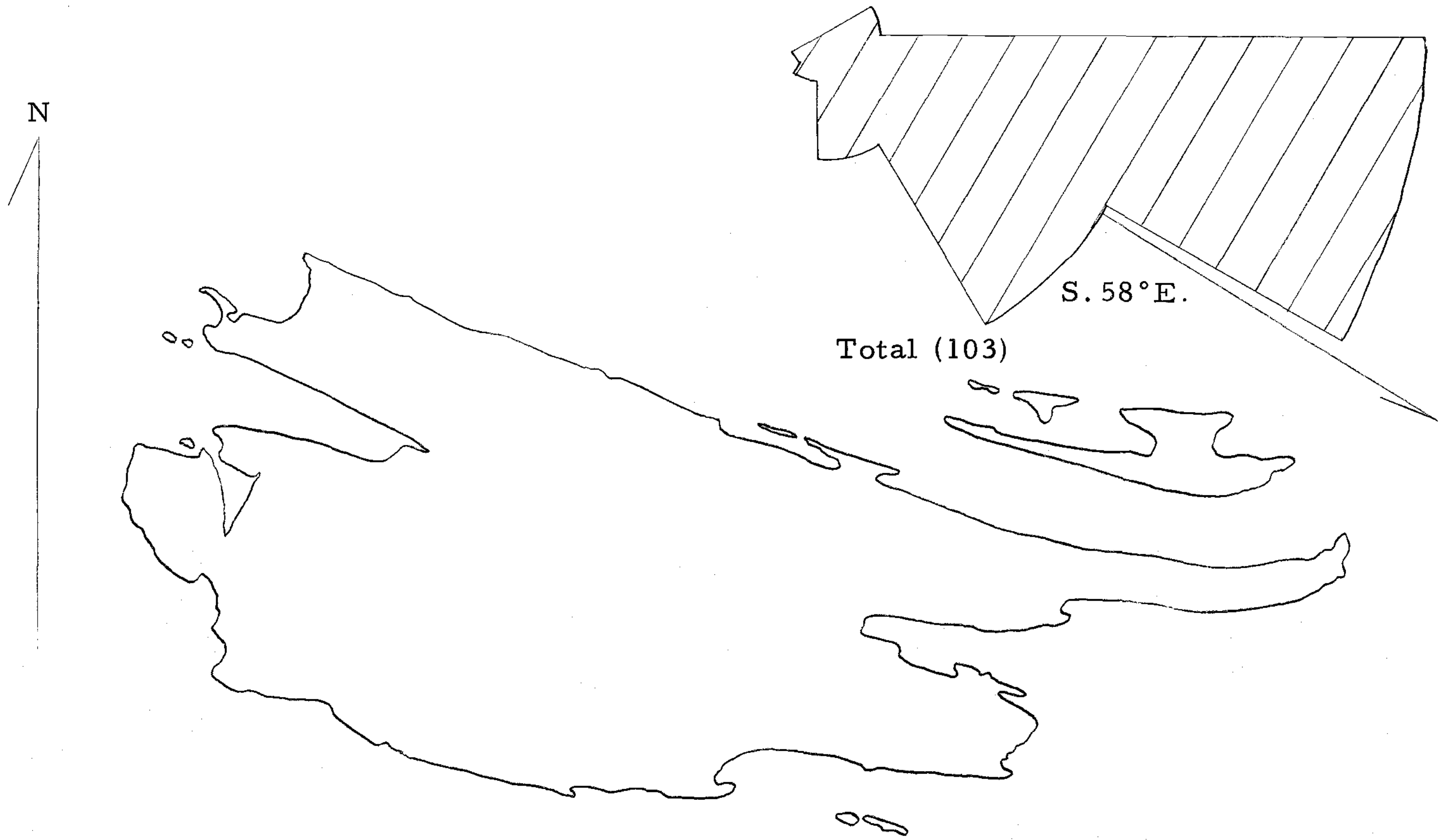


Figure 39. Paleocurrent data for the Cedar District Formation.

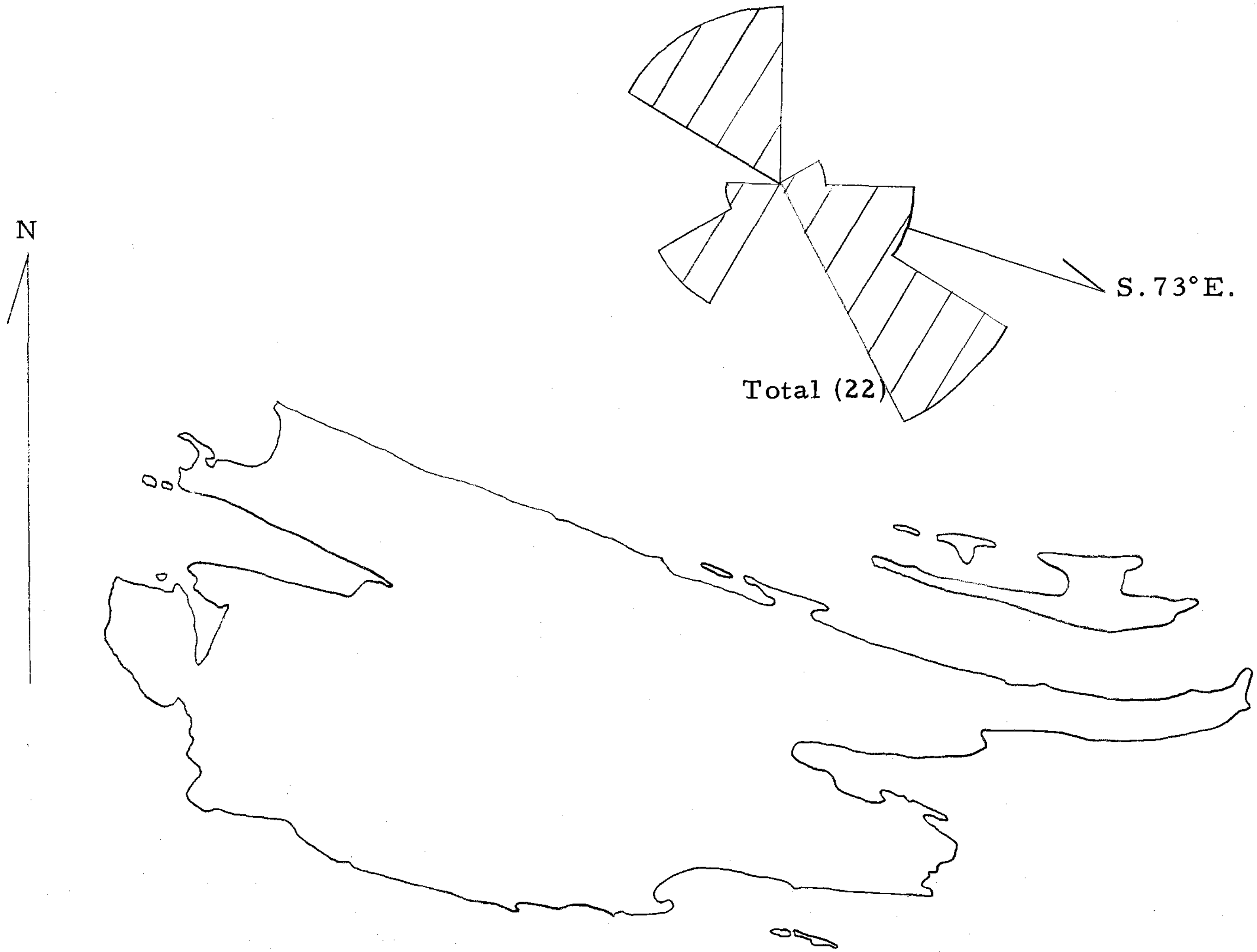


Figure 40. Paleocurrent data for the DeCourcy Formation.

Geoffrey Formation

The Geoffrey Formation is considered to be the upper part of the Northumberland-Geoffrey deltaic cycle. A total of 33 paleocurrent measurements were obtained from this formation. The plot of these measurements has a grand mean of S.01° E. (Figure 41). The intertonguing of the Geoffrey Formation with the Northumberland Formation west of Mt. David indicates a source to the northeast, but lateral facies changes to the northwest on Gabriola Island, where the Geoffrey Formation is predominantly fluvial conglomerates, indicates a source in that direction. The overall sequence indicates a fluvial source to the west depositing its load as channel-mouth bars, the longshore currents later reworked the sands from a north to south direction.

Postulated Source Areas

The pre-Cretaceous rocks of Vancouver Island are the Pennsylvanian to Permian Sicker Group, the Triassic to Early Jurassic Vancouver Group, and the Middle to Late Jurassic Island Intrusions. The Sicker Group is composed predominantly of greenstones and greenschist derived from andesite pyroclastic rocks, and also contains metamorphosed graywacke sandstones, argillites, conglomerates, limestone, and local chert (Muller and Carson, 1969).

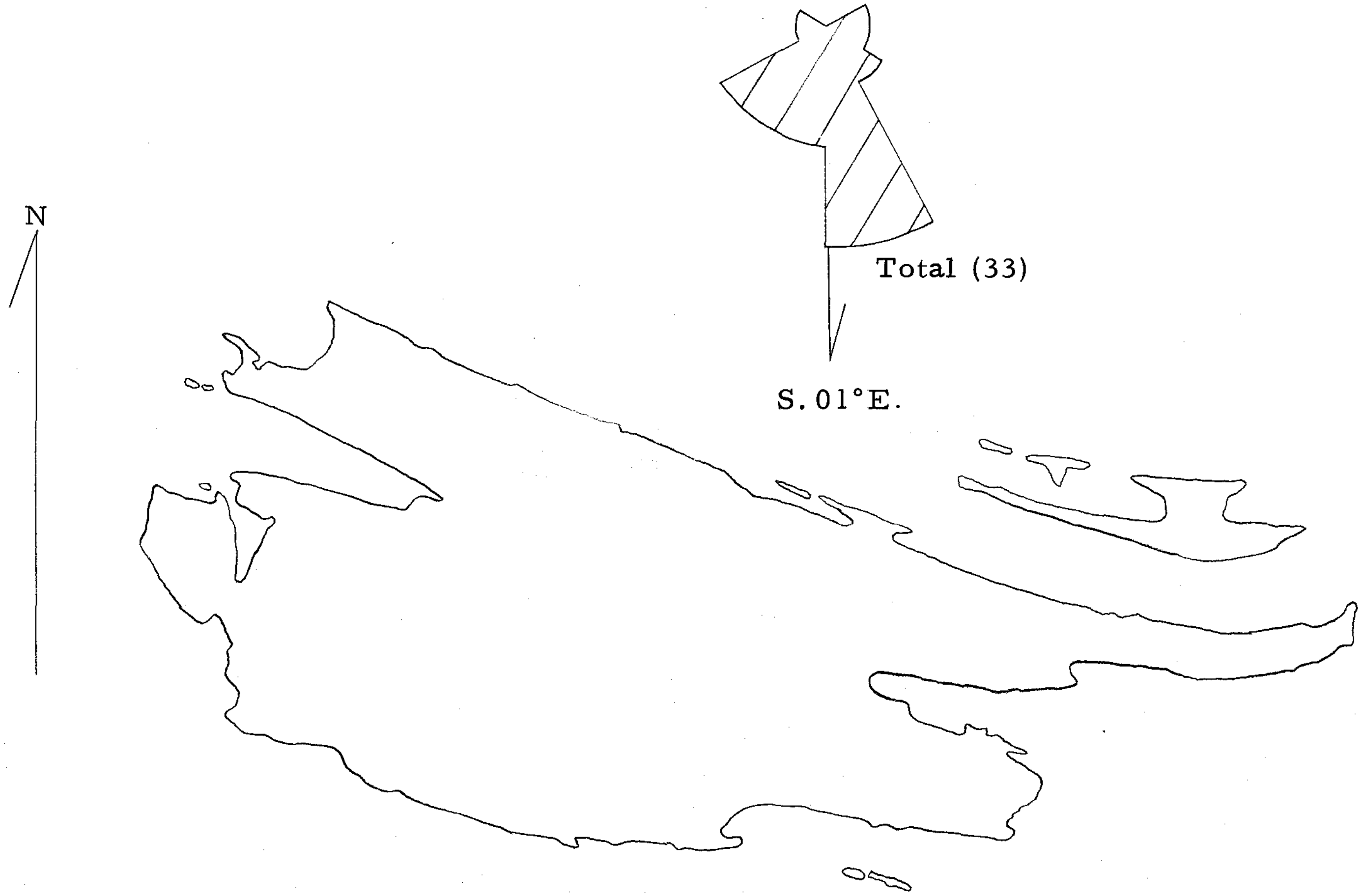


Figure 41. Paleocurrent data for the Geoffrey Formation.

The Vancouver Group is composed of metamorphosed basalts, andesitic pyroclastic rocks, limestones, and argillites. The Island Intrusions consist of granodioritic to quartz monzonitic batholiths (Muller and Carson, 1969).

The pebbles of the Extension-Protection Formation are dominated by argillite, basalt, and gneiss, with lesser amounts of quartzite, greenstone, chert, and rhyolites. Modal analysis (Appendix D) of a sample of Extension-Protection Formation sandstone reveals an abundance of quartz, plagioclase, micas, and volcanic and metamorphic rock fragments. This mineral and rock assemblage could have been derived from the pre-Cretaceous rocks of Vancouver Island.

A pebble count (Appendix B) of the Cedar District-DeCourcy deltaic cycle shows an abundance of chert, limestone, basalt, quartzite, and greenstone, with lesser amounts of foliated metamorphics and plutonic igneous rocks. Modal analyses of sandstone samples (Appendix D) show an abundance of quartz, plagioclase, and potassium feldspars, mica, and volcanic, metamorphic, and sedimentary rock fragments. This assemblage of rocks and minerals, coupled with paleocurrent data, indicate a source on Vancouver Island with detrital input coming from all three groups of pre-Cretaceous rocks.

Modal analyses of Northumberland and Geoffrey Formation sandstones (Appendix D) reveal an abundance of quartz, plagioclase and potassium feldspars, mica (especially chlorite), and volcanic and metamorphic rock fragments. The Geoffrey Formation differs from the DeCourcy Formation in that it does contain hornblende and pyrite, and it does not contain as much quartz, polycrystalline quartz or sandstone. This assemblage of rocks and minerals may have been derived from the pre-Cretaceous rocks of Vancouver Island, but the southerly dispersal direction derived from the paleocurrent data contradicts this idea. If, however, the channel-mouth bar sediments of the Geoffrey Formation were reworked by north to south longshore currents, as postulated, then it is conceivable that the sediments were derived from Vancouver Island.

A pebble count from the Gabriola Formation indicates an abundance of basalt, plutonic igneous rocks, quartzite, and chert. Modal analyses of Spray and Gabriola Formation sandstones closely resemble those of the Northumberland-Geoffrey deltaic cycle, having an abundance of quartz, plagioclase and potassium feldspar, and volcanic and metamorphic rock fragments. The Gabriola Formation, as does the Geoffrey Formation, differs from the DeCourcy Formation in that it does contain green hornblende, and it contains smaller amounts of a quartz, polycrystalline quartz and sandstone. In addition, the Gabriola contains a greater percentage of heavy minerals and less potassium feldspar. This assemblage of rocks and minerals may have been derived from the pre-Cretaceous of Vancouver Island, particularly the Vancouver Group and Island Intrusions. No paleo-current data were obtained, however, to substantiate this hypothesis.

Geologic History

The upper seven formations of the Late Cretaceous Nanaimo Group 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, generally had high matrix contents, contained both fresh and weathered feldspars, and are both texturally and compositionally immature. These factors suggest that erosion, deposition, and burial of the sediments was rapid, and that reworking by wave action was minimal.

Monger, Souther, and Gabrielse (1972), in their plate tectonic interpretation of the Vancouver Island vicinity, consider the Nanaimo and Comox Basins as successor basins formed after the collision of the North American plate with a Pacific plate during Jurassic time. The basins thus formed were protected by land masses from the more active shoreline processes of the Pacific Ocean.

Bell (1957) studied the fossil flora from Vancouver Island and vicinity. His studies indicate that the climate of the area during Late Cretaceous time was probably warm temperature, subtropical or tropical.

Sediments of the Comox and Haslam Formations were the initial deposits of the Nanaimo Basin (Muller and Jeletsky, 1970), but they are not exposed in the thesis area. The first record of sedimentation in the thesis area is the Extension-Protection Formation. These conglomerates were probably deposited in the bed load and point bar subenvironments by high energy streams. Pebble count lithologies indicate a source on Vancouver Island, to the southwest, and Hudson (1974), on the basis of paleocurrent dispersal patterns, hypothesized that the streams depositing the conglomerates drained a source from the south or southwest, possibly in a northerly prograding lobe of a delta forming off the northeast coast of Vancouver Island. The size of the cobbles in the conglomerates and the immaturity of the sandstone matrix indicate a tectonically active source with high relief. Following deposition of the fluvial conglomerates, basin subsidence continued. Clastic deposition in the form of delta-front sheet sands or topset sands occurred. Next, there was distributary channel abandonment, shifting the deposition of coarser clastic sediments elsewhere on the delta. Subsidence of the basin continued with little or no clastic deposition, resulting in an angular discordance.

Following the deposition of the Extension-Protection Formation, the coarse sediments of the Cedar District-DeCourcy deltaic cycle began to prograde over the thesis area from a tectonically active source area to the west-northwest. The first sediments of this cycle, mudstones and local turbidite sandstones, were deposited in a delta-slope environment. Slumping of sediments in the delta-slope environment resulted in contorted bedding. As the delta continued to prograde, the turbidite deposits became thicker and more abundant.

Filling and shallowing of the basin resulted as deltaic progradation continued, and the deposition of channel-mouth bars resulted. Distributary channel abandonment, lower sedimentation rates, increased rate of basin subsidence, raising of the sea level, or possibly a combination of all four, contributed to a marine transgression over the channel-mouth bar sands of the lower DeCourcy Formation, resulting in a return to delta-slope deposition of the upper Cedar District Formation. Turbidites or episodic flood deposits were again laid down. Progradation was renewed and channel-mouth bar sands of the upper DeCourcy Formation were deposited. Short periods of alternating delta-slope and channel-mouth bar deposition resulted in an intertonguing relationship between the Cedar District and DeCourcy Formations. Continued progradation resulted in the deposition of channel conglomerates by high energy streams. Degradation of the source area may have occurred, along with continued basin subsidence, resulting in a return to marine channel-mouth bar sands and finally back to delta-slope and prodelta deposition of the Northumberland Formation. The delta-slope deposits were laid down either as turbidites or as seasonal flood deposits. Transgression is evidenced by the prodelta mudstones that overlie the delta-slope deposits.

Deltaic progradation from the north or northwest started with the deposition of delta-slope turbidities and/or seasonal flood deposits of the upper part of the Northumberland Formation. Further progradation resulted in the deposition of channel-mouth bar sands of the Geoffrey Formation over the delta-slope deposits of the Northumberland Formation. These sands alternate with tongues of the Northumberland Formation west of Mt. David and probably represent distributary channel abandonment, shifting the deposition of coarse clastic sediments elsewhere on the delta. Other factors possibly contributing to this phenomenon were fluctuations in the rate of basin subsidence, tectonic events in the source area, or major fluctuations in sea level. The channel-mouth bar sands were deposited in a north to south direction by longshore currents around the mouths of distributary channels to the west and northwest. The unstable seaward slopes of the bars often slumped, creating submarine debris deposits consisting of mudstone rip-ups suspended in a matrix of sandstone. Alternations between deposition of channel-mount bar sands of the Geoffrey Formation and delta-slope sandstone-siltstone-mudstone sequences of the Spray Formation are recorded as tongues.

Basin subsidence or degradation of the source area followed with the deposition of marine Spray Formation mudstones, most of which are not exposed in the thesis area.

Tectonic uplift of the source area, presumably in the west, is the next event recorded in the thesis area. Fluvial conglomerates and sandstones of the Gabriola Formation, derived from the pre-Cretaceous of Vancouver Island, were deposited in the area now occupied by Tumbo Island. The streams supplying the sediments were of high competence. A marine transgression is noted next with the deposition of channel-mouth bar sands, which resemble those of the Geoffrey Formation. The unsorted nature of these sandstones indicates rapid erosion, deposition, and burial of the sediments, but the low clay matrix content implies that there was some reworking of the sediments before burial. Continued transgression followed with the deposition of a tongue of marine Spray Formation mudstone, all of which is covered in the thesis area. Filling and shallowing of the depositional basin began next with the progradation of channel-mouth bar sands over the marine mudstones. The final depositional event recorded in the thesis area is the continued progradation of the delta, resulting in the deposition of fluvial conglomerates, possibly as topset beds. The currents that transported the sediments were of high competence and drained a nearby source area, probably on Vancouver Island.

Two major episodes of faulting have acted in post-Cretaceous time to deform and incline the strata of the thesis area. The first set of faults, trending north-south, may have resulted from east-west compressional forces. Later, a second fault system, including the Lyall Creek fault, and related folds (the Kulleet Syncline) may have developed in response to north-south compressional forces. Recent geological investigators (Muller and Jeletsky, 1970; Sutherland-Brown, 1966), believed that the faults and folds are surface expressions of basement fault movements. Several minor faulting episodes have occurred, but the total number is undetermined.

Following the faulting, the thesis area was carved and gouged by Pleistocene continental glaciers. These glaciers excavated the mudstones of the Cedar District, Northumberland, and Spray Formations and the shattered zones of the faults. The last episode of glaciation grooved the resistant sandstone beds of the Cedar District Formation at Veruna Bay on Saturna Island, and it deposited a thin veneer of glacial till over most of the island. The most recent geologic events in the thesis area are erosional processes, which are discussed in the geomorphology section.

ECONOMIC GEOLOGY

Coal

The discovery of coal on Vancouver Island by Dr. W. F. Tolmie in 1835 spurred both the geologic and economic interest in the Nanaimo and adjacent areas. Production of coal from the Nanaimo Group rocks commenced in 1852 (Dawson, 1890), and to the mid-1960's the area had yielded over 72 million metric tons of coal (Muller and Carson, 1969). Mining of coal has been terminated, because in recent years it has become uneconomic. The major seams have largely been exhausted, and the remaining seams are too deep to mine economically.

Coal on Saturna Island has not been mined commercially, but a small deposit of coal at Monarch Head has been used to power private boats in past years (Cowan, 1974, pers. com). Test holes were drilled on Tumbo Island, in the course of exploration for coal, by the government of Victoria in 1893. One hole, drilled on the west side of the island near sea level, encountered bituminous mudstone and coal at a depth of 280 feet, but the hole was flooded by groundwater (Poole, 1906).

Brick Products

British Columbia Lightweight Aggregates, Ltd. operates a quarry on Saturna Island north of Lyall Harbor, from which they mine Northumberland Formation mudstone. The mudstone is expanded under heat and is used in the manufacture of lightweight aggregate bricks. The bricks are fired in a rotary kiln and are transported to various parts of British Columbia for construction purposes (Begon, pers. com.).

Groundwater

The availability of groundwater is a problem of utmost concern, not only to the inhabitants of Saturna Island, but to all the people of the Gulf Islands. The porosity and permeability of the sandstones, as noted previously, is very low because of tight packing, high clay content, and calcite cement, and this inhibits the infiltration of surface water into the strata. Shallow wells can be pumped dry in a relatively short period of time, and recharge is very slow, requiring on the order of several days to weeks (Vincent, 1974, pers. com.).

The catch basin on Saturna Island is sufficiently large at most places to permit some infiltration of water and recharge of the water table. East Point, however, has a very limited area, so very little water infiltrates the strata. Wells drilled at the East Point lighthouse have produced marine salt water, and because of this problem, the only source of water here comes from retaining rainwater as it sheds from the roofs of buildings (Chapman, 1974, pers. com.).

Because many houses are built along the coastline of the islands, another problem is often encountered. Excessive drawdown of private wells often causes an influx of salt water. This situation can be reversed only where the aquifer is allowed to recharge or by pumping in fresh water. Another interesting phenomenon that occurs in some wells located along the coastline is that the water level in the wells fluctuates with the tides (Tomlin, 1974, pers. com.).

Because the strata of Saturna Island are inclined, and because the impermeable mudstone formations intertongue with the relatively permeable sandstone formations, a hydraulic head is established (Davis and De Wiest, 1966). As a consequence, many of the deep wells are artesian.

Several procedures can be followed in alleviating the often critical groundwater supply problem. One method is controlling runoff. By building small dams across intermittent streams and creating reservoirs, enough water could be retained for general use during the dry summer months. This would, however, result in political problems, such as the development of municipal water supplies and would involve the purification of the water. Provincial law requires that a reservoir, supplying water to all parts of any island, must have a purification plant. Furthermore, if the reservoir is owned by a private party, that party must provide the purification plant (Money, 1974, pers. com). Another possibility would be to drill wells in faults and fracture zones. Faults and fractures greatly increase the permeability of a reservoir rock and provide zones where groundwater can more easily accumulate (Davis and DeWiest, 1966).

Petroleum Potential

The potential for petroleum entrapment in the Nanaimo Basin is nearly ideal. However, the only thing missing is an adequate permeable reservoir rock, as indicated by the tight surface rocks. The deltaic model, as presented in this thesis, provides excellent stratigraphic traps. Potential source beds are the organic-rich marine mudstones of the prodelta sequences, such as the Cedar District, Northumberland, and Spray Formations, which are overlain by and intertongue with marine and fluvial sandstones and fluvial conglomerates of the DeCourcy, Geoffrey, and Gabiola Formations, respectively. Anticlines and faults which juxtapose mudstone with sandstone provide numerous adequate structural traps for the entrapment of hydrocarbons.

The lack of porosity and permeability of the sandstone-conglomerate formations at and near the surface is the only limiting factor to the production of petroleum from the Nanaimo Group sedimentary rocks. The modal analyses (Appendix D) of the sandstones on Saturna and Tumbo Islands reveal an average porosity of less than 1%. Surface rocks may be better cemented as a result of the effects of groundwater and weathering, and the same strata, at depth, may be more porous and permeable.

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APPENDICES

APPENDIX A

Measured Section A-A', Cedar District Formation, DeCourcy Formation, and Northumberland Formation

All sections were measured with a five-foot Jacobs staff mounted with an Abney level, a 50-foot tape measure, and a Brunton compass. Description of the measured sections was aided by the use of a 20x hand lens, a sand gauge chart, and the Rock-Color Chart of the Geological Society of America (1963). Stratification terms are modified from McKee and Weir (1953). The Wentworth (1922) size scale was used, the sorting terms of Folk (1968) were utilized, and the rounding terminology of Powers (1953) was applied.

Section A-A' encompasses part of the lower DeCourcy Formation, the upper Cedar District Formation, the upper DeCourcy Formation, and the Northumberland Formation. The section was measured along the northwestern shoreline of Saturna Island from Lyall Harbor to Winter Point to demonstrate the typical development of the DeCourcy Formation, the Cedar District Formation, and the Northumberland Formation, and to help determine the displacement of the fault that extends from Mikuni Point to Fiddler's Cove.

Terminal point (A', Plate 1) is the westernmost tip of Winter Point on the northwestern end of Saturna Island at Boat Passage.

Several features were observed in all measured sections including pseudoconcretions, pyrite concretions, burrows, and Bouma sequences.

Pseudoconcretions is a term first coined by Packard (1972) for the onion-skin-like weathering phenomenon of the thick mudstone sequences of the Nanaimo Group sedimentary rocks. These pseudoconcretions develop concentric, onion-skin-like peels of mudstone that are ellipsoidal in shape and resemble concretions. The only difference between pseudoconcretions and true concretions is that the former have no nucleus to which consecutive layers can adhere.

Pyrite concretions were observed in both the Cedar District and Spray Formations. The concretions are spherical to ellipsoidal in shape and contain finely disseminated pyrite in a matrix of very fine-grained sandstone. They range in size from 1/4 inch in diameter to 1 by 4 inches (Figure 7). The sandstone around the concretions has been stained yellow by limonite. For analytical techniques used in the determination of pyrite, see Appendix F.

Burrowing is common in the Cedar District and Spray Formations. Both vertical and horizontal burrows were observed, and they were identified by C.K. Chamberlain (written commun., 1975) as Thalassinoides. Many of the burrows displayed branching and back filling structures. They range in diameter from 1/2 to 1 inch (Figure 12) and are usually straight rather than curved.

Incomplete Bouma sequences are a common occurrence in the sandstone beds of the Cedar District and Northumberland Formations. The Bouma sequence is a series of different sedimentary features that occur in graded beds and is often associated with turbidite deposits. The Bouma sequence is divided into various parts based upon flow regime and sedimentary structures. Part A is the lower graded sand interval of the graded bed, part B is a series of parallel sand laminations, and division C is festoon cross-laminations or convolute laminations of very fine-grained sand. Division D is parallel silt laminations, and part E is mudstone.

Interval (feet)	Description

The Geoffrey Formation consists of thickly bedded (1 to 15 feet thick) medium- to coarse-grained sandstones separated by thin mudstones (up to 10 inches thick). The fresh color of the sandstones is medium light gray (N 6), and it weathers to yellowish gray (5Y 7/2). The dominant sedimentary structure is festoon cross-bedding.

Contact: Geoffrey Formation and Northumberland Formation, Tongue 1 (Kn_1); sharp, planar, and concordant.

1668.9-1666.3	Mudstone: nonresistant; laminated; olive gray (5Y 4/1) fresh, light olive gray (5Y 6/1) weathered; upper contact is sharp and planar.
1666.3-1665.7	Sandstone: fine-grained; light olive gray in color (5Y 5/2); well sorted; resistant; structureless; upper contact is sharp and planar; quartz, feldspar, rock fragments, minor biotite, muscovite, and hornblende; calcareous.
1665.7-1656.7	Covered: by vegetation, probably mudstone with intercalations of siltstone and sandstone as at 0.

Interval (feet)	Description
1656.7-1646.7	Mudstone: with intercalations of siltstone and sandstone as at 0.
1646.7-1636.7	Covered: by vegetation, probably mudstone with intercalations of siltstone and sandstone as at 0.
1636.7-1621.7	Mudstone: with intercalations of siltstone and sandstone as at 0.
1621.7-1620.9	Sandstone: fine-grained; resistant rib-former; well sorted; laminated (8/inch); burrows parallel to laminations; upper contact is sharp and planar; medium light gray (N 6.5) fresh, light gray (N 7) weathered; subangular grains of quartz, feldspar, biotite, muscovite, lithic fragments; calcareous. Sample CDS-37-74 of sandstone.
1620.9-1613.8	Mudstone: as at 0; upper contact is sharp and planar.
	Offset 100 feet west along top of bed to avoid grass covered slope; attitude is N.77 W., 43°N.
1613.8-1592.4	Mudstone: with intercalations of siltstone and very fine sandstone up to 2-1/2 inches thick. The contacts between sandstone-siltstone and siltstone-mudstone are gradational over an interval of 1/2 inch. The lower contacts of the very fine-grained sandstone beds are sharp and undulating (scour-and-fill and load casts) (maximum relief of 1 inch).
	Mudstone: as at 0, except there are true concretions up to 3 inches in diameter. Siltstone: as at 347.7. Sandstone: as at 1561.2. Sample CDS-36-74 of mudstone.
1592.4-1592	Argillaceous limestone: as at 606; lower contact is sharp and planar, upper contact grades within 1/2 inch into overlying mudstone.

Interval (feet)	Description
1592-1566.5	Mudstone: with intercalations of siltstone and very fine sandstone as at 1561.2. Attitude is N.77 W., 43°N.
1566.5-1565.9	Argillaceous limestone: as at 606; lower contact is sharp and planar, upper contact grades within 1/2 inch into overlying mudstone.
1565.9-1563.8	Mudstone: with intercalations of siltstone and very fine sandstone as at 35 7.
1563.8-1561.2	Mudstone: with intercalations of siltstone and very fine sandstone as at 0, except lower contacts of the very fine sandstone beds are load deformed (maximum relief of 1/2 inch).
	Offset 110 feet west along strike to reach outcrop, attitude is N.77 W., 43°N.
1561.2-1404.2	Covered: by beach mud, probably as at 1305.2.
	Offset 53 feet east along strike and proceed upsection through covered interval, attitude is N.89 W., 39°N.
1404.2-1395.2	Mudstone: with intercalations of siltstone, very fine sandstone, and limestone as at 1305.2.
	Offset 53 feet west along strike to reach outcrop, attitude is N.89 W., 39°N.
1395.2-1305.2	Mudstone: with intercalations of siltstone, very fine sandstone, and sandy limestone as at 797.5.
	Offset 110 feet west along strike to avoid mud-covered interval, attitude is N.89 W., 39°N.
1305.2-1295.2	Mudstone: with intercalations of siltstone and very fine sandstone as at 35.7.

Interval (feet)	Description
1295.2-1203.2	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 35.7.
1203.2-1172.7	Mudstone with intercalations of siltstone and very fine sandstone as at 35.7.
1172.7-1160.2	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 35.7.
	Offset 42 feet west along strike to avoid road, and proceed upsection through mud-covered interval, attitude is N. 89 W., 39°N.
1160.2-1145.2	Mudstone: with intercalations of siltstone and very fine sandstone as at 35.7.
1145.2-1144.5	Argillaceous limestone: as at 606.
1144.5-1092.7	Mudstone: with intercalations of siltstone and very fine sandstone as at 35.7. Offset 20 feet west at 1142.7 and 57 feet west at 1102.7 across top of beds to avoid mud-covered intervals, attitude is N. 89 W., 30°N.
1092.7-935.5	Covered: by beach mud, probably mudstone with intercalations of siltstone, very fine sandstone, and sandy limestone as at 526.5.
	Offset 42 feet east across top of bed to avoid incoming tide and proceed upsection through covered interval; attitude is N. 89 W., 39°N.
935.5-797.5	Mudstone: with intercalations of siltstone, very fine sandstone, and sandy limestone as at 526.5, except with isolated lenses of limestone, up to 15 feet wide and 4 inches thick, as at 606.
	Offset 100 feet along strike to avoid covered interval, attitude is N. 84 W., 36°N.

Interval (feet)	Description
797.5-637.5	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 0.
637.5-628	Mudstone: with intercalations of siltstone, very fine sandstone, and sandy limestone as at 526.5.
628-627.5	Argillaceous limestone: as at 606; wedges out 12 feet to the east into mudstone.
627.5-622.8	Mudstone: with intercalations of siltstone as at 347.7, but without calcareous concretions.
622.8-617.8	Mudstone: as at 347.7; upper contact with overlying unit is gradational over an interval of 12 inches.
617.8-607.8	Interbedded mudstone, siltstone, and very fine sandstone as at 595.7. Attitude is N.84 W., 36°N.
607.8-606	Argillaceous limestone: resistant rib-former; bedding shows only on weathered surfaces; lower contact is sharp and planar; upper contact grades within 1/2 inch into overlying mudstone; mottled texture; dark gray (N 3.5) fresh; light gray (N 7) weathered; microcrystalline calcite. Sample CDS-35-74 of limestone.
606-595.7	This interval consists of interbedded very fine-grained sandstone, siltstone, and mudstone that create normally graded packets which range in thickness from 3-1/4 inches to 14 inches. Incomplete Bouma sequences have formed (BCDE) and (CDE). The very fine sandstone comprises about 1/3 of the total thickness of the graded packets. The siltstone comprises very little of the graded packets, whereas the mudstone comprises almost 2/3 of the total thickness. The upper contacts of the mudstones commonly display reverse grading over an interval of 1/2 inch into the overlying sandstone.

Interval (feet)	Description
	Sandstone: as at 0, except lower contact exhibits reverse grading. Siltstone: as at 347.7. Mudstone: as at 347.7.
595.7-526.5	Mudstone: with intercalations of siltstone and sandy limestone. Mudstone: as at 0, but comprises about 85% of this interval. Siltstone: as at 0. Sandy limestone: resistant rib-former; thin laminations, festoon cross-laminations; lower contacts usually are sharp and planar, rarely load deformed; medium light gray (N 6) fresh, very light gray (N 8) weathered; ranges in thickness from 1-1/4 inches to 7-1/2 inches; subangular grains of quartz biotite, and muscovite in crystalline (sparry) calcite.
526.5-463.5	Mudstone: with intercalations of siltstone and calcareous concretions as at 347.7.
463.5-434	Covered: by beach mud, probably mudstone with intercalations of siltstone and calcareous concretions as at 347.7.
434-347.7	This interval consists of 95% + mudstone with intercalations of siltstone laminae up to 1/2 inch thick and concretionary beds up to 2-1/2 inches thick. Weathered fractures throughout the mudstone look like clastic dikes. The mudstone is dominated by pseudoconcretions that vary in size from 3 inches to over 20 inches in diameter. Mudstone: non-resistant; weathers out in chips 1-1/4 inches by 3/4 inches; thinly laminated except where pseudoconcretions form; upper contacts with overlying siltstone are sharp and planar; lower contacts grade from siltstone below; medium gray (N 5) fresh, light olive gray (5Y 6/1) weathered; non-calcareous.

Interval (feet)	Description
	Siltstone: resistant, forms insignificant ribs in the mudstone; laminated, about 14/inch; non-calcareous. Concretions: resistant; forms isolated nodules 2 by 6 inches to 4 by 12 inches along bedding planes; medium gray (N 5) fresh, light gray (N 7) weathered; very calcareous, generally micritic, but calcite rhombs occur in the center (perhaps recrystallized fossils). Sample CDS-29-74 of mudstone obtained at 347.7. Sample CDS-30-74 of undetermined ammonite obtained at 351. Sample CDS-33-74 of calcareous concretions obtained at 401.
	Offset 20 feet east along strike to reach best outcrop, attitude is N. 84 W., 36°N.
347.7-184.7	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 0.
	Offset 40 feet east across top of bed to avoid incoming tide and proceed upsection through covered interval, attitude is N. 81 W., 45°N.
184.7-142.7	Mudstone: with intercalations of siltstone and very fine sandstone as at 0.
	Offset 49 feet east along strike to reach outcrop, attitude is N. 84 W., 40°N.
142.7-131.7	Covered: by beach mud, probably mudstone with intercalations of siltstone and very find sandstone as at 35.7.
	Offset 118 feet east along strike to avoid incoming tide and proceed upsection through covered interval, attitude is N. 84 W., 40°N.

Interval (feet)	Description
131.7-96.7	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 35.7. Offset 150 feet each across top of bed to avoid incoming tide, and proceed upsection using attitude N.84 W., 40°N.
96.7-35.7	Mudstone: with intercalations of siltstone and very fine sandstone as at 0, except mudstone comprises about 70% of the interval. Offset 50 feet east across top of bed at 77.7 and offset 60 feet east across top of bed at 60.7 to reach best outcrop. Sample CDS-28-74 of mudstone obtained randomly throughout this unit. Attitude is N.84 W., 34°N.
35.7-0	Mudstone: with intercalations of siltstone and very fine sandstone. Mudstone comprises about 50% of this interval, very fine sandstone comprises about 30% and siltstone comprises about 20%. Mudstone: non-resistant; weathers out in chips 1-1/2 inches by 1 inch; clastic dikes up to 1 inch wide originate from sandstone beds and cross-cut the laminae of the mudstone; thinly laminated; pseudoconcretions (1-4 inches in diameter) found in some parts; upper contacts are usually load deformed (maximum relief of 1/2 inch), rarely sharp and planar; medium dark gray (N 4) fresh, olive gray (5Y 4/1) weathered; non-calcareous; ranges in thickness from 3 inches to 15 feet. Siltstone: resistant rib-former; thinly laminated; upper contacts grade within 1 inch into overlying mudstone; olive gray (5Y 4/1) fresh; brownish gray (5YR 4/1) weathered; non-calcareous; ranges in thickness from 1/2 to 3 inches. Sandstone: very fine-grained; very well sorted; resistant rib-former; laminated up to 4/inch; festoon cross-laminations; upper contacts usually grade within 1 inch into overlying siltstone, locally

Interval (feet)	Description
	sharp and planar; non-calcareous, quartz, muscovite, and biotite; medium gray (N 5) fresh, medium light gray (N 6) weathered; ranges in thickness from 1/2 to 4 inches. Sample CDS-27-74 obtained at 34.9.

Contact: Northumberland Formation, Tongue 1 (Kn_1) and DeCourcy Formation, Tongue 5 (Kdc_5); sharp and planar, is concordant at this point.

DeCourcy Formation, Tongue 5 (Kdc_5) (thickness = 76+ ? feet).

Interval (feet)	Description
	Offset 1980 feet west across top of bed.
120.4-101.4	Sandstone: as at 96.4. Attitude is N. 88 E., 27°N.
101.4-96.4	Covered: by beach mud, fault interpreted here that eliminates part of the DeCourcy Formation.
	Offset 85 feet east across top of bed to reach best exposed outcrop.
96.4-57.4	Sandstone: medium- to coarse-grained with pebble lenses up to 6 feet wide and 4 inches deep; moderately sorted; resistant ledge-former that creates Mikuni Point and Minx Reef; thinly laminated in places, bedded (up to 3 inches thick) in other places; planar foresets, rib-and-furrow, and festoon cross-beds and cross-laminations; calcareous; subangular grains of quartz, chert, feldspar, biotite, muscovite, and lithic fragments; light olive gray (5Y 6/1) fresh. Sample CDS-26-74 obtained at 90.0.
	Offset 65 feet west across top of bed to avoid grass-covered interval.
57.4-55.9	Sandstone: medium- to coarse-grained; moderately well sorted; resistant cliff-former; bedded (3.4 inch to 13 inches thick); upper 5 inches display

Interval (feet)	Description
	laminations; non-calcareous; quartz, feldspar, biotite, and muscovite; light olive gray (5Y 6/1) fresh, dusky yellow (5Y 6/4) weathered.
55.9-54.4	Siltstone: interlaminated siltstone and mudstone; non-resistant; upper contact sharp and planar, lower contact sharp and planar; burrows parallel and perpendicular to laminations; olive black (5Y 2/1) fresh; non-calcareous.
54.4-44.4	Sandstone: as at 19.1, except lower part is structureless and upper part is bedded; upper part contains planar foresets, indicating a paleocurrent dispersal direction to the east.
	Offset 248 feet west across top of bed to avoid mud-covered interval.

Contact: DeCourcy Formation, Tongue 5 (Kdc_5) and Cedar District Formation, Tongue 4 (Kcd_4); sharp and planar.

Cedar District Formation, Tongue 4 (Kcd_4) (thickness = 15 feet).

44.4-24.9	Mudstone: with intercalations of siltstone and mudstone as at 368 of Kcd_2.

Contact: Cedar District Formation, Tongue 4 (Kcd_4) and DeCourcy Formation, Tongue 4 (Kdc_4) covered.

DeCourcy Formation, Tongue 4 (Kdc_4) (thickness = 10.3 feet).

	Offset 173 feet west across top of bed to avoid gravel- and mud-covered interval.
29.4-19.1	Sandstone: coarse- to medium-grained; resistant ledge-former; lower 1/2 shows bedding on weathered surface (2 inches to 8-1/2 inches thick), upper 1/2 shows rib-and-furrow structure, and isolated calcareous concretions up to 2 feet in diameter that weather out as knobs, upper contact is covered; very

Interval (feet)	Description
	calcareous; subangular to subrounded grains of quartz, feldspar, muscovite, lithic fragments, and biotite; light olive gray (5Y 6/1) fresh, dusky yellow (5Y 6/4) weathered.
	Offset 95 feet west across top of bed to attain better outcrop.

Contact: DeCourcy Formation, Tongue 4 (Kdc_4) and Cedar District Formation, Tongue 3 (Kcd_3); sharp and planar.

Cedar District Formation, Tongue 3 (Kcd_3) (thickness = 2.2 feet).

19.1-16.9	Mudstone: with intercalations of ripple-laminated siltstone and very fine sandstone up to 1-1/2 inches thick; non-resistant; thinly laminated; lower contact covered by barnacles and seaweed; upper contact sharp and planar; burrows perpendicular and parallel to laminae; non-calcareous; medium dark gray (N 4) fresh.

Contact: Cedar District Formation, Tongue 3 (Kcd_3) and DeCourcy Formation, Tongue 3 (Kdc_3); covered by beach gravel.

DeCourcy Formation, Tongue 3 (Kdc_3) (thickness = 16.9 feet).

16.9-13.9	Sandstone: as at 0, only less resistant.
	Offset 59 feet west across top of bed to avoid beach-covered interval.
13.9-9	Sandstone: medium- to coarse-grained; moderately well sorted; resistant ledge-former; shows festoon cross-bedding and cross-laminations; mudstone ripups up to 4 inches in diameter occur in the lower 2 feet of the bed; lower contact is covered; calcareous; subrounded to angular grains of quartz, chert, biotite, muscovite, lithic fragments, and hornblende; 60% in quartz and chert; light olive gray

Interval (feet)	Description
	(5Y 6/1) fresh, dusky yellow (5Y 6/4) weathered.
Contact:	DeCourcy Formation, Tongue 3 (Kdc_3) and Cedar District Formation, Tongue 2a (Kcd_{2a}); covered. This contact is chosen as the base of the second major tongue of DeCourcy Sandstone because from this point up, sandstone is more abundant than mudstone.
Cedar District Formation, Tongue 2a (Kcd_{2a}) (thickness = 8.1 feet).	
686.6-684.1	Mudstone: as at 661, but no pseudoconcretions.
	Offset 47 feet west across top of bed to avoid beach-covered interval.
684.1-679.7	Sandstone: as at 673.5, except it is lens-shaped, wedging out completely 30 feet to the west and 12 feet to the east, where the underlying mudstone increases in thickness.
	Offset 9 feet west across top of bed to reach better outcrop.
679.7-678.5	Mudstone: non-resistant; thinly laminated; upper contact displays scour-and-fill; non-calcareous; light olive gray (5Y 6/1) fresh; light gray (N 7) weathered.
	Offset 14 feet west across top of bed to reach better outcrop.
Contact:	Cedar District Formation, Tongue 2a (Kcd_{2a}) and DeCourcy Formation, Tongue 2 (Kdc_2); gradational over an interval of 1 inch.
DeCourcy Formation, Tongue 2 (Kdc_2) (thickness = 5 feet).	
678.5-678	Sandstone: fine- to very fine-grained; well sorted; resistant rib-former; parallel laminations; lower contact is irregular and load deformed on the

Interval (feet)	Description
	underlying debris flow (maximum relief of 2 inches); upper contact grades within 1 inch into overlying mudstone; quartz, feldspar, biotite, and muscovite; medium light gray (N 6) fresh, yellowish gray (5Y 7/2) weathered.
678-676.5	Submarine debris flow consisting of a jumble of mudstone and sandstone clases up to 15 inches in diameter with no preferred orientation; matrix is mudstone.
676.5-673.5	Sandstone: medium-grained; moderately well sorted; resistant ledge-former; upper 6 inches appear laminated on weathered surface, the rest is structureless; lower contact is undulatory due probably to contortions caused by the fault crossed at 669; upper contact is obscured by the overlying debris flow; subangular quartz, feldspar, biotite, and muscovite, and subrounded chert; medium light gray (N 6); mudstone ripups up to 20 inches long occur in this bed. Sample CDS-25-74 of sandstone.

Contact: DeCourcy Formation, Tongue 2 (Kdc_2) and Cedar District Formation, Tongue 2 (Kcd_2); shapr and planar.

Cedar District Formation, Tongue 2 (Kcd_2) (thickness = 673.5 feet).

Interval (feet)	Description
	Offset 14 feet across a small strike-slip fault, with a displacement of about 6 feet, to top of sandstone bed. Bearing of offset N. 70 W.
669-668.75	Sandstone: coarse-grained; moderately sorted; resistant rib-former; structurless; upper contact obscured by minor fault; 75% angular to subangular quartz; muscovite, biotite, feldspar, lithic fragments, quartzite fragments, and hornblende; light olive gray (5Y 6/1) fresh.

Interval (feet)	Description
668.75-661	Mudstone: non-resistant; pseudoconcretions up to 18 inches in diameter; numerous clastic dikes up to 1 inch wide; upper contact is sharp and planar; burrows perpendicular to laminae; non-calcareous; medium dark gray (N 4) fresh, light gray (N 7) weathered. Attitude is N. 84 E., 24°N.
661-660.7	Sandstone: as at 659.2, except lower contact is sharp and displays scour-and-fill (maximum relief of 1 inch), upper contact is sharp and irregular (maximum relief of 2 inches), pyrite concretions, and no contorted laminations.
660.7-660	Mudstone: with intercalations of siltstone and very fine sandstone as at 368.
660-659.2	Sandstone: very fine-grained, well sorted; one mudstone intercalation shows contorted laminations and flames in the sandstone; lower contact is sharp and planar; upper contact is sharp and undulating due to the contorted laminations (maximum relief of 5 inches); non-calcareous; quartz, feldspar, muscovite, and biotite; very light olive gray (5Y 6/2) fresh, dark yellowish brown (10YR 4/2) weathered; 4 feet east is a sandstone dike 4 feet wide composed of medium-to coarse-grained sandstone; some mudstone has been engulfed by the intrusion of the dike.
	Offset 15 feet west across top of bed to reach best outcrop.
659.2-655.8	Mudstone: with intercalations of siltstone and very fine sandstone as at 368, except isolated pyrite concretions up to 1 inch in diameter occur here.
655.8-501.8	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 368.

Interval (feet)	Description
	Offset 50 feet east along strike to avoid incoming tide and proceed upsection using attitude N. 86 W., 35°N.
501.8-441.8	Mudstone: with intercalations of siltstone and very fine sandstone as at 368. Attitude is N. 84 W., 35°N.
441.8-439.8	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as as 368.
439.8-436.3	Mudstone: with intercalations of siltstone and very fine sandstone as at 368.
436.3-434.8	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 368.
434.8-429.8	Mudstone: with intercalations of siltstone and very fine sandstone as at 368.
429.8-425	Covered: by beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 368.
425-423.5	Mudstone: with intercalations of siltstone and very fine sandstone as at 368.
	Offset 87 feet west along strike to obtain more outcrop; attitude is N. 86 W., 36°N.
423.5-419.5	Covered: be beach mud, probably mudstone with intercalations of siltstone and very fine sandstone as at 368.
419.5-368	Monotonous section of mudstone with intercalations of siltstone and very fine-grained sandstone laminae and beds.

Interval (feet)	Description
	Mudstone comprises 95%+ of this interval. Burrowing parallel and perpendicular to laminations occurs throughout this interval. Mudstone: non-resistant; sandstone dikes cross-cut laminations; lower contacts are gradational, within 1 inch from siltstone below; upper contacts, are sharp and load deformed (maximum relief of 1 inch); non-calcareous; medium gray (N 5) fresh, light gray (N 7) weathered. Siltstone: resistant rib-former; laminations up to 10 per inch, and festoon cross-laminations; upper contacts usually grade within 1/2 inch from sandstone below, otherwise sharp and planar; very calcareous; medium gray (N 5) fresh, dark yellowish orange (10 YR 6/6) weathered; ranges in thickness from 1/8 inch to 2 inches. Sandstone: very fine-grained; well sorted; festoon cross-laminations; parallel laminations rare; calcareous concretions; 90%+ quartz, accessory biotite, muscovite, and heavy minerals. Sample CDS-23-74; mudstone.
378-359	Covered: by beach mud, probably mudstone as at 107.6.
359-354	Mudstone: as at 107.6.
	Offset 60 feet west along strike to reach better outcrop; attitude is N. 86 W., 35°N.
354-259	Covered: by beach mud, probably interbedded mudstone, siltstone, and sandstone as at 167.4.
	Offset 124 feet east along strike using attitude N. 86 W., 30°N. and proceed upsection through covered interval.
259-178	Covered: by beach mud, probably interbedded mudstone, siltstone, and sandstone as at 167.4.

Interval (feet)	Description
178-167.4	Interbedded mudstone, siltstone, and very fine sandstone that form 6 normally graded packets ranging in thickness from 11 inches to 35.5 inches. Mudstone predominates, comprising about 85% of the interval. Siltstone intervals are less than 1/2 inch thick. Mudstone: as at 136.9. Siltstone: as at 5.7. Sandstone: as at 150.5 Offset 50 feet east at 174 and 95 feet east at 169.1 across top of bed to reach more outcrop. Attitude is N. 84 E., 30° N.
167.4-166.9	Argillaceous limestone: as at 155.9, except thin mudstone partings, up to 1/2 inch thick, separate the limestone into beds that range in thickness from 1 to 2 inches; upper contact grades within 1 inch into overlying sandstone.
166.9-162.7	Interbedded mudstone, siltstone, and very fine sandstone that form 2 normally graded packets. Mudstone comprises about 80% of this interval. Upper contact of the interval is sharp and planar. Mudstone: as at 156.2. Siltstone: as at 5.7. Sandstone: as at 159.
162.7-159.5	Mudstone: with intercalations of siltstone and very fine sandstone laminae as at 107.6, except the intercalations display horizontal burrowing and contain pyrite concretions.
159.5-159	Sandstone: very fine-grained; well sorted; resistant rib-former; lower contact shows scour-and-fill (maximum relief of 3 inches); upper contact grades within 1 inch into overlying mudstone; burrowing parallel to upper surface; festoon cross-laminations and parallel laminations.
159-156.45	Mudstone: with intercalations of siltstone and very fine sandstone as at 107.6, except intercalations are up to 1 inch thick.

Interval (feet)	Description
156.45-156.3	Limestone: as at 155.9; upper contact grades within 1 inch into overlying mudstone.
156.3-156.2	Mudstone: non-resistant; thinly laminated; upper contact is sharp and planar; burrowing parallel and perpendicular to laminations; medium dark gray (N 4) fresh.
156.2-155.9	Limestone: very silty; semi-resistant; lower 1/3 is laminated; upper 2/3 is structureless; upper contact grades within 1 inch into overlying mudstone; burrows in lower 1/3; very calcareous; medium dark gray (N 4) fresh. Sample CDS-21-74 of limestone.
155.9-150.5	Interbedded mudstone, siltstone, and very fine sandstone that form 5 normally graded packets ranging in thickness from 7 to 15 inches. Mudstone comprises approximately 70% of the unit. Offset 40 feet west at 154.6 across top of bed to avoid mud-covered interval. Mudstone: non-resistant; contains pseudoconcretions 3 to 12 inches in diameter; upper contact is sharp and usually load deformed by overlying sandstone (maximum relief of 1 inch); burrows parallel to laminae; non-calcareous; medium dark gray (N 4) fresh; contains rare intercalations of siltstone laminae up to 1/4 inch thick. Siltstone: as at 111.5. Sandstone: very fine-grained; resistant ribformer; thinly laminated; upper contact grades within 1/4 inch through siltstone into mudstone; bioturbation perpendicular and parallel to laminae; non-calcareous, quartz, biotite, and muscovite; light gray (N 7) fresh. Sample CDS-19-74 of mudstone obtained at 151.9.
150.5-145.3	Interbedded mudstone, siltstone, and very fine sandstone that form 3 graded packets. Mudstone comprises about 80% of the unit, and sandstone comprises about 19%.

Interval (feet)	Description
	Mudstone: non-resistant; pseudoconcretions 2 to 5 inches in diameter; upper contact with overlying sandstone is sharp and planar; burrows perpendicular and parallel to laminations; non-calcareous; medium dark gray (N 4) fresh; contains thin siltstone intercalations up to 1/2 inch thick, but contain pyrite concretions up to 1 inch in diameter. Siltstone: as at 5.7. Sandstone: very fine-grained; well sorted; resistant rib-former; planar cross-laminations; pyrite concretions; upper contact grades within 1/2 inch into overlying mudstone; non-calcareous, quartz, biotite, and muscovite.
145.3-143.4	Interbedded mudstone, siltstone, and very fine sandstone that form 3 graded packets as at 141.
143.4-142	Mudstone: as at 125.5, but exhibits pseudoconcretions up to 24 inches in diameter. Attitude is N. 84 E., 25°N.
142-141	Interbedded mudstone, siltstone, and very fine sandstone that form 2 graded packets. Mudstone comprises about 55% of the interval. Mudstone: as at 125.5. Siltstone: as at 5.7. Sandstone: as at 131.35, except lower contact contains burrows parallel to laminae, and contains much carbonaceous material.
141-138.7	Interbedded mudstone, siltstone, and very fine sandstone that form 2 graded packets. Mudstone comprises about 70% of the interval. Offset 14 feet west along top of bed at 140.25 to reach best outcrop. Mudstone: as at 107.6. Siltstone: as at 5.7. Sandstone: as at 131.35.
138.7-138.5	Mudstone: as at 125.5.

Interval (feet)	Description
138.5-138.4	Sandstone: as at 131.35, except upper contact is sharp and planar.
138.4-137.3	Graded packet of very fine sandstone to mudstone. Forms an incomplete Bouma sequence (BCDE). Mudstone: as at 107.6. Siltstone: as at 5.7. Sandstone: as at 131.35.
137.3-137.1	Mudstone: as at 125.5.
137.1-136.9	Sandstone: as at 131.25, but contains burrows perpendicular to laminations.
136.9-136.2	Mudstone: as at 107.6.
136.2 135.8	Argillaceous limestone: very silty; well sorted; resistant rib-former; laminations (6 per inch); festoon cross-laminations, and planar cross-laminations; upper contact grades within 1 inch into overlying mudstone; very calcareous, quartz, biotite, and muscovite; mica separates laminae; medium gray (N 5) fresh; grayish orange (10YR 7/4) weathered. Sample CDS-18-74 of limestone.
135.8-134.7	Mudstone: as at 107.7, except contains sand-filled burrows perpendicular and parallel to laminae.
134.7-134.4	Sandstone: as at 131.35.
134.4-131.35	Interbedded mudstone, siltstone, and very fine sandstone that form graded packets with incomplete Bouma sequences (CDE). Mudstone: as at 107.6. Siltstone: as at 111.5. Sandstone: as at 1.6, except with pyrite concretions.
131.35-131	Sandstone: as at 1.6, but exhibits convolute laminations.

Interval (feet)	Description
	Offset 11 feet west along top of bed to avoid cliff.
131-129.45	Mudstone: with intercalations of siltstone and very fine sandstone as at 107.6, except upper contact with overlying sandstone unit exhibits slight load deformations (maximum relief of 1/2 inch).
129.45-129.3	Sandstone: very fine-grained; very weathered; contacts obscured by weathering; calcareous; grayish orange (10YR 7/4) weathered.
129.3-129	Mudstone: as at 125.5.
129-128.6	Sandstone: as at 1.6, but very weathered.
128.6-126.4	Mudstone: as at 107.6.
126.4-126.2	Mudstone: as at 125.5, except upper contact has miniature load deformations (maximum relief of 1/2 inch).
126.2-126	Sandstone: as at 1.6, except lower contact shows miniature load deformations and flames (maximum relief of 1/2 inch).
126-125.5	Mudstone: non-resistant; weathers out in chips 3/4 by 1/4 inches; thinly laminated; contains large (1/2 inch in diameter) vertical, sand-filled burrows; olive gray (5Y 4/1) fresh.
125.5-125	Sandstone: fine- to very fine-grained; well sorted; festoon cross-laminations, many pyrite concretions; upper contact is sharp and planar; quartz, feldspar, biotite, and muscovite; light gray (N 7) fresh. Sample CDS-17-74 of sandstone.
	Offset 61 feet east across top of bed to avoid mud covered interval.
125-120.25	Interbedded mudstone, siltstone, and very fine sandstone that form 3 graded packets as at 66.9. Attitude is N. 84 E., 20° N.

Interval (feet)	Description
	Offset 49 feet west across top of bed to avoid cliff.
120.25-119.8	Sandstone: as at 1.6, except contains pyrite concretions.
119.8-118.7	Mudstone: as at 107.6.
118.7-118.6	Sandstone: very fine-grained; very well sorted; resistant rib-former; festoon cross-laminations; lower contact shows load casts (maximum relief of 2 inches); upper contact grades within 1/2 inch into overlying mudstone; slightly calcareous, quartz, muscovite, and biotite; olive gray (5Y 4/1) fresh.
118.6-117.8	Mudstone: as at 107.6.
117.8-117	Sandstone: fine- to very fine-grained; very well sorted; resistant rib-former; pyrite concretions; laminations (5 per inch), contorted laminations; upper contact grades within 1/2 inch into overlying mudstone; slightly calcareous; light gray (N 7) fresh.
	Offset 24 feet across top of bed to reach best outcrop.
117-113.2	Interbedded mudstone, siltstone, and very fine sandstone that form 3 graded packets as at 83, except the first sandstone bed shows load deformations that resemble interference ripple marks.
	Offset 28 feet west across top of bed to avoid cliff.
113.2-112.5	Mudstone: as at 0, except with minor intercalations of siltstone laminae and a few silt-filled burrows.
	Offset 14 feet west across top of bed to avoid cliff.
112.5-112.2	Sandstone: very fine-grained; very well sorted; resistant rib-former; laminations (6 per inch) and festoon cross-laminations; upper contact is sharp and planar; very calcareous, mica, quartz; medium dark gray (N 4) fresh.

Interval (feet)	Description
112.2-111.5	Graded packet consisting of very fine-grained sandstone, siltstone, and mudstone. Sandstone comprises 90% of this interval. An incomplete Bouma sequence exists (BCDE). Mudstone: as at 0, except shows extensive bioturbation perpendicular to laminations. Siltstone: too thin to obtain a sample. Sandstone: very fine-grained; very well sorted; resistant rib-former; thin laminations and festoon cross-laminations; upper contact grades within 1/4 inch into overlying mudstone; calcareous, quartz, feldspar, biotite, and calcite rhombs between laminations (probably as a result of diagenesis).
	Offset 50 feet west across top of bed to avoid mud-covered interval.
111.5-110.35	2 normally graded packets as at 83.
110.35-107.6	Mudstone: non-resistant; thinly laminated; pseudoconcretions; upper contact is sharp and load deformed (maximum relief of 1/2 inch); non-calcareous; olive gray (5Y 4/1) fresh; contains intercalations of very fine sandstone and siltstone laminae that crop out as thin ribs on weathered surface.
107.6-107.5	Sandstone: as at 1.6.
107.5-107.3	Mudstone: as at 0, except upper contact shows reverse grading into overlying sandstone.
	Offset 21 feet west across top of bed to avoid mud-covered interval.
107.3-107	Sandstone: as at 1.6, except burrowed parallel to laminae.
107-106.2	Mudstone: non-resistant; pseudoconcretions up to 6 inches in diameter; upper contact is sharp and load deformed (maximum relief of 1/4 inch); much carbonaceous debris; olive gray (5Y 4/1) fresh.

Interval (feet)	Description
106.2-105.8	Sandstone: as at 1.6. Offset 18 feet west across top of bed to avoid mud-covered interval.
105.8-92.2	A series of interbedded mudstone, siltstone, and very fine-grained sandstone that form 20 graded packets as at 83. Offset 31 feet east across top of beds to avoid high water.
92.2-91.2	2 graded packets of sandstone, siltstone, and mudstone as at 83. Attitude is N. 83 E., 29°N. Offset 48 feet west across top of bed to avoid mud-covered interval.
91-90.3	Sandstone: as at 1.6, except upper contact is sharp and planar. 15 feet to the west a mudstone lens, 5 inches thick and 32 feet in length, occurs in the sandstone and has aided in the formation of soft sediment deformations (ball and pillow structure and flames). The flames indicate a north to northwest paleoslope.
90.3-83	Interbedded mudstone, siltstone, and very fine-grained sandstone that form 10 normally graded packets as at 66.7, except the sandstone is calcareous and the incomplete Bouma sequences are (BCDE) and (CDE).
83-80.6	Interbedded mudstone and very fine-grained sandstone. Mudstone: as at 0. Sandstone: as at 1.6, except upper and lower contacts are sharp and planar, and it is calcareous.
80.6-77	Interbedded sandstone, siltstone, and mudstone that form 7 normally graded packets as at 66.9.

Interval (feet)	Description
77-76	Sandstone: as at 1.6, except it is calcareous, the upper contact is irregular due to the predominance of festoon cross-laminations; and it is not gradational.
76-66.9	Interbedded mudstone, siltstone, and very fine-grained sandstone that form 17 normally graded packets as at 18.6, except the graded packets range in thickness from 3-1/4 inches to 14 inches, and each displays incomplete Bouma sequences (BCDE), (CDE), or (DE).
66.9-65.9	Mudstone: as at 0. Attitude is N.84 E., 34°N.
65.9-38.9	Covered: probably interbedded mudstone, siltstone, and very fine sandstone as at 18.6. Offset 55 feet west along strike to reach best outcrop, attitude is N.86 W., 34°N.
38.9-18.6	Rhythmically interbedded mudstone, siltstone, and very fine-grained sandstone that form 21 normally graded packets. These graded packets form incomplete Bouma sequences (BCDE), (CDE), or (DE), and they range in thickness from 4 to 20 inches. Mudstone comprises about 60% of the interval, while siltstone comprises about 10%, and sandstone comprises about 30%. At 31.5, offset 20 feet west across top of bed to avoid covered interval. Mudstone: as at 0. Siltstone: as at 5.7, except where parts (DE) of the Bouma sequence occurs, siltstone overlies mudstone and load casts are formed. Sandstone: as at 1.6, except in a few beds, the upper surface shows burrows parallel to the laminae. Offset 12 feet east across top of bed to avoid water.

Interval (feet)	Description
18.6-18.1	Sandstone: as at 1.6, except sandstone dikes originate from this bed and extend into the underlying beds, barrowed parallel to laminations on the top surface, and pyrite concretions occur.
18.1-13.2	Interbedded siltstone and mudstone that form 2 incomplete Bouma sequences (DE). Mudstone: as at 0, except the sedimentary structure is dominated by pseudoconcretions. Siltstone: as at 5.7.
13.2-12	Sandstone: very fine-grained; well sorted; resistant rib-former; planar cross-laminations, and festoon cross-laminations; upper contact is sharp and planar; quartz, biotite, and muscovite; light gray (N 7) fresh; this unit wedges out 3 feet to the west into mudstone of the underlying bed.
12-10.9	Mudstone: as at 0, except the upper contact displays scour-and-fill (maximum relief of 2 inches).
10.9-5.8	Interbedded mudstone (3 to 25 inches thick) and very fine-grained sandstone (1/2 to 6 inches thick). Mudstone comprises about 75% of this interval. Mudstone: as at 0. Sandstone: as at 1.6, except upper contact grades within 1/2 inch into the overlying mudstone.
5.8-5.7	Siltstone: slightly resistant; thin festoon cross-laminations; upper 1/2 inch is gradational into overlying mudstone; non-calcareous; medium dark gray (N 4) fresh.
5.7-5.5	Mudstone: as at 0.
5.5-5.3	Sandstone: as at 1.6, except upper contact is sharp and planar.
5.3-3.4	Mudstone: non-resistant; thinly laminated; minor intercalations of festoon cross-laminated very fine-grained sandstone; upper contact is sharp and

Interval (feet)	Description
	slightly load deformed (maximum relief of 1/2 inch); burrows perpendicular to laminations; non-calcareous; medium dark gray (N 4) fresh.
3.4-3	Sandstone: as at 1.6, except upper surface is irregular due to the presence of festoon troughs (maximum relief of 1/2 inch), indicating a southeast paleocurrent.
3-2	Mudstone: as at 0, except upper contact shows scour-and-fill (maximum relief of 1 inch).
2-1.6	Sandstone: very fine-grained; well sorted; resistant rib-former; planar and festoon cross-laminations; upper contact grades within 2 inches into the overlying mudstone; non-calcareous, quartz, biotite, and muscovite; mica separates the laminations; light gray (N 7) fresh.
1.6-0.0	Mudstone: non-resistant; thinly laminated; upper contact is sharp and slightly load deformed (maximum relief of 1/2 inch); non-calcareous; medium dark gray (N 7) fresh.

Contact: Cedar District Formation, Tongue 2 (Kcd_2) and DeCourcy Formation, Tongue 1a (Kdc_{1a}); sharp and planar.

DeCourcy Formation, Tongue 1a (Kdc_{1a}) (thickness = 75 feet).

149.5-147	Sandstone: as at 109.75, except festoon cross-laminations are rare; dominant structures are slightly undulating laminae (13 per inch). There are some vertical and horizontal burrows filled with coarse-grained sandstone. Upper contact is sharp and planar.
	Offset 5 feet east along top of bed to reach best outcrop.

Interval (feet)	Description
147-145.3	Sandstone: medium- to coarse-grained; moderately sorted; resistant ledge-former; thinly laminated (6 per inch); alternating laminae of coarse- and medium-grained sandstone; upper contact grades within 1/2 inch into overlying very fine sandstone; subrounded quartz, feldspar, biotite, muscovite, and hornblende; medium light gray (N 6) fresh.
145.3-138.3	Sandstone: coarse-grained; moderately well sorted; resistant ledge-former; small pebbles of basalt, chert, and plutonic igneous rocks (up to 3/16 inch in diameter) are aligned, and show as laminations; upper contact is gradational within 5 inches into overlying sandstone; subrounded quartz, feldspar, biotite, muscovite, and hornblende; medium light gray (N 6) fresh.
	Offset 32 feet west across top of bed to avoid cliff.
138.3-136.8	Sandstone and siltstone: lower 3 inches are fine-grained sandstone; upper part is sandy siltstone; very well sorted; non-resistant; flames, laminae, asymmetric cross-laminae, and scour-and-fill at contact between sandstone and siltstones; upper contact grades into 1/4 inch of clay drape; upper contact of clay drape is sharp and planar; non-calcareous, quartz, and mica; medium olive gray (5Y 5/1) fresh.
136.8-131.8	Sandstone: as at 124.9, except it grades upward into a coarse-grained sandstone; beds average 4-1/2 inches thick.
131.8-124.8	Sandstone: as at 117.8, except more uniformly bedded (beds average 5-1/4 inches thick); some beds contain chert and lithic pebbles up to 3/8 inch in diameter, and the upper surfaces of beds show rib-and-furrow structure.
124.8-117.8	Sandstone: medium-grained; moderately well sorted; resistant ledge-former; bedded (1-1/2 inches to 13

Interval (feet)	Description
	inches thick), a hint of planar foresets on weathered surfaces, and some beds show laminations (as many as 4 per inch); upper 3 inches grades into overlying sandstone; subrounded quartz, feldspar, biotite, muscovite, and hornblende; medium light gray (N 6) fresh.
117.8-111.8	Covered: by beach gravel, probably interbedded mudstone, siltstone, and very fine grained sandstone as at 59.25.
	Offset 50 feet west across top of bed.
111.8-110.6	Mudstone: as at 108.1, except upper contact is covered by beach gravel.
110.6-109.75	Sandstone: very fine-grained; well sorted; resistant rib-former; festoon cross-laminations; upper contact grades within 1/4 inch into the overlying mudstone; quartz, and minor muscovite; light olive gray (5Y 6/1)fresh.
109.75-108.45	Siltstone: non-resistant; thin laminations; festoon cross-laminations; upper contact is sharp and planar; non-calcareous, quartz, biotite, and muscovite; light olive gray (5Y 5/2) fresh.
108.45-108.1	Mudstone: non-resistant; thinly laminated; upper contact grades within 1 inch into overlying siltstone; light olive gray (5Y 5/2) fresh.
	Offset 28 feet east to exposure in low sea cliff.
108.1-106.6	Sandstone: coarse- to medium-grained; moderately well sorted; resistant ledge-former; normally graded from coarse- to medium-grained sandstone; lower contact is sharp, but undulating (maximum relief of 2 inches); subangular quartz, feldspar, biotite, lithic fragments, and non-calcareous; light olive gray (5Y 5/2) fresh. Attitude is N.78 E., 34°N.

Interval (feet)	Description
106.6-106.1	Mudstone: as at 56.4.
106.1-95.4	Sandstone: as at 79.5, but without pebbles; contains one mudstone bed, 6 inches in thickness and about 20 feet wide, 15 feet to the east; this unit is a prominent hogback.
95.4-94.1	Sandstone: very fine-grained; very well sorted; resistant ledge-former; festoon cross-laminations; upper contact is undulating, but is poorly exposed; quartz and feldspar; light gray (N 7) fresh; grades laterally along strike to the east into mudstone.
94.1-88.8	Sandstone: medium- to coarse-grained; moderately sorted; resistant ledge-former; thickly bedded (up to 3 feet thick); upper contact is sharp and planar; quartz, feldspar, biotite, muscovite, and lithic fragments; very light olive gray (5Y 6/2) fresh.
	Offset 25 feet west across top of sandstone bed.
88.8-87	Sandstone: as at 59.25, except not graded and upper contact is sharp and irregular (maximum relief of 1-1/2 inches).
87-79.5	Sandstone: as at 0, except structureless and upper contact grades within 1/2 inch into overlying very fine-grained sandstone.
79.5-77.5	Mudstone: as at 59.25.
77.5-76.3	Sandstone: very fine-grained; very well sorted; resistant; contorted laminations, parallel laminations, and load deformations; upper contact is load deformed (maximum relief of 2 inches); lower contact is slightly undulatory (maximum relief of 1/2 inch); non-calcareous, quartz, feldspar, lithic fragments, accessory hornblende and muscovite; light olive gray (5Y 5/2) fresh.
76.3-73.8	Sandstone: as at 0.

Interval (feet)	Description
	Contact: DeCourcy Formation, Tongue 1a (Kcd_{1a}) and Cedar District Formation, Tongue 1 (Kcd_1); sharp and planar.
	Cedar District Formation, Tongue 1a (Kcd_{1a}) (thickness = 17.4 feet).
73.8-72.3	Mudstone: as at 59.25, except lower 3 inches are siltstone as at 56.4.
72.3-71.7	Sandstone: as at 59.25.
71.7-71.2	Graded packet as at 59.25.
71.2-71.1	Mudstone: as at 59.25.
71.1-71	Sandstone: as at 0, except without pebbles, and it wedges out 6 feet to the east into mudstone.
71-70	Interbedded mudstone, siltstone, and sandstone that form 2 normally graded packets as at 59.25.
70-68.6	Sandstone: very fine-grained; very well sorted; resistant ledge-former; festoon cross-laminations, parallel laminations in upper 1/2; burrows parallel to laminations; quartz, feldspar; non-calcareous; light gray (N 7) fresh.
68.6-66.6	Sandstone: as at 59.25; interlaminated with medium-grained sandstone as at 0, except without pebbles. Mica separates laminae.
66.6-65.4	Sandstone: as at 59.25.
65.4-59.25	Rhythmically interbedded mudstone, siltstone, and sandstone that form 6 normally graded packets that range in thickness from 6 inches to 19 inches. Mudstone: non-resistant; thinly laminated; upper contact appears sharp and planar; non-calcareous; olive gray (5Y 4/1) fresh.

Interval (feet)	Description
	Siltstone: as at 56.4, except lower contact is gradational from sandstone below. Sandstone: very fine-grained; resistant rib-former; upper contact grades within 1/2 inch into overlying siltstone; burrows parallel to laminations; quartz, feldspar; non-calcareous; light gray (N 7) fresh.
59.25-56.4	Interbedded siltstone and mudstone. Mudstone: non-resistant; thinly laminated; weathers out in chips 1/4 inch by 1/2 inch; non-calcareous; medium gray (N 4) fresh; beds range in thickness from 1 to 2 inches. Siltstone: slightly resistant rib-former; lower contact sharp and undulating (maximum relief of 1/4 inch) ;burrows parallel to laminations; non-calcareous, quartz, and biotite; medium light gray (N 6) fresh; beds range in thickness from 2 to 14 inches.

Contact: Cedar District Formation, Tongue 1a (Kcd_{1a}) and DeCourcy Formation, Tongue 1 (Kdc_1); sharp and slightly undulatory.

DeCourcy Formation, Tongue 1 (Kdc_1) (thickness = 56.4 feet).

56.4-55.55	Sandstone: as at 50.5.
55.55-55.5	Mudstone: non-resistant; thinly laminated; non-calcareous; medium dark gray (N 4) fresh.
55.5-55	Sandstone: as at 0, except with 1/2 inch laminations.
55-54.25	Sandstone: as at 29.
54.25-50.5	Sandstone: medium-grained; well sorted; resistant ledge-former; structureless; upper contact is sharp and slightly undulatory; subangular quartz, feldspar, muscovite, minor biotite, and lithic fragments; medium olive gray (5Y 5/1) fresh.

Interval (feet)	Description
	Offset 105 feet west across top of bed to reach best exposure.
50.5-43.1	Sandstone: as at 0.
43.1-41.1	Conglomerate: resistant; poorly sorted; pebbles range in size from 1/16 inch to 3/8 inch; lower contact shows scour-and-fill (maximum relief of 3 inches); upper contact is irregular; sandstone matrix as at 0; pebble composition as at 32.1; grayish orange (10YR 7/4) weathered. Wedges out 20 feet to the east into sandstone.
41.1-32.1	Sandstone: as at 0, except pebbles are concentrated near the bottom. Clasts average 1/4 inch in diameter, and are composed of mudstone, chert, quartzite, schist, basalt, and plutonic igneous rocks.
	Offset 5 feet west along top of bed to avoid overhanging ledge.
32.1-31.2	Sandstone: as at 29, except upper 2 inches are siltstone.
31.2-30.1	Sandstone: as at 0.
	Offset 10 feet west along top of bedding plane to reach better exposure.
30.1-29	Sandstone: very fine-grained; very well sorted; resistant; very fine laminations and festoon cross-laminations; lower contact is sharp and planar, upper contact is sharp but irregular (maximum relief of 1 inch); quartz, feldspar, muscovite, and biotite; medium olive gray (5Y 5/1) fresh.
19-20.5	Sandstone: as at 0.
20.5-19.5	Sandstone: medium-grained grading into very fine-grained above; well sorted to very well sorted; lower 1/2 is graded; upper 1/2 is laminated (12 per

Interval (feet)	Description
	per inch); non-calcareous, quartz, feldspar, biotite, muscovite, lithic fragments; light olive gray (5Y 6/1) fresh, grayish yellow (5Y 8/4) weathered.
19.5-17.5	Sandstone: coarse- to medium-grained; moderately well sorted; resistant ledge-former; laminated (10 per inch); lower part grades up from coarse- to medium-grained sandstone; both upper and lower contacts are sharp and planar; non-calcareous, quartz, feldspar, biotite, muscovite, lithic fragments; medium olive gray (5Y 4/2) fresh.
17.5-17.25	Sandstone: as at 0, except more pebbles (about 40%).
17.25-15.25	Sandstone: as at 0.
15.25-14	Sandstone: as at 0, only it contains pebbles up to 1 inch in diameter (they average 3/8 inch in diameter); it wedges out 6 feet in either direction into sandstone as at 0.
14-0.0	Sandstone: medium- to coarse-grained with 5% rounded pebbled of chert, basalt, and granitics up to 3/16 inch in diameter; poorly sorted; resistant cliff-former; beds from 1-1/2 inch to 28 inches thick; non-calcareous, quartz, feldspar, biotite, muscovite, and lithic fragments; medium olive gray (5Y 4/2) fresh, pale yellowish brown (10YR 6/2) weathered. Attitude is N. 80 E., 40°N.

Initial Point: SW 1/4, SE 1/4, NE 1/4, NE 1/4 section 6, Saturna Island. Digby Point is on a bearing of N. 23 W. from the initial point. Crispin Rock in Lyall Harbor is on a bearing of S. 48 E., and the ferry landing is on a bearing of S. 15 E. from the initial point. Measurement was started at the base of a 14 foot thick coarse- to medium-grained pebbly sandstone bed on the northwest shoreline of Lyall Harbor directly below the blue, white, and yellow BC Tel Cable sign. This pebbly sandstone has a variety of jointing patterns and forms part of the cliffs along the north shore of Lyall Harbor. The first unit measured has been determined to be a tongue of DeCourcy

Sandstone within Cedar District Mudstone. There are two major tongues of Cedar District Formation on Saturna Island, which are separated by a major tongue of DeCourcy Sandstone, about 210 feet thick (Muller and Jeletsky, 1970). There is more sandstone below the initial point, but it is all below the waters of Lyall Harbor.

APPENDIX B

Measured Section B-B', Northumberland Formation and DeCourcy Tongue

Section B-B' encompases the shoreline of Fiddler's Cove, northeast of Narvaez Bay. The section was measured to define the displacement of the fault that extends from Mikuni Point through Fiddler's Cove and to demonstrate the thickness change of the Northumberland Formation from Winter Cove to Fiddler's Cove.

The terminal point (B', Plate 1) is at the base of the Geoffrey Sandstone cliffs on the north shore of Fiddler's Cove. It is located about 150 feet east of the edge of the forest.

Contact at D: The contact of the Geoffrey Formation with the underlying Northumberland Formation is covered by talus; consequently, it was arbitrarily chosen at the break in slope (steeper upward).

Interval (feet)	Description
	Northumberland Formation.
238.4-228.4	Covered: by brush, probably mudstone with intercalations of siltstone and very fine sandstone as at 178.4.
228.4-203.4	Mudstone: with intercalations of siltstone and very fine sandstone as at 178.4.
203.4-178.4	Mudstone: with intercalations of siltstone and very fine sandstone up to 2 inches thick. Mudstone comprises about 75% of this interval. Mudstone: non-resistant; thinly laminated, spherical calcareous concretions up to 2 inches in diameter; sand-filled burrows perpendicular and parallel to laminae; calcareous; medium gray (N 5) fresh, light gray (N 7) weathered. Siltstone: resistant; thinly laminated; upper contacts grade within 1/2 inch into overlying mudstone; calcareous; medium light gray (N 6) fresh, yellowish gray (5Y 8/1) weathered.

Interval (feet)	Description
	Sandstone: very fine-grained; well sorted; resistant rib-formers; thin laminations, festoon cross-laminations indicating an east-southeast paleocurrent direction; lower contacts are usually sharp and irregular, some are load deformed, some display scour-and-fill; upper contacts usually grade within 1-1/2 inches into overlying siltstone; burrows parallel to laminations; calcareous; quartz, biotite, and muscovite; medium light gray (N 6) fresh, yellowish gray (5Y 8/1) weathered.
	Offset 30 feet east across top of bed to reach best outcrop.
178.4-82.4	Covered: by beach gravel, probably mudstone with intercalations of siltstone and very fine sandstone as at 3. Attitude is N. 88 W., 23°N.

Contact: Northumberland Formation, Tongue 7 (Kn_7) and DeCourcy Formation, Tongue 10 (Kdc_{10}); covered by beach gravel.

DeCourcy Formation, Tongue 10 (Kdc_{10}) (thickness = 68.9 feet).

82.4-67.4	Sandstone: pebbly in lower 1/2, and grades upward into a coarse-grained sandstone; resistant; forms beds about 13 inches thick; upper contact covered by beach gravel; pebbles of quartzite, chert, and lithic fragments up to 1/2 inch in diameter are suspended in a matrix of coarse-grained sandstone as at 13.5.
67.4-13.5	Sandstone: medium-grained; well sorted; resistant cliff-former; beds up to 10 feet thick, upper 2 feet are laminated; upper contact shows scour-and-fill (maximum relief of 1 foot); quartz, chert, feldspar, biotite, lithic fragments; non-calcareous; light olive gray (5Y 6/1) fresh, grayish orange (10YR 7/4) weathered.

Interval (feet)	Description
	Contact: DeCourcy Formation, Tongue 10 (Kdc_{10}) and Northumberland Formation, Tongue 6 (Kn_6) covered by beach mud and gravel.
	Northumberland Formation, Tongue 6 (Kn_6) (thickness = 13.5 feet).
13.5-10	Covered: by beach mud, probably mudstone as at 3.
	Offset 165 feet east along strike to reach more outcrop. Attitude is N. 88 W., 23°N.
10-6-25	Mudstone: as at 3.
6.25-5.5	Sandstone: very fine-grained; very weathered; thinly laminated; contacts obscured by weathering; non-calcareous; quartz, biotite, and muscovite; very pale orange (10YR 8/2) weathered, no fresh available.
5.5-3	Mudstone: non-resistant, forms part of a pocket; contains laminar of siltstone; contacts are weathered; non-calcareous, olive gray (5Y 4/1) fresh.
3-0	Mudstone: very weathered, probably same as at 3.

Contact at C: The contact of Northumberland Formation Tongue 6 (KN_6) over DeCourcy Formation, Tongue 9 (Kdc_9) is sharp and planar.

Initial point (C, Plate 1) is at the top of a medium-grained sandstone bed in a notch on the southern part of Fiddler's Cove where a mudstone unit of 10 feet in thickness is exposed in the low sea cliff and is sandwiched between sandstone tongues of the DeCourcy Formation. This initial point is northwest of the most southerly projection of sandstone that separates Narvaez Bay from Fiddler's Cove. It is located in the NW 1/4, SW 1/4, SE 1/4, SW 1/4, section 13 of Saturna Island.

APPENDIX C

Measured Section C-C', DeCourcy Formation with Cedar District and Northumberland Tongues

Section C-C' encompasses the southeastern shoreline of Saturna Island, northeast of the Jave Islets, the shoreline around Monarch Head, and the bluffs overlooking Monarch Head. The section was measured to show the intertonguing relationships involved in the DeCourcy Formation, and to show the true thickness of the formation, which aids in the determination of the displacement on the fault that extends from Mikuni Point through Fiddler's Cove.

The terminal point (C', Plate 1) is at the top of the sandstone bluff overlooking Monarch Head. It is located in the NE 1/4, NE 1/4, SE 1/4, SE 1/4, sec. 1.

Contact at F: the contact of the Northumberland Formation with the underlying DeCourcy Formation is not exposed. The section measurement was terminated here because of the end of exposures.

Interval (feet)	Description
815.6-811.6	Sandstone: as at 791, except upper contactis covered by undergrowth.
811.6-811.5	Mudstone: thinly laminated; upper contact sharp and load deformed (maximum relief of 1/2 inch); non-calcareous; olive gray (5Y 4/1) fresh; weathers out in chips 1/4 inch by 1/4 inch.
811.5-811.3	Sandstone: as at 810.9.
811.3-811.2	Mudstone: as at 808.1.
811.2-810.9	Sandstone: very fine-grained; well sorted; resistant rib-former; festoon cross-laminations indicating a paleocurrent direction to the southwest; upper contact grades within 1 inch into overlying mudstone; quartz, biotite, muscovite, and non-calcareous; grayish orange (10YR 7/4) weathered, no fresh available.

Interval (feet)	Description
810.9-810.7	Mudstone: as at 808.1.
810.7-810	Sandstone: as at 806.1
810-808.3	Sandstone: as at 791.1, except no festoon cross-beds; only bedding up to 1 inch thick.
808.3-808.1	Mudstone: thinly laminated; upper contact shows small-scale load deformation (maximum relief of 1-1/2 inches); non-calcareous; grayish orange (10YR 7/4) weathered, no fresh available; weathers out in chips 1/4 inch by 1/4 inch.
808.1-806.1	Sandstone: fine-grained; upper 5 inches grades upwards into very fine-grained; very well sorted; resistant; festoon cross-laminations; upper contact covered by beach mud; non-calcareous; quartz, biotite, muscovite, and feldspar; grayish orange (10YR 7/4) weathered, no fresh available.
806.1-791.1	Sandstone: medium-grained; moderately well sorted; resistant; festoon cross-bedding indicating a paleocurrent dispersal direction to the west; upper contact grades within 3 feet into overlying fine-grained sandstone; sub-rounded grains of quartz, feldspar, muscovite, and lithic fragments; grayish orange (10YR 7/4) weathered, no fresh available. Attitude is N. 82 E., 16°N.
791.1-491.1	Sandstone: coarse-, medium-, and fine-grained sandstone; thickly bedded; forms a 300 foot cliff. Structures seen in this interval are large scale planar foresets, multiple scour-and-fill, festoon cross-bedding, festoon cross-laminations, and laminations Galleries and honeycomb weathering are extensive in the wave and spray zone. Mudstone ripups can be seen in some of the units, and no conglomerates were observed. Flames were observed at the contact between medium- and coarse-grained sandstone in a boulder in the talus pile. This unit was measured by dropping a rope

Interval (feet)	Description
	down the cliff until it reached the water, then the dry portion of the rope was measured. Lowermost sandstone: medium-grained; well sorted; resistant cliff-former; planar cross-beds indicating a paleocurrent dispersal direction to the east; sub-angular grains of quartz, feldspar, biotite, muscovite; non-calcareous; light olive gray (5Y 6/1) fresh, grayish yellow (10Y 8/4) weathered. Fine-grained sandstone: well sorted; slightly non-resistant; laminated (20 per inch); non-calcareous; quartz, feldspar, muscovite, and biotite; medium dark greenish gray (5G 5/1) fresh, yellowish gray (5Y 8, 4) weathered.
491.1-437.1	Covered: by talus, probably sandstone as above.

Contact: DeCourcy Formation, Tongue 9 (Kdc_9) and Northumberland Formation, Tongue 5 (Kn_5); covered by talus, but arbitrarily chosen at base of slope (steeper upsection).

Northumberland Formation, Tongue 5 (Kn_5) (thickness = 4.9 feet).

Interval (feet)	Description
437.1-435.4	Covered: by talus, probably mudstone as below. Attitude is N. 88 W., 20°N.
435.4-434.2	Mudstone: with intercalations of siltstone and very fine sandstone as at 290.7.

Contact: Northumberland Formation, Tongue 5 (Kn_5) and DeCourcy Formation, Tongue 8 (Kdc_8); sharp and planar.

DeCourcy Formation, Tongue 8 (Kdc_8) (thickness = 11.95 feet).

Interval (feet)	Description
432.2-420.25	Sandstone: as at 335.4.
	Offset 40 feet east across top of bed to avoid cliff.

Interval (feet)	Description

Contact: DeCourcy Formation, Tongue 8 (Kdc_8) and Northumberland Formation, Tongue 4 (Kn_4); sharp and planar.

Northumberland Formation, Tongue 4 (Kn_4) (thickness = 30.5 feet).

420.25-389.75 Mudstone: with intercalations of siltstone and very fine sandstone, as at 290.7, but with micritic limestone concretions, medium dark gray (N 4) in color. Upper contact is sharp and load deformed, locally exhibits scour-and-fill (maximum relief of 12 inches), and is sharp and planar at other places.

Offset 87 feet west across top of bed to avoid high water.

Contact: Northumberland Formation, Tongue 4 (Kn_4) and DeCourcy Formation, Tongue 7 (Kdc_7); slight angular discordance (3° maximum).

DeCourcy Formation, Tongue 7 (Kdc_7) (thickness = 33 feet).

389.75-356.75 Sandstone: medium-grained in lower 1/3, coarse-grained in upper 2/3; pebbles of chert and basalt up to 1/8 inch in diameter in coarse-grained sandstone; resistant cliff-former; well sorted to poorly sorted; scour-and-fill and soft sediment deformations occur at the contact between medium- and fine-grained sandstone (maximum relief of 5 inches); bedded (about 1/2 inch thick), rare festoon cross-beds; weathered surface displays calcareous concretions up to 5 feet in diameter; upper contact shows slight angular discordance (3° maximum); non-calcareous, subangular quartz, feldspar, muscovite, and biotite; light olive gray (5Y 6/1) fresh, light yellowish gray (5Y 8/2) weathered.

Attitude is N. 72 W., 24°N.

Offset 89 feet east across top of bed to avoid cliffs.

Interval (feet)	Description
	Contact: DeCourcy Formation, Tongue 7 (Kdc_7) and Northumberland Formation, Tongue 3 (Kn_3); sharp and planar.
	Northumberland Formation, Tongue 3 (Kn_3) (thickness = 11 feet).
356.75-345.75	Mudstone: with intercalations of siltstone and very fine sandstone as at 290.7.
	Contact: Northumberland Formation, Tongue 3 (Kn_3) and DeCourcy Formation, Tongue 6 (Kdc_6); sharp and planar.
	DeCourcy Formation, Tongue 6 (Kdc_6) (thickness = 10.35 feet).
345.75-335.4	Sandstone: coarse-grained, upper 8 inches grades into medium-grained sandstone; well sorted except for mudstone clasts in upper 8 inches; resistant cliff-former; faint traces of bedding (1-1/2 inch thick) on weathered surface; upper contact is sharp and planar; angular to subangular grains of quartz, feldspar, biotite, and muscovite; non-calcareous; light olive gray (5Y 6/1) fresh, light yellowish gray (5Y 8/2) weathered.
	Contact: DeCourcy Formation, Tongue 6 (Kdc_6) and Northumberland Formation, Tongue 2 (Kn_2); shapr and planar.
	Northumberland Formation, Tongue 2 (Kn_2) (thickness = 44.7 feet).
335.4-290.7	Mudstone: with intercalations of siltstone and very fine sandstone. Mudstone comprises about 95% of this interval. The upper contact with the overlying sandstone is sharp and planar. Mudstone: non-resistant; thinly laminated; upper contacts exhibit load deformations, including flames (maximum relief of 1/2 inch); vertical and horizontal burrows; non-calcareous; medium-dark gray (N 4) fresh, light gray (N 7) weathered. Siltstone: non-resistant; thin laminations, festoon cross-laminations; upper contacts usually

Interval (feet)	Description
	grade within 1/2 inch into overlying mudstone; non-calcareous; quartz, biotite, and muscovite; medium dark gray (N 4) fresh, light gray (N 7) weathered. Sandstone: very fine-grained; well sorted; resistant rib-former; festoon cross-laminations, indicating a paleocurrent dispersal pattern to the west; upper contacts usually grade within 1 inch into overlying siltstone, but rarely are sharp and planar; subangular grains of quartz, muscovite, biotite, and feldspar; abundant carbonaceous debris; calcareous; medium light gray (N 6) fresh, yellowish gray (5Y 7/2) weathered.

Contact: Northumberland Formation, Tongue 2 (Kn_2) and DeCourcy Formation, Tongue 5 (Kdc_5); sharp and planar.

DeCourcy Formation, Tongue 5 (Kdc_5) (thickness = 4.1 feet).

290.7-288.6	Sandstone: as at 286.6, except upper contact is sharp and planar.
288.6-288.5	Mudstone: as at 279.6, except no load deformation.
288.5-286.6	Sandstone: medium-grained; well sorted; resistant rib-former; laminated up to 1/2 inch thick; upper 3 inches displays vertical and horizontal burrows; non-calcareous; quartz, biotite, and muscovite; light olive gray (5Y 6/1) fresh, yellowish gray (5Y 8/1) weathered.

Contact: DeCourcy Formation, Tongue 5 (Kdc_5) and Northumberland Formation, Tongue 1 (Kn_1); scour-and-fill (maximum relief of 5 inches).

Northumberland Formation, Tongue 1 (Kn_1) (thickness = 7 feet).

286.6-284.6	Mudstone: with intercalations of very fine sandstone as at 279.6, except mudstone comprises 80% of the interval and the upper contact shows scour-and-fill (maximum relief of 5 inches). Sand-filled burrows occur parallel and perpendicular to the laminae.

Interval (feet)	Description
284.6-282.6	Sandstone: very fine-grained; well sorted; 5% mudstone clasts; resistant ridge-former; displays contorted laminations; lower contact is sharp and planar; upper contact is sharp and undulatory (maximum relief of 1 inch); slightly calcareous; subangular to subrounded quartz, feldspar, biotite, and muscovite; medium light gray (N 6) fresh, light gray (N 7) weathered; wedges out 30 feet to the west into mudstone.
282.6-279.6	Mudstone: with intercalations of very fine sandstone up to 1 inch thick. Mudstone comprises about 95% of the interval. Upper contact is sharp and planar. Mudstone: non-resistant, weathers out in chips 1/4 inch by 1/4 inch; thinly laminated; upper contacts display scour-and-fill (maximum relief of 1/2 inch); burrows parallel to laminae; non-calcareous; olive gray (5Y 4/1) fresh, light gray (N 7) weathered. Sandstone: very fine-grained; very well sorted; festoon cross-laminations; sandstone dikes (up to 1 inch wide) originate from sandstone and cross-cut laminae of mudstone; upper contacts sharp and undulatory due to the festoon cross-laminations (maximum relief of 1/2 inch); subangular grains of quartz, feldspar, biotite, and muscovite; non-calcareous; greenish gray (5G 6/1) fresh, yellowish gray (5Y 7/2) weathered. Offset 217 feet west across top of bed to avoid high water.

Contact: Northumberland Formation, Tongue 1 (Kn_1) and DeCourcy Formation, Tongue 4 (Kdc_4); shapr and undulatory (maximum relief of 3 inches).

DeCourcy Formation, Tongue 4 (Kdc_4) (thickness = 145.25 feet).

279.6-248.6	Sandstone: coarse- to fine-grained with pebbles of quartzite, chert, and basalt up to 1/4 inch in diameter in matrix support; moderately to well sorted;

Interval (feet)	Description
	resistant cliff-former; calcareous concretions up to 4 feet in diameter, rib-and-furrow, festoon cross-bedding, one pebbly sandstone channel with normal grading above it, no orientation can be determined; flames occur where coarse-grained sandstone overlies fine-grained sandstone; upper contact is sharp and undulatory (maximum relief of 3 inches); mudstone ripups up to 14 inches in length and elongate in an east-west direction occur in the upper part; quartz, chert, feldspar, muscovite, biotite, and lithic fragments; non-calcareous; light olive gray (5Y 6/1) fresh, yellowish gray (5Y 8/1) weathered.
	Offset 50 feet east across top of bed to avoid cliff. Attitude is N.76 W., 23°N.
248.6-248.5	Mudstone: non-resistant, weathers out in chips 1/2 inch by 1/2 inch; thinly laminated; lower contact is irregular as a result of intraformational slumping below (maximum relief of 2 inches); upper contact shows load deformations including flames and diapirs (maximum relief of 2 inches); sand-filled burrows; non-calcareous; medium gray (N 5) fresh, light olive gray (5Y 6/1) weathered.
248.5-244	Interbedded sandstones and mudstone that have undergone penecontemporaneous deformation resulting in contorted bedding and laminations and isoclinal and recumbent folding without disturbing the underlying or overlying strata. Medium-grained sandstone: as at 232.2. Very fine-grained sandstone: as at 209.4. Mudstone: as at 237.3.
244-242.6	Sandstone: fine-grained; well sorted; non-resistant; bedded up to 9 inches thick; upper contact sharp and planar; non-calcareous; quartz, biotite, muscovite, and lithic fragments; medium gray (N 5) fresh, yellowish gray (5Y 8/1) weathered.
242.6-242.2	Mudstone: as at 237.3

Interval (feet)	Description
242.2-237 8	Sandstone: as at 232.2, except upper contact is sharp and planar.
	Offset 36 feet west across top of bed to avoid cliff.
237.8-237.3	Mudstone: as at 224.4, but no lensing occurs; the upper contact is sharp and planar; one sandstone dike 1/2 inch wide was observed.
237.3-232.2	Sandstone: coarse-grained grading upwards in upper 1/2 into medium-grained; well sorted; resistant cliff-former; shows calcareous concretions up to 1 foot in diameter on weathered sufrace; festoon cross-bedding is assumed to be present because of the scour-and-fill of the lower contact, but it appears structureless; upper contact grades within 1 inch into overlying mudstone; subangular grains of quartz, chert, feldspar, biotite, and muscovite; non-calcareous; light olive gray (5Y 6/1) fresh, grayish yellow (5Y 8/4) weathered.
232.2-231.1	Mudstone: with intercalactions of very fine sandstone as at 209.4, except upper contact exhibits scour-and-fill and load deformations (maximum relief of 6 inches).
231.1-224.5	Sandstone: as at 210.4, except upper contact is sharp and planar.
	Offset 50 feet east across top of bed to avoid cliff.
224.5-224.4	Mudstone: as at 209.4, except no intercalations. Wedges out 100 feet to the west into sandstone and thickens to 10-1/2 inches 75 feet to the east.
224.4-210.4	Sandstone: medium-grained with 3% pebbles (mostly chert) up to 1/8 inch in diameter; upper 1 foot grades into fine-grained sandstone; moderately sorted, resistant cliff-former; calcareous concretions up to 2 feet in diameter occur on weathered surface, otherwise it is structureless; lower contact

Interval (feet)	Description
	sharp and nearly planar (slight load deformations with a maximum relief of 1/2 inch occur); upper contact sharp and undulatory (maximum relief of 4 inches); slightly calcareous; quartz, chert, feldspar, biotite, muscovite, and lithic fragments; light olive gray (5Y 6/1) fresh, grayish yellow (5Y 8/4) weathered.
	Offset 233 feet east across top of bed to avoid cliff.
210.4-209.4	Mudstone: with intercalations of very fine sandstone. The unit is non-resistant, non-calcareous, and is thoroughly burrowed (Figure 22), upper contact is sharp and load deformed (maximum relief of 2 inches). Mudstone: non-resistant; thinly laminated; weathers out in chips 1/4 inch by 1 inch; medium dark gray (N 4), fresh. Sandstone: very fine-grained; very well sorted; weather out as resistant ribs; festoon cross-laminations, laminations up to 3/4 inch thick; quartz, biotite, and muscovite; yellowish gray (5Y 7/2) weathered, no fresh available.
209.4-196.4	Sandstone: coarse-grained with pebbles of quartzite, chert, and basalt up to 1/8 inch in diameter, last 1 foot grades into medium-grained sandstone; moderately sorted; resistant cliff-former; shows faint bedding (about 1 foot thick) and faint festoon cross bedding; upper contact weathered, but appears to be sharp and planar; lower contact shows load deformations and scour-and-fill (maximum relief of 2 inches); vertical burrows throughout; subangular to subrounded grains of quartz, chert, feldspar, biotite, lithic fragments, and muscovite; non-calcareous; light olive gray (5Y 5/2) fresh, yellowish gray (5Y 7/2) weathered.
196.4-186.4	Interbedded sandstone, siltstone, and mudstone, as at 118.9, except sandstone dominates here with beds up to 4 feet thick, intraformational slumping has

Interval (feet)	Description
	occurred, and small coal lenses are present (Figure 24).
	Offset 187 feet east across top of bed to avoid cliff.
186.4-162.4	Sandstone: very coarse-grained, upper 2 feet grades into medium-grained sandstone; moderately well sorted; resistant cliff-former; calcareous concretions up to 6 feet in diameter occur on weathered surfaces; upper contact covered by talus, subangular grains of quartz, chert, feldspar, biotite, muscovite, and lithic fragments; light olive gray (5Y 6/1) fresh, yellowish gray (5Y 8/1) weathered.
	Offset 149 feet east across top of bed to avoid cliff.
162.4-161.4	Sandstone: as at 159.3, except upper contact shows scour-and-fill (maximum relief of 1 inch).
161.4-160.2	Sandstone: as at 153.2, but upper contact grades within 1/2 into overlying sandstone.
160.2-159.3	Sandstone: very fine-grained; very well sorted; non-resistant; contorted laminations, coarse-grained sandstone dikes up to 1-1/2 inches wide cross cut laminae; upper contact load deformed, exhibits flames and load casts (maximum relief of 3 inches); quartz, biotite, muscovite; non-calcareous; light olive gray (5Y 6/1) fresh, light gray (N 7) weathered.
	Offset 132 feet east across top of bed to avoid cliff.
159.3-153.2	Sandstone: coarse-grained, grades upwards in upper 1/2 through medium-grained into fine-grained sandstone; well sorted; resistant cliff-former; galleries have formed where the waves have cut into the cliffs; bedded about 1 foot thick; upper contact sharp and undulatory (maximum relief of 2 inches); subangular to subrounded grains of quartz, chert, biotite, muscovite, feldspar, and lithic fragments;

Interval (feet)	Description
	calcareous; very light olive gray (5Y 6/2) fresh, grayish yellow (5Y 8/4) weathered.
153.2-147.9	Interbedded mudstone, siltstone, and very fine-grained sandstone as at 118.11, but consists of 6 normally graded units, and contains low grade bituminous coal lenses up to 2 inches thick by 5 feet wide.
	Offset 30 feet east across top of bed to avoid overhanging cliff.
147.9-133.75	Sandstone: coarse-grained, grades upwards in upper 1/3 into fine-grained sandstone; moderately well to well sorted; resistant cliff-former; mudstone ripups up to 1 foot in length in lower 1/4, calcareous concretions up to 5 feet in diameter in middle, festoon cross-bedding indicating a paleocurrent dispersal direction to the east or southeast; thin beds 1/2 to 2 inches thick show on weathered surface; upper contact sharp and planar; angular to subangular grains of quartz, chert, feldspar, biotite, hornblende, muscovite, and lithic fragments; calcareous; light gray (N 7) fresh, yellowish gray (5Y 8/1) weathered.
	Offset 145 feet east across top of bed to avoid overhanging cliff.

Contact: DeCourcy Formation, Tongue 4 (Kdc_4) and Cedar District Formation, Tongue 4 (Kcd_4); sharp and load deformed (maximum relief of 1 inch).

Cedar District Formation, Tongue 4 (Kcd_4) (thickness = 14.85 feet).

133.75-118.9	Interbedded mudstone, siltstone, and very fine-grained sandstone that display a series of repeated graded beds (at least 19 throughout the unit). Burrows occur throughout the interval perpendicular and parallel to laminae. Carbonaceous debris occurs

Interval (feet)	Description
	throughout this non-resistant unit. The upper contact is sharp and load deformed (maximum relief of 1 inch). Some sandstone dikes up to 1 inch wide extend down from the overlying sandstone bed.
	Mudstone: non-resistant; thinly laminated; upper contacts are load deformed and commonly exhibit flames (maximum relief of 1/2 inch); calcareous; medium dark gray (N 4) fresh, medium light gray (N 6) weathered.
	Siltstone: non-resistant, thinly laminated; upper contacts grade within 1/2 inch into mudstone above; quartz, biotite, muscovite; slightly calcareous; medium light gray (N 6) fresh.
	Sandstone: very fine-grained; well sorted; resistant rib-former; laminated (22 per inch), festoon cross-laminations indicating a paleocurrent direction to the southeast, contorted laminations; upper contact grades within 1 inch into siltstone above; quartz, biotite, muscovite; non-calcareous; light olive gray (5Y 6/1) fresh, yellowish gray (5Y 8/1) weathered.
	Sample CDS-42-74 of sandstone obtained at 118.8 foot level.

Contact: Cedar District Formation, Tongue 4 (Kcd_4) and DeCourcy Formation, Tongue 3 (Kdc_3); sharply gradational (grades within 1/2 inch into overlying unit).

DeCourcy Formation, Tongue 3 (Kdc_3) (thickness = 19.3 feet).

118.9-116.9	Sandstone: very fine-grained; well sorted; non-resistant; laminated (20 per inch), small scale festoon cross-laminations, festoon troughs and asymmetric ripple marks indicate a paleocurrent direction of north to north northeast; upper contact grades within 1/2 inch into overlying mudstone; burrows parallel to upper surface; non-calcareous, quartz, biotite, and muscovite; light gray (N 7) fresh, very pale orange (10YR 8/2) weathered.

Interval (feet)	Description
116.9-116.2	Sandstone: very fine-grained; well sorted; non-resistant; cut by many sandstone dikes, up to 1 inch wide, that originate from the underlying bed; lower contact is irregular due to the clastic dikes; upper contact is indistinct and grades over an interval of 2 inches into the overlying bed; quartz, muscovite, biotite, non-calcareous; light gray (N 7) fresh, very pale orange (10YR 8/2) weathered. Attitude is N.74 W., 31°N.
116.2-99.6	Sandstone: coarse-grained; moderately well sorted; resistant cliff-former; calcareous concretions up to 5 feet in diameter weather out as large knobs; the concretions occur in the middle of the unit and split it into 3 distinct parts; subangular to subrounded grains of quartz, chert, feldspar, and biotite; non-calcareous (except for the concretions); light gray (N 7) fresh, yellowish gray (5Y 8/1) weathered.
	Offset 92 feet east across top of bed to avoid cliff.

Contact: DeCourcy Formation, Tongue 3 (Kdc_3) and Cedar District Formation, Tongue 3 (Kcd_3); sharp and planar.

Cedar District Formation, Tongue 3 (Kcd_3) (thickness = 29.7 feet).

Interval (feet)	Description
99.6-98.1	Sandstone: very fine-grained; very well sorted; resistant, forms part of a cliff; laminations (10 per inch) and contorted laminations; upper contact load deformed (maximum relief of 1 inch); lower contact exhibits flames and diapirs (maximum relief of 4 inches); non-calcareous; quartz, biotite, and muscovite; light gray (N 7) fresh, yellowish gray (5Y 7/2) weathered.
98.1-92	Intraformational slump consisting of contorted beds of mudstone, siltstone, and sandstone. Lower contact is only slightly deformed (maximum relief of 2 inches) while upper contact is deformed with a maximum relief of 4 inches. Lithology as Kcd_2 at initial point.

Interval (feet)	Description
	Offset 428 feet east across top of bed to avoid cliff.
92-84.3	Mudstone: with intercalations of siltstone and very fine-grained sandstone as Kcd_2 at initial point.
84.3-81.3	Sandstone: fine-grained; well sorted; resistant ledge-former; laminated more than 10 per inch, but shows only on weathered surface as festoon cross-laminations; upper contact grades within 1/2 inch into the overlying mudstone; non-calcareous; quartz, biotite, muscovite, and carbonaceous debris (twigs); light gray (N 7) fresh.
81.3-69.9	Mudstone: with intercalations of siltstone and very fine-grained sandstone as Kcd_2 at initial point.

Contact: Cedar District Formation, Tongue 3 (Kcd_3) and DeCourcy Formation, Tongue 2 (Kdc_2); sharp and planar.

DeCourcy Formation, Tongue 2 (Kdc_2) (thickness = 69.9 feet).

69.9-46.2	Sandstone: as at 36.2, but contains mudstone partings up to 2 inches thick, contains about 1% mudstone clasts up to 1 inch in diameter, and is bedded (2 to 9 feet thick).
46.2-40	Sandstone: as at 36.2, except contains contorted laminations, ripups of mudstone and very fine-grained sandstone from underlying unit, upper contact is load deformed (maximum relief of 4 inches).
	Offset 100 feet east across top of bed to avoid cliff.
40-38.2	Mudstone: interbedded with very fine grained sandstone. Unit is non-resistant. Mudstone: as at 8.1, but not a lens. Sandstone: as at 23.1, except upper contacts grade within 1/4 inch into overlying mudstone.

Interval (feet)	Description
38.2-36.2	Sandstone: medium-grained with pebbles of quartzite, chert, and basalt up to 1/8 inch in diameter in lower 2 inches; moderately well sorted; resistant lege-former; structureless; upper contact is sharp and planar; non-calcareous; quartz, feldspar, biotite, and muscovite; light olive gray (5Y 6/1) fresh, yellowish gray (5Y 7/2) weathered.
36.2-35.25	Mudstone: as at 8.1, except not a lens and contains laminae of siltstone.
35.25-33.7	Sandstone: as at 23.1, but contains contorted laminations.
33.7-25.2	Sandstone: pebbly and coarse-grained in lower 1/3, grades upwards into medium-grained sandstone in upper 2/3; moderately sorted; resistant cliff-former; upper contact grades within 1 inch into overlying mudstone; subrounded grains of quartz, feldspar, hornblende, muscovite, and biotite; chert pebbles up to 1/4 inch in diameter; light olive gray (5Y 6/1) fresh, light dusky yellow (5Y 7/2) weathered.
	Offset 330 feet east across top of bed to avoid cliff.
25.2-24.4	Mudstone: non-resistant; thinly laminated; upper contacts display load deformations and scour-and-fill (maximum relief of 1/2 inch); non-calcareous; medium gray (N 5) fresh.
24.4-23.1	Sandstone: very fine- to fine-grained; well sorted; resistant cliff-former; laminations (about 4 per inch) and festoon cross-laminations indicating a paleocurrent dispersal direction to the east; upper contact sharp and planar; non-calcareous; quartz, biotite, and muscovite; light gray (N 7) fresh, light olive brown (5Y 5/4) weathered.
23.1-9.4	Sandstone: coarse-grained in lower 1/2, grading into medium grained in upper 1/2; moderately

Interval (feet)	Description
	sorted; resistant cliff-former; structureless; upper contact sharp and planar; subrounded to sub-angular grains of quartz, chert, feldspar, lithic fragments, biotite, muscovite, and accessory hornblende or augite; non-calcareous; light olive gray (5Y 6/1) fresh, medium light gray (N 6) weathered.
9.4-9.25	Mudstone: as at 8.1, except it wedges out within 5 feet in either direction into sandstone of overlying bed.
9.25-8.7	Sandstone: as Kcd_2 sandstone at initial point.
8.7-8.1	Mudstone: lens; non-resistant; thinly laminated; upper contact sharp and planar; non-calcareous; medium gray (N 5) fresh; wedges out within 5 feet in either direction into sandstone of underlying unit.
8.1-0	Sandstone: coarse- to medium-grained; moderately sorted; resistant cliff former; thickly bedded; upper contact sharp and planar; angular to subrounded grains of quartz, feldspar, chert, muscovite, and biotite, light gray (N 7) weathered, no fresh available; burrows parallel to the lower contact.

Contact at E: is sharp and concordant. There is a distinct change from the interbedded mudstone, siltstone, and sandstone of the Cedar District Formation, Tongue 2 (Kcd_2) to the thick sandstone cliffs of the DeCourcy Formation, Tongue 2 (Kdc_2).

Initial point (E, Plate 1; Figure) is at an undercut notch, where the less resistant Cedar District Formation has eroded back under the overlying DeCourcy Sandstone cliffs. This point is where the dipping strata of the DeCourcy Sandstone cliffs that form Brown Range intersect the beach. Boulders and blocks of DeCourcy Sandstone have fallen from the cliffs above creating a very rugged and rocky coastline. The bearing to the east tip of the eastern Java Islet is S. 34 W. The bearing to the Northwest tip of Waldron Island is S. 18 W. The initial point is located in the S 1/2, SE 1/4, SE 1/4, SW 1/4, section 1.

Description of the Cedar District Formation at the initial point: Consists of interbedded mudstone, siltstone, and very fine-grained sandstone that displays repeated graded beds. Incomplete Bouma sequences have formed (BCDE), (CDE), and (DE). The unit, as a whole is non-resistant.

Mudstone: non-resistant; finely laminated; weathers out in chips 3/4 inch by 1/2 inch; lower contacts exhibit small scale load deformations, including some flames (maximum relief of 1 inch); medium dark gray (N 4) fresh, medium gray (N 5) weathered.

Siltstone: non-resistant; thin lamination, festoon cross-laminations; upper contact grades within 1/2 inch into the overlying mudstone; non-calcareous; quartz, biotite, and muscovite; medium dark greenish gray (5GY 5/1) fresh.

Sandstone: very fine-grained; very well sorted; resistant rib-former; thin laminations and festoon cross-laminations that appear to indicate a paleocurrent direction to the west; upper contacts grade within 1/2 inch into overlying siltstone; non-calcareous; quartz, biotite, and muscovite; greenish gray (5GY 6/1) fresh, yellowish gray (5Y 7/2) weathered.

APPENDIX D

MODAL ANALYSES OF SANDSTONE SAMPLES

Mineralogy \ Sample	Kep	Kcd		Kdc		
	CDS-10	CDS-44	CDS-17	CDS-5	CDS-9	CDS-11
Stable grains						
quartz	32.3	35.6	43.3	30.6	40.0	35.2
poly-x quarts	6.6	3.0	0.6	7.0	10.3	8.0
chert	0.6	1.0	--	3.7	0.3	1.6
Feldspars						
K-spar	7.3	0.6	3.0	7.3	10.0	14.7
plagioclase	8.3	5.0	4.3	16.3	13.3	15.4
Mica						
Biotite	3.6	6.0	7.3	6.0	6.7	7.4
muscovite	1.0	0.6	4.3	1.7	0.3	1.3
chlorite	2.6	6.3	2.7	3.3	5.0	2.9
Pyroxenes						
orthopyroxene	T	--	T	0.3	1.3	0.3
clinopyroxene	T	--	--	1.0	0.3	0.3
Fe-rich minerals						
pyrite	--	0.3	--	--	--	--
limonite	1.0	T	--	--	--	T
hematite	T	0.3	1.0	T	--	0.3
magnetite	T	0.3	1.0	1.3	0.3	T
Cements						
calcite	24.0	33.3	26.6	--	--	--
undifferentiated clay matrix	--	--	--	--	--	--
Heavies						
zircon	T	T	0.6	T	0.3	T
hornblende	--	--	--	--	--	--
sphene	T	--	0.3	0.3	--	T
epidote	--	--	--	--	T	--
leucoxene	1.0	0.6	--	T	--	--
garnet (almandite)	T	T	--	--	--	T
apatite	--	--	--	--	T	T
Alteration products						
laumontite	--	T	--	--	--	--
sericite	T	T	0.3	3.0	1.3	1.3
Rock fragments						
phyllite	2.6	5.3	1.7	--	0.3	1.9
schist	2.3	0.3	--	1.3	0.6	2.6
greenstone	3.3	0.6	1.0	3.0	1.7	2.6
basalt	1.6	0.3	--	9.3	2.0	4.2
sandstone	--	--	--	3.3	0.3	2.2
mudstone	--	0.6	1.3	0.3	--	--
gneiss	--	--	--	--	--	--

APPENDIX D (continued)

Mineralogy \ Sample	Kn		Kg		Ks	Kga	
	CDS-37	CDS-8	CDS-3	CDS-50	CDS-49	CDS-46	CDS-47
Stable grains							
quartz	28.0	35.4	27.7	23.0	31.6	17.7	23.0
poly-x quartz	2.3	0.9	3.0	3.0	1.3	6.3	4.7
chert	0.6	0.3	--	4.6	1.0	1.7	1.7
Feldspars							
K-spar	7.3	4.6	8.5	8.0	4.0	5.0	5.3
plagioclase	19.5	12.4	28.3	21.3	12.3	15.0	17.6
Mica							
biotite	4.0	6.6	6.8	4.7	3.0	2.0	0.6
muscovite	0.6	3.0	1.6	1.7	2.3	0.3	T
chlorite	T	2.6	3.9	7.6	1.7	1.0	0.3
Pyroxenes							
orthopyroxene	T	0.3	0.3	0.6	0.6	T	T
clinopyroxene	T	T	1.6	0.3	0.3	1.3	0.3
Fe-rich minerals							
pyrite	0.6	1.0	0.3	0.3	1.7	--	0.3
limonite	0.3	--	--	--	0.6	--	--
hematite	T	0.3	0.3	0.3	0.3	0.3	--
magnetite	0.3	0.3	0.3	0.6	T	2.3	T
Cements							
calcite	26.0	0.3	--	--	25.7	19.3	24.3
undifferentiated clay matrix	--	21.3	3.9	7.0	2.7	1.3	1.0
Heavies							
zircon	T	--	--	--	T	T	--
hornblende	--	--	1.0	0.6	--	5.0	1.7
sphene	0.3	T	0.3	T	0.t	0.6	0.3
epidote	T	--	1.0	T	T	0.6	0.6
leucoxene	T	--	--	--	--	--	--
garnet (almandite)	T	--	0.3	0.3	T	1.0	T
apatite	T	T	T	--	--	T	T
Alteration products							
laumontite	--	--	0.3	--	--	--	--
sericite	T	4.2	1.0	0.3	T	T	1.0
Rock fragments							
phyllite	1.0	0.9	T	0.3	0.3	2.0	3.3
schist	0.6	0.3	0.3	0.3	--	2.3	2.7
greenstone	0.6	--	1.9	6.6	0.6	5.0	2.3
basalt	6.9	1.6	3.5	4.0	2.3	5.0	6.3
sandstone	--	--	--	0.3	--	--	0.3
mudstone	--	--	--	--	T	--	--
gneiss	0.6	--	T	--	--	0.6	1.3

APPENDIX E

Clay Mineralogies and Pebble Count Lithologies

Mineralogy \ Sample	Lower Cedar District	Upper Cedar District	Northumberland	Spray
Montmorillonite	x	x	xx	xx
Chlorite	x	x	x	x
Vermiculite	?	x	?	x
Mica	x	x	x	x
Antigorite	?	x	x	-
Kaolinite	xx	xx	x	x
Mixed layer clay	?	?	x	x

Clay mineralogies: x = present; xx = common; ? = questionable occurrence.

Lithology \ Sample	DeCourcy	Gabriola
Chert	28	14
Limestone	16	--
Quartzite	10	18
Basalt	12	25
Greenstone	9	3
Granite	5	23
Granodiorite	3	--
Gneiss	3	1
Rhyolite	3	2
Schist	2	--
Phyllite	6	--
Gabbro	1	9
Mudstone	1	--
Andesite	--	5
Petrified Wood	1	--

Pebble count lithologies.

APPENDIX F

Analytical Techniques

X-ray Diffraction of Mudstones

Samples of mudstone from the upper and lower Cedar District, Northumberland, and Spray Formations were prepared in the following manner:

Samples were crushed into chips with a mortar and pestle and soaked in a solution of Calgon and distilled water to extract the clays. The clays were then removed from suspension by twice centrifuging at high speed and washing with distilled water. The mud samples were then treated with 15 ml of 30% hydrogen peroxide for the removal of carbonaceous matter. The samples then were twice centrifuged at high speed and washed with distilled water. The mud samples were next treated with dilute calcium carbonate and centrifuged for five minutes at 750 rpm to remove all silt-sized particles. The clay suspension was then centrifuged for seven minutes at 6,000 rpm to separate all material finer than 0.2 microns. The 2-0.2 micron fraction was used for X-ray analysis.

The clay samples were each separated into three parts. One part was resuspended in distilled water, then the suspension was evaporated onto a glass slide and X-rayed. The second part of each sample was saturated with potassium ions by boiling the clays in a solution of one normal potassium acetate. The clays were then centrifuged and washed in distilled water several times, evaporated onto a glass slide and X-rayed. The third part of each sample was saturated with calcium ions by washing three times in a solution of one normal calcium chloride and centrifuging at high speed after every washing. After this, the samples were washed and centrifuged several times with distilled water, and the solutions were then evaporated onto glass slides and X-rayed. This process of ion saturation allowed more accurate control of the atomic lattices.

The samples were analyzed with a Norelco X-ray diffractometer. The clays were scanned a total of four times each over a range of 3-28° 2θ. The treatments before each scan were as follows: 1) untreated, 2) ethylene glycolated for 24 hours, 3) heated to 400° Centigrade for 30 minutes, and 4) heated to 550° Centigrade for 30 minutes. Each of the heated samples was analyzed under 0% humidity. Instrument settings were as follows:

Radiation:	Copper (Cu)Ka (broad focus)
KV:	35
MA:	35
Filter:	Nickel
Resolution Slit:	.006 inch
Scatter Slit:	.006 inch

Rate Meter Settings

Multiplier:	5×10^2
Time Constants:	2.0 seconds
Scan Rate:	1° 2θ/minute

Pyrite Determination by X-ray Diffraction

Pyrite concretions from the Cedar District and Northumberland Formations were crushed in a ceramic mortar with a pestle and then sieved through a 200 mesh Tyler Standard Sieve. The powder was then placed into a powder pack slide and scanned from 24-60° 2θ using a Norelco X-ray diffractometer. Instrument settings were the same as those for the analysis of the mudstones. Six peaks similar to those of pyrite (ASTM file card number 6-0710) were identified. No marcasite peaks were noted, therefore the sample was predominantly pyrite.